



Soil water repellency and infiltration in coarse-textured soils of burned and unburned sagebrush ecosystems

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ABSTRACT

Millions of dollars are spent each year in the United States to mitigate the effects of wildfires and reduce the risk of flash floods and debris flows. Research from forested, chaparral, and rangeland communities indicate that severe wildfires can cause significant increases in soil water repellency resulting in increased runoff and erosion. Few data are available to document the effects of fire on the spatial and temporal variability in soil water repellency and potential impacts on infiltration and runoff on sagebrush-dominated landscapes. Soil water repellency, infiltration and runoff were assessed after two wildfires and one prescribed fire in three steep, sagebrush-dominated watersheds with coarse-textured soils. Water repellency was generally greater on unburned hillslopes and annual variability in water repellency had a greater impact on infiltration capacity than fire effects. The most significant impact of fire was canopy and ground cover removal on coppice microsites. Infiltration rates decreased on coppice microsites after fire even though soil water repellency was reduced. Fire-induced reduction in infiltration resulted from the combined effect of canopy and ground cover removal and the presence of naturally strong water repellent soils. Removal of ground cover likely increased the spatial connectivity of runoff areas from strongly water repellent soils. The results indicate that for coarse-textured sagebrush landscapes with high pre-fire soil water repellency, post-fire increases in runoff are more influenced by fire removal of ground and canopy cover than fire effects on soil water repellency and that the degree of these impacts may be significantly influenced by short-term fluctuations in water repellent soil conditions.

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1. Introduction

Soil water repellency has been well documented in burned and unburned soils on semi-arid rangeland (Salih et al., 1973; Pierson et al., 2001, 2008), chaparral (Hubbert et al., 2006), and forested environments (Robichaud, 2000; Huffman et al., 2001; MacDonald and Huffman, 2004; Doerr et al., 2006; Lewis et al., 2006). Wildfires have often been associated with the formation of water repellent soil conditions thought to decrease infiltration and increase runoff and soil erosion (DeBano et al., 1998; Robichaud, 2000). During combustion hydrophobic organic compounds in litter and topsoil are volatilized and released upwards to the atmosphere and downwards into the soil profile along a temperature gradient. Downward translocated hydrophobic compounds condense on cooler soil particles at or below the soil surface forming water repellent conditions (DeBano et al., 1976). Natural water repellent soil conditions also occur in unburned plant communities due to coating of soil particles with hydrophobic

compounds leached from organic matter accumulations, by-products of microbial activity, and or fungal growth under thick layers of litter and duff material (Savage et al., 1972; DeBano, 2000; Doerr et al., 2000). Under unburned conditions litter and vegetation cover promote water storage and mitigate water repellency impacts on infiltration and erosion (Rauzi et al., 1968; Blackburn et al., 1986). Fire removes this protective covering, exposing the soil to raindrop impact and removing barriers to overland flow (Moffet et al., 2007; Pierson et al., 2008).

Recent studies have identified seasonal variability in the presence and strength of soil water repellency under burned and unburned conditions (Doerr and Thomas, 2000; Dekker et al., 2001; Huffman et al., 2001). Doerr and Thomas (2000) observed seasonal patterns in soil water repellency correlated to rainfall patterns, biological productivity, and spatial variations in water repellency during soil wetting. Dekker et al. (2001) demonstrated that soil water repellency is a function of soil water content, that critical soil water thresholds demarcate wettable and water repellent soil conditions, and that the relationship between moisture content and soil water repellency is affected by drying regime. In a multiple fire study, Huffman et al. (2001) found that time since burning was not a significant predictor of soil water repellency in pine forests of the Colorado Front Range and noted the water repellent soils became

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wettable when soil moisture levels exceeded 12 to 25%. These studies indicate that seasonal variability in site characteristics that influence soil water repellency can confound assessment of long-term soil water repellency persistence (Doerr et al., in press).

The temporal dynamics of soil water repellency and respective impacts on rangeland hydrology and erosion have received little attention in the literature. Pierson et al. (2001, 2002) used rainfall simulations to investigate infiltration, runoff, and erosion processes on burned and unburned steeply-sloped sagebrush sites with coarse-textured soils. Burned shrub coppice microsites (areas underneath shrub canopy) had significantly lower infiltration compared to unburned shrub coppices in both studies. The lowest infiltration rates were observed on unburned interspaces (areas between shrub canopies) that were densely covered in very dry litter and senescent grasses. Pierson et al. (2001) developed a Water Repellency Index (WRI) to quantify the relative impact of soil water repellency on infiltration. The index differs from a previous water repellency index presented by Tillman et al. (1989) that is a ratio of the intrinsic sorptivity of ethanol to that for water. The Pierson et al. (2001) index scales the difference in final and minimum infiltration rates by the final infiltration rate. Using this WRI, Pierson et al. (2001) found burned coppice microsites had an average reduction of 28% in infiltration immediately post-fire with relatively little variability between plots. Pierson et al. (2002) attributed results to naturally strong soil water repellency, but did not explicitly measure soil water repellency in their experiment.

The goal of this paper is to document the effects of fire on the spatial and temporal variability in soil water repellency and potential impacts on infiltration and runoff on sagebrush-dominated landscapes. The objective of this paper is to test if relationships exist between directly measured soil water repellency, and the spatial and temporal variation in infiltration capacity and runoff generation on burned and unburned microsites within coarse-textured sagebrush-dominated ecosystems. The results of Pierson et al. (2001, 2002) are extended by adding data, analysis, and interpretation. Data from an additional independent study is also included to broaden the inference space of conclusion.

2. Study areas

2.1. Eighth Street Wildfire (1996)

The Eighth Street Wildfire study area (43°40'00" latitude 116°06'48" longitude) is located 5 km north of Boise, Idaho, USA, in the Boise Foothills. The fire burned 6070 ha at low to high intensities in late summer 1996 and was the focus of the hydrologic experiments presented in Pierson et al. (2002). The research area mean elevation is 1400 m. Annual precipitation ranges from 350 mm at lower elevations to 750 mm near ridgelines, most of which falls between November and May. Mean annual air temperature ranges from 8 to 11 °C. Soils of the area are derived from granite and consist of gravelly coarse sandy loams (Ultic Haploxerolls), on slopes of 35–60% (USDA-NRCS, 1997). Typical vegetation consists of big sagebrush (*Artemisia tridentata* ssp. *wyomingensis* Beetle & Young), and Idaho fescue (*Festuca idahoensis* Elmer). Some slopes are characterized by increases in three-awn (*Aristida* L. spp.), Sandberg bluegrass (*Poa secunda* Vasey), cheatgrass (*Bromus tectorum* L.) and rabbitbrush (*Chrysothamnus* Nutt. spp.) (Interagency Fire Rehabilitation Team, 1996).

2.2. Denio Wildfire (1999)

The Denio Wildfire study area is located approximately 24 km southwest of Denio, Nevada, USA, in the Pine Forest Range, 41°45'00" latitude 118°41'09" longitude. The fire severely burned 34,400 ha in 1999 and was the focus of hydrologic investigation by Pierson et al. (2001). The research area mean elevation is 2050 m. Average annual

precipitation is 350–400 mm and mean annual air temperature ranges from 5 to 7 °C. The study area is located within Major Land Resource area 23 (Malheur High Plateau) (USDA-SCS, 1981). The soils are mapped as Ola bouldery sandy loam, which consists of moderately deep soils formed in residuum from granite on mountain sideslopes. The Ola soil classification is coarse-loamy, mixed, frigid Pachic Haploxerolls (USDA-NRCS, 2001). Slopes in the study area range from 35 to 40%. Vegetation is dominated by mountain big sagebrush [*A. tridentata* ssp. *vaseyana* (Rydb.) Beetle], Idaho fescue and blue-bunch wheatgrass [*Pseudoroegneria spicata* (Pursh) A. Löve] (USDA-NRCS, 1990). Subdominant grasses consist of Sandberg bluegrass, bottlebrush squirreltail [*Elymus elymoides* (Raf.) Swezey], California brome (*Bromus carinatus* Hook & Arn.), basin wildrye [*Leymus cinereus* (Scribn. & Merr.) A. Love] and Columbia needlegrass [*Achnatherum nelsonii* (Scribn) Barkworth]. Subdominant shrubs are green rabbitbrush [*Chrysothamnus viscidiflorus* (Hook.) Nutt.] and common snowberry [*Symphoricarpos albus* (L.) Blake]. Major forb species include lupine (*Lupinus* spp.), longleaf hawksbeard (*Crepis acuminata* Nutt.), Indian paintbrush (*Castilleja* spp.), rosy pussytoes (*Antennaria rosea* Greene) and low scorpionweed (*Phacelia humilis* Torr & Gray).

2.3. Breaks Prescribed Fire (2002)

The Breaks study area (43°6'30" latitude 116°46'50" longitude) is located on the Reynolds Creek Experimental Watershed in the Owyhee Mountains, southwestern Idaho, USA. The prescribed fire was ignited in late September and a head fire burned over the study site. The burn severity across the study site was moderate to severe due to high fuel loads and the late afternoon time of day when the fire reached the site. Mean elevation of the research site is 1750 m. Mean annual precipitation is approximately 600 mm and mean annual air temperature is approximately 8 °C. The soils are mapped as Kanlee–Ola–Quicksilver association (Harkness, 1998). The plots in this study are on the deeper Kanlee (fine-loamy, mixed, superactive, frigid Typic Argixerolls) and Ola (coarse-loamy, mixed, superactive, frigid Pachic Haploxerolls) series. The hillslopes of the study area are east facing with 35 to 50% slope angles above granite bedrock. Soil textures are coarse sandy loam at and near the surface (0–30 cm depth) and loam or coarse sandy loam in the subsoil that extends beyond 100 cm depth. Rock fragment (>2 mm diameter) content near the soil surface is about 5 to 15% and ranges between 5 and 50% in the subsoil. Vegetation includes mountain big sagebrush with sub-dominant shrubs of rabbitbrush (*Chrysothamnus viscidiflorus*), antelope bitterbrush [*Purshia tridentata* (Pursh) D.C.], and widely scattered juniper (*Juniperus occidentalis*). Dominant grasses are bluebunch wheatgrass, and Idaho fescue. Additional site description details can be found in Moffet et al. (2007).

3. Methods

3.1. Experimental design

The Eighth Street site was sampled with 10 rainfall simulation runoff plots (0.5 m²) for each treatment 1 year after the fire (Pierson et al., 2002). Treatments included slope, aspect (north and south) and fire severity (unburned, moderate, and high). Additional plots were sampled 2 years after the fire only on the high fire severity treatments. The plots were arranged with half the plots randomly placed on coppice microsites and half on interspace microsites. Burned sites were closely matched to the soil type, slope, aspect and pre-existing vegetation found on unburned controls. All study sites were located on steep hillsides (approximately 40% slopes) at an approximate elevation of 1220 m. The severely and moderately burned and unburned north aspect sites were the only sites comparable to the Breaks and Denio sites. Therefore, data from the south aspects were not included in this analysis. The sample sizes in this analysis were 10

burned and 10 unburned plots 1 year post-fire and 10 burned plots 2 years post-fire.

At the Denio site, three randomly selected study sites on burned and unburned hillslopes were each sampled with 20 and 10 runoff plots (0.5 m²) respectively. The plots were arranged with half the plots randomly placed on coppice microsites and half on interspace microsites. Plot frames were installed in 1999, immediately post-fire, and left in place for sampling in subsequent years. Sampling the year of the fire occurred 6 weeks post-fire, before any natural rainfall events. A greater number of sample plots were used on burned hillslopes in anticipation of greater variability in response variables compared to the control hillslopes. Burned hillslopes were separated by approximately 1000 m and unburned hillslopes were separated by an average of 400 m. The unburned hillslopes were located 7–8 km from the burned hillslopes. All study sites were located on steep (35–40%) slopes with north-facing aspect.

At the Breaks site 6 burned and 6 unburned 0.5 m² runoff plots were sampled on the same hillslope immediately post- and pre-fire respectively. The plots were arranged with half the plots randomly placed on coppice microsites and half on interspace microsites. The same plots were again sampled 1 year after the fire. In addition, six more replicates of each burned and unburned microsite were sampled the year after the fire. All plots were located on east aspects with 30 to 40% slopes.

3.2. Soils and vegetation

Immediately before simulated rainfall was applied soil samples were collected adjacent to each runoff plot. Soil samples were analyzed gravimetrically for soil water content (0–2 cm depth). Soil bulk density was sampled (1–4 cm and 5–8 cm depths) using the core method (Blake and Hartge, 1986), and soil texture (0–2 cm depth) was analyzed using the hydrometer method (Bouyoucos, 1962). Canopy and ground cover in each runoff plot at the Eighth Street and Breaks sites were measured by recording first and last hits of 98 and 65 pin-points respectively with a point frame using 5-cm pin spacing (Mueller-Dombois and Ellenberg, 1974). Canopy and ground cover in each runoff plot at Denio were ocularly estimated to the nearest percent for standing dead, stumps, rocks, and each plant species (Elzinga et al., 2000). Circular paper discs were prepared corresponding to 0.1, 0.5, 1.0, 5.0, 10.0, and 15.0% for the 0.5 m² plots and were used to calibrate ocular cover estimates. Accuracy of the ocular method at Denio was evaluated on random plots by recording 500 points with a point frame. Corresponding percent differences between ocular and point cover measurements did not exceed 5%.

3.3. Soil water repellency

Soil water repellency at the Denio and Breaks sites was tested before rainfall simulation using the water drop penetration time (WDPT) procedure (Van't Woudt, 1959; DeBano, 1981). Eight water drops were applied to the mineral soil surface immediately adjacent to each runoff plot. If a water drop penetrated within 5 s, 1-cm of soil was excavated and another drop applied. This was done until the water drop stayed on the soil surface for at least 5 s or until a 5-cm depth was reached. The length of time the water drop stayed on the surface was recorded up to a maximum time of 300 s. Soils were considered water repellent when the WDPT exceeded 5 s and were classified slightly water repellent when WDPT ranged from 5 to 60 s, and strongly water repellent when WDPT exceeded 60 s (Dekker and Jungerius, 1990). Mean strength of water repellency for each plot was recorded as the arithmetic mean of the respective 8 WDPT measurements. Mean depth of water repellency at each plot was calculated as the mean depth, from 8 water drops, in which water repellent soil conditions were observed. The strength of soil water repellency at soil depths 0, 1, 2, 3, 4, and 5 cm on each microsite by treatment by year was calculated as the average of all WDPT at the respective depth across all plots for the respective microsite, treatment, and year. The percent coverage of

water repellent soils at soil depths 0, 1, 2, 3, 4, and 5 cm depth on each microsite by treatment by year was calculated as the percentage of all WDPT exceeding 5 s at the respective depth across all plots for the respective microsite, treatment, and year.

An infiltrability (see Wilcox et al., 1988) index was used to assess soil water repellency at all three study sites in terms of infiltration of simulated rainfall. We present a modified notation and naming of the Pierson et al. (2001) water repellency index, WRI. Although intended as a measure of water repellency by Pierson et al. (2001), the index captures differences in final and minimum infiltration rates. Therefore, the index actually represents infiltrability, which is related to water repellency, other soil characteristics, and canopy and ground cover (Wilcox et al., 1988). The infiltrability index (INI) was calculated for each plot using the following equation (Pierson et al., 2001):

$$\text{INI} = \frac{i_{\text{fin}} - i_{\text{min}}}{i_{\text{fin}}} \times 100 \quad (1)$$

where i_{min} is the minimum infiltration rate and i_{fin} is the final infiltration rate. INI ranges from 0% when i_{min} equals i_{fin} to 100% when i_{min} is zero and i_{fin} is greater than zero. INI is particularly useful for interpreting the influence of soil water repellency on infiltration when minimum infiltration occurs within the first 10 to 15 min of rainfall followed by increasing infiltration through the remainder of simulation (see Pierson et al., 2001).

3.4. Rainfall simulation

Small plot rainfall simulation techniques were used to test the impact of burning on spatial and temporal patterns of infiltration (Pierson et al., 2001, 2002, 2008). A portable oscillating-arm rainfall simulator with specifications as described by Meyer and Harmon (1979) was used to apply rainfall to each runoff plot for 60 min. Rainfall with similar raindrop size and terminal velocity to that of natural rainfall (Meyer and Harmon, 1979) was quickly passed back and forth over each runoff plot. The desired rainfall intensity was achieved by delaying the movement of the spray nozzle at the end of each oscillation, decreasing the amount of time the spray was hitting the plot. All plots within each year were sampled during 10 day periods under uniform hot and dry conditions.

Rainfall application rates differed by study site given each study was conducted independently. Site specific rainfall application rates were chosen to ensure runoff generation under burned and unburned conditions. A rainfall rate of 67 mm h⁻¹ was applied at the Eighth Street site. The application rate for the Eighth Street site was approximately equal to the rainfall intensity of a 10-min thunderstorm with a 5- to 10-year return period (Hanson and Pierson, 2001). Rainfall at the Denio site was applied at 85 mm h⁻¹, equivalent in intensity to 5-, 10-, and 15-min storms with respective return intervals of 25, 70, and 125 years as measured at Station 26-7443, Sheldon, Nevada (Bonnin et al., 2006). A rainfall rate of 85 mm h⁻¹ was applied at the Breaks site, approximately equal to the rainfall intensity of a 10-min thunderstorm with a 10-year return period (Hanson and Pierson, 2001). All statistical comparisons in the study are site specific and therefore restricted to the respective site specific rainfall application rate.

Runoff from each plot was routed through a collection tray at the bottom of the respective plot and collected in 1000 ml bottles on 1- or 2-min time intervals throughout the entire rainfall simulation. The first sample interval was from the start of runoff to the end of the next 1-min time interval, then 1-min sample intervals were used for the next 16 min, followed by 2-min sample intervals throughout the remainder of the simulation. Runoff samples were analyzed for volume and suspended sediment by weighing, drying at 105 °C, and re-weighing each sample.

In addition to measured response variables, a number of derived response variables were generated for each runoff plot. Average runoff

rate (mm h^{-1}) was calculated for each sample interval as the runoff volume for the interval divided by the time of the interval. Cumulative runoff (mm) was calculated as the integration of runoff rates over the total time of runoff. A runoff/rainfall ratio (mm mm^{-1}) was calculated by dividing cumulative runoff by the total amount of rainfall applied. An average infiltration rate (mm h^{-1}) for each sample interval was calculated as the difference between applied rainfall and measured runoff divided by the time of the sample interval. The final infiltration rate (mm h^{-1}) was estimated as the average infiltration rate of the 58–60 min time interval. The minimum infiltration rate (mm h^{-1}) was chosen as the lowest average infiltration rate of all sample intervals.

3.5. Wetting patterns

Wetting patterns at the Denio and Breaks sites were investigated immediately following simulated rainfall by excavating a 50-cm long trench to a depth of 20-cm immediately adjacent to each plot where it received approximately the same rainfall as the runoff plot. The percent wetted area of the exposed 1000 cm^2 soil profile was measured using a 4 cm^2 grid where each grid area was determined to be wet or dry based on the dominant condition found in the grid area. The area wet to 20 cm depth was calculated as the percentage of wetted area within the 1000 cm^2 excavated trench. Wetting patterns at 0- to 10-cm soil depth

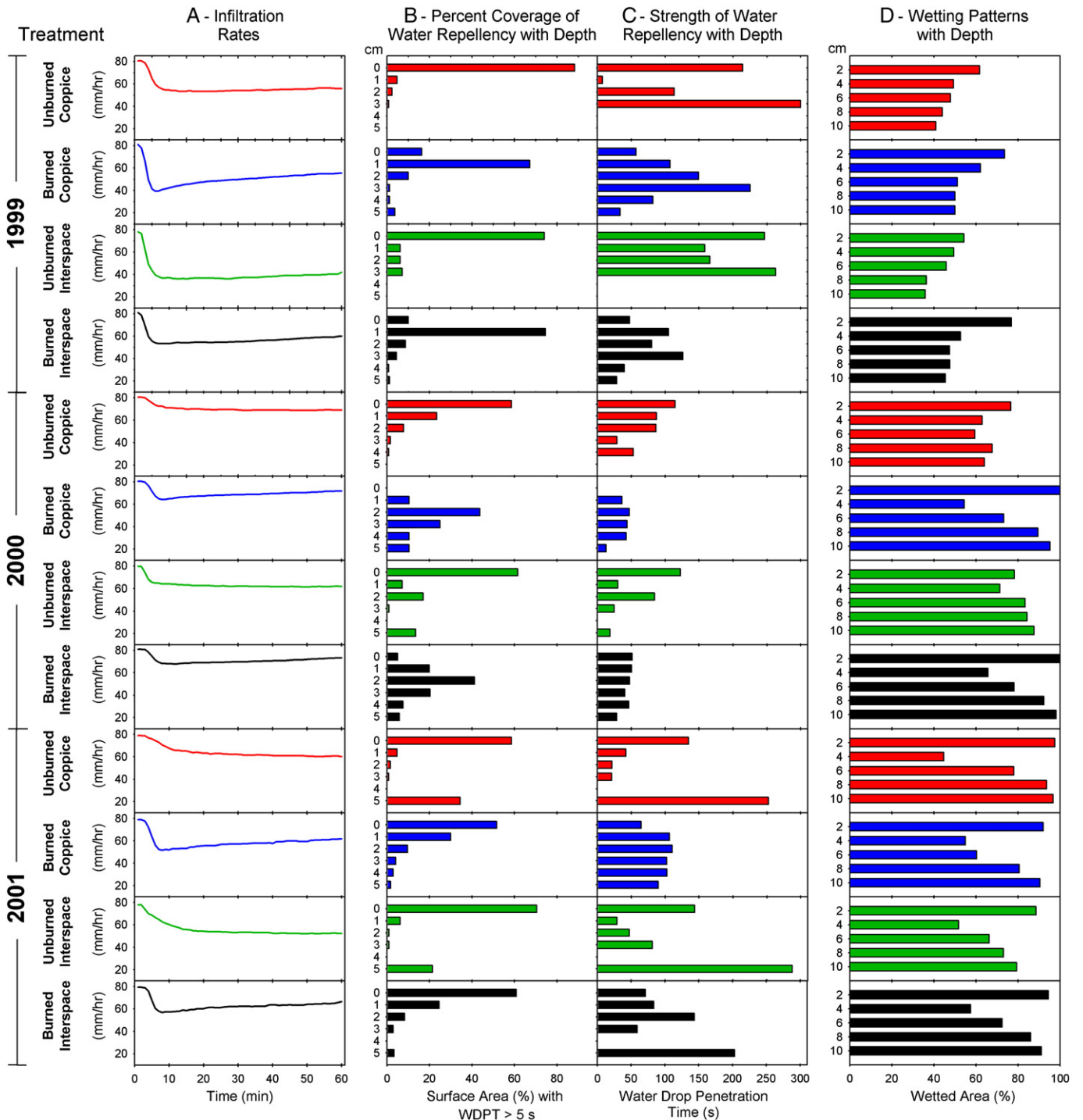


Fig. 1. Infiltration rates (A), depth of water repellent layer (B), strength of water repellency (C), and wetting patterns (D) measured at the Denio Wildfire, 1999–2001.

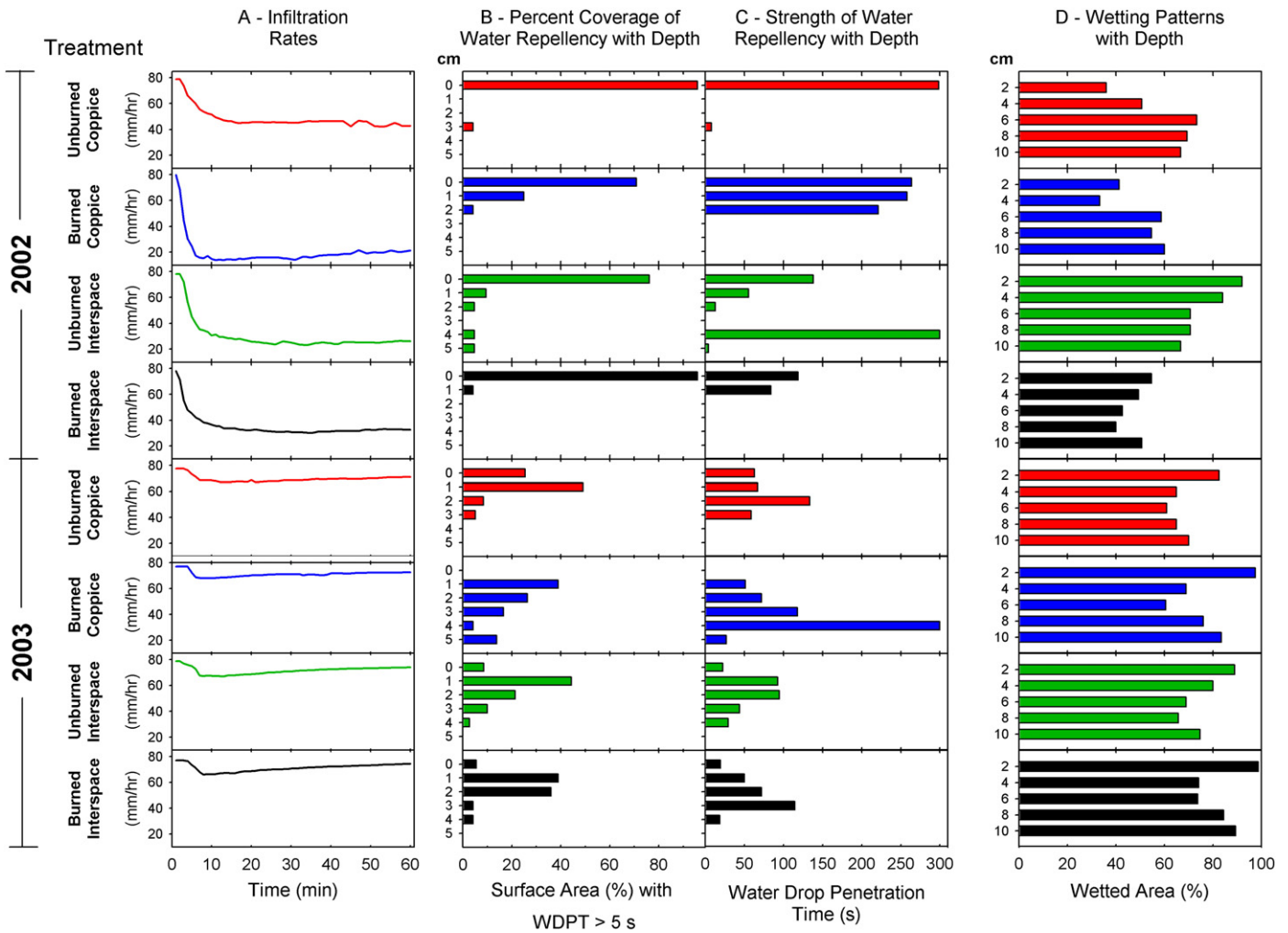


Fig. 2. Infiltration rates (A), depth of water repellent layer (B), strength of water repellency (C), and wetting patterns (D) measured at the Breaks Prescribed Fire, 2002–2003.

across microsites by treatment and year were measured as percent wetted area in 2-cm depth increments (cross-sections 2 cm deep \times 50 cm wide) within the 1000 cm² excavated trench.

3.6. Data analysis

Analysis of variance (ANOVA) was used to test for significant treatment effects on rainfall simulations and soil water repellency data (presented in Table 2) using a complete randomized design, and treatment means were separated using the Fisher's Protected LSD test with a 90% confidence level (SAS Institute Inc., 1999). No log transformations were necessary to achieve normality. A linear mixed-effects model was fit considering the intercept as a random effect and burn treatment and sample year were considered fixed effects. The degree of linear association of hydrology variables with water repellency variables was determined using a Pearson's correlation matrix (SAS Institute Inc., 1999). Infiltration curves and soil water repellency and wetting patterns by microsite (Figs. 1–3) were interpreted by visual inspection.

4. Results

4.1. Soils and vegetation

All sites had similar coarse texture soils and soil water contents. Average sand content ranged from 69 to 84% (Table 1). Antecedent surface soil water contents were low for all hillslopes during all years

of each study (Table 1). Bulk densities were similar across all sites but were 30% higher on burned than unburned hillslopes at the Eighth Street and Denio sites (Table 1). Bulk density at the Breaks site was nearly equal under burned and unburned conditions.

All study sites had similar vegetation prior to burning with hillslopes densely covered with shrubs (mountain big sagebrush), bunchgrasses, forbs and litter. Ground cover was greatly reduced by fire at all three sites (Table 1). Total herbaceous cover decreased by 80 to 100% across all burned sites following fire and remained 80% less on burned than on unburned plots 2 years post-fire at the Eighth Street wildfire site. Total herbaceous cover on burned hillslopes at the Denio site 1 year following fire was similar to unburned hillslopes due to a factor of 5 post-fire increase in forb cover on burned plots compared with unburned. Shrub and grass cover were reduced by 85 to 100% across all burn sites following fire and remained 60 to 90% lower on burned than unburned plots 1 and 2 years post-fire at the Denio and Eighth Street sites respectively. Shrub cover on burned plots at the Breaks site was 90% less than on unburned plots 1 year post-fire while grass cover had recovered to unburned levels. Litter cover was reduced by nearly 100% on the Eighth Street and Denio wildfire sites and by 60% during the Breaks prescribed fire (Table 1). Litter cover at the sites 1 year post-fire was similar to the year of the fires. Litter cover on burned hillslopes at the Eighth Street and Denio sites 2 years post-fire remained nearly 95% less than that observed on unburned hillslopes. The fire-induced litter cover reduction on the Eighth Street and Denio sites is indicative of severe wildfire and high burn

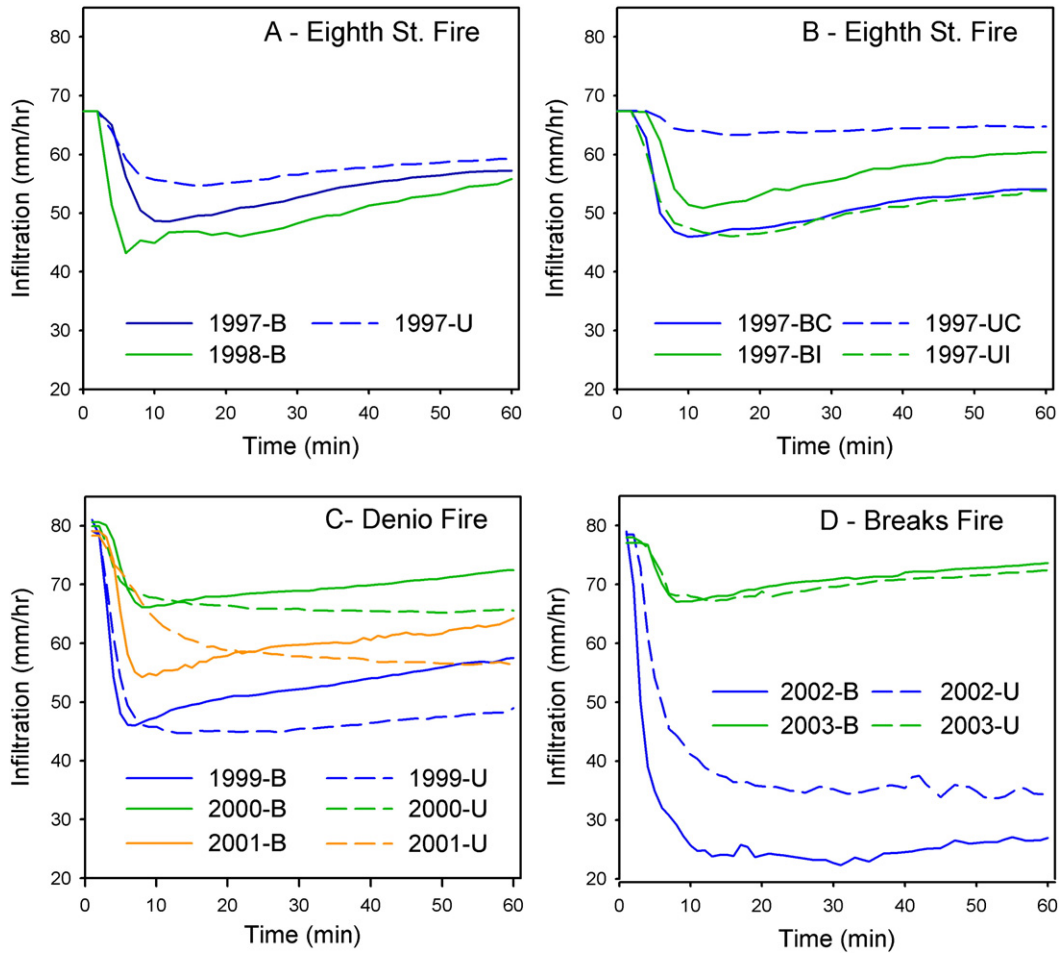


Fig. 3. Average infiltration rates over time for rainfall simulations on burned and unburned hillslopes – Eighth Street Fire (A), burned and unburned coppice and interspace microsities – Eighth Street Fire (B), and burned and unburned hillslopes – Denio Fire (C) and Breaks Fire (D).

temperatures, while litter consumption during the Breaks prescribed fire was consistent with moderate intensity prescribed burning.

4.2. Water repellency

WDPT data show significant fire treatment effects on soil water repellency and exhibit significant between-year variability in soil

water repellency for burned and unburned conditions (Table 2). The mean strength of water repellency on unburned hillslopes at Denio was twice that of burned hillslopes each year, indicating a reduction in soil water repellency with or following burning (Table 2). Mean strength of water repellency at the Breaks site was similar for burned and unburned conditions (Table 2). A significant year effect was observed for water repellency strength at both sites (Table 2). Mean

Table 1

Average soil and cover variables for all burned and unburned hillslopes on the Eighth Street Wildfire, Denio Wildfire and the Breaks Prescribed Fire

	Sand content 0–2 cm (%)	Clay content 0–2 cm (%)	Bulk density 1–4 cm ($g\ cm^{-3}$)	Bulk density 5–8 cm ($g\ cm^{-3}$)	Soil water content 0–2 cm (%)	Total herbaceous cover (%)	Grass cover (%)	Shrub cover (%)	Forb cover (%)	Litter cover (%)
<i>Eighth Street Fire</i>										
1997 Burned	77.6	5.8	1.20	–	4.6	9.1	6.8	0.0	2.3	0.8
1998 Burned	–	–	–	–	–	10.9	6.8	0.0	4.1	3.3
1997 Unburned	71.2	7.0	0.82	–	13.8	56.6	52.5	23.0	4.1	72.8
<i>Denio Fire</i>										
1999 Burned	83.5	6.5	1.09	1.33	0.6	2.5	2.4	0.0	0.1	0.9
2000 Burned	–	–	–	–	1.0	50.2	16.2	3.0	34.0	0.0
2001 Burned	–	–	–	–	1.7	55.9	14.1	6.4	41.8	1.2
1999 Unburned	68.6	7.1	0.82	1.04	5.0	68.5	63.7	37.5	4.8	96.3
2000 Unburned	–	–	–	–	3.6	51.9	44.4	37.7	7.5	91.5
2001 Unburned	–	–	–	–	2.7	66.3	54.5	36.7	11.8	94.7
<i>Breaks Fire</i>										
2002 Burned	72.2	3.3	1.13	1.32	3.6	0.0	0.0	0.0	0.0	27.4
2003 Burned	–	–	–	–	2.1	48.1	13.5	2.6	34.6	21.0
2002 Unburned	74.3	3.4	1.13	1.34	5.6	12.0	11.5	44.9	0.5	82.8
2003 Unburned	–	–	–	–	3.3	46.7	13.2	25.8	33.4	67.4

Table 2
Average runoff, infiltration and soil water repellency variables for all burned and unburned hillslopes on the Eighth Street Wildfire, Denio Wildfire, and the Breaks Prescribed Fire

	Time to runoff (min)	Time to peak runoff (min)	Runoff/rainfall×100	Minimum infiltration (mm h ⁻¹)	Final infiltration (mm h ⁻¹)	INI (%)	Plots with INI >10%	Mean strength of water repellency (s)	Mean depth of water repellency (cm)	Area wet to 20-cm depth (%)
<i>Eighth Street Fire</i>										
1997 Burned	3.4 Ab	12.6 Aa	19 Aa	48.0 Aa	57.2 Aa	16.3 Ba	80	–	–	–
1998 Burned	1.9 a ^a	11 a	26 b ^a	41.4 a ^a	55.5 a	25.2 a ^a	90	–	–	–
1997 Unburned	3.7 A	13.8 A	14 A	53.9 A	59.3 A	10.2 A	30	–	–	–
<i>Denio Fire</i>										
1999 Burned	1.9 Aa	5.6 Aa	34 Ac	45.2 Aa	57.6 Aa	22.5 Bc	78	99 Ab	0.9 Aa	52.9 Aa
2000 Burned	4.2 Bb	8.8 Ab	13 Aa	65.2 Ac	72.4 Ac	10.7 Ba	43	44 Aa	2.3 Bb	90.8 Ab
2001 Burned	3.6 Ab	9.1 Ab	22 Ab	52.8 Ab	63.8 Ab	18.1 Bb	77	84 Aab	0.7 Aa	84.9 Ab
1999 Unburned	2.5 Aa	7.1 Aa	39 Ab	45.9 Aa	48.1 Aa	7.4 Ab	33	210 Bb	0.3 Aa	46.3 Aa
2000 Unburned	3.0 Aa	9.4 Aa	17 Aa	66.0 Ac	66.0 Ac	3.5 Aa	17	95 Aa	0.7 Aa	72.3 Ab
2001 Unburned	4.5 Ab	13.3 Ab	20 Aa	55.4 Ab	56.4 Ab	1.7 Aa	20	167 Bb	1.4 Aa	84.6 Ab
<i>Breaks Fire</i>										
2002 Burned	1.8 Aa	11.1 Aa	66 Ab	24.4 Aa	26.6 Aa	9.3 Ba	17	189 Ab	0.2 Aa	53.1 Aa
2003 Burned	5.1 Ab	9.4 Aa	10 Aa	62.1 Ab	72.7 Ab	14.8 Aa	50	66 Aa	1.7 Bb	85.5 Ab
2002 Unburned	2.5 Aa	19.0 Aa	51 Ab	36.7 Ba	33.9 Aa	0.1 Aa	0	198 Ab	0.5 Aa	66.1 Ba
2003 Unburned	5.7 Ab	13.3 Ba	10 Aa	65.3 Ab	72.3 Ab	10.0 Ab	44	74 Aa	1.2 Ab	79.2 Aa

Upper case letters within a column for a site indicate significant ($P<0.10$) differences between treatments within a year, and lower case letters within a column for a site indicate significant ($P<0.10$) differences between years within a treatment.

^a Significantly different ($P<0.10$) from 1997 unburned.

strength of water repellency at Denio 1 year following the fire was approximately 50% less across all plots than the year of the fire and 2 years post-fire. Mean strength of water repellency at the Breaks site was approximately 60% less on burned and unburned plots 1 year following the fire. The mean depth of water repellency at the Denio and Breaks sites followed similar annual patterns as mean water repellency strength and was greater under burned conditions 1 year post-fire at Denio and Breaks (Table 2). Mean depth of water repellency on burned and unburned plots at both sites was largely restricted to within 0–3 cm of the soil surface (Table 2).

Water repellency strength varied by microsite between the Denio wildfire and the Breaks prescribed burn (Figs. 1C and 2C). The strength of the water repellency at the Denio site was highest on unburned coppice and interspace microsites, with WDPT consistently exceeding 100 s at the surface of the soil profile and nearly reaching the maximum observation time of 300 s the year of the fire (Fig. 1C). The strength of the dominant water repellent soil layer (greatest surface coverage of water repellency) at Denio varied minimally between burned coppice and interspace microsites, with WDPT ranging from 40 to 115 s throughout the study (Fig. 1B and C). Water repellency strength across treatments and microsites at Denio was decreased by approximately 60% 1 year post-fire and increased approximately 70% from year 1 to 2 years post-fire (Fig. 1C). The strength of water repellency at the Breaks study site was highly variable between microsites and years, however the between years temporal pattern was consistent with observations at the Denio site (Fig. 2C). Burned and unburned coppice microsites had the strongest mean water repellency (average 266 s) the year of the Breaks fire and unburned interspaces had the strongest mean water repellency (81 s) 1 year following the fire. The coverage area of the strongly water repellent zone was similar across both sites for the respective microsites, ranging from 70 to 90% on all plots the years of the fires to approximately 45% 1 year post-fire (Figs. 1B and 2B).

The INI data reveal significant within-year and annual variation in infiltrability on burned and unburned conditions. INI at Denio was 3 to 10 times greater on burned than unburned hillslopes throughout the study (Table 2) and at Eighth Street and Breaks was significantly greater on burned than unburned plots 1 year and immediately post-fire respectively (Table 2). INI at Denio decreased on all plots 1 year following fire and increased on burned plots 2 years post-fire (Table 2). The percentage of plots with INI greater than 10% exhibited similar

between-year variability at the Denio and Breaks study sites and was generally higher for burned than unburned treatments across all sites (Table 2).

4.3. Infiltration

Within-year variability in infiltration between burned and unburned conditions across sites was minimal, but between-year variability in infiltration was significant at the Breaks and Denio sites (Table 2). Minimum infiltration was decreased 40% by burning immediately following the Breaks prescribed burn but was unchanged by fire at Eighth Street and Denio. Minimum infiltration doubled across all plots 1 year post-fire at the Breaks site and was 40% higher 1 year following and 20% lower 2 years after the fire on burned and unburned plots at the Denio site. Final infiltration rates were unchanged by burning, but at Denio and Breaks followed the same temporal trends between years as minimum infiltration. Final infiltration at Denio increased 30% across all plots 1 year post-fire and decreased 10% between years 1 and 2 post-fire. Final infiltration doubled at the Breaks on burned and unburned plots 1 year following the fire (Table 2).

Infiltration curves from the three sites (Figs. 1A, 2A, and 3B) reveal variation in microsite response to burning. The magnitude of burned response was much greater on coppices than on interspaces at the Eighth Street site (Fig. 3B). The Eighth Street fire reduced the minimum and final infiltration rates on coppice microsites 30 and 15% respectively while burning generally increased minimum and final infiltration rates by 10% on interspace microsites (Fig. 3B). Similar trends were seen in the infiltration curves from coppice and interspace microsites at the Denio site (Fig. 1A) and from coppice microsites at the Breaks study site (Fig. 2A) immediately following the fires. These trends were greatly dampened 1 year following the Denio and Breaks Fires, but returned 2 years post-fire at the Denio site (Fig. 1A). The dampening and reappearance of microsite variation (Figs. 1A and 2A) and similar site level responses (Fig. 3C and D) demonstrate a dramatic year effect for annual variability in infiltration at the Denio and Breaks study sites.

4.4. Runoff

Runoff began within the first 2–6 min of rainfall simulation and peaked within 20 min on burned and unburned plots at all three sites

throughout respective study periods (Table 2). No significant differences in runoff (runoff/rain) were measured within years for burned and unburned areas at the study sites, however, significant between-year variability in runoff was observed for burned and unburned conditions at the Denio and Breaks sites and for burned conditions at Eighth Street (Table 2). Runoff from burned and unburned hillslopes at Denio decreased by 60% from the year of the fire to 1 year post-fire. Runoff at the Breaks site was decreased by 80% on burned and unburned plots 1 year following the fire. Runoff at the Eighth Street site increased on burned plots by 30% 2 years post-fire (Table 2).

4.5. Wetting patterns

Wetting patterns at the Denio and Breaks sites exhibited similar between-year trends as infiltration and water repellency (Figs. 1 and 2). The percent wetted area to 20 cm depth (Table 2) generally increased with time after the fire at both sites on burned and unburned plots. Within-year variation between burned and unburned plots was minimal and was significant only at the Breaks site immediately following the fire (Table 2). No fire effects were detected in wetting patterns by microsite (Figs. 1D and 2D). Annual trends in wetting patterns at the microsite scale (Figs. 1D and 2D) were consistent with wetted area trends observed for burned and unburned conditions across all plots (Table 2).

4.6. Correlations

The analysis of selected hydrologic and water repellency variables from the Denio and Breaks sites found significant correlations in infiltration and runoff with water repellent conditions (Table 3). Minimal and final infiltration and runoff/rain were moderately to weakly correlated with mean strength and depth of water repellency and area wet to 20 cm depth (Table 3). The time to runoff was strongly to moderately correlated with minimum infiltration and moderately to weakly correlated with final infiltration, mean strength and depth of water repellency, and wetted area to 20 cm depth. Time to peak runoff was weakly correlated with water repellency variables at the Denio site and significantly correlated with INI solely at the Breaks site. The strongest correlation with INI was minimum infiltration at the Denio site. Overall, correlations among infiltration and runoff variables with water repellency were moderate to weak and were stronger at the Breaks site than at Denio.

5. Discussion

5.1. Patterns in water repellency

Experiments on two steeply-sloped sagebrush sites with coarse-textured soils found strongly water repellent soils under unburned conditions (Table 2). Background water repellency at the Denio and Breaks study sites was strong at the mineral soil surface immediately below the duff layer on coppices and interspaces (Figs. 1C and 2C). Water repellency on unburned semi-arid landscapes is commonly highest at the surface of the soil profile (Huffman et al., 2001). Surface WDPT at the Denio and Breaks sites were similar for unburned coppice and interspace microsites even though organic matter and litter accumulation were substantially less (by observation) in interspaces. We attribute the strong inherent water repellency on coppice and interspace sites in this study to uniform dry conditions during sampling and to the natural affinity of coarse-textured soils to coating with hydrophobic compounds leached from litter and duff layers (Meeuwig, 1971; DeBano, 1981; DeBano, 1991; DeBano, 2000; Doerr et al., 2000). Strong background water repellency on interspace sites likely resulted from hydrophobic compounds transported (lateral flow and subsequent infiltration) from upslope coppice mounds and from the thin litter layer in interspace zones.

Severe burning of sagebrush hillslopes in this study reduced water repellency, but the strength of water repellency was affected more by the annual variability of site characteristics that cause hydrophobic conditions than by burning (Table 2). The decrease in the strength of repellency on coppices and interspaces at Denio following burning was unexpected (Fig. 1C). Dense litter and duff layers under coppice microsites were expected to experience higher burn temperatures. Higher burn temperatures were expected to facilitate stronger water repellency (DeBano and Krammes, 1966; DeBano 2000; Doerr et al., 2005; Doerr et al., in press). Soil temperatures above 270 °C can break down or destroy pre-fire soil water repellency (DeBano et al., 1976). Stronger soil water repellency near the surface on unburned microsites rather than burned microsites at Denio (Fig. 1C) suggests that burn temperatures reduced background soil water repellency. The unchanged strength of soil water repellency on microsites following the Breaks prescribed fire (Fig. 2C) likely resulted from the more moderate burn intensity over strong pre-fire water repellent

Table 3
Correlation matrices of selected hydrologic and soil water repellency variables for the Denio Wildfire and the Breaks Prescribed Fire

	Time to peak runoff	Runoff/rainfall × 100	Minimum infiltration rate	Final infiltration rate	INI	Mean strength of water repellency	Mean depth of water repellency	Area wet to 20-cm depth
<i>Denio Fire</i>								
Time to runoff	0.60*	-0.43*	0.43*	0.31*	-0.33*	-0.11**	0.28*	0.30*
Time to peak runoff		-0.10	0.12**	-0.04	-0.29*	0.05	0.18*	0.12**
Runoff/rainfall × 100			-0.92*	-0.95*	0.26*	0.39*	-0.14*	-0.43*
Minimum infiltration rate				0.84*	-0.56*	-0.37*	0.19*	0.37*
Final infiltration rate					-0.06	-0.45*	0.17*	0.39*
INI						-0.04	-0.13*	-0.11**
Mean strength of water repellency							-0.17*	-0.29*
Mean depth of water repellency								0.20*
<i>Breaks Fire</i>								
Time to runoff	0.12	-0.64*	0.70*	0.61*	-0.17	-0.39*	0.40*	0.31*
Time to peak runoff		-0.12	0.10	-0.01	-0.34*	0.25	-0.06	-0.08
Runoff/rainfall × 100			-0.98*	-0.98*	-0.08	0.58*	-0.46*	-0.56*
Minimum infiltration rate				0.94*	-0.11	-0.56*	0.43*	0.56*
Final infiltration rate					0.23	-0.59*	0.46*	0.55*
INI						-0.15	0.14	0.04
Mean strength of water repellency							-0.49*	-0.53*
Mean depth of water repellency								0.64*

* Statistically significantly at P=0.05.
** Statistically significantly at P=0.10.

conditions. Significant reductions in the mean strength of water repellency on burned and unburned hillslopes at Denio and Breaks 1 year post-fire and the subsequent increase in water repellency across all plots 2 years post-fire at Denio suggest that annual fluctuations in site level conditions that control hydrophobic strength may exert greater influence than fire on post-fire soil water repellency (Table 2).

5.2. Infiltration and wetting patterns

The infiltration hydrographs from three similar sagebrush sites reflect the complexity of the pre- and post-fire site characteristics that influence rangeland hydrologic processes (Figs. 1A, 2A, and 3). Meeuwig (1971) investigated infiltration and wetting patterns in coarse grained and water repellent soils on forested and brush field sites northeast of Lake Tahoe, Nevada, using rainfall simulation and infiltrometer methodologies. The study identified multiple wetting front patterns and associated those patterns with specific infiltration curves. Infiltration curves that reach minimum levels near the onset of rainfall followed by increasing infiltration rates through the remainder of simulation were indicative of incomplete water repellency, gradual wetting up of the water repellent areas at the mineral surface, and subsequent rapid infiltration through preferential flow paths into wettable layers at depth (distributed flow) (DeBano, 1981; Ritsema et al., 1993; Ritsema and Dekker, 1994, 1995). Similar curves were observed in this study for burned coppices at all three fires (Figs. 1A, 2A, and 3B). In contrast, infiltration curves like those depicted on unburned coppice microsites in this study are indicative of high infiltration rates and numerous breaks in water repellent layers (Figs. 1A, 2A and 3B, Meeuwig, 1971). The disparity in high infiltration rates (Figs. 1A and 2A) and nearly 100% surface coverage of water repellent soils (Figs. 1B and 2B) on unburned coppices suggest that a large component of the measured infiltration rate is actually water stored in the canopy and litter material. Local storage allows more time for infiltration through preferential flow into wettable soils underneath the strongly water repellent surface layer (Meeuwig, 1971; DeBano, 1981; Ritsema et al., 1993; Ritsema and Dekker, 1994, 1995). Meeuwig (1971) also identified infiltration curves like those observed on burned and unburned interspaces at the Breaks site that depict slow penetration through strongly water repellent profiles, identified by equally low minimum and final infiltration rates (Fig. 2A).

Analysis of wetting patterns from the Denio and Breaks study sites the year of the fires indicates both preferential and distributed flow and gradual passing of near uniform wetting fronts (Figs. 1D and 2D). The non-uniform wetting patterns on burned coppices and interspaces and unburned coppices the year of the fires indicate applied rainfall infiltrated through breaks in water repellent layers within the upper 4 cm of the soil profile. Similar wetting patterns and infiltration rates on burned interspaces and unburned coppices immediately post-fire at Denio likely resulted from the heterogeneous nature of and reduced strength in water repellency post-fire. Lower percentage of wetted area and infiltration rates on burned interspaces at the Breaks site the year of the fire reflect nearly 100% surface coverage of strong water repellency at the soil surface (Fig. 2). Although infiltration rates on burned interspaces at Denio and the Breaks were different, wetting patterns were similar indicating preferential flow paths (Figs. 1 and 2). Minimum and final infiltration rates were nearly identical on unburned interspaces at both sites the year of the fires (Figs. 1 and 2), however wetting patterns varied between sites: the wetting pattern data from Denio reflect preferential flow and the wetting behavior at the Breaks reflects a slow and nearly uniform passing of the wetting front. We attributed the differences to stronger water repellency at Denio and potentially fewer breaks in the water repellent layer at the Breaks (Meeuwig, 1971).

The between-year variation in infiltration and wetting patterns suggest that annual fluctuations in soil water repellency strength

significantly influence infiltration and wetting front propagation. One year following fire at the Denio and Breaks study sites soil water repellency was greatly reduced and the percentage of wetted area at depth greatly increased on burned and unburned coppices and interspaces (Figs. 1 and 2). Minimum and final infiltration rates at both sites increased across all plots, burned and unburned, 1 year following the fires (Table 2). The subsequent (year 1 to year 2) increase in water repellency and decrease in minimum and final infiltration on most burned and unburned plots 2 years post-fire at Denio demonstrates that temporal variation in soil water repellency can be significant and that its degree can influence infiltration in the presence or absence of a litter layer (Table 2). The transient nature of soil water repellency has been well documented in literature (Dekker and Ritsema, 1994; Doerr et al., 2000; Dekker et al., 2001; Huffman et al., 2001; MacDonald and Huffman, 2004) and is often linked to variations in soil water content (Dekker et al., 2001). However, relatively little is known about the processes that control the persistence of soil water repellency (Doerr et al., 2006). Seasonal changes in soil water repellency are not solely linked to variability in soil water content, but also to other processes taking place during seasonal drying and or wetting of the soil (Doerr and Thomas, 2000; Dekker et al., 2001). In fires studied here, the annual variation in infiltration and wetting patterns due to strong background water repellent conditions was greater than the effects of the fires.

5.3. Implications for runoff generation

For all sites in this study, runoff was initiated at nearly the same time for both the burned and unburned hillslopes (Table 2) and was significantly correlated with variables representing soil water repellency (Table 3). Infiltration through the water repellent zone occurred on burned and unburned plots and wetting pattern data imply that infiltration occurs largely through preferential and distributed flow paths through the soil profile (Meeuwig, 1971; Dekker and Ritsema, 1994; Ritsema and Dekker, 1994, 1995). Although the physical evidence of preferential flow was not investigated in this study, the observed wetting patterns suggest that it is an important mechanism by which water moves through coarse-textured soils with strong water repellency. The between-year variability in runoff and infiltration in this study indicates that the influence of repellency on runoff generation is quite variable and that its persistence and recovery may be masked by short-term fluctuations in its strength. The data presented here imply that runoff generation from coarse-textured water repellent soils in steeply-sloped sagebrush-dominated landscapes is due in part to the strength of soil water repellency and the frequency of breaks in the water repellent layers and that these characteristics are highly variable over time.

Stratification of the landscape by microsite revealed different runoff patterns (infiltration differences) on burned and unburned coppices and interspaces although the temporal variability remained (Figs. 1, 2, and 3B). Fire removal of vegetation and ground cover on coppice microsites generally reduced the length of local storage time for rainfall reaching the ground surface and reduced minimum infiltration. The combined effect of strong pre-fire soil water repellency and the removal of ground cover facilitated runoff generation (infiltration less than applied rainfall) on burned coppice microsites. On interspace microsites runoff generation was generally reduced following burning. Infiltration on unburned interspaces occurred largely through gradual penetration of the strongly water repellent soils. Burning generally facilitated infiltration into the water repellent soils on interspace microsites and reduced runoff. Increased infiltration and reduced runoff following burning on interspaces resulted from decreased repellency and reduction in infiltration inhibiting vegetation (Pierson et al., 2008).

Runoff generation in sagebrush landscapes is highly heterogeneous and the amount of runoff arriving at the base of hillslope

depends on the spatial connectivity of runoff source areas (Huffman et al., 2001; Johansen et al., 2001). Blackburn (1975) demonstrated that interspaces serve as source areas for runoff generation and sediment yield while coppice dunes function as sink areas for lateral flow and sediment. Overland flow greatly depends on the infiltration capacity of lateral transport from source areas and hydrologic connectivity across the landscape. Therefore, soil water repellency facilitates runoff generation in source areas, but its influence on runoff at the hillslope scales is mitigated by sinks on the landscape. The sites studied here indicate fire removal of vegetation from soils with strong pre-fire soil water repellency increased runoff on coppice microsites. Pierson et al. (2001, 2002, 2008) demonstrated that the greatest impact of fire in coarse-textured and steeply-sloped sagebrush-dominated landscapes is on the dynamics of overland flow once water begins moving across the hillslope. The removal of vegetation allows overland flow to concentrate into rills where velocity and erosive energy increase (Pierson et al., 2008). The findings here imply burning on sites with strong pre-fire soil water repellency increases the spatial representation of source areas and that the combined effect of strong soil water repellency and removal of canopy and protective ground cover facilitates runoff generation over larger scales (Benavides-Solorio and MacDonald, 2001; Johansen et al., 2001). Runoff generation at the catchment scale was not investigated, but implications from this study and from literature (Imeson et al., 1992; Burch et al., 1989; DeBano, 2000; Dekker et al., 2001; Huffman et al., 2001; Hubbert et al., 2006; Doerr et al., in press) suggest that catchment scale runoff associated with water repellent soils is dependent on the spatial connectivity of highly variable, spatially and temporally, water repellent soils and overland flow source areas.

6. Conclusions

Runoff from two wildfires and one prescribed fire on coarse-textured and steeply-sloped sagebrush sites in this study was more influenced by the combined removal of vegetation and pre-fire strongly water repellent soils than fire influenced soil water repellency. Fire removal of vegetation on coppice microsites greatly reduced infiltration even though the water repellency strength generally decreased. Increased runoff on coppice microsites following burning then resulted from concurrent strong natural water repellency, pre- and post-fire, and reduced interception and storage capacity of canopy and ground cover. Although the timing of runoff was unaffected by fire, the spatial representation of source areas for runoff generation increased post-fire. The combined analyses of runoff generation, infiltration, and strength of soil water repellency by treatment and microsite demonstrate increases in post-fire runoff following moderate to severe fire in strongly water repellent sagebrush sites results primarily from reduction of protective canopy and ground cover and the subsequent increase in connectivity of runoff source areas rather than fire-induced soil water repellency.

The analysis of similar sites found soil water repellency on burned and unburned sagebrush hillslopes to be highly variable temporally and that between-year variability in the strength of soil water repellency exerted greater influence on runoff generation than the effects of the fires. Differences in infiltration rates and wetting patterns on burned and unburned hillslopes suggest that the expanse of preferential and distributed flow varied at all sites between years even though the general shape of infiltration curves by microsite varied little temporally. Soil water repellency on burned and unburned hillslopes followed similar between years patterns as infiltration rates. These temporal oscillations in the infiltrability and soil water repellency were not observed with canopy and ground cover levels however. These findings indicate that the mechanisms by which infiltration occurred did not differ much between years however influence of soil water repellency on infiltration, background or fire-induced, was dependent on other highly temporally variable site characteristics. The source contributing to the temporal variability was not assessed, but

identifying the temporal response further supports contentions that short-term oscillations in soil water repellency greatly hinder assessment of its effects and determination of its long-term persistence. Our results suggest that mitigation of fire effects on hydrology should consider disruption of the spatial connectivity in runoff generation created by removal of vegetation and ground cover and that the impacts of soil water repellency, natural or fire-induced, may be highly variable temporally and difficult to assess due to short-term oscillations in hydrophobic strength.

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