Soil Water Repellency within a Burned Piñon–Juniper Woodland: Spatial Distribution, Severity, and Ecohydrologic Implications

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Soil water repellency is commonly found in piñon (*Pinus* spp.)–juniper (*Juniperus* spp.) (P-J) woodlands and may limit site recovery after a fire. Understanding the extent of this problem and the impact it has on vegetation recovery will help guide land managers in conducting their restoration efforts. In this study, we (i) examined the spatial distribution and severity of post-fire soil water repellency in a burned P-J woodland, (ii) related ecohydrologic properties to pre-fire tree canopy cover and post-fire vegetation establishment, and (iii) demonstrated a geographic information system (GIS)-based approach to extrapolate observed patterns to the fire boundary scale. During a 2-yr period, several soil and vegetative measurements were performed along radial line transects extending from the trunk of burned Utah juniper [*Juniperus osteosperma* (Torr.) Little] trees to twice the canopy radius. Results indicate that water repellency patterns are highly correlated with pre-fire tree canopy cover. Critical water repellency extended from the base of the tree to just beyond the canopy edge, while subcritical water repellency extended half a canopy radius past the edge of the critical water repellency zone. At sites where critical water repellency was present, infiltration rates, soil moisture, and vegetation cover and density were significantly less than non-water-repellent sites. These variables were also reduced in soils with subcritical water repellency (albeit to a lesser extent). Results were exported into a GIS-based model and used in conjunction with remotely sensed imagery to estimate the spatial distribution of soil water repellency at the landscape scale.

Abbreviations: CR, canopy radius; GIS, geographic information system; P-J, piñon–juniper; RFE, radial feature extraction; SWC, soil water content; WDPT, water drop penetration time.

Since European settlement of the western United States, piñon (*Pinus* spp.) and juniper (*Juniperus* spp.) species have expanded their range to more than 40 million ha (Romme et al., 2009), encroaching on historical grassland and sagebrush (*Artemisia tridentata* Nutt.) communities (Miller et al., 2008). Proposed primary-causal factors include high-intensity grazing, fire suppression, increased atmospheric CO_2 concentrations, and climate change (Johnson et al., 1993; West, 1999; Miller and Tausch, 2001; Romme et al., 2009). This ecosystem shift has impacted soil resources, plant community structure and composition, forage quality and quantity, water and nutrient cycles, wildlife habitat, and biodiversity (Miller et al., 2008). As P-J woodlands mature, increased fuel loads and canopy cover can lead to large-scale, high-intensity crown fires (Miller et al., 2000, 2008; Miller and Tausch, 2001). After a fire, the ability of a site to recover depends on the extent that physical and biological processes controlling ecosystem function have been altered, both pre- and post-fire (Miller and Tausch, 2001; Briske et al., 2006; Petersen and Stringham, 2008). Ecological resilience may be compromised in these communities when feedback shifts are initiated that carry the site across additional ecological thresholds to undesirable alternate stable states (Briske et al., 2006). To develop an appropriate restoration strategy, successful post-fire management requires an understanding of the ecological thresholds that limit site recovery.

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Soil water repellency (or hydrophobicity) is well documented in P-J woodland systems (Krammes and DeBano, 1965; Scholl, 1971; Roundy et al., 1978; Jaramillo et al., 2000; Rau et al., 2005; Madsen et al., 2008; Pierson et al., 2009; Madsen, 2009; Robinson et al., 2010). This soil condition may be ecologically advantageous to P-J trees by promoting bypass flow from precipitation inputs through select wettable patches, thus reducing evaporative losses near the soil surface (Madsen et al., 2008; Robinson et al., 2010). Soil water repellency is caused primarily by a range of hydrophobic organic materials that form nonpolar coatings on soil particles (Doerr et al., 2000) and can originate from several sources including plant litter (DeBano et al., 1970; McGhie and Posner, 1980), microbial activity, and fungal hyphae (Bond and Harris, 1964).

This soil condition can be intensified during fire as heat volatilizes organic substances in the litter and upper antecedent water-repellent soil layers (DeBano et al., 1976). These volatilized compounds move downward into the soil, condensing around soil particles in the cool, underlying soil layers (Savage, 1974; DeBano et al., 1976). The result is a shallow, wettable layer at the soil surface and an intensified water-repellent zone below (DeBano et al., 1976).

Post-fire soil water repellency can act as an ecological threshold by increasing soil erosion (Krammes and Osborn, 1969; Letey, 2001; Leighton-Boyce et al., 2007; Pierson et al., 2009) and impairing the establishment of desired species within the first few years after a fire (Adams et al., 1970; Salih et al., 1973; Madsen, 2009). Understanding the extent, severity, and spatial patterns of post-fire soil water repellency may help guide land managers in conducting restoration efforts after a fire. Rau et al. (2005) found that surface heating from a prescribed fire was greater under the canopy of P-J trees than the microsite between the trees. Glenn and Finley (2010) found that within a sagebrush-steppe ecosystem, fire severity and infiltration rates were inversely related to distance from individual sagebrush plants. Madsen et al. (2008) also found that under unburned conditions, soil water repellency was confined to the soil directly below P-J tree canopies. Water repellency assessments performed in that study used the water drop penetration time (WDPT) test; however, this test is only sensitive to contact angles >90° (van't Woudt, 1959; Letey, 1969). In the same study, they found that unsaturated hydraulic conductivity continued to increase along a gradient, out to two times the canopy radius. These measurements may indicate that beyond the detected water-repellent zone, subcritical water repellency (i.e., soil particle surfaces partially coated with hydrophobic coatings at levels that are undetectable through the WDPT test but are sufficient to influence soil infiltration [Tillman et al., 1989; Hallett et al., 2001, 2004]) was suppressing infiltration.

Assuming there is a correlation between pre-canopy-cover and post-fire soil water-repellency patterns, this relationship could be used to estimate the extent of soil water repellency at the fire-boundary scale using a GIS and pre-burn remotely sensed imagery. For example, the integration of field-based measurements with feature extracted data acquired from remotely sensed imagery can enable the assessment of rangeland conditions across large land areas (Hunt et al., 2003). Feature extraction techniques for classifying tree cover using high-resolution panchromatic and multispectral data have been implemented to segment tree cover from the surrounding landscape on the basis of spatial, textural, and spectral data (i.e., Hunt et al., 2003; Weisberg et al., 2007). We propose that the spatial distribution of soil water repellency can be extrapolated to the fire-boundary scale by applying plot-scale spatial rules to patterns of preburn canopy cover obtained from remotely sensed imagery.

The objectives of this study were to: (i) quantify the spatial distribution and severity of post-fire soil water repellency and its correlation to soil moisture, infiltration capacity, and vegetation recovery; (ii) relate ecohydrologic properties to pre-fire P-J canopy cover and post-fire vegetation establishment; and (iii) demonstrate a GIS-based approach to scale up observed patterns in soil water repellency to the landscape scale, using pre-burn remotely sensed imagery. This research has the potential to fill important knowledge gaps concerning the characteristics of soil water repellency within burned P-J woodlands and provides a useful tool for land managers to assess water repellency at the landscape scale.

MATERIALS AND METHODS

Research was conducted in two field studies within the boundaries of the Milford Flat fire. This fire was ignited by lightning on 6 July 2007, and by its containment on 10 July 2007, the fire had burned 145,000 ha. Pre-burn vegetation types within the fire were derived from the Southwest Regional Gap Analysis Project (SWReGAP) (earth.gis.usu.edu/swgap/; verified 23 Apr. 2011) as follows: 34% sagebrush shrubland, 33% salt desert scrub, 21% P-J woodlands, 8% invasive forb and grasslands, 3% gambel oak (*Quercus gambelii* Nutt.), and the remaining vegetation (1%) was a mix of aspen (*Populus tremula* L.) mixed with conifer and montane vegetation types. Soils within the fire boundary were predominantly alluvium, derived from igneous and sedimentary rock from the Mineral Mountain range, with texture primarily ranging from loam to sandy loam (Soil Survey Staff, 2009).

Study 1: Winter Sampling

The first study was performed to quantify the spatial distribution and severity of water repellency and determine its correlation to soil water content throughout the fire boundaries. Fieldwork was conducted on 4 to 9 Jan. 2008. This study was timed to immediately follow a period of above-average air temperature and light rain that melted most of the surface snow and thawed the soil profile, thereby providing the conditions necessary for optimal field sampling when soil moisture differences between water-repellent and non-water-repellent soils would be greatest. In choosing sampling locations, spatial fire intensity data were acquired from burned area reflectance classification maps developed by the Remote Sensing Applications Center (Salt Lake City, UT). These maps quantify the change in normalized difference vegetation index values following fire and were used as proxy of soil surface fire intensity to determine areas likely to have experienced soil heating suf-

ficient to induce water repellency. We also determined the boundaries of P-J woodland vegetation from the SWReGAP. From these data, 47 reference points were randomly generated in Hawth's Analysis Tools for ArcGIS 3.2 extension (www.spatialecology.com/htools; verified 22 Apr. 2011) for ArcGIS 9.3 (ESRI, Redlands, CA) within moderate-to-high-intensity burned P-J woodlands.

In the field, a GPS 60 navigator (Garmin Ltd., Olathe, KS) was used to locate the preselected reference points, and the nearest tree was identified as a datum for the survey of soil properties. Soil water content (SWC) and soil water repellency were measured in situ at 20-cm intervals along one radial line transect per tree. Line transects extended outward from each tree trunk to a distance of one canopy radius past the canopy edge, in a direction selected in the field to avoid obstacles such as fallen logs, large rocks, and erosion features (e.g., rills, washes, and soil deposition areas). Soil water content was measured between 2.0 and 5.5 cm below the soil surface with an ML2x ThetaProbe (Delta-T Devices, Cambridge, UK). Water repellency was measured with the WDPT test (Krammes and DeBano, 1965). Soils were considered water repellent if WDPT exceeded 5 s (Krammes and DeBano, 1965; Dekker and Ritsema, 2000). To determine the depth of the water-repellent layer, WDPT tests were performed at 0.5-cm increments at a point midway between the trunk and canopy edge.

Study 2: Summer Sampling

The second study was designed to quantify parameters similar to those measured during the winter campaign under low soil moisture conditions and to test the persistence of water repellency, its influence on soil infiltration, and its correlation to vegetation reestablishment. Sampling for this study was performed on 3 June 2008 and 13 July 2009. To limit the effects of landscape-scale heterogeneity in soil moisture and texture and to minimize the time costs associated with conducting a fine spatial scale survey, this study was confined to five Utah juniper [*Juniperus osteosperma* (Torr.) Little] trees within a 0.5-ha area, with the tree being the experimental unit.

The soil within the 0.5-ha study area was a coarse sandy loam, a mixed, mesic Aridic Haploxeroll (Soil Survey Staff, 2009). Precipitation at the site averages 370 mm annually and follows a bimodal distribution, with peaks in the late winter to early spring and fall (PRISM Climate Group, 2009). Before the fire, the vegetation community was a Phase III P-J woodland (i.e., "trees are the dominant vegetation and primary plant layer influencing ecological processes," Miller et al., 2005). The site was aerially reseeded by the U.S. Bureau of Land Management and Division of Wildlife Resources at 3.6 to 5.4 kg (8–12 pounds) pure live seed ha^{-1}, with the mix primarily containing introduced grasses. These species are commonly seeded after a fire to stabilize soils, improve forage production, and prevent weed invasion (Epanchin-Niell et al., 2009).

To assess the influence of water repellency, seven ecohydrologic parameters were measured every 30 cm along a randomly oriented transect extending 5 m from the base of each tree, for a total of 85 sampling points per year. Measurements included: extent, depth, and severity of soil water repellency, SWC, unsaturated hydraulic conductivity [$K(h)$], and in 2009 the understory vegetation cover and density. The extent, depth, and severity of soil water repellency and SWC were measured as described above. Two in situ infiltration measurements were taken at each sampling interval, one using water [$K(h^w)$] and the second using a surfactant (wetting agent) solution [$K(h^s)$] of 2.04% (v/v) of IrrigAid Gold (a mixture of 10% alkoxylated polyols, 7% glucoethers, and water, Aquatrols Corp., Paulsboro, NJ). This approach allowed us to estimate the influence of soil water repellency on unsaturated infiltration even where water repellency was not detectable through the WDPT test (i.e., subcritical water repellency). The method used in this study was modified from that of Tillman et al. (1989), who performed sorptivity measurements with water and ethanol. Automation methods, measurement procedures, and calculations were performed according to Madsen and Chandler (2007). Measurements were conducted with a −2.0-cm head to maximize spatial replication at the expense of characterizing $K(h)$ at several head values. All $K(h)$ measurements were corrected to standard temperature (20°C) by the viscosity ratio approach of Constantz (1982). Ocular estimates of total vegetation cover were estimated by species, within 25- by 25-cm quadrates. Within the same quadrates, plant density was sampled by counting the total number of plants by species.

Data Analysis

To provide consistency among trees with variable pre-burn canopy widths, sampling locations were normalized spatially by dividing the distance of the measurement location from the tree trunk by the estimated pre-burn canopy radius of the tree from which it was measured. Following normalization, data were grouped into 0.25 canopy radius (CR) intervals for statistical analyses. For example, with 0.0 as the base of the tree, 0.50 CR is the point midway between the tree's trunk and the canopy edge and would include all normalized measurement intervals between 0.25 and 0.50 CR. Statistical analyses were performed with SigmaStat 3.1 (Systat Software, Richmond, CA). A significance level of $P < 0.05$ was used for all comparisons. Because the data did not meet assumptions of normality (tested using the Kolmogorov–Smirnov test), Mann–Whitney rank sum tests were used for all pairwise comparisons between quartiles. Correlations among the ecohydrologic parameters measured in this study were analyzed separately within each field campaign using a Spearman rank correlation test, with results presented as correlation coefficients r and significant P values.

The fine-scale critical and subcritical water repellency data obtained in the 2008 summer campaign were used to demonstrate how spatial field data, in conjunction with remote sensing and GIS technology, can be used to model ecohydrologic patterns at the landscape scale. In this study, critical and subcritical water repellency were modeled across a 50-ha area containing similar soil and vegetation properties as observed at the locations of the field plots. Modeling was accomplished using a technique developed in this research and designated as the *radial feature extraction* (RFE) technique. In woodlands where individual trees are relatively circular and isolated from each other, modeling the extent of water repellency with the RFE technique was relatively straightforward. First, pre-burn P-J cover was extracted from near-infrared 1-m^2 aerial photography obtained from the USDA National Agricultural Imagery Program. In ERDAS Imagine (ERDAS Inc., Norcross, GA), a three-by-three low-pass convolution filter was applied to reduce image variability. A supervised classification procedure was performed using a maximum likelihood parametric rule to produce a Boolean image of P-J and treeless areas. The Boolean image was converted into vector format,

in which areas classified as P-J were represented by polygons. Within the attribute table of the Boolean image, the radius of each tree was derived from the area, A_p, and multiplied by the normalized canopy radius distance of the water-repellency parameter of interest, z, to obtain a unique buffer distance, B, for each polygon:

$$B = z\sqrt{\frac{A_p}{\pi}}$$

This buffer distance was then applied to the original polygon or tree shapefile in ArcGIS to determine the area of effect for the water-repellency parameter of interest.

The 50-ha area selected in this study for modeling contained many tree clusters in which trees were often tightly grouped, and on converting the Boolean output file to vector format it was observed that single polygons often represented several trees. When tree clusters were present, use of the basic RFE technique outlined above led to overestimation of water repellency because polygons representing several trees were treated as one large tree, thereby greatly inflating the actual area of the water-repellency parameter of interest. To address this problem, for each cluster polygon, the number of trees were visually estimated directly from an aerial photograph. This estimate was then divided into the area of the clustered polygon to obtain an average area for each tree within the polygon. Buffer distances were then derived from this average area using the formula outlined above.

RESULTS

Study 1: Winter Sampling

In the winter campaign, soils were found to be water repellent below the burned canopy of 87.5% of the trees sampled. For trees with hydrophobic soils, water repellency was generally not found near the base of the tree but was detected just out from the base at 0.08 ± 0.01 CR. Water repellency extended from this point out to 0.74 ± 0.04 CR (Fig. 1), or in other words roughly 66% of the canopy region was found to be water repellent. At the center of the canopy, water-repellent soil averaged 4.8 ± 0.5 cm thick, with an average minimum depth of 1.4 ± 0.1 cm (Fig. 1).

Significant differences in SWC were found across our measured line transects when soil water repellency was present, with SWC ranging from 11 ± 1% at 0.50 CR to 25 ± 1% at CR 2.00 (Fig. 1). For water-repellent trees, the 0.25 to 0.50 CR SWC values were similar. Beyond 0.50 CR, SWC increased out to 1.25 CR. From 1.25 to 2.00 CR, there were only slight increases in SWC values; SWC values between 1.00 and 1.25 CR were significantly less than those between 1.5 and 2.00 CR, but no differences were observed between 1.25 and 2.00 CR. Conversely, for trees that did not exhibit soil water repellency, we found SWC to be similar regardless of distance from the tree trunk, with an average SWC of 27 ± 1%.

3.2 Study 2: Summer sampling

All trees measured in the summer campaign were water repellent in 2008 and 2009 (Fig. 2). In 2008, the depth to the water-repellent layer was similar between 0.25 and 0.75 CR,

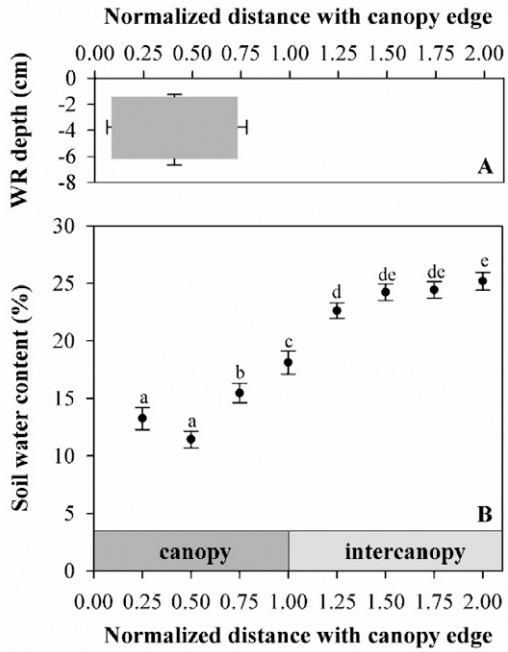

Fig. 1. Winter sampling measurements showing the (A) average extent and standard error of the water-repellent soil layer (WR) measured along radial line transects from the trees trunk to one canopy radius past the canopy edge (along the *y* axis, average depth to the WR layer and maximum depth of the WR soil layer measured in a soil pit dug halfway between the trees trunk and the burned canopy edge); and (B) mean soil water content and standard error from the same transects. Measurements were normalized with respect to canopy width by dividing the distance of the measurement location from the trunk by the canopy radius. Following normalization, data were grouped into 0.25 canopy radius intervals. Points with different letters are significantly different ($P < 0.05$).

with the average depth at these locations equal to 1.7 ± 0.2 cm. At 1.00 CR, the minimum depth to the water-repellent layer decreased to 0.92 ± 0.22 cm and further decreased to 0.37 ± 0.14 cm at 1.25 CR.

The thickness of the water-repellent layer was similar under the burned canopy region, averaging 4.5 ± 0.2 cm (Fig. 2). This value was similar to the water-repellency thickness obtained in the 2008 winter measurements. Beyond the canopy edge, the thickness of the water-repellent layer decreased to 1.7 ± 0.6 cm at 1.25 CR; beyond this distance water repellency was not detected. Depth to the water-repellent layer and water-repellency thickness in 2009 was similar to 2008, with the exception of measurements at 1.00 and 1.50 CR. At 1.00 CR, water-repellency thickness decreased by 2 ± 0.6 cm, and at 1.50 CR a thin, sporadic water-repellent layer was detected.

As expected, $K(h^w)$ was lowest where water repellency was most pronounced, whereas $K(h^s)$ was accentuated by water-repellent soil (Fig. 2; Table 1). In 2008, $K(h^w)$ was near zero from 0 to 0.75 CR; beyond this point, $K(h^w)$ steadily increased out to 1.50 CR. Measurements of $K(h^s)$ were significantly higher than $K(h^w)$ at all CR except for 2.00 CR. Because water repellency was only detected out to 1.25 CR with water drop tests, these results probably indicate that in 2008 there is a zone of subcritical water repellency that extended beyond 1.25 CR out to 1.75 CR.

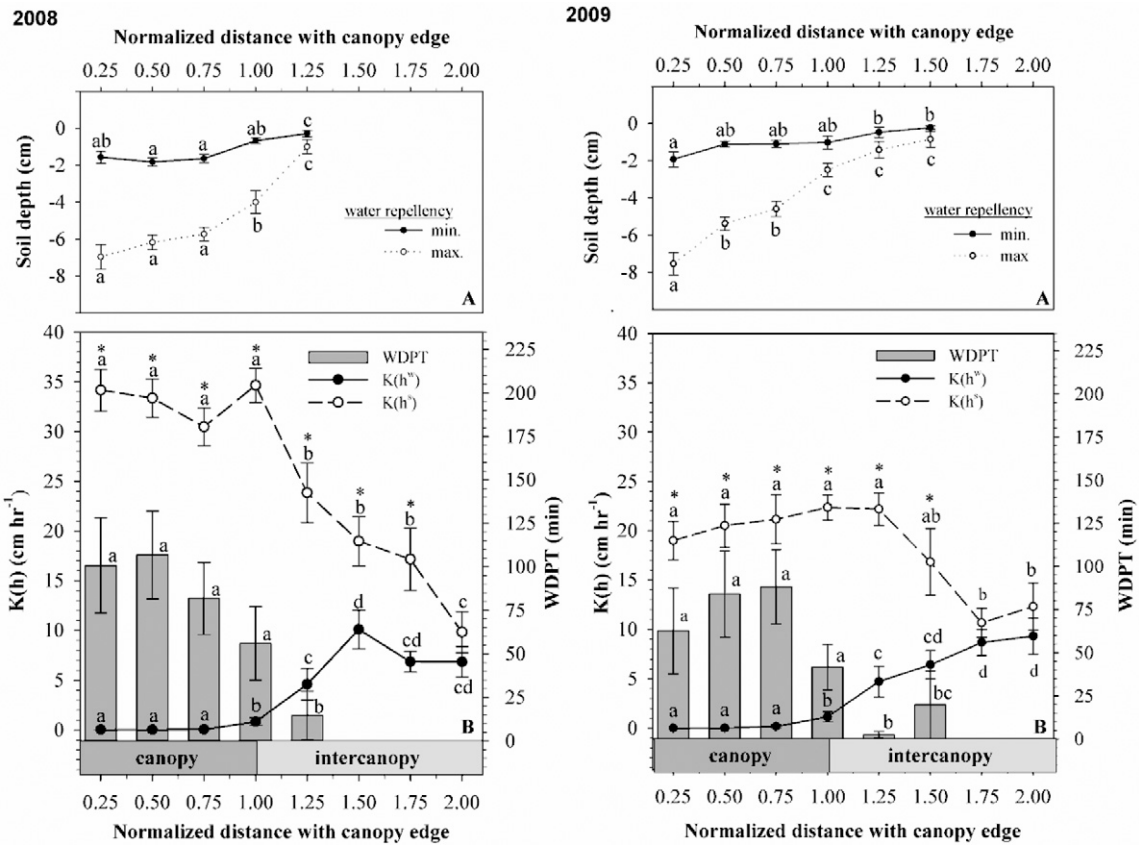

Fig. 2. Results of 2008 and 2009 summer sampling periods: (A) Minimum and maximum depths of the water-repellent layer; and (B) water-repellence severity measured through water drop penetration time (WDPT) tests and unsaturated hydraulic conductivity measured with water [$K(h^w)$] and a wetting agent [$K(h^s)$]. Measurements were normalized with respect to the canopy width by dividing the distance of the measurement location from the trunk by the canopy radius. Following normalization, data were grouped into 0.25 canopy radius intervals. All results are presented as mean and associated standard errors. Points with different letters are significantly different ($P < 0.05$). *Significant difference between $K(h^w)$ and $K(h^s)$.

For both summer measurements, SWC increased with distance from the tree trunk, similar to the pattern observed in the winter campaign (Fig. 3). Within the 2008 data set, SWC was near zero from 0.25 to 0.75 CR. A clear gradient in SWC emerged between 0.75 and 1.75 CR, but beyond that point SWC remained similar among canopy radii. Within the 2009 data set a similar relationship was found.

Establishment of seeded species was near zero, composing only 1.5% of the total density (0.5 plants m^{-2} seeded species and 31.1 plants m^{-2} of volunteer species). Total plant density in the canopy area was similar among quartiles, with an average of 3.1 $\pm$ 1.1 plants m^{-2}, and significantly less than in the intercanopy, where density averaged 60.9 $\pm$ 6.3 plants m^{-2} (Fig. 4). Within the intercanopy, plant density also appeared to increase with distance from the trunk (Fig. 4).

The three most dominant plant species at the site were shy gilia [*Gilia inconspicua* (Sm.) Sweet], cheatgrass (*Bromus tectorum* L.), and coyote tobacco (*Nicotiana attenuata* Torr. ex S. Watson). Within the burned canopy, the density of *G. inconspicua* and *B. tectorum* was near zero but increased in the intercanopy to 3.5 $\pm$ 0.4 and 0.09 $\pm$ 0.03 plants m^{-2}, respectively. The density of *N. attenuata* was the same between the canopy and intercanopy, with 0.02 $\pm$ 0.02 plants m^{-2} (Fig. 5). Changes in plant cover with distance from the tree trunk were less abrupt and more variable than plant density (Fig. 6). Much of the variability in plant cover was attributable to *N. attenuata*, which is a relatively large plant and infrequent at the site. Reanalysis of the cover data without *N. attenuata* reduced the variability among the quartiles. Without *N. attenuata*, no significant differences were observed between cover values from 0.25 to 1.25 CR (average 0.3 $\pm$ 1.0%); beyond 1.25 CR, cover values increased significantly but were similar among quartiles, averaging 2.3 $\pm$ 0.3%.

Remote Sensing and Geographic Information System Analysis

Within the 50-ha area selected for modeling water repellency, P-J cover was 23% as measured using the supervised classification techniques outlined above. Figure 7 shows the results of the proposed RFE method for extrapolating spatial field measurement data to the landscape scale. A visual assessment of the results shows that the modeling technique is accurate insofar as it can be determined without conducting in situ accuracy assessments. Using the proposed method and 2008 field data, we estimated that 56.5% or 28 ha of the 50-ha area would be affected by water repellency, with an estimated 34.4 and 22.1% of the

Table 1. Correlation matrix between water drop penetration time (WDPT), minimum distance to the water-repellent layer (WR), maximum depth of the water-repellent layer, thickness of the water-repellent layer, soil water content (SWC), and unsaturated hydraulic conductivity measured with water [$K(h^w)$] and a wetting agent [$K(h^s)$]. Data are shown from measurements taken in 2008 and 2009. In 2009, plant density and cover were also collected and results are presented with and without *Nicotiana attenuata*. Only significant ($P < 0.05$) correlation coefficients (r) are shown.

	Summer 2008							Summer 2009									
		Water repellent depth				Infiltration			Water repellency				Infiltration		Vegetation		
Variable	WDPT	Min.	Max.	Thickness	SWC	$K(h^w)$	$K(h^s)$	WDPT	Min.	Max.	Thickness	SWC	$K(h^w)$	$K(h^s)$	Density	Cover	Cover without *N. attenuata*
Tree distance	−0.60	0.69	−0.84	−0.83	0.75	0.66	−0.73	−0.46	0.56	−0.84	−0.81	0.70	0.73	−0.33	0.72	NS†	0.57
WDPT		0.52	0.68	0.69	−0.50	−0.43	0.62		0.40	0.43	0.37	−0.44	−0.40	0.26	−0.44	NS	−0.34
Min. WR			0.85	0.71	−0.66	−0.54	0.53			0.70	0.44	−0.52	−0.48	0.28	−0.53	NS	−0.38
Max. WR				0.98	−0.70	−0.66	0.71				0.95	−0.73	−0.62	0.30	−0.69	NS	−0.46
WR thickness					−0.66	−0.65	0.72					−0.69	−0.57	0.25	−0.63	NS	−0.41
SWC						0.61	−0.60						0.50	−0.35	0.66	NS	0.45
$K(h^w)$							−0.49							−0.35	0.71	NS	0.45
$K(h^s)$															−0.47	NS	−0.39

† NS, nonsignificant correlation.

Fig. 3. Soil water content (SWC) measured in 2008 and 2009 every 30 cm along radial line transects from the tree trunk to one canopy radius past the burned canopy edge. Measurements were normalized with respect to the canopy width by dividing the distance of the measurement location from the trunk by the canopy radius. Following normalization, data were grouped into 0.25 canopy radius intervals. All results are presented as mean and associated standard errors. Points with different letters are significantly different ($P < 0.05$).

Fig. 4. Total plant density in relation to distance from the tree's trunk. Measurements were normalized with respect to the canopy width by dividing the distance of the measurement location from the trunk by the canopy radius. Following normalization, data were grouped into 0.25 canopy radius intervals. All results are presented as mean and associated standard errors. Points with different letters are significantly different ($P < 0.05$).

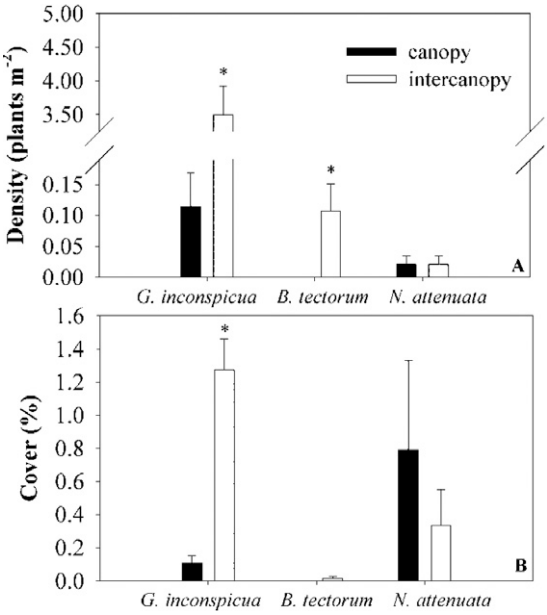

Fig. 5. Average and associated standard error values for canopy and intercanopy (A) plant density and (B) cover for *Gilia inconspicua*, *Bromus tectorum*, and *Nicotiana attenuata* by species. *Significant differences ($P < 0.05$) between canopy and intercanopy values.

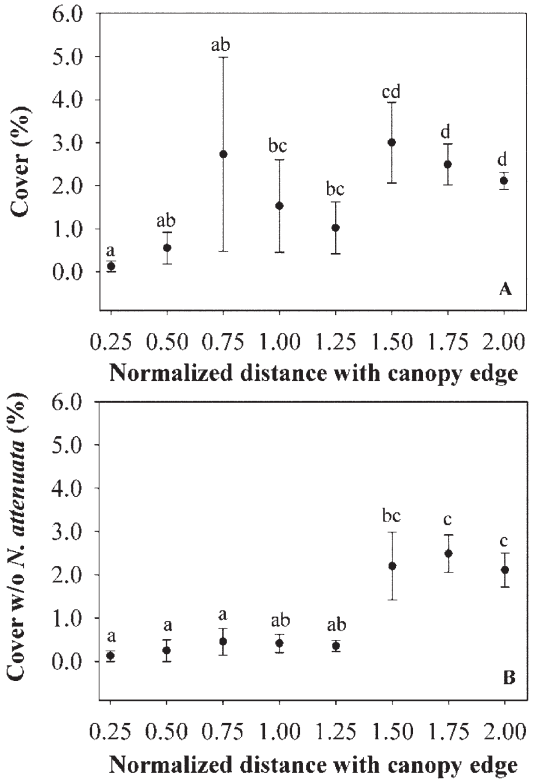

Fig. 6. Vegetation cover data in relation to distance from the tree's tree trunk (A) with and (B) without *Nicotiana attenuata*. Measurements were normalized with respect to the canopy width by dividing the distance of the measurement location from the trunk by the canopy radius. Following normalization, data were grouped into 0.25 canopy radius intervals. All results are presented as mean and associated standard errors. Points with different letters are significantly different ($P < 0.05$).

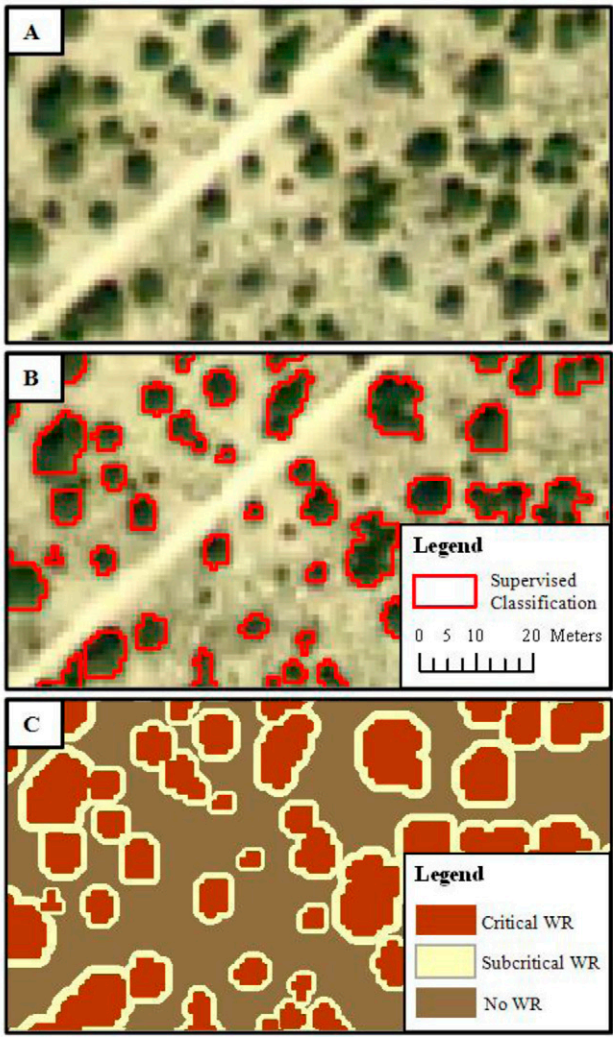

Fig. 7. (A) Example of the aerial photography of a burned piñon–juniper site used in this study; (B) extraction of tree cover using a supervised classification; and (C) estimate of the percentage of the landscape influenced by critical and subcritical water repellency (WR).

landscape affected by critical and subcritical water repellency, respectively (i.e., critical water repellency extends to 1.25 CR and subcritical water repellency continues to 1.75 CR).

DISCUSSION

This study is unique in that it is the first to quantify, within a P-J woodland, the spatial distribution of soil water repellency with respect to the canopy boundary and its correlation with post-fire revegetation success. Other P-J woodland studies have noted the presence of water repellency and its impact on infiltration (Roundy et al., 1978; Rau et al., 2005) but none have looked at the spatial distribution of water repellency in great detail and quantified its correlation to SWC, infiltration, and vegetation recovery. The results of this study are consistent with previous studies conducted in unburned P-J woodlands with similar sampling designs (Lebron et al., 2007; Madsen et al., 2008), where the total area influenced by soil water repellency was directly related to tree canopy cover (Table 1; Fig. 8).

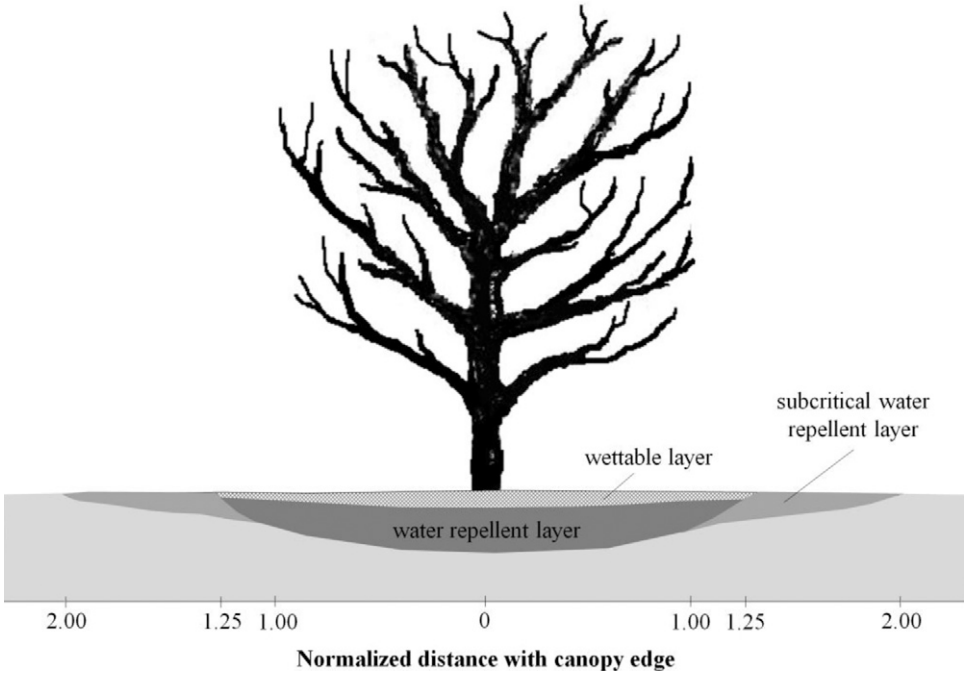

Fig. 8. Schematic diagram of a burned tree canopy, showing areas of water-repellent soil and subcritical water-repellent soil.

Field Sampling

In this study, the degree of water repellency was highly correlated with reductions in SWC, infiltration, and understory seedling density and cover. Even during the winter campaign when precipitation inputs were high, SWC was significantly lower where there was an indication of water repellency. The extent to which subcritical water-repellent soil was correlated with SWC, infiltration, and vegetation recovery was also clarified. The winter soil moisture survey showed that SWC did not increase abruptly immediately beyond the boundary of the strongly water-repellent zone, as determined by the 5-s WDPT criterion. There may be several reasons for this result; for example, snow distribution, and snowmelt patterns may be modified by the skeletal remains of the burned trees (Lebron et al., 2007). The results from the summer sampling periods, however, support the view that this may also be due to the presence of subcritical water repellency (Fig. 2). In the summer campaigns, infiltration analysis by $K(h^{w})$ and $K(h^{s})$ measurements found that the extent of critical water repellency was just beyond the pre-burn canopy edge (1.25 CR), whereas subcritical water repellency extended to 1.75 CR (Fig. 8), similar to conditions at an unburned site in a previous study (Madsen et al., 2008). With P-J trees being roughly circular in shape, this increase in water repellency extent from 1.25 to 1.75 CR translates into a 96% increase in the extent of the actual water-repellent area above that estimated by a WDPT criterion of 5 s. Because subcritical water repellency is also correlated with low SWC, infiltration, and understory seedling density and cover (albeit to a lesser extent than critical water-repellency levels), these results provide justification for measuring both critical water repellency and subcritical water repellency when assessing post-fire soil hydrologic conditions.

The effect of soil water repellency is rarely considered in post-fire rangeland revegetation efforts. Furthermore, this is the first research study that has investigated the correlation and potential impact of subcritical water repellency on post-fire hydrologic and vegetation responses. Particularly within forested and chaparral conditions in the United States, the extent and severity of soil water repellency is generally quantified through WDPT tests; however, the assessment of soil water repellency through standard WDPT tests can be highly subjective, time consuming, and limited in both degree and scope (Hallett et al., 2001; Lewis et al., 2006). Robichaud et al. (2008) proposed that the mini-disk infiltrometer can be used to estimate the severity of soil water repellency. Our study supports the findings of Robichaud et al. (2008) by showing that there is a significant correlation between WDPT tests and mini-disk infiltrometer measurements [$r = -0.40$ for both 2008 and 2009 samplings for correlation between $K(h^{w})$ vs. WDPT] (Table 1); however, the relationship between WDPT and $K(h^{w})$ was weak in this study. Weak correlation between the two measurements may be associated with the limitations of the two measurements. In this study, $K(h^{w})$ was near zero within the severely water-repellent soil sections under the tree; however, the WDPT tests showed variability within the severely water-repellent portions of the soil, which may indicate that the WDPT test has a greater ability to detect relative differences in severely water-repellent soil. In contrast, beyond the canopy edge, $K(h^{w})$ appeared to be sensitive to changes in subcritical water repellency, where WDPT tests were incapable of detecting repellency at this level.

Performing both $K(h^{w})$ and $K(h^{s})$ measurements appears to be an effective method for quantifying relative differences in soil water repellency from severe to subcritical levels. In contrast to $K(h^{w})$

measurements, infiltration rates of $K(h^s)$ are positively correlated with the severity of the water-repellent soil (Table 1) due to the surfactant solution being attracted to the hydrophobic material in the soil (Feng et al., 2002; Kostka and Bially, 2005). Therefore, as the difference between $K(h^w)$ and $K(h^s)$ increases, the degree of soil water repellency also increases. Future laboratory research is merited for determining the validity of using $K(h^w)$ and $K(h^s)$ measurements to assess relative changes in soil water repellency. It should also be mentioned that the infiltration response in this study may have also been influenced by other soil factors, such as post-fire pore clogging, bulk density, aggregate stability, and soil texture.

The results of this study complement those of previous studies that have correlated areas of pre-burn canopy cover with a lack of understory vegetation for one or more years following fire in P-J woodlands (Ott et al., 2001), desert scrub communities (Adams et al., 1970), and sagebrush communities (Salih et al., 1973). Although there was a decrease in subcritical water repellency during our study, soil water repellency persisted throughout the 2-yr study period, with its presence mirrored by an impairment of vegetation recovery.

Post-fire soil water repellency can limit revegetation success by decreasing soil moisture duration and availability to seeds and seedlings. As shown in Fig. 8, after a fire, the soil exhibits a shallow wettable layer that overlies a several-centimeter-thick, water-repellent layer. Even if the wettable zone contains sufficient moisture for seed germination, there may not be adequate moisture for seedling survival due to the water-repellent layer disconnecting the seedling from deeper soil moisture reserves. Moisture availability may also be decreased for seeds and seedlings as a result of the water-repellent layer creating preferential flow channels, thereby lowering the total volume of soil that is available for moisture retention in the upper centimeters of the soil profile (Dekker and Ritsema, 2000).

The total density of *N. attenuata* was relatively low; however, it is interesting to note that this species grew equally well throughout the burned woodland. This species is an early-successional, annual species that occurs for 1 to 3 yr after fire in *Artemisia–Juniperus* habitats (Baldwin and Morse, 1994). Understanding the mechanisms that allow this species to establish within severely water-repellent soils could potentially help land managers and plant breeders select species with similar characteristics for post-fire reseeding projects.

Application of Geographic Information System and Remote Sensing Technology

This research establishes the utility of using remotely sensed pre-burn P-J cover and GIS software in conjunction with spatial field data to model post-fire water repellency. The primary benefits of the proposed RFE technique are that (i) it allows fine-scale assessments of soil water repellency to be extrapolated to the landscape scale; (ii) with refinement, it has potential to support the prediction of ecohydrologic responses associated with water-repellent soils (e.g., SWC and vegetation recovery); and (iii) it is highly transferrable to land managers. This is realized in the relatively simple nature of the ArcGIS commands required and in the ability to make all calculations within the attribute table. In addition, while strong relationships between water repellency and various post-fire site characteristics such as ash (Lewis et al., 2006) are established, modeling these characteristics requires specific remotely sensed images that are not always readily available. In contrast, the proposed technique uses pre-burn imagery that is publicly available in many states and can be acquired immediately after a fire. Accordingly, this technique has the potential to produce highly accurate maps of water repellency with minimal time and material costs.

The capacity to efficiently map water repellency is valuable for several reasons. Woods et al. (2007) suggested that the spatial contiguity of water repellency across the landscape is an important predictor of overland flow. The results of this study further suggest that soil water repellency may also be an important predictor of vegetation recovery. The RFE approach can be applied to develop post-fire burn severity maps that represent the spatial contiguity of critical and subcritical soil, thereby providing vital information for the development of models that predict flood generation, water and wind erosion, and revegetation success. Such multiuse planning tools aid land managers in their allocation of limited resources across vast land areas.

In the United States, post-fire burn severity maps are typically produced by the U.S. Forest Service Burned Area Emergency Rehabilitation (BAER) teams to identify areas where fire-induced changes to soils have increased the potential for runoff and soil erosion (Lewis et al., 2006). The RFE method proposed in this study produces much finer scale maps and ecohydrologic predictions compared with those produced by the BAER team.

We recognize that the procedures used in this study are limited by not including an accuracy assessment component. Future work should be performed to test the accuracy of this water-repellency mapping technique. In addition, estimating the spatial distribution of soil water repellency using a combination of ground truth field measurements and remotely sensed data may be limited to similar ecological sites proximal to where the field data were collected. Future studies may improve the prediction of post-fire water repellency by developing models that incorporate various ecological site characteristics that have been shown to have an influence on soil water repellency (i.e., soil texture, soil organic matter content and nature, pH, soil temperature, seasonal soil moisture, microbial activity, fungal hyphae, and topographic position) (DeBano, 1991; Dekker and Ritsema, 2000; Doerr et al., 2000; Lewis et al., 2006).

CONCLUSIONS

Post-fire patterns of soil water repellency were highly correlated with pre-fire P-J woodland canopy structure, soil water content, infiltration, and revegetation success. Soil water repellency was found to extend just beyond the canopy edge, while subcritical water repellency extended almost a full canopy radius beyond the canopy edge. Water repellency in this zone was still strong 2 yr after the fire. Where soil water repellency was present, SWC, $K(h^w)$, and vegetation recovery were significantly lower than where soil water repellency was not present. These parameters

were most reduced where water repellency was detected through WDPT tests but were also decreased to a lesser extent on soils with subcritical soil water repellency. Consequently, the severity and extent of soil water repellency may significantly impair post-fire reseeding efforts by limiting seedling establishment.

There is a need for innovative management tools and practices that assist in the monitoring and treatment of post-fire P-J woodlands. Based on the strong relationship that we found between soil water repellency and pre-burn canopy cover, remotely sensed imagery appears to be an effective method for scaling up estimations of water repellency to the fire-boundary scale. While the GIS modeling concept proposed in this study for mapping soil water repellency has merit, the approaches proposed require further refinement and testing at different temporal and spatial scales.

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