Microbiotic Crust Influence on Unsaturated Hydraulic Conductivity

J. D. WILLIAMS

USDA Agricultural Research Service, Pacific West Area
Columbia Plateau Conservation Research Center
Adams, Oregon, USA

J. P. DOBROWOLSKI
N. E. WEST

Department of Rangeland Resources
College of Natural Resources
Utah State University
Logan, Utah, USA

Microbiotic crusts occur extensively in rangeland soils. Developed by filaments of cyanobacteria and algae, and thalli of lichen and moss entanglement of soil particles, they create a physical discontinuity in the surface profile with greater concentrations of clay, silt, and potentially hydrophobic organic matter. These conditions potentially contribute to variability in soil hydrology of arid land and should be considered in the development of hydrologic and erosion models. However, there is limited manipulative research examining the functional relationships between soil and microbiotic crusts. We investigated the influence of cyanobacterial-dominated microbiotic crust on measured hydraulic conductivity (K) *in a sandy loam soil at a southeastern Utah site. Using a tension infiltrometer, we determined* K *under three surface treatments: undisturbed, chemically killed (representing dead microphytes within the crust), and removed (scalped) microbiotic crusts. We applied treatments to spatially interspersed intact surface soils within shrub interspaces. Microbiotic crusts at this site and in this stage of successional development had no discernible influence on* K. *This finding supports results from research conducted in a variety of soils from sandy to silt dominated with a range of microbiotic development. Because this research was site and time specific, and because the role of microbiotic crusts in the environment continues to be debated, additional research is warranted to determine how stage of development of microbiotic crust influences soil hydrology.*

Keywords aridland processes, biocrusts, cryptobiotic crust, cryptogamic crust, microphytic crust, rangeland, soil.

Microbiotic crusts form at the soil surface of arid and semiarid land in the interspaces between shrubs and grasses and potentially contribute to small-scale spatial

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Address correspondence to Dr. J. D. Williams, USDA ARS Columbia Plateau Conservation Research Center, P.O. Box 370, Pendleton, OR 97810, USA. E-mail: JohnD.Williams@orst.edu

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variability in soil hydrologic conditions (Dobrowolski, 1994). Microbiotic crusts result from interactions of bacteria, small soil-dwelling animals, and microphytes, e.g., algae, fungi, lichens, and mosses. Cyanobacteria and microphytes exude gelatinous material and trap or physically entangle windblown clay and silt, thus concentrating them at the soil surface (Danin, 1978; Schulten, 1985; Tsoar & Möller, 1986; Eldridge, 1993). An aggregate structure is provided by the processes described above and soil arthropods (Danin, 1978). The resulting biotic/physical interaction, while dynamic, is unlike the transient seal formed by raindrop splash in tilled or fallow agronomic settings and might persist for years or continue to develop over decades.

Researchers have suggested that microbiotic crusts represent a discontinuity at the soil surface capable of influencing soil hydrologic properties (Harper & Marble, 1988; West, 1990). Dry microphytes swell and become turgid as they imbide water and, in highly disturbed conditions, reportedly restrict water flow (Bolyshev, 1964). However, in sand-dominated soils, scanning electron microscope images show that the swelling is insufficient to restrict water flow (Belnap & Gardner, 1993). Furthermore, the additional structure provided by the microbiotic activity would, under the conditions reported by Belnap and Gardner (1993), enhance hydraulic conductivity rather than reduce it. Alternatively, slaking of peds composed of silt and clay captured by microbiotic crusts could result in closed soil pores. Lee (1977) hypothesized that algal crusts reduce permeability in arid and semiarid soils of Australia but did not present supporting data.

Until recently, limited and inconclusive research, much of it designed post hoc (West, 1990), has been conducted to determine the influence of microbiotic crusts on measured saturated hydraulic conductivity (K). Loope and Gifford (1972) collected soil cores from disturbed sites on the Colorado Plateau in southern Utah and found K increased with greater lichen cover in ponded, laboratory experiments. Alternatively, K increased fourfold following the removal of lichen and algal crust from a control plot with a surface soil classified as loamy Typic Haplargids within a eucalypt woodland in New South Wales, Australia (Greene et al., 1990). In the same region, microbiotic crusts trampled by livestock were associated with larger steady state infiltration capacity values than measured within an ungrazed site (Eldridge, 1993). Greene et al. (1990) and Eldridge (1993) used a disc permeameter and ponded conditions, respectively, to obtain their results. Eldridge (1993) attributed the differences to the degree of structural development or disturbance by livestock, not to some intrinsic characteristic of microbiotic crust development. From a simulated rainfall experiment, Eldridge et al. (1997) extended the conclusion of Eldridge (1993) to include Calcic Aridisols with good condition vegetation across a wide range of microbiotic crust cover values (2–80%). Similarly, vesicular horizons in fine, montmorillonitic mesic, Xerollic Nadurargids, not the presence of abundant microbiotic crusts, controlled K at three sites located in northern Nevada and Utah (Dobrowolski, 1994).

Filaments of cyanobacteria and green algae grow to unknown depths in the soil profile. However, the highest concentration of microbiotic activity and associated concentration of silt and clay is within 10–50 mm of the soil surface. Thus we would expect the greatest impact on hydrologic conditions to result from microbiotic influences and physical differences from the coarse-textured subsurface soil. The K of an impeding layer theoretically controls the flow rate of water into and through the soil matrix. Thus K within a microbiotic crust is the controlling flow factor as long as it is less than the matrix below. Removal or disturbance of the microbiotic crust, in this case, should result in an increased flow rate. Alternatively, if the hydraulic conductivity through the microbiotic crust equals or exceeds K in a subtending soil, the microphytes should maintain aggregate stability and soil structure (e.g., Eldridge, 1993). In the case of Eldridge, removal of the microbiotic crust should not influence the hydraulic conductivity at a site.

Our objective was to determine if cyanobacteria-dominated microbiotic crusts, undisturbed for 3 years, influenced K in a sandy loam soil. Physical and chemical crusts and vesicular horizons (air trapped near the soil surface in silt-dominated soil) also influence soil hydrologic properties. Therefore we chose a site where these soil properties were not apparent throughout the research period and microbiotic crusts were present.

Materials and Methods

Study Site

We conducted the studies in the Hartnet Draw within Capitol Reef National Park (CARE), south-central Utah, approximately 60 km west of Hanksville, at an elevation of 1750 m (latitude 39°N, longitude 111°W). A meteorological station at the site during the study period from 1989 through 1991 recorded between 333 and 607 mm annual precipitation and maximum and minimum temperatures of 46.0°C in July and −27.5°C in February, with median annual temperatures ranging from 8.0°C to 12.0°C. Long-term CARE records at the headquarters, 15 km to the south at 1000 m elevation, document snowfall during all months, except June–September, with a maximum snow depth of 356 mm.

Hartnet Draw is an alluvial valley characterized by alternate broad and open basins with canyon sections overlaying an anticlinal fold (Billingsley et al., 1987). An ephemeral stream cuts through Jurassic period (135–180 million years before present) deposits, specifically the Brushy Basin Shale member of the Morrison and Summerville Formations (Billingsley et al., 1987). The study site is on an alluvial fan grading into a stream terrace consisting of gravel, sand, silt, and clay deposits. The slope at the site varies from 0 to 2% with a northern exposure. An order 4 soil survey, as per U.S. Department of Agriculture (USDA) Forest Service (1980) guidelines, was conducted, and soil at this site was classified in the Begay Series (Ustollic Camborthid, coarse-loamy, mixed, mesic) and Semidesert Sandy Loam (Fourwing Saltbush) range site (Swenson & Jarman, 1991). The vegetation type is classified as a Greasewood-Rabbitbrush (*Sarcobatus-Chrysothamnus*) Phase of the Intermittent Riparian Shrub Community Type (Romme et al., 1993). The microbiotic crust was predominantly composed of *Microcoleus vaginatus* and is typical of the crusts found in the Colorado Plateau Physiographic Province (Belnap & Gardner, 1993; Belnap et al., 1994).

Land-Use History

Year-round grazing of cattle and sheep began in the late 1800s in CARE (National Academy of Sciences, 1984). Since 1954, the Hartnet Draw and surrounding area served as winter pasture for cattle. The livestock grazing allotment now consists of three paddocks totaling ~36,000 ha and is in a rest-rotation grazing regime with use between November and June. Animal unit months (AUM) range from 1008 to 1500 with stocking at ~0.06 AUM ha^{-1}. Rabbits and rodents are the only native mammalian herbivores at the research site.

Six hectares fenced in 1987–1988 protected the experimental sites from humans and livestock. Small, bounded ephemeral drainage channels served as paths for human foot traffic while experiments were conducted.

Treatments

Treatments were applied to 1 m^2 areas in shrub and grass interspaces in August 1991, and one value of K was determined from within the area. Three surface treatments were evaluated for K. The treatments were as follows.

1. Control, in which no disturbance was allowed to the microbiotic crust and soil surface.
2. Microphytes chemically killed to determine the contribution of nonliving microphytes to soil stability. Microphytes were killed by application of 0.61 mm (0.6 L m^{-2}) commercial-grade calcium hypochlorite [65% $Ca(OCl)_2$, 35% inert material; 0.1 M $Ca(OCl)_2$ applied concentration], and crust was left in place. Calcium hypochlorite is an oxidizing agent that kills the microphytes by disrupting cell wall integrity. Tests to determine the most suitable agent and concentration to kill the microphytes showed that microphytes treated with this oxidizing agent no longer photosynthesized even though the filament structure remained intact.

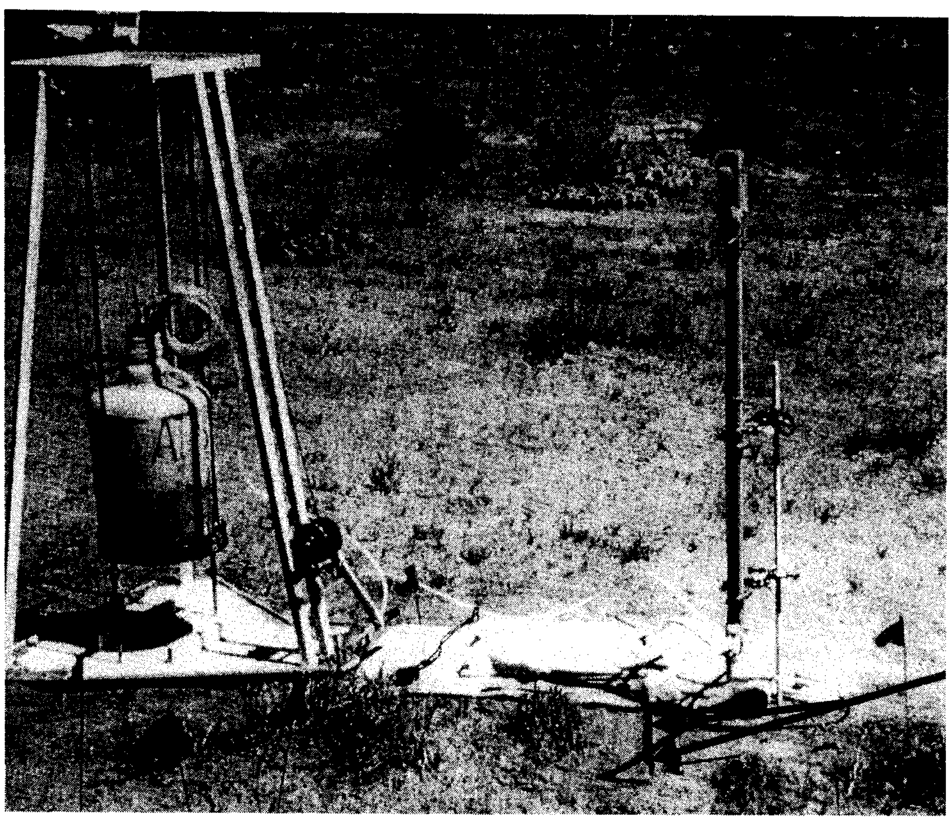

FIGURE 1 Dripper assembly for determining K tripod (left) to suspend deionized water, manometer (1 m, right), and dripper buttons (arrow) positioned over plot.

3. Scalped to approximate the absence of microphytes. The microbiotic crust and ~10–20 mm of the soil surface were carefully removed using a small putty knife (Eldridge, 1993; Dobrowolski, 1994).

Control and scalped plots were treated with 10 mm of calcium chloride (0.1 *M* $CaCl_2$) solution to ensure the same amount of calcium was applied to all treatments. Chemicals were applied from 1 to 2 weeks before *K* tests. The addition of $Ca(OCl)_2$ and $CaCl_2$ to a calcium-rich environment would be less likely to affect soil conditions than the alternatives that contained greater concentrations of sodium, e.g., commercially available sodium hypochlorite. Microbiotic crust development occurred within the 3-year time period of research and did not appear to be any deeper than 10–20 mm in the soil surface.

Experimental Methods

The field procedure to estimate in situ *K* follows that of Dobrowolski (1994). A 10-L Nalgene storage bottle suspended beneath a tripod acted as a water reservoir to a manometer tube (Fig. 1). The tripod was constructed to permit sensitive height adjustments of the reservoir, allowing for easy control of manometer levels. Attached to this reservoir-manometer configuration was a cluster of commercially available button drippers. The application of water at a constant discharge to a point on an unbounded area of soil surface creates a saturated zone. Initially, the saturated area increases with time, eventually approaching a constant circular or elliptical area (Bresler, 1977; Warrick, 1985). Once the area of the ponded zone becomes constant, steady state conditions prevail, and steady state solutions of the two-dimensional water flow equation can be applied to solve for the flux (q) from the ponded zone. By using multiple discharge rates, a family of flux values can be determined. Shani et al. (1987) built upon the theory behind Wooding's (1968) hydraulic conductivity-metric head (*K-h*) relationships to produce an equation for the flux (mm s^{-1}):

$$q = K + \frac{4K}{\alpha\pi}\frac{1}{r} \tag{1}$$

where r is the measured radius (in meters) of the ponded zone and α can be estimated by

$$\alpha = \frac{4K}{b\pi} \tag{2}$$

where b is the slope and K is the intercept of the linear regression of q versus $1/r$. The matrix flux function as rewritten by Shani et al. (1987) into Eq. (2) is linear, so that estimates of K can be determined from a linear regression of q versus $1/r$ if three to five discharge rates are used. Shani et al. (1987) found good agreement between K values produced by the conventional one-dimensional infiltrometer, drainage profile (Bresler & Kemper, 1970) and air-entry permeameter (Russo & Bresler, 1980) methods. More recently, Shani and Or (1995) and Or (1996) have demonstrated the efficacy of this method, both in nonhomogeneous soils and in comparison to other methods used for in situ determination of K. This method was adapted to a rangeland environment in order to characterize the relative importance of microbiotic crusts on the control of vertical soil moisture flux. We used 2297, 3953, 5568, and 8868 mL h^{-1} discharge rates.

Antecedent soil moisture was determined from samples taken outside of the plots in a 2-week period leading up to the data collection period. After K measurements, bulk soil samples were collected from the upper 150 mm of soil within each plot. An integrated measure of particle size distribution (Gee & Bauder, 1986), organic matter (Jackson, 1955), pH and EC (McLean, 1982), and extractable cation concentrations, namely, Na^+, K^+, Ca^{2+}, and Mg^{2+} [Rhoades (1982) adapted for arid land soils by R. D. Gavlak, D. A. Horneck, and R. O. Miller, Utah State University Soils Laboratory, Logan, Utah], were determined from these soil samples. Particle size distribution was also determined for soil within the microbiotic crusts removed in the scalped treatment. Except for these soil characteristics, we assumed that blocks and plots were homogeneous. We based this assumption on descriptions and analysis of plot characteristics in companion simulated rainfall and wind tunnel experiments (Williams et al., 1995a, 1995b). The plots in this study were spatially and temporally interspersed among the other plots utilized in studies previously reported by Williams et al. (1995a, 1995b).

Experimental Design

A factorial-randomized block design and analysis of variance (ANOVA) were used to test for treatment differences in K and plot characteristics (Hicks, 1993; Hintze, 1991). Treatment means were separated by Scheffe's multiple range test, considered the most conservative of the available tests (Ott, 1988). Tests for normality, skewness, and kurtosis were conducted to satisfy the basic assumptions for conducting ANOVA. Forty-eight plots were evenly distributed across the research site in four blocks. Treatments were randomly assigned to plots in a balanced design.

Data from calculated K values from the first 24 runs of four discharge rates were used to determine the sample size (n) needed to determine if a true difference in δ exists at $\alpha = 0.05$ and $P = 0.80$ (Sokal & Rohlf, 1981). A sample size of 45 K values was calculated using the largest variance(s) within the three treatments. An a posteriori test, of the largest σ value, allowed for an n of 32 K values. Thus our a priori choice of n of 48 K values offered adequate control for α and β errors. Simple linear correlation analysis [$\alpha = 0.05$ and $R^2 = 0.50$ (Neter et al., 1983)] was used to establish relationships between plot soil characteristics and K.

Results and Discussion

There was no correlation between plot characteristics and K values. Soil pH and EC values differed statistically between control and scalped treatments (Table 1); however, the difference had no hydrologic or biological significance. Microbiotic crusts removed from the scalped treatments contained significantly ($P = 0.04$) more silt (5.5%) than did the subtending soil. Antecedent soil moisture across the research area in the surface 50 mm was 0.13 m^3 m^{-3}.

Treatment variance or mean values were not significantly different (Table 2). These values match well with end-point infiltration values, which we determined using rainfall simulation (Table 2) (Williams et al., 1995a). These findings strongly suggest that microbiotic crusts did not significantly influence soil hydrology at this site. This finding contrasts with the results of Loope and Gifford (1972), who found low K values in undisturbed lichen crusts in southeastern Utah. Loope and Gifford

TABLE 1 Treatment mean separation results from analysis of soil characteristics, dripper method, and end-point infiltration determined by rainfall simulation

	Treatment		
Parameter	Control	Chemically killed	Scalped
Bulk density (Mg m^{-3})	1.5 ± 0.0 a	1.6 ± 0.0 a	1.5 ± 0.0 a
Porosity (%)	0.4 ± 0.0 a	0.4 ± 0.0 a	0.4 ± 0.0 a
Soil water content (m^3 m^{-3})	18.9 ± 0.4 a	19.2 ± 0.5 a	18.8 ± 0.5 a
K^+ (mg L^{-1})	7.96 ± 0.38 a	8.42 ± 0.41 a	8.31 ± 0.41 a
Ca^{2+} (mg L^{-1})	240.46 ± 8.38 a	244.47 ± 5.11 a	248.50 ± 5.88 a
Mg^{2+} (mg L^{-1})	5.17 ± 0.22 a	5.02 ± 0.18 a	5.36 ± 0.15 a
Na^+ (mg L^{-1})	0.53 ± 0.13 a	0.65 ± 0.14 a	0.91 ± 0.12 a
Soil organic matter (%)	0.30 ± 0.03 a	0.30 ± 0.02 a	0.25 ± 0.02 a
Sand (%)	67.4 ± 1.1 a	64.5 ± 1.5 a	67.7 ± 1.1 a
Silt (%)	27.2 ± 1.0 a	29.6 ± 1.5 a	26.3 ± 1.0 a
Clay (%)	5.4 ± 0.3 a	5.9 ± 0.2 a	6.0 ± 0.2 a
Soil pH	8.15 ± 0.18 a	8.41 ± 0.04 ab	8.56 ± 0.06 b
Soil EC (S m^{-1})	25.9 ± 1.3 a	25.4 ± 1.5 ab	19.1 ± 2.5 b

Means with different letters are significantly different at $\alpha = 0.05$.

(1972) arrived at this conclusion by observing that portions containing extensive algal-lichen crust cover resulted in more annual runoff, not from direct experimental evidence. Graetz and Tongway (1986) and Greene et al. (1990) reported that removal of algal-lichen crust resulted in a fourfold increase in hydraulic conductivity values in studies conducted in western New South Wales, Australia. The implication of these studies is that undisturbed lichen-dominated crusts create a more impervious layer at the soil surface than do cyanobacterial crusts. Our results support Eldridge's (1993) and Dobrowolski's (1994) observations and have more recently been supported by Eldridge et al. (1997), i.e., soil characteristics and vegetation development in sandy loam soil are more important than microbiotic crusts as predictors of soil hydrologic properties. Eldridge et al. (1997) conducted their work in microbiotic crusts on sites that had not been impacted by foot, hoof, or vehicular

TABLE 2 Treatment means and variance for measured hydraulic conductivity determined by dripper method and end-point infiltration determined by rainfall simulation

Treatment	K^a (mm s^{-1})	Variance	Infiltration[b] (mm s^{-1})	Variance
Control	0.02	0.0002	0.02	0.0001
Chemically killed microphytes	0.02	0.0003	0.01	0.0001
Microphytic crusts removed	0.03	0.0002	0.02	0.0001

Sample size for both methods is $n = 48$.
[a] *K* determined by dripper method after Shani et al. (1987).
[b] Infiltration determined by simulated rainfall.

traffic for 20 years, a time period adequately long enough for recovery to have begun. They speculate that microbiotic crusts might be important for the redevelopment of soil structure in recently disturbed and otherwise structureless soil. However, it seems apparent from our measurements taken within 3 years after cessation of disturbance that microbiotic crusts are not hydrologically important in recently disturbed sandy-loam soils, either.

Conclusion

Cyanobacteria-dominated microbiotic crusts, living or dead, did not significantly affect K values at this research site with sandy loam soils. Sample size was adequate to control for both α and β errors. These results support research reports obtained from sites in the United States and Australia. The accumulated evidence suggests microbiotic crusts, in stages of early or multiple-decade-old recovery, have little utility in rangeland hydrologic models. Nevertheless, the degree of microbiotic crust development is continuous (life-form composition, depth of influence, and degree of organic matter accumulation within the microbiotic crust), and potential for a threshold exists beyond which soil hydrologic properties are influenced. Additionally, because of the site and time specific nature of this research, further inquiry is warranted to determine if these results would be consistent in soils without a sandy loam surface texture and in seasons other than summer.

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