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Fine gravel controls hydrologic and erodibility responses to trampling disturbance for coarse-textured soils with weak cyanobacterial crusts

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ABSTRACT

We compared short-term effects of lug-soled boot trampling disturbance on water infiltration and soil erodibility on coarse-textured soils covered by a mixture of fine gravel and coarse sand over weak cyanobacterially-dominated biological soil crusts. Trampling significantly reduced final infiltration rate and total infiltration and increased sediment generation from small (0.5 m^2) rainfall simulation plots ($p<0.01$). Trampling had no effect on time to runoff or time to peak runoff. Trampling had similar effects at sites with both low and very low levels of cyanobacterial biomass, as indicated by chlorophyll *a* concentrations. We concluded that trampling effects are relatively independent of differences in the relatively low levels of cyanobacterial biomass in this environment. Instead, trampling appears to reduce infiltration by significantly reducing the cover of gravel and coarse sand on the soil surface, facilitating the development of a physical crust during rainfall events. The results of this study underscore the importance of carefully characterizing both soil physical and biological properties to understand how disturbance affects ecosystem processes.

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1. Introduction

The effects of soil surface disturbance on water infiltration into arid and semi-arid soils have been widely debated in both the popular and scientific literature. Disturbance nearly always increases soil erodibility. Soil surface disturbance can affect several site factors that influence infiltration, including soil surface cover and structure. Infiltration is generally increased and soil erosion is reduced by greater cover, which protects the soil from raindrop impact and increases flowpath tortuosity. Rock cover, however, can increase or decrease infiltration (Poesen et al. 1990; Valentin 1994; Cerda 2001; Descroix et al. 2001). Several studies have shown that embedded gravel reduces infiltration, while free gravel can increase it relative to soils without gravel cover (Valentin and Casenave 1992; Cerda 2001).

Good soil structure, as reflected in high aggregate stability and macroporosity, generally increases infiltration capacity. However, several studies demonstrate that disturbance to soils with biological crusts (biocrusts), which generally have higher surface aggregate stability than soils without biocrusts, may either increase, decrease or have no effect on infiltration rates (Warren, 2003). Biocrusts are ubiquitous on arid and semi-arid soils (Belnap and Lange, 2003) and are often particularly well-developed in undisturbed plant interspaces. Warren (2003) proposed that biological crusts should increase infiltration for soils with a sand content of less than 80% and reduce infiltration into soils with a sand content above 80%; in the absence of organic matter, fine-textured soils often disperse when wetted, filling water-conducting pores with silt and clay. Cyanobacteria, lichens and mosses bind soil particles together, limiting dispersion and maintaining higher pore volume and continuity. Conversely, soils with a high sand content tend to be relatively porous, even when the particles are not aggregated and soil organisms fill the textural pores, effectively reducing infiltration (Eldridge and Greene, 1994a; Kidron et al., 1999).

Eldridge (1993) and Eldridge et al. (1997) concluded that variability in crust cover had a negligible effect on infiltration rates, except where lichen and moss cover have been reduced below 20% by historic disturbance. On structurally degraded soils, microbiota should increase infiltration by binding soil particles and preventing dispersion. On historically undegraded soils, their contribution is inconsequential because structural macropores that are independent of the crusts dominate the infiltration process (Eldridge, 1993). Given these arguments, effects of microbiotic crust on infiltration should be more accurately predicted where both soil texture and recent and historic regimes are known.

Biological crusts nearly always reduce soil erosion (Eldridge and Greene, 1994a,b; Williams et al., 1995; Eldridge, 1998; Warren, 2003). One exception has been described for sandy soils, where upslope high

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crust cover can increase downslope erosion by increasing runoff (Talbot and Williams, 1978).

We investigated the effects of short-term, soil-surface disturbance on infiltration characteristics and soil erodibility of cyanobacterially-crusted, coarse-textured soils in the Mojave Desert. The cyanobacterial crusts were generally covered with a thin (1–5 mm) layer of coarse sand and fine gravel, a pattern we have observed on granitic soils in arid and semi-arid regions throughout the world. We subjected these soils to simulated, high-intensity rainstorms, as high-intensity storms are the only events that generate significant runoff and sediment, and thus these storms, while rare, are of considerable concern to land managers.

Most studies of disturbance effects on infiltration and erodibility for biologically-crusted soils suffer from two limitations. The first is that they include only soils with well-developed biological crusts, and often conclude that disturbance effects can be attributed solely to crust removal or destruction. This design fails to account for the possibility that short-term disturbance effects on infiltration and erodibility are independent of the presence of a biocrust. The second limitation is that many studies are completed at only one location. This results in pseudo-replication at the landscape level. We addressed both limitations by replicating our study at three sites where cyanobacterial biomass was relatively high compared to our other sites, where cyanobacterial biomass was very low.

2. Materials and methods

2.1. Overview

Two studies are reported here. Both studies were initiated and completed in May 2000. A preliminary study ("site characterization") was used to confirm the assignment of each of the six sites to high (H1–H3) and low (L1–L3) chlorophyll *a* site types, and to ensure that comparisons are not confounded by textural or bulk density differences among the two types of sites. The main study ("disturbance") was designed to test the hypotheses that soil surface disturbance (trampling) would increase infiltration at the high chlorophyll *a* sites and have no effect at the low chlorophyll *a* sites. Trampling was expected to increase sediment production at the high chlorophyll *a* sites and have a negligible effect at the low chlorophyll *a* sites.

2.2. Site selection

The two studies were completed at six sites on and adjacent to Fort Irwin U.S. Army National Training Center, San Bernardino County, California. These sites were previously characterized by Johansen et al. (2001) and additional information is included in Belnap et al. (2007a, b). Site designations used in Johansen et al. (2001) and GPS locations recorded during the study reported here are listed in Table 1. Average annual precipitation in the area was 101 mm and is bimodally distributed. Total precipitation for May, 1999–April 2000 was 46 mm. The area received 23 mm of precipitation during the four months immediately preceding the experiments. The six sites were located on coarse-textured alluvial soils formed from primarily granitic parent material (Johansen et al., 2001). Perennial plant canopy cover was less than 10% at all sites. It was dominated by the shrubs *Larrea tridentata* and *Ambrosia dumosa* (Johansen et al., 2001).

The chlorophyll *a* data reported in Johansen et al. (2001) were used to stratify the six sites into two site types. Chlorophyll *a* concentrations are often used to estimate cyanobacterial biomass (Karsten and Garcia-Pichel, 1996) and therefore reflect the level of biocrust development in this ecosystem. The three low chlorophyll *a* sites (L1–L3) were located in areas regularly used for military training activities involving tanks, wheeled vehicles and ground troops (R. Sparks, Fort Irwin, Barstow, CA., pers. comm.). The three high chlorophyll *a* sites (H1–H3) were located in areas protected from training activities. These three sites had moderately high cover of cyanobacterial crusts, although the cyanobacterial biodiversity was poor. *Microcoelus vaginatus*, *M. steenstrupii*, and *Schizothrix calcicola* were common, but heterocystous taxa were rare (Johansen et al., 2001). These sites also had a trace (<1%) of lichen (predominantly *Collema tenax*, *Placidium squamulosum*, and *Petula obscurans* var. *hassei*) and moss (mostly *Bryum* spp.) cover. The low chlorophyll *a* sites completely lacked lichens and mosses, and had greatly decreased abundance of cyanobacteria (Johansen et al., 2001). All measurements for both studies were made in plant interspaces where the sum of grass, forb and litter cover was visually estimated to be less than 3%.

Table 1
Corresponding site codes from Johansen et al. (2001), soil series definitions from Fahnestock and Novak-Echenique (2002), and GPS locations (NAD 83) for the center of each site for the current study.

	Study sites					
	H1	H2	H3	L1	L2	L3
	n = 4	n = 6	n = 4	n = 4	n = 4	n = 4
Johansen et al. (2001)	PR2	PR3	FISS	LIZ3	RPL3	RPL4
Northing	3891200	3891050	3886928	3892596	3907988	3906474
Easting	512250	511800	546083	541107	559361	558505

2.3. General soil and site characterization

Slope was measured using a clinometer. Soil series for four of the sites were identified using a recently published soil survey (Fahnestock and Novak-Echenique, 2002) together with soil profile descriptions for a single pit located at the center of each site. These data were supplemented by data from the site characterization study (below). No soil or geomorphic maps or soil surveys were available for the other two sites (R. Sparks, Fort Irwin, Barstow, CA, pers. comm.). Additional soil surface observations were made to assist with data interpretation.

2.4. Site characterization study

The objective of the site characterization study was to test the assumptions that (1) soil texture and bulk density were similar at the two site types (H and L), and (2) that the two site types had significantly different levels of cyanobacterial biomass. Prior to trampling, we measured soil particle size distribution, bulk density, chlorophyll *a* content and soil aggregate stability at each of the four to six pairs of plots at each site.

Particle size distributions, including sand size fractions, were determined for 0–0.5, 0.5–2 and 2–10 cm depths based on a composite of four subsamples at each pair of plots. Soil texture was determined using the hydrometer method after dispersal with sodium hexametaphosphate (Gee and Bauder, 1986). The sand fraction was further divided into the following fractions by sonic sieving for five min: 0.053–0.106 mm, 0.106–0.25 mm, 0.25–0.5 mm, 0.5–1 mm and 1–2 mm. Gravel content was measured gravimetrically.

Bulk density was quantified using four composited 45 mm diameter, 100 mm deep soil cores per pair of plots. Samples were oven dried to constant weight at 105 °C in order to determine pre-simulation gravimetric moisture and calculate dry bulk density.

Chlorophyll *a* content was measured on a composite of eight 0–5 mm samples collected from random locations around the edges of each pair of plots. Samples were extracted with dimethylsulfoxide (DMSO) in the dark for 45 min at 65 °C (Ronen and Galun, 1984). Samples were then shaken and centrifuged. The supernatant was immediately placed in a Turner Designs Inc. Fluorometer and fluorescence was measured. Fluorescence values were compared to a calibration curve obtained