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Post-Fire Soil Water Repellency: Extent, Severity and Thickness Relative to Ecological Site Characteristics Within Piñon-Juniper Woodlands

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A thesis submitted to the faculty of
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Master of Science

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ABSTRACT

Post-Fire Soil Water Repellency: Extent, Severity and Thickness Relative to Ecological Site Characteristics Within Piñon-Juniper Woodlands

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Erosion and weed dominance often limit the recovery of burned piñon-juniper woodlands. Soil water repellency (SWR) is one factor that may contribute to this by increasing overland flow and impeding seedling establishment. In spite of these effects, the extent of SWR within piñon-juniper woodlands is unknown. In this study, the extent, severity and thickness of SWR were sampled across 41 1,000 m^2 plots within three 2009 Utah wildfires. Predictive models of SWR were built from ecological site characteristic data collected at each site. Across the study, SWR was found at 37% of the points sampled. SWR extent was strongly related to piñon-juniper canopy cover ($r^2 = 0.60$) and was found to be significantly higher in tree/shrub mound zones (71%) as compared to interspaces (16%). Endorsed predictive models of SWR extent and severity had R^2_{adj} values of 0.63 and 0.61; both models included piñon-juniper canopy cover and relative humidity the month before the fire as coefficient terms. These results suggest that as piñon-juniper canopy cover increases due to infilling processes in the coming years, post-fire SWR extent and severity will increase. As the effects of a changing climate in the Intermountain West link additively with infilling processes to increase the frequency and intensity of wildfires, the net effect will be stronger SWR over a greater spatial extent. To cope with these changes, land managers can apply the predictive models developed in this study to prioritize fuel control and post-fire restoration treatments with respect to SWR.

Keywords: woodland encroachment, hydrophobicity, wildfire, restoration, climate change, ecological site characteristics

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Post-Fire Soil Water Repellency: Extent, Severity and Thickness Relative to Ecological Site Characteristics within Piñon-Juniper Woodlands

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1. Introduction

Piñon (*Pinus sp.*) and juniper (*Juniperus sp.*) woodlands have replaced historically-dominant sagebrush/bunchgrass vegetation types throughout the western United States (Miller and Rose 1995; Miller and others 2008) and now cover over 40 million hectares (Romme and others 2009). This expansion has been associated with favorable climatic conditions (Graumlich 1987; LaMarche 1974) and fire frequency reductions brought about by livestock grazing (Burkhardt and Tisdale 1976; Miller and Rose 1999) and historic fire suppression policies (Agee 1993). In addition to supporting expansion, fire frequency reductions have led to increased piñon-juniper fuel loads and improved crown fuel continuity (Tausch 1999*a*), thereby facilitating stand-replacing crown fires. As a result, high intensity wildfires in piñon-juniper woodlands have increased in size and frequency throughout the Intermountain West (Gruell 1999; Miller and Tausch 2002).

Following fire, the recovery of pre-expansion communities is dependent on the extent that physical and biological processes controlling ecosystem function have been altered (Miller and Tausch 2001; Briske and others 2005). If extensive, alterations can trigger feedback mechanisms that lead to the crossing of biotic and abiotic ecological thresholds (Davenport and others 1998; Tausch 1999*b*; Briske and others 2008). When thresholds are crossed in expansion piñon-juniper woodlands, sites transition to undesirable alternative stable states, recovery from which may not be possible without intensive intervention (Tausch 1999*b*; Miller and others 2000).

One factor that may alter hydrologic processes following fire is soil water repellency (SWR). Soil water repellency develops or is intensified during fire as organic material accumulations in the tree/shrub mound zones of woody species volatilize, are forced downward by a pressure gradient, and condense in the cooler underlying soil layer, creating a non-polar soil coating with a reduced affinity to polar molecules, including water (DeBano and others 1976; Letey 2001). Water repellency directly influences hydrology by reducing infiltration and percolation rates (DeBano 1971; Doerr and Thomas 2000; Pierson and others 2001; Doerr and others 2003; Spaeth and others 2007; Madsen and others 2011). This primary effect has many secondary effects, including reduced soil moisture (Wallis and Horne 1992; Madsen and others 2011) and enhanced runoff and erosion (DeBano 2000; Benavides-Solorio and MacDonald 2001; Martin and Moody 2001; Leighton-Boyce and others 2007). In modifying soil moisture dynamics and increasing erosion rates, SWR may reduce the germination and establishment success of herbaceous species (Wallis and Horne 1992; Madsen and others 2012), particularly grasses (Letey 2001), after fire rehabilitation seeding. This in turn can increase invasibility and accelerate site degradation (Young and Evans 1978; Wisdom and others 2003).

The magnitude of these SWR responses is related to the continuity and strength of the water repellent layer (Pierson and others 2001; Woods and others 2007; Doerr and others 2009). Typically, overland flow generated in water repellent zones infiltrates as it contacts adjacent hydrophilic patches or conduits (Shakesby and others 2000); however, when SWR continuity is high, hydrophilic patches are sparse and inadequate to accommodate infiltration of surface runoff excesses generated in the water repellent areas (Woods and others 2007). Woods and others (2007) intensively studied the continuity of SWR at multiple spatial scales and concluded that whenever water repellent soils comprise more than 75% of sampled points (i.e. 75% SWR extent) within a slope or watershed, there is a high probability that continuous overland flow will be generated.

Soil water repellency has been documented in piñon-juniper woodlands (Scholl 1971; Jaramillo and others 2000; Madsen and others 2008; Roundy and others 1978; Rau and others 2005; Madsen and others 2011); however, studies have been localized and the continuity and strength of this soil condition have not been clearly shown. In addition, data is lacking that links SWR to specific ecological site characteristics, leaving land managers without tools to identify areas where SWR may be a problem in the absence of *in situ* data.

Links between SWR and specific site characteristics have been established in various other systems (e.g. eucalyptus and conifer forests, grasslands, cultivated land, subalpine meadows, chaparral, and turf grass; Doerr and others 2000a and references therein). Of the many tested characteristics, soil organic matter (Scholl 1971; Varela 2005; Mataix-Solera and others 2007a), pH (Roberts and Carbon 1971; Steenhuis and others 2001; Mataix-Solera and others 2007b; Hurraß and Schaumann 2006; Martinez-Zavala and others 2009), texture (DeBano 1991; Mataix-Solera and others 2007; Jordan and others 2009), soil moisture (Doerr and others 2000b; Letey 2001), burn severity (Pierson and others 2002; Jordan and others 2011), litter (McGhie and Posner 1981; Scott 2000), vegetation type/land use (Doerr and others 2000a; Doerr and others 2006; Mataix-Solera and others 2007b; Tessler and others 2008), and topography (Pierson and others 2002; Tessler and others 2008; Doerr and others 2009) have received the most attention.

While strong relationships between these variables and SWR have been found in many cases, inconsistencies between studies are common (Doerr and others 2000a). For example, in the eucalyptus forest watersheds near Sydney, Australia, Doerr and others (2006) found soil organic matter to be a poor predictor of SWR, while in the Mediterranean heathlands of southern Spain, Martinez-Zavala and others (2009) found organic matter the be a "main factor" influencing water repellency. Conflicts such as this preclude the extrapolation of documented links between site characteristics and SWR to other systems where SWR data is lacking.

The objectives of this research were to: 1) quantify the extent, severity, and thickness of SWR within burned piñon-juniper woodlands across a range of ecological sites, 2) determine which ecological site characteristics are most closely related to SWR within these woodlands, and 3) develop predictive models of SWR that could be used by land managers without the need to gather extensive *in situ* data. It was hypothesized that SWR would have a close association with piñon and juniper individuals, with soil attributes and topography playing important roles in defining SWR extent, severity and thickness.

2. Methods

2.1. Site Selection

Three major wildfires that burned in the state of Utah in 2009 were selected for SWR sampling: Big Pole, Broken Ridge, and Mill Flat. These fires burned primarily in piñon-juniper woodlands, were ignited on 25 July, 2 August, and 7 August and burned 17,775, 1,995, and 4,856 hectares. To increase the likelihood of capturing the natural variability typical in SWR, study sites were spread across the distributions of five ecological site characteristics shown important to the formation of SWR in other systems: soil texture, soil pH, soil organic matter content, precipitation and heat load. Precipitation and heat load were used as proxies for soil moisture and topography, respectively. Heat load is an index of potential soil heating resultant from the timing of solar radiation relative to aspect, slope, and latitude (McCune and Keon 2002).

In addition to their support in the literature, these variables were selected for their availability in GIS format and public accessibility. Accessibility and GIS availability were central to the remote identification of suitable study sites and to our objective of developing predictive models of SWR independent of extensive *in situ* data.

Geospatial fire boundary data for the three fires were post-processed in ArcGIS$^{\circledR}$ 9.3 (ESRI, Redlands, CA) to represent exclusively piñon-juniper woodlands. Usable areas for the Big Pole, Broken Ridge, and Mill Flat fires were 7,359, 981, and 2,080 hectares, respectively. Soil and precipitation data were obtained from the NRCS Soil Data Mart (http://soildatamart.nrcs. usda.gov) and the PRISM Climate Group (http://www.prism.oregonstate.edu). Heat load data were developed using methods established by McCune and Keon (2002), using data derived from 10 m digital elevation models (DEMs), acquired online from the Utah GIS Portal (http://gis.utah.gov). Piñon-juniper woodland fire boundaries were then further refined to exclude areas where data for these five variables were not available.

To obtain study sites distributed across the five variables, each variable was broken into three equal interval groups (i.e. low, medium, high) using the “Reclassify” tool in Spatial Analyst, an extension to ArcGIS. Within ArcGIS, all potential combinations of the three groups by the five variables were identified. Of the total 243 potential combinations (3 groups$^{\wedge 5\ \text{variables}}$ = 243), 41 were found within the refined piñon-juniper woodland fire boundary dataset. Polygons representing each of these 41 combinations were created using the “Intersect” tool. A random point was then generated within each of these polygons using the “Create Random Points” tool. These random points became the southwest corners of the study sites.

2.2. Sampling Protocol

Random points were located in the field using a handheld Trimble GeoXH global positioning system (GPS) receiver (Trimble, Sunnyvale, CA). At each random point, a 30 x 33 m (~1000 m^2) plot was established with the 33 m axis oriented N–S and the random point serving as the southwest corner. Five 21 m transects were systematically placed along the 30 m E-W axis at 2, 7, 15, 23, and 28 m, with a 4.5 m buffer between the start and end of each transect and the plot edge. Measurements were taken every 3 m along each 21 m transect for a total of 9 sampling points per transect and 45 sampling points per plot.

Water repellency was measured at each sampling point with the water drop penetration time (WDPT) test (Krammes and DeBano 1965), with soils considered water repellent if WDPT time exceeded five seconds (Bisdom and others 1993). Where SWR was found, depth of the WR layer was determined by performing WDPT tests every 5 mm. Severity of water repellency was assessed by recording the time for a drop of water to enter into the soil. For sample locations that had WDPTs over 2 minutes in the field, a soil sample was collected and WDPT tests were conducted in the lab.

Following SWR sampling, the nearest woody plant to each point was located, species was determined, distance between the sampling point and the trunk and canopy edge of that species was measured, and microsite (i.e. tree mound or interspace) was recorded. If the nearest woody species was a piñon or juniper individual, a radial growth core was extracted and crown height and width, trunk diameter, and burn severity were measured.

Radial growth cores were extracted 30 cm above the soil surface using a 30 mm, 3-thread, 5.15 mm diameter increment borer (Haglöf Company Group, Långsele, Sweden). In the laboratory, cores were polished and growth rings counted under binocular magnification to record the number of rings (Ferguson 1970). Piñon and juniper species are notorious for having false and missing rings (Despain 1989); to accurately determine age, cross-dating is necessary. This level of accuracy was outside the scope of this project, consequently the absolute age of the cored trees was not determined.

Tree crown width was measured at both the overall widest point, and the widest point perpendicular to this first point. These two measurements were averaged. Stem diameter was measured just above the root crown. Burn severity was based on a subjective five point scale. Within this scale, classes were defined as follows: 1 - burned piñon-juniper trees with the majority of the needles still attached, 2 - needles lacking, major branches still present, 3 - major branches lacking, trunk still intact, 4 - trunk hollowed out or otherwise not intact, but still present, and 5 - trunk lacking.

At the plot level, four soil subsamples were taken from both the interspace and tree/shrub mound regions. The top 6 cm of soil, excluding the ash layer, were taken as this is typically where SWR forms within the profile (Madsen and others 2011). Subsamples were combined for each region, and acidity, soil organic matter, and texture were analyzed in the lab using saturation extract (Rhodes 1982), dichromate oxidation (Walkley and Black 1934), and hydrometer (Day 1965) methods.

Heat load data were extracted at the plot level from the DEM dataset retrieved previously in the study site selection process, as were elevation, aspect, and slope. Piñon-juniper canopy cover was manually digitized from 1-m resolution digital orthophoto quarter quads (DOQQ) acquired from the National Agriculture Imagery Program (US Department of Agriculture 2008). Climate data, including annual and July 2009 (the month before ignition for all three fires in this study) precipitation, temperature, and dewpoint were extracted for each study site from the Prism

Climate Group dataset. Relative humidity was calculated from temperature and dewpoint using the Goff-Gratch Equation (Ahrens 1994).

2.3. Data Analysis

Statistical analyses were conducted at both the sampling point and plot levels using JMP 10.8 (SAS Institute; Cary, USA). Soil water repellency severity data were classified using the following 4-point scale suggested by Bisdom and others (1993): Slight SWR = WDPT 5-60 s, Strong SWR = WDPT 60-600 s, Severe SWR = WDPT 600-3600 s, and extreme SWR = WDPT > 3600 s. At the plot level, SWR extent was defined as the percentage of points within a plot where SWR was present. The number of sites where SWR extent was greater than 75% was then calculated. Water repellency thickness and severity were averaged across all water repellent sampling points.

Data from all 1,845 sampling points (41 sites x 45 sampling points per site = 1,845) were pooled in the sample point analysis and site was set as a random effect. Mantel's test was performed in R (R Core Development Team; Vienna, Austria) to verify that these data were not spatially autocorrelated (Sokal and Rohlf 1995). Comparisons of SWR extent between microsites and species were conducted with Fisher's Exact test, while comparisons of SWR severity and thickness were conducted with Welch's test. Between species comparisons were restricted to the two primary overstory species, singleleaf pinyon (*Pinus monophylla* Torr. & Frém.) and Utah juniper (*Juniperus osteosperma* (Torr.) Little). Differences in the distance to the canopy and distance to the trunk between sampling points where SWR was present/absent were also determined with Welch's test. Welch's test was used due to the non-normal distribution and unequal variance of these response data (Skovlund and Fenstad 2001).

The plot level dataset was refined prior to analysis to eliminate correlated explanatory variables. All variables were regressed against each other and a 0.60 correlation coefficient threshold was set. Variable pairs exceeding this threshold were resolved by eliminating the variable having the weakest relationship to SWR. When two correlated variables were similarly related, their strength in the literature was reviewed and the variable having the most support was retained.

A model list was developed for each SWR characteristic from this refined plot level dataset. All models were limited to three coefficients due to the limited number of replications (i.e. study sites). All coefficient estimates were required to be significant. Top models were selected based on their Bayesian Information Criterion (BIC) values; models with the lowest BIC values ranked highest (Burnham and Anderson 1998). Outliers and influential points were identified using studentized residuals and Cook's distance values (Cook and Weisberg 1982).

A single model was selected from within the top model lists for use in predicting each SWR characteristic. These models were selected based on their parsimony and the remote accessibility of their coefficient terms. Model parsimony was a key criterion in the selection process as it reduces the likelihood that the selected model is an artifact of the data, rather than the observed phenomenon. Remote coefficient accessibility ensures that selected models can be effective in the absence of *in situ* data.

The relative importance of individual ecological site characteristics was determined through the following procedure. A model average with a three coefficient maximum was developed for each SWR characteristic and a model averaged formula was derived. Within each formula, median field values were input for all coefficients but one. For the one remaining coefficient, coefficient *x*, the maximum field value was input and the product of the formula,

Max_x, was recorded. This process was repeated using the minimum field value of the one remaining coefficient to produce Min_x. Max_x and Min_x were computed for all coefficients. A normalized influence statistic, $Norm_x$ was calculated from these values for each ecological site characteristic according to equation 1:

$$Norm_x = \frac{Max_x - Min_x}{\sum_{x=1}^{n}(Max_x - Min_x)} \tag{1}$$

where the difference between Max_x and Min_x for a single coefficient was divided by the summed difference between Max_x and Min_x for all coefficients. $Norm_x$ is a measure of the influence of a coefficient on the SWR characteristic of interest relative to the other coefficients within the model average formula. $Norm_x$ values range between 0 and 1; more influential coefficients have higher $Norm_x$ values.

A significance level of $P < 0.05$ was used for all comparisons. The normality of continuous data was tested in normal quantile plots. Data not following a normal distribution were log transformed when appropriate. For the general linear models developed, equal variance and independence were tested with Levene’s Equal Variance test and the Durbin-Watson test.

3. Results

3.1. Soil Water Repellency Extent, Severity, and Thickness

Across the study, SWR was found at 37% of all points tested, exceeding 75% at 10% of the sites. Among fires, 0%, 10%, and 38% of sites at Big Pole, Broken Ridge, and Mill Flat exceeded the 75% SWR extent threshold. Sampling points that fell in the tree/shrub mound zones of woody species were water repellent 71% of the time, interspace points were water repellent 16% of the time ($P < 0.001$). Between microsites, SWR thickness and severity (i.e. WDPT) were significantly greater for tree/shrub mounds as compared to interspaces, averaging 1476 s and 858 s for WDPT ($P = 0.008$), and 1.90 cm and 1.42 cm for thickness ($P = 0.003$). In the interspace, water repellent points were found closer to the canopy edges of woody species (0.92 m) as compared to non-water repellent points (1.98 m) ($P < 0.001$).

Soil water repellency extent, severity, and thickness were higher under singleleaf pinyon as compared to Utah juniper. Between the two species, SWR extent averaged 79% and 69% ($P = 0.017$), WDPTs averaged 2328 s and 1188 s ($P = 0.020$), and SWR thickness averaged 2.86 cm and 1.62 cm ($P < 0.001$).

3.2. Ecological Site Characteristic Modeling

Models of SWR extent evidenced strong relationships with ecological site characteristics. The best ten extent models had R^2_{adj} values above 0.60. The top model produced a 0.74 R^2_{adj} and included the following three coefficients: piñon-juniper canopy cover, tree mound soil pH, and average relative humidity for July 2009 (Table 1). Models of SWR severity showed relatively weaker relationships; R^2_{adj} values within the top ten models ranged from 0.35 to 0.61. The top model included the following two coefficients: piñon-juniper canopy cover and average relative humidity for July 2009 (Table 1). Soil water repellency thickness models were consistently weak, only six models were found to meet the established criterion; the top model had a 0.44 R^2_{adj} and included piñon-juniper canopy cover and tree mound clay content.

As per the criteria outlined in the methods, the 5th model of SWR extent and the 1st model of SWR severity were selected for use in predicting SWR. Both models included piñon-juniper canopy cover and relative humidity as coefficients, the estimates of which are provided in Table 3. Top models that included tree mound soil variables were not considered for predicting SWR extent in spite of their high R^2_{adj} values. We found tree mound soil clay content, soil pH, and soil organic matter data gathered in the field related poorly to the NRCS soil survey data publicly available online (r = 0.11, 0.30, and 0.30), therefore these models fail to meet the criteria as their terms are not truly remotely extractable. A predictive model of SWR thickness was not endorsed as no models were found that met the established criteria.

Within the model average of SWR extent, piñon-juniper canopy cover had the strongest influence, having a normalized influence statistic ($Norm_x$) of 0.62 (Table 2). Other piñon-juniper attributes (i.e. width, height, and trunk diameter) were unimportant. Soil attributes, including tree mound soil pH and clay content ranked 2nd and 4th in influence, having $Norm_x$ values of 0.18 and 0.05. Climate and topographic data played minor roles within the SWR extent model average, with the exception of July 2009 relative humidity, which was the 3rd most important variable, showing a $Norm_x$ value of 0.11.

The two most important variables for predicting SWR severity were piñon-juniper canopy cover and July 2009 relative humidity ($Norm_x$ = 0.47 and 0.34). Piñon-juniper biomass and precipitation for July 2009 were moderately important, both having $Norm_x$ values of 0.07. All other ecological site characteristics were lacking in their ability to influence the SWR severity model average product. Much like SWR severity, SWR thickness had two coefficients that were relatively influential, tree mound clay content and piñon-juniper canopy cover ($Norm_x$ = 0.48 and 0.39), while the remaining coefficients, excepting annual average minimum temperature, were unimportant. Annual average minimum temperature was weakly influential, having a $Norm_x$ value of 0.06.

Among woody species, the percentage of tree/shrub mound sample points that were water repellent varied: Utah juniper (69%), singleleaf pinyon (79%), two needle pinyon (*Pinus edulis* Engelm., 92%), Gambel oak (*Quercus gambelii* Nutt., 60%), Stansbury cliffrose (*Purshia stansburiana* (Torr.) Henrickson, 73%), and Saskatoon serviceberry (Amelanchier alnifolia (Nutt.) Nutt. ex M. Roem., 70%). Soil water repellency was also found under big sagebrush (*Artemisia tridentata* Nutt.), antelope bitterbrush (*Purshia tridentata* (Pursh) DC.), Sonoran scrub oak (*Quercus turbinella* Greene), alderleaf mountain mahogany (*Cercocarpus montanus* Raf.), curl-leaf mountain mahogany (*Cercocarpus ledifolius* Nutt.), Yucca (*Yucca* L.), and pointleaf manzanita (*Arctostaphylos pungens* Kunth), but sample sizes were too small (i.e. <10) for us to be confident in reporting summary statistics.

4. Discussion

4.1. Soil Water Repellency Extent, Severity and Thickness

The impact of SWR on hydrologic patterns is related to the continuity and strength of the water repellent layer (Pierson and others 2001; Woods and others 2007; Doerr and others 2009). Thus, as SWR extent and severity increase, the influence of this soil condition on post-fire recovery increases. Ten percent of our sites evidenced SWR extent above 75%, suggesting that SWR affected post-fire hydrology and recovery within many of the expansion woodlands studied. However, variability of SWR extent was high; almost half of the Mill Flat sites exceeded the 75% threshold while none of the Big Pole sites had SWR extent above 75%.

This variation in SWR extent may be explained by differences in woody species composition. Piñon-juniper canopy cover was 73% greater at the Mill Flat fire as compared to the Big Pole fire. Microsite comparisons indicate that SWR extent, severity, and thickness are greater beneath woody species. Even in the interspaces, closer proximity to woody plants resulted in greater probability of SWR presence. Comparisons between singleleaf piñon and Utah juniper indicate that overstory species differences may also influence SWR. All SWR attributes were greatest under singleleaf piñon, with the greatest differences being found in severity and thickness; WDPTs were 96% longer and water repellency was 77% thicker under singleleaf piñon compared to Utah juniper. Singleleaf piñon was entirely lacking at the Big Pole fire, while at the Mill Flat fire this species was a major overstory component.

Variation in SWR between woody species is well-noted in the literature. Soil water repellency has often been related to woody species composition (Doerr and others 2000a and references therein). The resins, waxes and aromatic oils contained in woody species, particularly evergreens, are one of the primary sources of water repellent compounds. Indeed, water repellency develops as the litter (McGhie and Posner 1981; Scott and others 2000) and root exudates (Doerr and others 1998) of these species are incorporated into the soil (Doerr and others 2000a). Differences in the chemical composition of the litter between singleleaf piñon and Utah juniper may be one of the driving factors leading to differences in SWR.

These findings give weight to the argument that the effect of SWR on post-fire recovery is closely tied to the prevalence, arrangement, and species of woody vegetation within a slope or watershed. Where cover of some woody species is high, SWR extent is liable to be contiguous enough to induce overland flow and thereby accelerate site degradation post-fire. In addition, intensified levels of SWR under specific species may result in increased SWR persistence (Doerr and Thomas 2000). For areas where SWR continuity is high, this increased persistence could effectively lengthen the recovery period.

4.2. Ecological Site Characteristic Modeling

Piñon-juniper canopy cover was found in all of the top models of SWR extent. It was also a coefficient in many of the top models of SWR severity and thickness. In every case it exhibited a positive relationship with SWR. Piñon-juniper canopy cover had a greater influence on SWR extent than that of all the remaining variables combined, and was the most influential variable for SWR severity and the second most influential variable for SWR thickness. Overall, piñon-juniper canopy cover had the strongest and most consistent relationship to SWR.

In the Intermountain West, the majority of piñon-juniper woodlands are only in the mid-stages of stand closure (Miller and others 2008). Infilling is expected to increase canopy cover and the number of closed canopy woodlands for the next 30-50 years (Weisburg and others 2007; Miller and others 2008). As crown closure continues the frequency of large-scale, high intensity wildfires rise (Tausch and others 1999; Gruell and others 1999; Miller and Tausch 2001). As this occurs, the overall proportion of burned areas crossing the 75% SWR extent threshold of influence will increase.

Tree mound soil pH, tree mound soil clay content, and relative humidity held the greatest importance to SWR next to piñon-juniper canopy cover. The observed negative relationship between SWR and tree mound soil pH is likely due to the fact that litter is one of the primary sources of water repellent particles (McGhie and Posner 1981; Scott and others 2000) and as litter is incorporated into the soil, pH typically declines (Facelli and Pickett 1991; Frost and Edinger 1991). In addition, the solubility of water repellent molecules is tied to pH. As pH declines solubility decreases (Crockford and others 1991).

Clay content, and thereby texture influences the number of water repellent particles necessary to induce water repellency. Fine-textured soils have a much higher surface area than coarse-textured soils, requiring a relatively greater quantity of water repellent compounds per unit volume to effectively render the soil water repellent (Blackwell 1993). This surface area effect influences the susceptibility of a soil to water repellency, but once induced, severity is often similar between textures (Doerr and others 2000a). This theory is supported in the results; texture had a stronger influence on SWR thickness (i.e. vertical susceptibility) and extent (i.e. horizontal susceptibility) than on SWR severity.

Relative humidity the month prior to fire was important in many of the top predictive models of SWR extent and severity. The importance of relative humidity to SWR is understood relative to its strong positive relationship to soil moisture at the time of fire (Mahfouf 1991; Dourville and others 2000). Soil moisture is a key variable influencing SWR formation, moderating soil temperatures at the time of fire and thereby controlling which areas reach the temperatures necessary to generate SWR (DeBano and others 1976, Letey 2001). As soil moisture (and therefore relative humidity) increases, SWR will decrease (Doerr and others 2000a, Doerr and others 2006; Horne and McIntosh 2000; Doerr and Thomas 2000).

Reductions in soil moisture and relative humidity brought on by climate change could intensify SWR in piñon-juniper woodlands. If this occurs, the result may be the realization of the postulates forwarded by Goebel and others (2001). Namely, that climate-change intensified SWR may exacerbate the effects of climate drought and detrimentally affect vegetation and microbial community structure. In combination with the predicted continuing crown closure and subsequent increasing fire frequency and intensity in these woodlands, the results of this study effectively support the claim that the negative effect of SWR on the recovery of piñon-juniper woodlands will intensify in the near future.

To meet this threat, this study provides tools that allow land managers to predict SWR at the scale of their treatments without having to gather *in situ* data. These tools are realized in the predictive models of SWR severity and extent endorsed herein. Both models include the same two variables, piñon-juniper canopy cover and relative humidity. Piñon-juniper canopy cover can be quickly extracted over large spatial extents from remotely sensed imagery (Madsen and others 2011; Davis and others 2010) and relative humidity data can be easily calculated from climate datasets available in GIS format online. The parsimonious nature of these models, in combination with the remote accessibility of their coefficients, increases the likelihood that these models will be accurate when employed. Additional research is needed to validate the models endorsed herein.

5. Conclusions

Post-fire SWR is widespread within piñon-juniper woodlands and is almost always found in the tree mound zones of piñon-juniper individuals or closely adjacent. Indeed, of the ecological site characteristics studied, piñon-juniper canopy cover has the strongest relationship to SWR extent and severity. Relative humidity and soil pH were also important; they were found in many of the best models and had strong normalized influence statistic values. The balance of the ecological site characteristics studied lacked strong, consistent relationships with SWR. Of the three SWR attributes measured, SWR extent and severity produced the strongest models; SWR thickness related poorly to the ecological site characteristics studied.

The strong relationship between piñon-juniper canopy cover and SWR extent leads us to conclude that where piñon-juniper canopy cover is high, SWR is likely contiguous enough to induce changes in overland flow and negatively alter hydrologic processes. This is worrying as infilling processes in piñon-juniper woodlands are expected to continue for several decades. As these woodlands increase in cover, a greater proportion of piñon-juniper woodlands will develop SWR during wildfires. In addition, decreases in relative humidity and soil moisture brought about by a changing climate in the Intermountain West will link additively with infilling processes in piñon-juniper woodlands to increase the frequency and intensity of wildfires, and also strengthen the resultant post-fire SWR. The net effect of infilling and climate change will likely be stronger SWR over a greater spatial extent, i.e. a greater proportion of post-fire landscapes will respond poorly to restoration efforts.

The results of this study suggest that piñon-juniper canopy cover and relative humidity data can be used in concert to effectively predict SWR following fire. These data are remotely available and can be quickly derived from high resolution aerial photography and cloud-based climate datasets. Using these data in conjunction with the predictive models endorsed herein, managers are provided with a means to identify potential problem areas and thereby prioritize treatment. As land managers typically have limited resources to monitor the extensive landscapes they are responsible for, this study provides an economical means for assessing a detrimental soil condition that is commonly found in the post-fire piñon-juniper landscapes of the Intermountain West. As threats to natural landscapes intensify in the coming years, tools such as those provided in this study will be increasingly sought after to aid managers in making informed decisions.

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Tables

Table 1. Top models of soil water repellency (SWR) extent, severity, and thickness in piñon-juniper (PJ) woodlands. Models endorsed for the prediction of SWR in bold.

	Model #	Explanatory Variables[a]	K^b	$R^2_{adj}{}^c$	BIC^d	BIC^e	$w_i{}^f$
Extent	1	PJ canopy cover, Tree mound soil pH, July 2009 relative humidity	3	0.74	-44.7	0.00	0.59
	2	PJ canopy cover, Tree mound clay content, July 2009 relative	3	0.73	-42.6	2.01	0.22
	3	PJ canopy cover, Tree mound soil pH, Burn severity	3	0.72	-41.3	3.32	0.11
	4	PJ canopy cover, Tree mound clay content	2	0.67	-38.7	5.93	0.03
	5	**PJ canopy cover, July 2009 relative humidity**	**2**	**0.66**	**-38.0**	**6.63**	**0.02**
	6	PJ canopy cover, July 2009 precipitation, Slope	3	0.68	-36.3	8.34	0.01
	7	PJ canopy cover, PJ Height, Slope	3	0.67	-35.0	9.62	0.00
	8	PJ canopy cover, PJ Height, Burn severity	3	0.66	-34.6	10.05	0.00
	9	PJ canopy cover, Slope	2	0.63	-33.7	10.96	0.00
	10	PJ canopy cover, July 2009 precipitation	2	0.63	-33.3	11.33	0.00
Severity	**1**	**PJ canopy cover, July 2009 relative humidity**	**2**	**0.61**	**39.2**	**0.00**	**0.81**
	2	Tree mound soil pH, July 2009 relative humidity, July 2009	3	0.57	43.5	4.33	0.09
	3	Tree mound soil pH, July 2009 relative humidity, PJ trunk diameter	3	0.58	44.1	4.94	0.07
	4	July 2009 relative humidity, July 2009 precipitation	2	0.54	46.7	7.47	0.02
	5	July 2009 relative humidity, Tree mound soil pH	2	0.48	49.6	10.38	0.00
	6	July 2009 precipitation	1	0.41	52.6	13.41	0.00
	7	Tree mound soil pH, PJ trunk diameter	2	0.41	54.4	15.23	0.00
	8	July 2009 relative humidity, PJ trunk diameter	2	0.40	55.2	15.95	0.00
	9	PJ canopy cover, Aspect, PJ trunk diameter	3	0.40	57.3	18.13	0.00
	10	July 2009 relative humidity, PJ height	2	0.35	57.6	18.38	0.00
Thickness	1	Tree mound clay content, PJ canopy cover	2	0.44	80.9	0.00	0.88
	2	Tree mound clay content	1	0.31	85.0	4.13	0.11
	3	PJ canopy cover	1	0.20	91.8	10.92	0.00
	4	Tree mound soil pH	1	0.16	93.5	12.60	0.00
	5	PJ height	1	0.12	95.2	14.33	0.00
	6	Annual minimum temperature	1	0.11	95.9	15.01	0.00

[a] Variables included in the model

[b] Number of model terms

[c] Adjusted coefficient of determination

[d] Baysian Information Criterion

[e] BIC relative to the top model

[f] Model weight

Table 2. Relative influence of ecological site characteristics on soil water repellency, ranked based on their ability to induce variation within a model average having a three maximum coefficient threshold and a 0.90 AIC$_c$ cutoff weight. $Norm_x$ values range between 0 and 1; more influential coefficients have higher $Norm_x$ values.

	Coefficient x [a]	Max_x [b]	Min_x [c]	$Norm_x$ [d]	*Relationship* [e]
Extent	Piñon-juniper canopy cover	0.08	0.95	0.621	+
	Tree mound soil pH	0.25	0.50	0.179	-
	July 2009 relative humidity	0.30	0.45	0.111	-
	Tree mound clay content	0.34	0.42	0.053	-
	Burn severity	0.36	0.39	0.021	+
	Piñon-juniper height	0.37	0.38	0.008	+
	July 2009 precipitation	0.37	0.38	0.006	+
Severity	Piñon-juniper canopy cover	1.15	2.86	0.470	+
	July 2009 relative humidity	1.12	2.36	0.342	-
	July 2009 precipitation	1.64	1.91	0.072	+
	Piñon-juniper biomass	1.70	1.95	0.068	+
	Tree mound soil pH	1.68	1.76	0.022	-
	Piñon-juniper trunk	1.71	1.78	0.019	+
	Aspect	1.71	1.73	0.004	+
	Tree mound clay content	1.72	1.72	0.001	-
Thickness	Tree mound clay content	0.90	2.70	0.483	-
	Piñon-juniper canopy cover	1.03	2.48	0.388	+
	Annual minimum	0.08	0.31	0.061	-
	Annual maximum	1.47	1.58	0.030	-
	Piñon-juniper height	1.50	1.59	0.024	+
	Burn severity	1.51	1.56	0.012	+
	Tree mound soil organic	1.52	1.52	0.002	-
	Tree mound soil pH	1.52	1.52	0.001	+

[a] Coefficients found to be significant in the model average

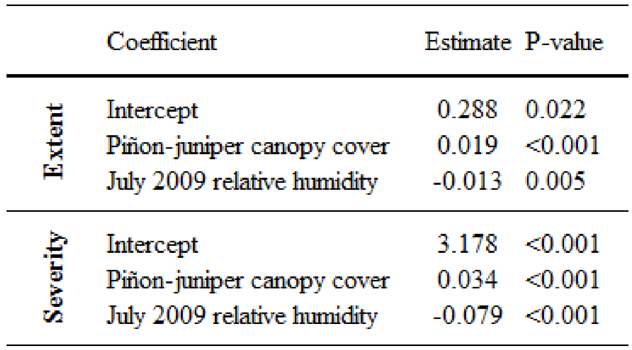
[b] Model average product when coefficient x is held at its maximum field value and all others are held at their median

[b] Model average product when coefficient x is held at its minimum field value and all others are held at their median

[e] Normalized influence statistic; Max_x-Min_x divided by the sum of all Max_x-Min_x values

[f] Relationship to the soil water repellency characteristic of interest

Table 3. Estimates and p-values of coefficients in the endorsed predictive models of soil water repellency extent and severity.



	Coefficient	Estimate	P-value
Extent	Intercept	0.288	0.022
	Piñon-juniper canopy cover	0.019	<0.001
	July 2009 relative humidity	-0.013	0.005
Severity	Intercept	3.178	<0.001
	Piñon-juniper canopy cover	0.034	<0.001
	July 2009 relative humidity	-0.079	<0.001