Investigating the connections between soil, fire, and water: The characteristics of soil water repellency following fire in the Pacific Northwest

Jalene Ann Weatherholt

A thesis
submitted in partial fulfillment of the
requirements for the degree of

Master of Science

University of Washington
2021

Committee:
Brittany Johnson
Brian J. Harvey
Daniel Vogt

Program Authorized to Offer Degree:
School of Environmental and Forest Sciences

©Copyright 2021
Jalene Ann Weatherholt

University of Washington

Abstract

Investigating the connections between soil, fire, and water: The characteristics of soil water repellency following fire in the Pacific Northwest

Jalene Ann Weatherholt

Chair of the Supervisory Committee:
Brittany Johnson
School of Environmental and Forest Sciences

Land area burned annually in the western US has risen in association with shifting climatic conditions as a result of global climate change. Successional processes greatly rely on soils as a foundational medium for the establishment of new plant communities following disturbance. During a wildfire, the combustion of organic materials releases hydrophobic compounds that contribute to the formation of water repellent soils below the surface. Soil water repellency (SWR) can greatly increase erosion risk and overland flow events in an already vulnerable, post-fire system. The myriad of environmental and burn conditions that contribute to the formation, destruction, and perseverance of SWR result in extremely heterogeneous spatial patterns across a landscape. Managers could benefit from a clearer understanding of SWR properties to best aid in successional management practices. This document reports not only the findings of my thesis research work but also explores the journey to my current understanding of SWR in the Pacific Northwest (PNW). Seed data collected in 2018 throughout post-fire ecosystems 1 year following disturbance in the PNW was reflective of the heterogeneous nature of soil water relations. Largely indistinguishable variation of SWR across burn severity classes and naturally occurring hydrophobicity patterns did not provide any clear differences across the landscape. We hypothesized that the scale used to assess relationships between burn severity metrics and SWR from this field design, consisting of four measurement locations per plot across multiple fires was not appropriate to the process itself. Learning from this work, a new protocol measuring 81 locations within a 44x20m rectangle was adapted to explore spatial scales and environmental factors that managers can use to predict SWR behavior on their post-fire forests. This adapted protocol was implemented on the Green Ridge fire that burned in the summer of 2020 in the Deschutes National Forest in Oregon state. Soils within this forest were found in the 2018 data to experience both natural and fire-induced SWR as a process of this mixed-conifer system. We found that soil burn severity is a significant factor in predicting the variability of SWR conditions compared to unburned areas but does not identify a clear pattern across management-relevant distinctions of burn severity. While SWR density significantly diminishes with depth into the soil horizon, little evidence of management-relevant scalable spatial patterns of SWR horizontally throughout a stand were identified. The influence of environmental factors on SWR density will be a key component in the ability to predict post-fire conditions through satellite inputs for landscape level modelling. The future of SWR research will rely on advancements made in remote sensing products of soil qualities and wildfire severity in addition to improved SWR sampling standards.

Table of Contents

List of Figures

B= severe surface, C= light surface, and D= unburned. The count of points at each class across all depths is shown above each violin plot distribution. Individual violins are scaled to contain the same area within their range as all others SWR classes of that plot.

Figure 8. The distribution of SWR responses on the small horizontal scale from each water droplet placed at 5, 10, and 15 cm depths of the additional sampling subsites where vertical soil core responses were shown not to be hydrophobic (A= Crown, B= Severe Surface, C= Light Surface, D= Unburned; N= number of droplets from the horizontal plane).

Figure 9.The first two principal components from a principal components analysis of SWR measured at each centimeter depth of the soil core taken at all 81 sampling points across all four plots.

Figure 10. The first two principal components from a principal components analysis of the relationship between environmental variables and SWR conditions at the additional sampling points of all four plots.

Figure 10: Relationships between field and remotely sensed measurements of soil burn severity for the six fires sampled (A: Jolly Mountain, B: Norse Peak, C: Lolo Peak, D: Milli, E: Rice Ridge, F: Liberty Fire). Plotted values of soil burn severity correspond to the ordinal values assigned to each severity class (high, 3; moderate, 2; low, 1; unburned, 0). Data point size indicates the frequency of relationship occurrence and color the canopy burn severity class represented by that point. Points represented by two canopy burn severity classes are given their own color identifier. The dashed line indicates a 1:1 relationship between predicted and measured values while projected linear relationships are shown as solid lines (* = significant linear regression).

Figure 11. Variation (expressed as % of plot subsites) between field and remote data soil burn severity classifications. Here, a value of “0” indicates that the classifications were a match. If a value is positive, the BARC map underestimated the soil burn severity by x categories and if negative, the BARC map overestimated severity. For example, if soil classified as “low” in the remote data but the field assessment yielded “high”, that soil would be given a value of “2” indicating that the map has underestimated the severity by two categories of burn severity. BARC map distribution is separated by high soil burn severity = A, moderate= B, low=C, and unburned= D.

List of Tables

2 Chapter 1: State of Soil Water Repellency in Pacific Northwest Post-Fire Ecosystems…35

Acknowledgements

A big thank you to the funding sources that have made this work possible. The 2018 seed data collection was funded under the *United States Forest Service Geospatial Technology and Applications Center 17-CS-11130400-010.* Continued work on this and other projects was awarded by the School of Environmental and Forest Sciences through the SEFS Fellowship in addition to funding from the McIntire-Stennis program. Many thanks to the Royalty Research Fund for their essential role in the sampling of the Green Ridge Fire. I would love to thank and acknowledge all past field members for help with data collection for this thesis work, training for field methods and skills, and for the lifetime of memories and friendships: Conamara Burke, Nick Braun, Malory Lund, Theodora Ratu, Chris Scelsa, Saba Saberi, Callie Zender, and Peter Walsh. Our experiences in the field together have been the most fulfilling part of my time at UW. A thank you to my advisor, Dr. Brittany Johnson, for the years of guidance and growth. The faith and confidence you showed in me even after just our first conversation has sparked the start of my career and lifetime interest in the connections of soil and wildfire. This work would not have been possible without your mentorship. Your incredible ability to impart pure excitement and joy for soils has made you a pillar in the foundation of the SEFS community and in your students' lives. I cannot thank you enough for allowing me to be one of those students. Additionally, thank you to my other committee members, Dr. Brian J. Harvey and Dr. Daniel Vogt, for your enthusiasm and involvement in my education and career development. It has been a wonderful opportunity to learn from you. Finally, thank you to all of the family and friends that have entered my life and encouraged me to pursue my passion for the natural sciences and for adventure. To my mom, Kellie, my dad, Carey, and my brother, Austin, I love you more than anything. Thank you for standing by my side through all the highs and lows.

1 Introduction

1.1 Climate Change and Wildfire Disturbance

Global climate change impacts are observed by both scientists and the greater population alike through erratic weather conditions, increasing temperature averages, and disturbance events uncharacteristic of previously anticipated patterns (Eckstein et al., 2019). An average warming of 0.3° C per decade modeled for the Pacific Northwest (PNW) ecoregion links these planetary changes to alterations in local climate conditions for land managers across private and public lands. New standards of wildfire severity and frequency may be primarily driven by widespread drought conditions as a result of climate change (e.g. Westerling et al., 2006; Rogers et al., 2011). Drought has impacted wildfire regimes throughout history and is specifically linked to fire occurrence in the PNW since the 1700s (Hessl et al., 2004). Higher projected temperatures and drought conditions by end of the 21st century are anticipated to be met with an increase in the total area burned and the burn intensity from current averages by 76-310% and 29-41% respectively in the PNW (Rogers et al., 2011). Impacts of modern climate stressors can be observed in real time as increased wildfire frequency since the 1980s is matched with an average fire season length increase from one week now up to five weeks (Westerling et al., 2006). Limited seasonal moisture inputs in the Northern Rockies and regions west of the Cascade Mountains have also resulted in high vulnerability to increases in wildfire activity (Westerling et al., 2006). Land area affected by changes in climate-induced drought and exacerbated disturbance from wildfire events is expanding in the PNW. With fire on the rise, it is critical to understand the role of wildfire in essential ecosystem processes and how altered relationships between climate and fire will impact forest health.

1.2 The Role of Wildfire

Dramatic shifts in climate and the encroachment of communities into the wildland-urban interface have led to mass tragedy in the human sector, shaping the public view of fire; however, wildfire remains an essential process in the fruition of healthy forests and ecosystem function (Moritz et al., 2014). Patchwork matrices of fire regimes ranging across high, moderate, and low severity responses to fire are found across the western US, reflecting the variety of coevolved strategies ecosystems have developed to respond to wildfire disturbance (Agee, 1998). High-severity fire regimes are associated with ecosystems that will experience stand replacement from fire while low-severity regimes will usually not see a turnover of vegetative structure (Agee, 1998). These landscapes are adapted to and some even require fire disturbance to sustain ecosystem function. Frequent fire ecosystems exhibit a highly optimized tolerance for this disturbance through vegetation structure and adaptation by the frequent removal of ladder fuel buildup such as with *Pinus ponderosa* (Ponderosa pine) stands (Moritz et al., 2005). Some species even require the influence of fire to release seeds held in cones from an adaptation called serotiny. Interval times between fire in addition to its severity are significantly linked to the ability of serotinous species to reestablish and impact their resulting densities (Schoennagel et al., 2003). With global shifts in fire regimes, the ranges of serotinous species adapted to their historical fire regime may shift dramatically (Turner et al., 1998).

Ecosystems developed under conditions of more infrequent fire return intervals will still rely on fire to maintain ecosystem function. Characteristic late-seral species of an area may only establish and mature after a certain time since wildfire disturbance. A study looking at the distribution of late-successional vegetation structures found that the density of balsam fir (*Abies Balsamae*) increased steadily with time after fire while black spruce (*Picea Mariana*) density only rose for the first 90 years since wildfire followed by a decline in population abundance in the same ecoregion (Bouchard et al., 2008). The total area characterized as a black spruce dominated system, with its associated biodiversity, relies heavily on the fire return interval. From reproductive success to ecosystem resilience, wildfire is a necessary factor in promoting ecosystem resilience and health across fire return intervals.

Years of misinformed fire management has resulted in changes to vegetation structure of some forest ecosystems alongside the buildup of available fuels to form a positive feedback loop between fire risk, suppression, and combustible fuel buildup (Calkin et al., 2015). While not applicable to all forest ecosystems (Schoennagel et al., 2004), this condition can cause more severe, stand-replacing wildfire (Van Wagtendonk, 1985). One commonality across ecosystems facing catastrophic wildfire concern and those well adapted to current conditions is the importance of soil as the foundation of the ecosystem. Active changes to our climate, compounded by increased fuel load and vulnerable forest structures, weaken ecosystem recovery to disturbance; understanding the relationship between wildfire and the soil is essential to the implementation of effective management practices.

1.3 Soils in a Fire-Affected System

Soils are the base of forest systems as they provide the structural and nutritional conditions needed for plant and microbial life. An increased understanding of the important roles soil fulfills in a forest ecosystem has resulted in more intensive research and management efforts focused on chemical, physical, and biological characteristics supporting overall soil health (Schoenholtz et al., 2000). Investigating the impact of wildfire disturbance on soil health and function is essential to managing for effective succession as the area of fire-affected soils increases each wildfire season. A component of great interest on a post-fire landscape is the interaction between soil and water.

Organic matter inputs ranging from bark and needles in accumulated forest litter to fungal hyphae may contain hydrophobic compounds with the potential to form a subsurface water repellent layer in the mineral horizon (e.g. García et al., 2005; Passialis and Voulgaridis, 1999; DeBano et al., 1970; Rillig et al., 2010). These layers often fluctuate seasonally in intensity and spatial distribution with maximum effects following extended periods of dryness and wildfire influence (Crockford et al., 1991). A mere two percent fraction of organic matter in a soil can result in fire-induced soil water repellency (SWR) when hydrophobic compounds vaporize, diffuse into soil capillaries, cool, and condense onto particles to form a subsurface layer of hydrophobic substrate (Debano and Krammes, 1966; DeBano et al., 1979; DeBano, 1981; Figure 1). Even soils burned under severe conditions can still act as a strong insulator from heating just five centimeters into the mineral horizon, allowing for condensation of hydrophobic compounds just under the soil surface reported typically down to 20 cm depths (Debano et al., 1971; Debano et al., 1976). Once created, layers can persist for just a few seconds or last for several years in forest soils following a wildfire (Dyrness, 1976). Undisturbed soils can also contain SWR from organic matter inputs through the leaching of hydrophobic compounds into the horizon (Garcia et al., 2005). SWR was found to form in patches ranging from 1 m^2 to 10 m^2 with increased density and intensity of hydrophobic conditions following a fire in Rocky Mountain soils (Woods et al., 2007). Small scale variation of SWR density is further spatially fragmented by the inherent environmental heterogeneity found across landscapes.

Ecosystem factors and pre-fire soil qualities play a role in SWR patterns. At the base mineral level, soils composed of smaller particle sizes have been shown to exhibit increased SWR intensity than coarser substrates often in volcanic soils as the result of fine particles of hydrophobic organic matter covering the larger surface area of clay (Doerr et al., 1996; de Jonge et al., 1999), while contrasting work has found that coarser textures were associated with SWR because the amount of hydrophobic compounds present in the system can cover a larger percent of the mineral surface area (Crockford et al., 1991). Other studies found no relationship between particle size and SWR, attributing conditions to other environmental factors such as the composition of surface organic material (Mainwaring et al., 2013). In addition, the distribution of mineral size classes along with soil moisture levels impact how deeply the volatile compounds can infiltrate before condensing to form a hydrophobic layer (Huffman et al., 2001). These inconsistent findings show the dynamic relationship between soil qualities and highlight that a list of factors are at play when attempting to predict patterns in SWR.

Bark and needles from pine species have been shown to contain hydrophobic compounds (Passialis and Voulgaridis., 2005) along with many other species ranging from other evergreen species to shrubs (Doerr et al., 2000). When accumulated in topsoil and burned, vaporized hydrophobic components of surface litter can form SWR with varying intensity and persistence in part due to the type and amount of organic matter present. The variability characterizing SWR conditions may be a result of soil quality and ecosystem factors but has been most often linked in the literature to soil heating and burn severity patterns from wildfire (DeBano et al., 1979; Doerr et al., 2000; Woods et al., 2007). SWR formation and destruction are impacted by highly variable temperatures and durations of burn across a landscape in a single fire event (e.g. Zavala et al., 2010; DeBano 1981; DeBano et al., 1976). In a controlled laboratory setting, shorter periods of soil burning (5-10 minutes) generated a strongly hydrophobic layer at higher temperatures (>600° C) while longer duration burns (15-20 minutes) created SWR at temperatures up to 600-700° C, but SWR was then destroyed at temperatures between 800-900° C SWR (DeBano and Krammes 1966). In the field, the ability to accurately predict patterns in SWR enhancement and destruction on larger ecosystem scales following a fire remains a challenge in forest areas all over the globe due to the myriad of burning durations and temperatures in a single event. The full extent of factors that shape the complex patterns of SWR observed remains a mystery due to the complexity of post-fire landscapes and soil qualities. Variation in SWR characteristics and their impacts on ecosystem resilience through soil health must be a primary objective for post-fire management strategies and continued research.

Soils are crucial for ecosystem recovery. They provide water and nutrients to surviving and establishing vegetation (Huddlestons and Kling, 1996) as well as a habitat for complex microbial communities essential to succession (e.g., Booth et al., 2002; Lakshmanan et al., 2014; Huebner et al., 2012). Soils made vulnerable from fire disturbance can experience increased erosion after the creation of SWR ultimately leading to nutrient losses and limited water availability for roots that would have provided crucial structural stability (Helvey, 1980). A study observing the interaction between SWR and slope on the amount of lost topsoil found that water repellent soils were more vulnerable to erosion on steeper grades, reporting that 4.85 Mg ha^{-1} were eroded after just 10 mm of rain (Lowe et al., 2021). It may come with no surprise that seedlings and other plant species may even struggle to establish or not germinate entirely in these conditions (e.g., Osborn et al., 1967; Vacchiano et al., 2014). As drought and elevated temperatures continue to drive fire patterns in the PNW, resources for managing these lands become increasingly strained. Variation in SWR characteristics and their impacts on ecosystem resilience through soil health are a primary objective for post-fire management practices.

1.4 Post-Fire Soil Management

The 2020 wildfire season recorded the largest burned area since 1960 with 4.16 million hectares consumed in the US (Hoover and Hanson, 2021). Between the US Forest service and other Department of the Interior agencies, fire suppression costs exceeded $2.27 billion (NIFC, 2020) just in 2020 alone. A portion of fire-related spending is directed toward ecosystem resilience and erosion management to sustain effective succession following wildfire disturbance; a case study of the Bobcat Gulch fire burned in the Roosevelt National forest during the year 2000 found that $823,854 was spent on rehabilitation and erosion control in addition to the $3,840,319 already spent on suppression efforts during the incident (Lynch, 2004). The growing sink of wildfire management for government funds has drawn the attention of taxpayers to the US Forest Service and scientists for an explanation of the current conditions and what steps need to be taken in response. Managers rely heavily on Burn Area Emergency Response (BAER) team recommendations for post-fire management prescriptions designed to assuage risk to human life, property, and ecosystem health as a result of weakened forest soils and vegetative structures (USFS, 2020). BAER teams are called on scene immediately upon containment of larger wildfires to map the general patterns of soil burn severity and develop recommendations for minimizing erosion risk and further damage to natural resources. The input of BAER teams can ultimately reduce cost to managers and time to action by providing explicit instructions for effective strategies to implement at the most vulnerable locations. Burn area reflectance classification (BARC) maps are thus a critical piece of post-fire assessment. Spectral frequencies of burned vs. unburned areas derived from satellite imagery are used to create the initial map predicting patterns of soil burn severity. These predictions are then validated and corrected on the map by the BAER team soil expert. Ground-truthing for conditions of soil burn severity, ash, soil texture, and SWR in addition to other variables is a key factor in training the BARC map to conditions within the burn perimeter (O’Brien, 1999). Testing for SWR is done both by the water drop penetration time test, recording the amount of time it takes for a droplet to infiltrate on a soil surface (>5 seconds indicates hydrophobicity), or with a mini-disk infiltrometer, measuring the infiltration rate on a soil surface, as is the standard protocol used by BAER teams protocols (DeBano, 1981; Robichaud et al., 2008). The implementation of these methods are necessary to pinpoint locations of SWR for immediate management of soils at high risk for overland flow (Doerr et al., 2006). BAER teams deliver a final BARC map of the burn area, identify locations at highest risk of erosion, and provide a budgeted timeline for management action that must be carried out immediately upon report completion.

To account for potential erosion risk from SWR, BAER teams can provide an arsenal of recommendations from the *Burn Area Emergency Response Treatments Catalog* (Napper, 2006). Erosion control methods available for forest soil management include the installation of erosion control mats onto the soil surface for emergency stabilization intended to physically hold vulnerable soils in place. A similar solution is to spread slash on the soil surface; however, this is rarely used due to the limited availability of excess material following a burn. Instead, straw or mulch can be applied by hand or dropped by helicopter to weigh down the soil surface and provide immediate organic inputs across the landscape. One consideration with this method is monitoring the proximity of a straw mulch treatment site to watersheds as it may degrade water quality (Napper, 2006). Log erosion barriers are also prescribed along steeper hillslopes for burned trees to be felled with the contour of the slope to catch moving sediments. This strategy is mimicked with straw filled tubes, silt fences, and hay bales all with the intention to slow down the movement of sediment before vegetation is able to reestablish (Napper, 2006). One method specifically targeted to SWR is soil scarification which physically breaks up water repellent soils with hand tools or larger machinery, thus allowing for sufficient water infiltration. The results of this prescribed treatment have been variable and even detrimental in some highly burned soils.

Additionally, soil scarification may be difficult to implement over large areas identified with SWR conditions (Napper, 2006). BAER teams seek to provide the best available science and management strategies targeted to the most vulnerable locations within the burn, saving overall cost in labor and minimizing degradation of natural resources (USFS, 2020). BAER teams are sent all over the country, adapting to new ecosystems and soil types constantly. Variation in SWR at small ranges is not easily scaled up to a whole fire incident for effective management prescriptions. A pitfall of BAER SWR sampling methodology is the direct comparison between burn severity conditions and SWR patterns through the BARC map. As discussed previously, many more ecosystem attributes are at play. As the importance of SWR is further understood on a landscape scale, a base inventory of the current state of soils pre-fire and the expected patterns of hydrophobic conditions post-fire must be cataloged and studied on the forest level for BAER teams to best apply their time and resources once called to a region.

This thesis manuscript is an initial overhaul step to fill the research gap in the mapping and understanding of SWR in PNW forest soils. Presented below are two chapters; the first exhibits the findings from a seed dataset collected across multiple wildfires burned in 2017 followed by a second chapter of data collected in 2020 from a single wildfire in the Deschutes National Forest. The zoomed-in approach of whole stand to fine scale methodology used in the second chapter was guided from the lessons learned through the seed project. A much closer look into SWR patterns is required before working to scale up predictions across the whole burn acreage of a wildfire. While core components of SWR sampling are maintained throughout both chapters, development of the methods used has been tailored in the second study to more closely coincide with the behavior and potential scale of the process. This is indicative of the need for additional research across scales to inform managers of the current SWR conditions of their forest and to advance post-fire protocols in SWR assessment.

Figures

Figure 1: Soil core collected in a post-fire system with soil water repellency (SWR) (A; photo: Weatherholt). Surface organic litter creates some SWR conditions pre-fire (B; adapted from Fry, 2016) but can ultimately alter soil properties from wildfire disturbance as hydrophobic compounds deeper into the soil (C; adapted from Fry, 2016). Ineffective infiltration of water can result in increased overland flow and erosion of saturated surface soils as a result of SWR (D; adapted from Fry, 2016).

2 Chapter 1: State of Soil Water Repellency in Pacific Northwest Post-Fire Ecosystems

2.1 Abstract

The Pacific Northwest (PNW) hosts a wide variety of ecosystem types with a range of wildfire disturbance regimes. This diverse environment relies on soils as the foundation for ecosystem health and resilience. As the acreage and intensity of fire increases in some areas due to changes in climate and fuel buildup from historic fire suppression, there is increasing concern regarding the effects of nutrient-rich topsoil loss due to post-fire erosion. Post-fire erosion risk is greatly exacerbated by the influence of vaporized, hydrophobic compounds from burned organic matter that condense on soil particles below the surface (typically through to 20 cm depths) and can create subsurface soil water repellency (SWR). While SWR can occur naturally without fire disturbance, wildfire has been linked to the formation, intensity, and even destruction of SWR in forest soils. Because SWR has been shown to be a greatly variable and understudied process in the PNW, this work aims to examine the distribution of SWR across four 2017 PNW fires (Milli, Norse Peak, Lolo Peak, and Liberty) one year after each incident as well as the dependence of SWR occurrence on soil and canopy burn severity. Results indicated that two of the four fires contained soils with naturally occurring SWR in unburned control sites. Across all fires, SWR occurrence generally increased in more severe fire conditions; however, no significant difference was found between canopy burn severity crown data and unburned conditions nor high soil burn severity and unburned conditions. Soil burn severity was only slightly correlated with SWR in the Norse Peak wildfire while canopy burn severity was not found to correlate with SWR in any wildfire. The lack of consistency in results between fire burn severity measurements highlights the need for additional environmental variables in conjunction with intensive mapping of baseline SWR conditions across forest lands.

2.2 Introduction

The PNW region of the United States is characterized by some of the most diverse and productive ecosystems across the globe encompassed within a relatively small geographic area (Odion and Sarr, 2007). Ecoregions here span old-growth forests and dry grasslands to alpine tundra and shrub-steppe where the historical frequent-fire regime has dictated many aspects of regional biodiversity (Agee, 1996). Varied forest structures and dynamic fire regimes make the PNW an ideal place to examine relationships between fire, soil, and water to support management strategies. Soil water repellency (SWR) induced by fire has long been described in PNW soils (Boyer and Dell, 1980; Campbell and Morris, 1988), but while the occurrence of SWR is documented, baseline patterns and variance of SWR across different degrees of burn severity in the PNW have not been thoroughly researched.

The study presented in this chapter, conducted as an opportunistic protocol supplement for a larger study investigating vegetative responses to fire, examined a subset of PNW fires burned in the 2017 wildfire season: Norse Peak/American Fire, Milli Fire, Liberty Fire, and the Lolo Peak Fire one year following the burn event (Table 1). Each of these wildfires burned in unique forest systems of the PNW. With little data available in this region for widescale SWR conditions, understanding relationships between burn severity, SWR, and post-fire erosion is crucial for managers to address soil-water relations in their forests and the impact of wildfire. There are three questions investigated with this study; i) What is the baseline level of SWR in each of these forests before wildfire disturbance?; ii) Does the occurrence of SWR in soils across a landscape depend on the burn severity of both canopy and soil?; and iii) Which measure of burn severity (canopy or soil) best reflects the SWR conditions found post-fire and can these variables be used interchangeably?

2.3 Methods

2.3.1 Site Descriptions

Liberty Fire, Montana

The Liberty Fire in the Flathead National Forest was the result of a lightning strike and burned 11,661 hectares in July 2017. The primary forest types in this area consist of mixed Spruce-fir, Douglas-fir *(Pseudosuga menzeisii*), lodgepole pine, Engelmann Spruce (*Picea engelmannii*), western larch (*Larix occidentalis*) and whitebark pine (*Pinus albicaulis*) (O'Brien, 1999). Average fire return intervals in the Flathead National Forest area range from under 21 years in Ponderosa Pine ecosystems to over 30 years in Douglas-fir dominated forest areas (Barrett, 1998) with variable return intervals across the valley. Interspersed Alfisols, Inceptisols, and Andisols are found in this region with alpine till and volcanic ash as the parent material (Soil Survey Staff, 2021).

Lolo Peak Fire, Montana

The Lolo Peak Fire was also the result of a lightning strike in an area of 40-50% pre-fire overstory mortality, burning through 21,951 hectares of the Lolo Peak National Forest and the Selway-Bitterroot Wilderness along with state and private lands in July 2017 (USFS, 2017; Mutch, 2018). Regional vegetation is primarily composed of mixed conifer forests including lodgepole pine (*Pinus contorta*), western larch (*Larix occidentalis*), Douglas-fir (*Pseudotsuga menziesii*), subalpine fir (*Abies lasiocarpa*) and ponderosa pine (*Pinus ponderosa*). The fire regime for the majority of the burn perimeter is classified as mixed severity with an average of 25-100 years between wildfire disturbances (Landfire, 2016). Soils are primarily Inceptisols (limited horizonation and slow development) within this burn perimeter derived from granite, gneiss, and mica schist parent materials (Soil Survey Staff, 2021).

Milli Fire, Oregon

The Milli Fire burned over 9,744 hectares in August 2017 the Deschutes National Forest just outside of Sisters, Oregon. Dominated by ponderosa pine (*Pinus ponderosa*) in much of the burned area, a fire return interval from 3-42 years in this vegetation class characterizes many aspects of the landscape (Arabas et al., 2006). Mixed conifer vegetation structures in the greater Deschutes area experience fire return intervals ranging from 9-80 years (Eckert, 2005). Although soil survey data is not available for the plot locations within the fire perimeter, soils just outside the border in similar ecosystems (vegetation, slope, aspect) consist of Andisols and Mollisols with volcanic ash, glacial till, and basalt parent materials (Soil Survey Staff, 2021).

Norse Peak Fire, Washington

The Norse Peak Fire and American Fire (hereby referred to as the Norse Peak Fire) ignited from a series of lightning strikes on steep topography and was fueled by organic matter buildup in this conifer-dominated system ultimately consuming 24,112 hectares (USFS, 2017). This fire was unique as it spanned both the east and west sides of the Cascade Mountains, burning in areas of the Mt. Baker-Snoqualmie National Forest, Okanogan-Wenatchee National Forest, Norse Peak Wilderness, and William O. Douglas National Forest. The historic fire return interval is an average 434 years in the western cascades (Hemstrom and Franklin, 1982) and can range from under a decade to over 300 years on the eastern side of the cascades (Agee, 1994). The forest structure of this region results in a climax species of western hemlock (*Tsuga heterophylla*) below 900 m elevation and Pacific silver fir (*Abies amabilis*) as the dominant climax species above 900 m to the tree line (Hemstrom and Franklin, 1982). A mosaic of Spodosols and Inceptisols are found within this burn perimeter developed from volcanic ash, basalt, and glacial till parent materials (Soil Survey Staff, 2021).

2.3.2 Field Methods

Fires were sampled one year following the burn incidents. Each of these wildfires exhibited a mosaic pattern of burn intensities reported with BARC map products produced immediately post-fire. These maps were used to locate potential areas of varying burn severity within the fire for the establishment of 30-m diameter plots. Once on site, the Composite Burn Index (Key and Benson, 2006) was used to categorize canopy burn severity categories (crown, severe surface, light surface, and unburned control; Table 2) and select plot locations with consistent canopy burn severity over the plot area (Table 3). All plots were located >400 m from the road and other plots to avoid pseudo-replication and effects from the forest road system (Harvey et al., 2013).

In each plot, soil burn severity was categorized (high, moderate, low, unburned) at eight locations (4, 8, 22, and 26m along E-W and N-S transects) using methodology in the *Field Guide for Mapping Post-Fire Soil Burn Severity* (Parson et al., 2010; Table 2) which includes the assessment of surface soil color, mineral soil burn severity, mineral soil color, depth of ash layer (mm), condition of soil structure, condition of roots. The vertical distribution of SWR within the top 10 cm was measured at four locations per plot (8 and 22m along the N-S and E-W transects; Appendix: Figure A1) with the Water Drop Penetration Time (WDPT) method (Woudt, 1959). In this method, the infiltration time of a water droplet is observed and those that remain intact on the surface for more than five seconds are recorded as hydrophobic (Figure 1A, Bisdom et al., 1993). SWR presence and absence was tested at 1-cm increments down the 10 cm column.

2.3.3 Statistical Methods

Data entry, clean-up, and organization were carried out in Excel with all analysis completed using R Studio (RStudio Team, 2020). Burn classes were given an ordinal identifier for statistical analysis where the most intense classes of canopy and soil burn severity (crown and high respectively) were recorded as 3, mid-level severities (severe surface and moderate) a 2, lowest severity (light surface and low) a 1, and unburned as 0. A correlation between the numeric identifier of canopy/soil burn severity class with counts of SWR presence (value of 1) and absence (0) at each fire was used to assess the strength of their impact on soil-water relations. An assessment of the differences of SWR levels across burn severity categories required a Fisher test to compare the counts of presence and absence for subsites at each fire. The percent values of SWR presence was compared graphically across burn classes and the unburned controls for all fires to investigate the role of burn severity and fire behavior on proportions of SWR. Finally, the distribution of soil burn severity found within each canopy burn severity class were averaged across all four fires and distributions compared by pairwise correlations. The corrplot package (Wei et al., 2017) was used to produce a graphical representation of the correlation between soil and canopy burn classes. To differentiate between the composition of soil burn variation within a single canopy burn severity class, each unique pair of canopy classes were compared with a Fisher test across count values of subsites from all fires.

2.4 Results

2.4.1 Baseline SWR levels

An equivalent baseline standard of SWR in undisturbed soils was not seen across all four PNW wildfires. Two general conditions were found, those with SWR in unburned soils in

Oregon and Washington, Milli and Norse Peak, as well as two fires without in Montana, Liberty and Lolo (Figure 2; Table 4). These groups would be maintained if compared by shortest distance between fires; similar conditions linked by close range and ties of ecosystem characteristics add to their association. Milli and Norse Peak both exhibited naturally high background levels of SWR in undisturbed soils with 69% and 92% presence respectively while no evidence of pre-fire SWR was found at the Lolo nor Liberty fires (Table 4). Soils throughout the study points of these fires do not exhibit the same responses of baseline SWR pre-fire.

2.4.2 Relationships between SWR occurrence and burn severity

Burned subsites were found to differ in SWR presence by >5% from the unburned control levels for the majority of the canopy and soil burn severity classes. In the case of all four fires, the highest severity classes of both canopy and soil (crown and high, respectively) were characterized by larger percentages of SWR than unburned subsites (Table 4); though the Fisher tests revealed no significant differences (Table 5). In the Milli and Norse Peak fires, where natural SWR was present in pre-fire soils, SWR generally increased with increasing burn severity, though SWR occurrence generally exceeded unburned levels only at the highest soil burn severity while the less severe soil burn severity resulted in a decline in SWR (Figure 2E-H). However, only the relationship between soil burn severity and SWR at Norse Peak produced even moderately significant results (p=0.09; Table 4). SWR was not significantly correlated to canopy burn severity at any of the wildfires (Table 4) . No statistical differences were detected between SWR levels of canopy burn severity classes in the Milli, Norse Peak, or Liberty fires (Table 5).

SWR was created by the fire event in the naturally hydrophilic soils from Lolo and Liberty fires (Figure 2A-D). Within the highest and lowest canopy burn severities, SWR occurred in 8-25% of subsites following fire with no change in severe surface plots or in moderately burned soils in the Lolo Fire (Figure 2A and C). From the Lolo Fire, SWR levels in subsites underneath crown fire conditions were significantly different than unburned plots but not from severe surface and light surface (Table 5). The Liberty fire saw the largest significant increase in SWR from unburned levels (33%) at the moderate soil burn severity but had no evidence of SWR in severe surface plots. Liberty was missing low soil severity data (Figure 2B and D, Table 5). The significant rise in SWR under a crown fire from severe surface and light surface at Lolo and with moderate soil burn severity at Liberty supports a general pattern of increasing SWR as burn severity increases.

4.2.3 Relationships between soil and canopy burn severity

When comparing the overall distribution of soil burn severity levels within each canopy burn severity across all plots and all fires, there was a significant difference among the fraction of plots of a given soil burn severity within each canopy burn severity ($p<0.01$). As expected, soil burn intensity decreases as canopy burn severity decreases (Figure 3A). Positive correlations are found between the most intense canopy, crown, and most intense soil, high, burn severity while a strong negative correlation was found between the most and least intense of each variable (Figure 3B; Table 6). Although the relationship between canopy and soil burn severity is not 1:1 (i.e., patterns in soil burn severity occurs on a finer scale than canopy), the distribution of soil burn across a landscape seems to be fairly well associated with canopy burn severity.

2.4 Discussion

Although previous laboratory studies have shown that SWR layers are commonly destroyed in high severity fires as long burn durations and high temperatures vaporize and remove volatile compounds that often cause hydrophobic layer formation (e.g., DeBano and Krammes, 1966; Doerr et al., 2004; Wieting et al., 2017; King, 1981), our results show high levels of SWR under even the most intensely burned conditions. High severity crown fires may not cause substantial heating at the soil surface because they sweep so rapidly over the landscape that the majority of the heat is concentrated in the canopy rather than being generated and left to smolder at the soil surface (Neary et al., 2005). Large proportions of high soil burn severity were found in crown severity stands sampled, opposing this trend of limited soil burn severity underneath crown fire behavior. SWR in these locations seems to be driven both by temperature changes during fire and other ecosystem factors. In the case of Milli and Norse Peak, two fires with naturally occurring SWR, moderate and low soil burn severity classes may have lower levels of SWR than unburned if the conditions allowed for the loss of vaporized hydrophobic compounds from the soil system rather than layer formation. These two fires may illustrate a common fire management goal which indicates that an effective way to decrease or remove SWR is through frequent prescribed burning with low and moderate soil burn intensities (e.g., Doerr et al., 2006; Fernandes, 2015; Tolhurst and McCarthy, 2016).

However, this guidance may only be appropriate for sites with naturally occurring SWR. In the Lolo and Liberty fires, which had no pre-fire SWR, fire generally created hydrophobicity regardless of the burn severity. This was less evident in the moderately burned plots of these two wildfires potentially because the critical heating threshold for SWR destruction was met under this burn condition (Simkovic et al., 2008) or due to sample size issues. Although the threat of SWR-driven erosion may be lessened at moderately burned sites without natural SWR, the structure of these soils is likely still impacted by fire and thus are still vulnerable (Mataix-Solera et al., 2002).

The apparent lack of significant differences found between burned classes and unburned SWR conditions may be a result of two potential factors: 1) the extent of SWR variation made comparisons across burn conditions difficult at this scale, and 2) unburned control sample sizes were limited in this study, especially in the Lolo and Liberty fires. These results act as a call for further study of PNW characteristics at a variety of scales to isolate SWR responses to wildfire and examine other environmental factors which could contribute soil-water relations (Doerr et al., 2000).

Currently, SWR levels over large wildfire scars following containment are translated to mangers through stand and landscape scale metrics of canopy and soil burn severity. Although these metrics are not completely interchangeable, results from this study have illustrated that there is a strong relationship between soil and canopy burn severity with local fire behavior driving these patterns as a result of heterogeneous fuel availability which impacts fire activity and burn severity differently at soil and canopy scales (Kane et al., 2015). This logical relationship of increasing proportions of higher soil burn severity with more intense canopy burn may be useful for general patterns but will not give a clear distinction as to the persistence of SWR in a system from the limited significant differences between burn severity categories of both the canopy and soil. Ultimately, the reports provided by BAER teams translate pivotal information of ecosystem vulnerability and SWR conditions essential to post-fire management. In addition to post-fire reports, a baseline understanding of SWR conditions must be obtained in areas at risk of wildfire. PNW managers should be amply informed that in forest areas with pre-disturbance SWR an increasing pattern of presence with increasing soil and canopy burn severity following a wildfire event can be expected; likewise, managers of forests without hydrophobic soils should anticipate an increase in SWR across all soil burn classes. Management objectives as a result of this research should aim to gain knowledge of forest conditions under their jurisdiction in addition to allowing frequent, controlled burns to decrease levels of SWR over time. Isolating SWR responses is critical as populations inhabiting the wildland urban interface grow and decreasing fire intensity, especially in forests with pre-fire SWR, must be an essential objective in wildfire management strategies to mitigate high-risk erosion.

2.5 Conclusion

The land area and number of homes comprising the wildland urban interface in the United States has expanded expeditiously and is currently the fastest-growing land use type in the contiguous United States (Radeloff et al., 2018). These communities are exposed to greater levels of post-fire erosion and landslide risk due, in part, to the exacerbation of SWR associated with wildfire (Chas-Amil et al., 2013; Radeloff et al., 2018). While the general trend of increasing SWR with increasing burn severity is evident, additional publicly available variables must be explored to identify ecosystem factors that could contribute to this process. Vegetation classification, soil qualities, and seasonal climate must be examined in continued research efforts to account for the many environmental and climatic facets of SWR patterns. Data should be drawn from publicly-available sources to ensure the widescale applicability of this project's findings: *USGS Landfire*, *U.S. Landsat Analysis Ready Data (Landsat-8 images courtesy of the U.S Geological Survey), Soil Web (UC Davis)*, and *PRISM (Prism Climate Group)*. Fine-scale variation observed within individual plots may not be captured through the pixel grain from these sources; however, the data products available still offer applicable information to SWR patterns. The ambiguity found in this study may reflect that the methods of sampling were carried out at too large of a scale to isolate the various local SWR conditions. Assessment of SWR patterns must begin at an initial small range that can then be scaled up for the landscape needs of managers. To fill the research gap still remaining following this project, patterns and baseline SWR conditions of forest land throughout the PNW must be documented. Conditions found from these four fires provide useful insight to the state of forest soils post-fire and offer an initial step in describing this process throughout the region.

Figures

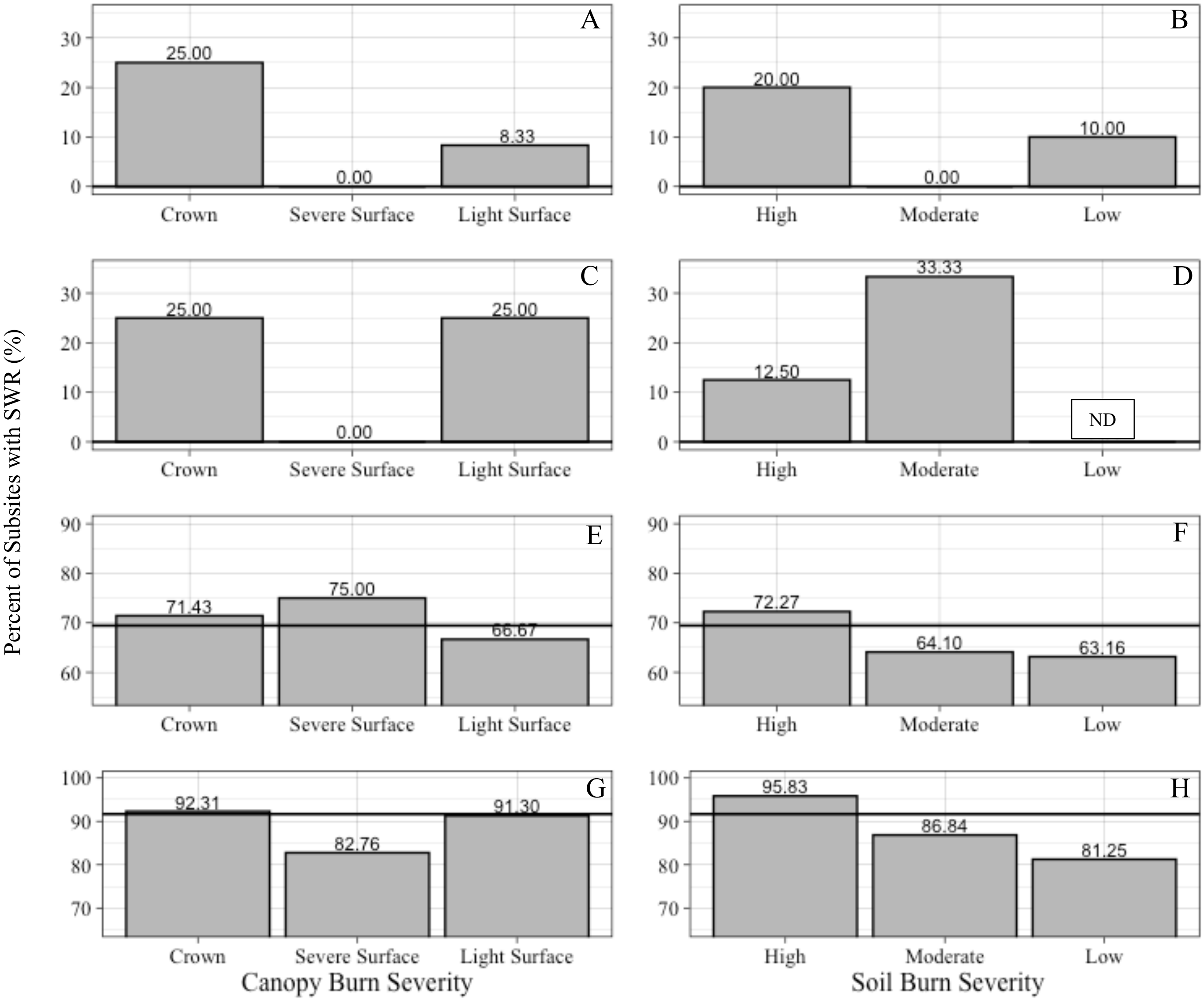

Figure 2: The percent of subsites with SWR present in the soil horizon found at Lolo (A, B), Liberty (C, D; ND= no data), Milli (E, F), and Norse Peak (G, H) wildfires across canopy and soil burn severity classes. Control levels of SWR from unburned subsites bisects each figure with a bold, horizontal black line.

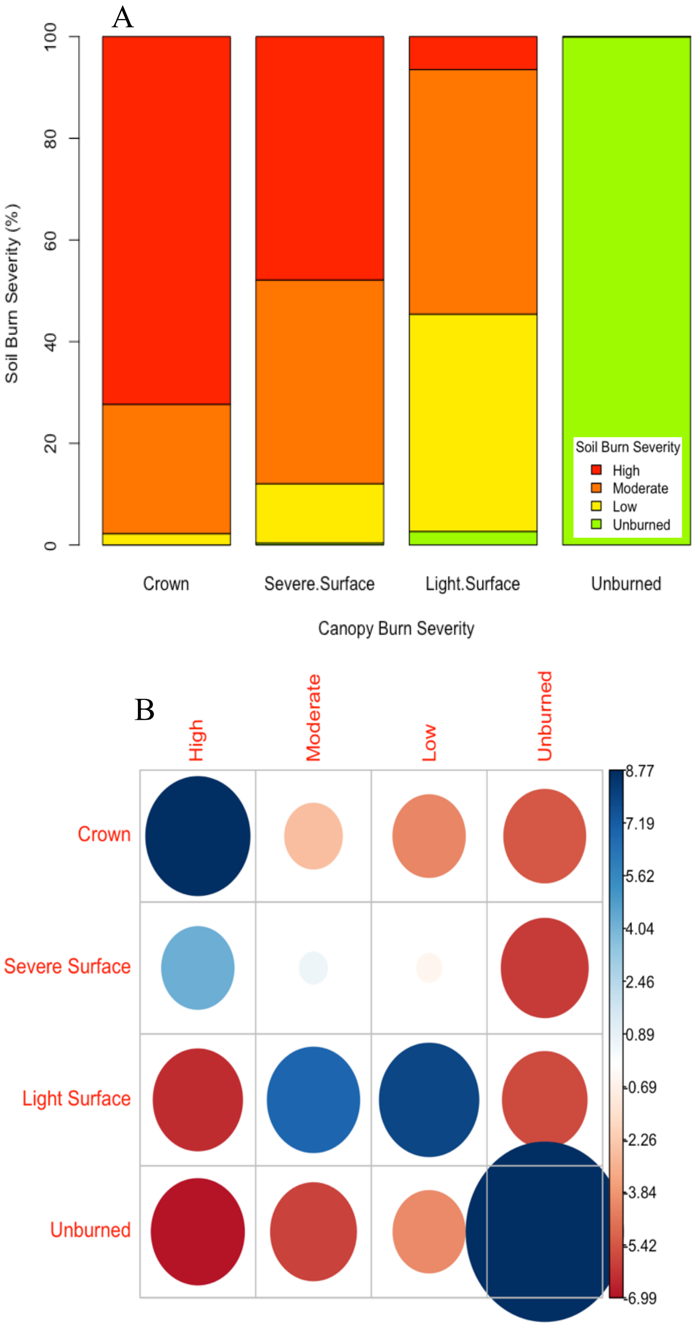

Figure 3: Proportions of soil burn severity found under each canopy burn severity class averaged across the Milli, Norse Peak, Lolo and Liberty wildfires (A). A correlation matrix compares canopy burn severity classes with its corresponding proportions of soil burn severity. Large, dark blue circles indicate highly, positively correlated pairs of canopy and soil conditions while large, dark red circles imply a negatively correlated relationship (B).

Tables

Table 1: Fire information. Data courtesy of Monitoring Trends in Burn Severity (EcoWest, 2021).

Fire	**National Forest(s) (State)**	**Size (Hectares)**	**Ignition Date**	**Control Date**
Liberty	Flathead (MT)	11,661	7/22/2017	09/18/2017
Lolo Peak	Lolo Bitterroot Nez Pierce-Clearwater (MT)	21,951	7/17/2017	09/17/2017
Milli	Deschutes (OR)	9,744	8/11/2017	09/24/2017
Norse Peak	Mt. Baker-Snoqualmie Okanogan-Wenatchee (WA)	24,112	8/12/2017	11/1/2017

Table 2: Evaluation criteria for assessing canopy (CBS) and soil (SBS) burn severity following a wildfire disturbance (modified from Hudak et al., 2004; Key and Benson, 2006).

CBS	**Trees**	**Needles**
Crown	Dead, blackened to top, fine branches consumed	Dead, completely consumed
Severe Surface	Dead, trunk partially blackened	Dead, orange
Light Surface	Live, some scorching of tree bowl	Live, some browning on lower branches
Unburned	Live	Live, green
SBS	**Soil Characteristics**	
High	All organic matter consumed, soil aggregation and structure destroyed, Charred or consumed fine roots in surface soil, surface color orange/ black/gray	
Moderate	Most of the organic matter consumed, fine roots scorched in surface soil, soil structure minimally degraded, black/brown/gray surface color	
Low	Organic matter is not completely consumed, no change to structure, surface color black/brown	
Unburned	No appearance of recent fire disturbance	

Table 3. Total plot and subsite counts (n≈8 per plot) from each fire broken down by plot level canopy burn severity class and subsite soil burn severity.

	Milli					**Norse Peak**				
	Plot Count	High	Moderate	Low	Unburned	Plot Count	High	Moderate	Low	Unburned
Crown	7	56	0	0	0	6	29	11	1	0
Severe Surface	12	75	20	1	0	7	9	24	23	0
Light Surface	12	10	54	31	0	6	1	32	14	0
Unburned	9	0	0	0	72	3	0	0	0	24
	Lolo					**Liberty**				
	Plot Count	High	Moderate	Low	Unburned	Plot Count	High	Moderate	Low	Unburned
Crown	2	12	4	0	0	3	18	6	ND	0
Severe Surface	4	18	8	0	1	2	8	6	ND	0
Light Surface	3	0	5	18	1	1	3	5	ND	0
Unburned	1	0	0	0	8	3	0	0	ND	23

Table 4: Correlation results and percent change from unburned for each fire and class of canopy and soil burn severity. The correlation value ranges between -1 and 1 where 0 is no distinguishable difference. Marginally significant p-values (<0.1) are indicated with an *.

	Milli	**Norse Peak**	**Lolo**	**Liberty**
n	160	90	38	34
UB SWR (%)	69.4	91.7	0.0	0.0
CBS correlation (p)	-0.6 (0.61)	-0.1 (0.94)	0.0 (1.00)	-0.7 (0.55)
Crown – UB (%)	2.0	0.6	25.0	25.0
Severe Surface – UB (%)	5.6	-8.9	0.0	0.0
Light Surface – UB (%)	-2.8	-0.4	8.3	25.0
SBS correlation (p)	-0.9 (0.30)	-1.0 (-0.09*)	-0.5 (0.67)	-0.4 (0.76)
High	7.8	4.2	20.0	12.5
Moderate	-5.3	-4.8	0.0	33.3
Low	-6.3	-10.4	10.0	ND

Table 5: Pairwise Fisher test results comparing the SWR levels of burn severity categories. Marginally significant p-values (<0.1) are indicated with an * while significant p-values (<0.05) a **.

Canopy Burn Severity	**Milli**	**Norse Peak**	**Lolo**	**Liberty**
Crown/ Severe Surface	0.79	0.43	0.04***	0.52
Crown/Light Surface	0.80	1.00	0.04*	0.51
Crown/Unburned	1.00	1.00	0.49	0.22
Severe Surface/Light Surface	0.50	0.22	0.46	0.40
Severe Surface/Unburned	0.80	0.65	1.00	1.00
Light Surface/ Unburned	0.81	1.00	1.00	0.25
Soil Burn Severity				
High/ Moderate	0.18	0.64	0.53	0.29
High/Low	0.24	0.02**	0.63	ND
High/Unburned	0.63	1.00	0.54	0.49
Moderate/Low	1.00	0.42	1.00	ND
Moderate/Unburned	0.62	1.00	1.00	0.10*
Low/ Unburned	0.55	0.55	1.00	ND

Table 6: Correlations in proportions of degrees of soil burn severity (high, moderate, and low) present as canopy burn severity (CBS) increases in the Milli, Norse Peak, Lolo, and Liberty fires. Correlation values ranges between -1 and 1 where 0 is no distinguishable difference. P-values followed with * are marginally significant (<0.1) while those with ** are significant (<0.05).

SBS	**Milli**		**Norse Peak**		**Lolo**		**Liberty**	
	Corr	p	Corr	p	Corr	p	Corr	p
High	0.69	0.52	0.97	0.15	0.66	0.55	1	0.01**
Moderate	-0.99	0.10*	-0.99	0.08*	-0.24	0.24	-1	0.02**
Low	-0.88	0.32	-0.51	0.70	-0.87	0.33	ND	ND

3 Chapter 2: Investigation of the Connections Between Soil, Fire, and Water in the Deschutes National Forest

3.1 Abstract

Increasing annual land area affected by wildfires is attributed to current climate change conditions in conjunction with years of fuel build up from fire suppression efforts. Following containment of these growing fires, local managers and Burn Area Emergency Response teams are especially concerned with the increased risk of topsoil erosion as a result of weakened soil structures and impeded water infiltration. Soil water repellency (SWR), a subsurface layer of substrate coated with hydrophobic compounds from organic material, prevents water infiltration and greatly increases surface soil erosion risk. SWR can occur naturally in a soil and may also be formed by or increase in spatial density after wildfire. This study examines four 44x20 m plots in the Deschutes National Forest across varying degrees of burn severity to 1) examine the relationship between SWR and management relevant burn severity classes, 2) quantify an appropriate spatial scale over which to evaluate SWR properties, and 3) determine which environmental factors drive patterns in SWR. We found that both canopy and soil burn severity metrics did significantly explain some variation in SWR following fire; however, there were few patterns in SWR within burned soils aside from an increase in the heterogeneity of hydrophobic conditions after fire. SWR significantly dissipated with depth while the range of spatial dependence of SWR only extended to, on average, ~5 m. Due to fine-scale variation, soils measured at just a few point locations within a post-fire ecosystem may misrepresent the true levels of SWR, or even fail to record any SWR presence. Future work should focus on determining a post-fire protocol with adequate density and scale of sampling over which to evaluate SWR while also incorporating the influence of environmental factors (e.g., soil texture, conductance, organic matter, soil moisture, and pH) to inform management decisions.

3.2 Introduction

SWR is a soil condition that limits the ability for water to infiltrate, most notably following wildfire, as a result of a coating of organic material on subsurface particles. In addition to the creation of SWR immediately following wildfire, approximately 92% of soils from temperate ecosystems in the US display some degree of hydrophobicity (Seaton et al., 2019). Even this value, which was derived from 1300 diverse sites, does not address the drastic variation observed at fine scales with naturally occurring, pre-fire SWR. For example, Bodí et al. (2013) found comparable degrees of SWR spatial heterogeneity at both the 1 ha and 10x10 cm scales in forests of eastern Spain. The persistence, intensity, and spatial variation of hydrophobic conditions in soil is an extremely variable process (Bodí et al., 2013). Specifically, the spatial variation of SWR has been shown to be impacted by climate, soil characteristics, and geologic conditions (Lemmnitz et al., 2008). During and immediately following a fire, Burn Area Emergency Response (BAER) teams, made up of resource specialists and professionals often working in collaboration with other stakeholders from federal agencies to local governments, assess the landscape and prescribe treatments which promote human safety and minimize impacts on cultural and natural resources. While previous studies have acknowledged this high level of spatial heterogeneity (e.g. Woods et al., 2007), the amount of time and resources available for BAER teams does not allow for extensive sampling across scales within a burn perimeter. With 404,6856 hectares burned in the 2020 fire season in Oregon state alone (Urness, 2020), understanding the influence of wildfire on soil-water relations in these forests is essential for managers as more arid conditions of limited moisture availability encroach deeper into the western US (Higuera and Abatzoglou, 2021).

Areas with high naturally-occurring SWR, like the Deschutes National Forest in Oregon State, must have coordinated management efforts to work through the impacts of an intensifying fire regime on erosion risk. The Deschutes National Forest can experience fire return intervals from under 10 years up to 80 years, fairly typical of the mixed conifer, ponderosa pine ecosystem found there (Arabas et al., 2006; Eckert, 2005). A shift in vegetation structure has yielded a higher density of younger grand fir (*Abies grandis*) and lodgepole pine (*Pinus contorta*) individuals while the area of true ponderosa pine forest decreases. This makes the landscape more vulnerable to stand replacing fire (Perry et al., 2004). Changes observed in plant community composition and ultimately the relationship between ecosystems and fire must be examined holistically, from the trees to the soil. However, a fundamental question remains unanswered: How can a BAER team anticipate the SWR conditions in an area with naturally-occurring SWR following a wildfire? This study seeks to answer this question in the Deschutes National Forest by addressing three main objectives: i) examine the relationship between SWR and burn severity classes; ii) quantify an appropriate spatial scale over which to evaluate properties of SWR; and iii) determine which environmental factors drive patterns in SWR.

3.3 Methods

3.3.1 Site description

On August 16, 2020, the Green Ridge Fire was ignited by lighting 19 km north of Sisters, Oregon. The burn perimeter encompasses 1,756 hectares of both private and federally managed lands in the Deschutes National Forest (InciWeb, 2020). Although not the largest nor most severe fire in the 2020 PNW wildfire season, the Green Ridge Fire was selected for sampling due to the variety of aboveground fire behaviors (i.e., severity) noted by the Incident Commander during containment operations in addition to the high levels of naturally-occurring SWR identified within unburned soils of the Deschutes National Forest from seed data collected during the pilot study in the nearby Milli Fire (Ch 1: Table 1, Table 4).

3.3.2 Field Methods

Plots were selected based on the following sampling requirements: 1) consistency of a single canopy burn severity class over the entire plot area; 2) similar aspect and slope among all plots; and 3) location in a forested ecosystem. A total of four 44 x 20 m rectangular plots, one in each canopy burn severity class (crown, severe surface, light surface, or unburned; see Ch 1, Table 2 for severity classification descriptions), were established and oriented to traverse the slope with a longer plot edge situated as the downhill perimeter. Sample points were dispersed in a spatially explicit, cyclic sampling grid (N=81 points per plot, Figure 4). Plots consisted of nine rows spaced 2-m apart each of which contained three 14-m cycles of sampling locations spaced 2, 4, and 6 m apart within each cycle (e.g., samples at distance 0, 2, 6, and 14 m in cycle 1). Cycles were reversed and offset by 6 m in the center three rows to avoid potential anisotropy (Burrows et al., 2002). The outermost two meters of each plot acted as a buffer to further reduce soil disturbance of sampling points during plot setup. A constant compass bearing was used to pull parallel lines from a tape measure of each column of sampling points perpendicular to the downhill boundary to avoid additional soil disturbance from tracking. Pin flags were placed at each designated sampling location to ensure limited disturbance before sampling.

Surface soil burn severity was classified at all 81 points using the *Field Guide for Mapping Post-Fire Soil Burn Severity* (Parsons et al., 2010; Ch 1 Table 1); measurements of surface soil color, mineral soil color, depth of ash layer, effect on soil structure, and condition of roots were assessed and recorded to interpret the overall soil burn severity of each point following the Forest Service standards. A 3-cm diameter core was taken with a soil auger to 20 cm and tested with the water drop penetration time test for SWR at each centimeter down the horizon (Letey, 1969). In addition to SWR presence/absence, the SWR intensity (infiltration time) was classified as not hydrophobic (infiltrated in <5 seconds), slight (5-15 sec), moderate (16-30 sec), and extreme (>30 sec). At a subset of plot points (rows at 2 and 8 m, n=18, Figure 4), soils were tested for small-scale horizontal variations in SWR by placing approximately 14 evenly-spaced drops of deionized water sequentially within an 8.5 cm diameter ring placed on a flat, uniform soil surface at the mineral soil surface, 5 cm, 10 cm, and 15 cm depths. The number of drops that infiltrated at each SWR intensity was recorded. Soil volumetric water content, electrical conductivity, and temperature were quantified at 0-5, 5-10, and 10-15 cm depths (TDR 150 Soil Moisture Meter-MSFS-TDR150 Field Scout, Spectrum Technologies Inc., Aurora, IL). Following these measurements, a 0-15 cm soil sample was collected for textural (hydrometer), pH (1:1 soil:water, glass electrode), and organic matter (loss on ignition, ~20 g soil at 550° C for 4 hours) analysis. In addition to below ground sampling, overstory vegetation species identification, diameter at breast height (DBH), location, and status (live or dead) were recorded for all trees contained within the plot.

3.3.3 Statistical Methods

All analyses were performed in R Studio (RStudio Team, 2020). Infiltration times used to reflect the intensity of SWR were converted from categorical into average time equivalents; 0 seconds where no hydrophobicity was found, 10 seconds in slight SWR, 23 seconds in moderate, and 34.5 seconds for extreme (mean seconds interval increase of 10 and 13 from groups 0-1 and 1-2 are averaged to 11.5, 23+11.5=34.5 seconds for group 3). A Permutational multivariate analysis of variance (PERMANOVA) analysis (vegan: Community Ecology Package; Oksanen et al., 2020) was used to address our first objective, examining the relationship between SWR and burn severity classes of canopy and soil. A distance matrix of all depth infiltration times across all sampling points at each plot was created using the Euclidean distance metric as the response in a PERMANOVA. A type I sequential sum of squares was applied to the distribution of variance explained by the explanatory variables to allow the plot scale of canopy burn severity to account for the noise surrounding the soil burn variable. The Euclidean distance metric was chosen because SWR grouping classes are based on a continuous factor of seconds. The explanatory variables of canopy burn severity, soil burn severity, and their interaction were run against the distance matrix. To visualize the SWR distribution across plots and soil burns, a test of homogeneity of dispersions (PERMDISP) was used to compare these grouping variables to variation observed in their SWR responses. The PERMDISP visual output represents each group (classes of canopy and soil burn severity) with a centroid and outlining polygon to show if grouping variables differ in average response (centroid) and range of recorded responses (polygon). Additionally, an analysis of similarity (ANOSIM) was then applied to further understand if conditions are independent across grouping variables in this ecological system.

In order to explore the spatial scale on which SWR should be evaluated (Objective 2), a principal components analysis (PCA) was used to compare the influence of depth on SWR response across all sampling points (stats; R Core Team, 2020). Principal components were directly input to a PERMANOVA with a type I sequential sum of squares for further investigation of the role depth plays in SWR. SWR responses from an aerial perspective across each plot were analyzed for each depth separately through a Moran's I correlation coefficient (sp; Bivand and Pebesma, 2013) to detect any evidence of spatial autocorrelation. The two matrices input to the correlation (the distance matrix of physical subpoint locations within the plot in meters and SWR responses at all depths for each plot) are compared with a series of random permutations. Resulting correlations of the two matrices are reported as observed and expected between -1 and 1, with those values depicting the bounds of perfectly opposite and synonymous results respectively and 0 showing no relationship. A significant p-value with differing observed and expected results supports that the presence of some degree of autocorrelation is present. Each plot depth was additionally assessed with semivariogram analysis (gstat; Gräler et al., 2016) to detect a physical range of SWR response dependence. To further understand how responses measured at the stand level compare to fine scale SWR patterns, a Mantel Test (ape; Paradis and Schliep, 2019) was used to correlate the average responses found in each horizontal plane at 0, 5,10, and 15 cm depths of the 18 additional sampling points with the corresponding single vertical soil core measurement. The Mantel statistic ranges between 1 and -1 where 0 represents no correlation.

A final PCA was used to investigate the environmental explanatory factors (Objective 3) of organic matter content, pH, field moisture, conductance, percent sand, percent silt, and percent clay. A square root transform was applied to field moisture, conductance, and percent silt variables to best fit within the qualities of a normal distribution. Principal components explaining the majority of the reported variation were used in a PERMANOVA to observe the significance of the environmental parameter weights on SWR with a Type I sequential sum of squares. Canopy burn severity was listed as the first explanatory factor before the principal components in this PERMANOVA to account for the noise in variation between plots. This was done to isolate the sampled environmental factors over the inherent variation of SWR at the whole plot level.

3.4 Results

3.4.1. Burn severity and Soil Water Repellency

SWR within the Green Ridge Fire perimeter was found to vary widely across depths and plots. Canopy burn severity significantly accounted for 12.4% of the variation in SWR down the soil horizon (p=0.003) while soil burn severity accounted for 6.8% with marginal significance in a PERMANOVA (p=0.046). The interaction effect of canopy:soil accounted for 9.3% of the variation (p=0.014). The PERMDISP of canopy burn severity groups did not reveal differences between overall SWR responses from the four classes (p=0.16) while soil burn was found to be a significant variable for grouping of SWR responses (p= 0.001; Figure 5). The centroids of classes, both in canopy and soil groups, appear to be very similar in the plotted SWR results. Unburned soil responses have a more confined distribution of SWR characteristics when compared to the more spread dispersion of burned soil classes. The ANOSIM analysis highlights the lack of distinction between groups both for canopy and soil classes by showing that the responses are well mixed across all groups rather than unique patters of soil-water relationships within each (canopy grouping: R=0.012 p=0.026; soil grouping: R=0.021 p=0.051; Figure 5).

3.4.2. Spatial distribution of SWR

Results from PCA analysis of SWR response to depth reflect the visual trends of the data that deeper samples were more negatively associated with intensely water repellent soils (Figure 8). PCA weightings from the second principal component switched to negative at the 14 cm depth (Table 7); SWR occurs less frequently as depth increases. The first four principal components were run through a PERMANOVA, all of which explained statistically significant percentages of overall data variation (Table 7). Probability of SWR for all intensity classes dissipates down the horizon and concordantly the abundance of hydrophilic soils increases with depth (Figure 7). The unique shape of the moderately hydrophobic category of the unburned plot is attributed to the relatively small sample size of that SWR severity in the plot.

SWR responses did not form in consistent, clear sections of the horizon in all plots with spatial autocorrelation based with the Moran's I in any plot (Table 8). Locations with potential spatial dependence were spaced throughout the soil columns and thus the overall effects of fire were inconsistent along the profile (Figure 6). The severe surface plot does have a section of the soil horizon from 4-11 cm with significant and marginally significant Moran's I p-values (Table 8). Semivariogram analysis used to find ranges of spatial dependence produced variable results at all plots. When ranges could be identified, distances varied between 1.06-48.42 m with an average of 5.32 m (Table 8). Comparisons of vertical measurements and fine scale averages from horizontal measurements of SWR at 0, 5, 10, and 15 cm of the additional sampling points across plots were found to be moderately but significantly correlated (Mantel statistic r= 0.40, p=0.001).

3.4.3. Environmental controls on SWR

PCA of environmental factors from the additional sampling points returned two significant principal components when run through a PERMANOVA (Table 9). Visual representation of the weightings from the first and second principal component was created to show correspondence of environmental variables to SWR conditions (Figure 10). More basic soils (higher pH) and those with higher field moistures are least associated with extreme SWR conditions in the first principal component. In contrast, soils with more organic content (LOI method), higher conductance, and larger percentages of clay are found more commonly with SWR in the first principal component. Higher levels of coarse textured sand in a soil is found less often with SWR while higher percentages of silt are found more often with SWR.

3.5 Discussion

While monitoring the creation and distribution of SWR layers within post-fire environments is a priority for BAER teams, the confounding influence of natural hydrophobicity on these patterns is not yet understood. This study is another step forward in filling the knowledge gap of soil responses to wildfire when SWR is present prior to the disturbance, a condition characteristic of most temperate ecosystems in the US (Seaton et al., 2019). Observing the impacts of wildfire within soils prone to inherent SWR layer formation and its spatial variation is necessary to the application of effective management strategies in a changing climate and fire regime. Managers of the Deschutes National Forest and other forest land with similar SWR and landscape characteristics would greatly benefit from understanding how this process varies across burn severity classes, what spatial distributions and patterns can be relied on when assessing a landscape, and finally what environmental factors drive hydrophobic conditions.

Soil burn severity and slope aspect are the two main factors used in the landscape scale assessment of SWR induced erosion risk by BAER teams (Parson et al., 2010); yet burn severity variables have been shown in this study to only marginally explain the heterogeneous nature of the process. It was surprising that so little variation in SWR was explained by canopy and soil burn severity in this system, 12.4% and 6.8% respectively, as wildfire severity has been shown to be a largely significant indicator of post-fire SWR patterns (Lewis et al., 2006); the results could reflect the complex of pre-fire SWR which is present in this environment. In other words, simply relating canopy and soil burn severity to SWR in ecosystems with naturally hydrophobic soils may not be reliable. Soil burn severity classes, which did exhibit statistically significant differences in SWR, may more accurately reflect the fire temperature and smoldering duration experienced at a specific point (as compared to canopy burn severity) that drives the formation and destruction of SWR layers (DeBano and Krammes 1966). As canopy burn severity in this study may capture both the class of canopy burn and also the differences between stand characteristics of the plots themselves (as reflected by the PERMANOVA analysis), results support the incorporation of additional environmental factors (e.g., texture, pH, moisture, organic matter) in predicting SWR. This also emphasizes the importance of increasing the accuracy of soil burn severity assessment in conjunction with the collection of aboveground vegetation data when predicting SWR. However, before additional environmental variables can be explored, it is essential to first understand the scale of soil-water responses; although we were anticipating a stronger dependence of SWR on soil burn severity, results highlight the impact of fine-scale variation in SWR even within a given soil burn severity.

When examining this fine-scale spatial variability, it appears that the burned locations were actually more heterogeneous than the unburned locations, making accurate predictions of landscape-scale SWR even more challenging. When examining vertical changes in SWR, hydrophobic conditions are much more common in surface soils, dwindling deeper (especially below 14 cm) in the soil column. This is crucial for post-fire soil loss as hydrophobicity in surface soils have been associated with increased erosion and overland flow events because it takes less water to saturate the topsoil and saturated soils easily lose structural stability, allowing them to shift and erode easily in a disturbed system (Shakesby et al., 2000). In areas like the Green Ridge Fire which have both natural and fire-driven shallow SWR layers, the effect of fire on aboveground mortality and loss of structure from organic matter content could further increase the risk of soil degradation in already vulnerable soils over the impacts in changes to SWR.

SWR density dependence on depth is much more easily identified than horizontal patterns across the landscape. Wildfire has been shown to homogenize the relationships between soil and water in other systems (Ebel, 2012); our initial interpretation of homogenization in the context of SWR was the redistribution of hydrophobic conditions in clearer sections of the soil horizon over a large range. While little evidence of these patterns were found in the crown and light surface plots, the horizontal plot patterns across the severe surface stand at each depth from 4-11 cm showed evidence of spatial dependence. This range of soil depths with spatially dependent SWR responses over the whole plot area may be an example of SWR homogenization from fire. Wildfire behavior in a severe surface fire may provide the appropriate scenario for this assimilation of soil water relations compared to crown and light surface stands. With a mean range for similar SWR conditions of approximately 5 m across all plots, the ability to scale up conditions from the stand level to the entire fire perimeter remains a challenge. This variation over a short distance is most dramatically observed between responses of our two sampling methods 1) WDPT test on the vertical soil core and 2) WDPT of 14 points on a small horizontal plane (8.5 cm diameter) at 0, 5, 10 and 15 cm. Locations identified as hydrophilic at 5,10 and 15 cm of the soil core were often found to have highly variable amounts of infiltration (up to 40% of points) and intensities (up to 25% of points measuring extremely hydrophobic) of SWR in the immediately adjacent horizontal plane (Figure 8). This presents the true challenge of assessing and up-scaling SWR in these environments. A deeper look into the applicability and improvement of BARC maps as a tool for SWR predictions is necessary for accurate information of variability to be accessible to managers . From these results, the homogenization of SWR observed in areas with naturally occurring soil water repellency may actually materialize as the consistent degree of variability itself observed across all burned plots.

BARC maps of large wildfire events have a resolution of 30x30m pixels; however, the spatial heterogeneity found in this study does not appear to allow for the assumption of similar SWR responses even pixel to pixel for soils with pre-existing SWR. To improve SWR interpretation from BARC maps, BAER teams should consider including data from increase ground truthing across scales of burned soils and include additional assessment of the variation in unburned soils for SWR to be written into BAER reports. This will allow managers to further understand the relationship between BARC maps and SWR conditions on the ground. The current methods for assessing SWR on a landscape for these maps rely on dispersed, and generally limited, measurements of the water drop penetration time with a soil auger or infiltration rates with a mini-disk infiltrometer (Robichaud et al., 2008). Soil infiltration assessment methods have been structured around a general assumption of increased SWR with increased burn severity formed from prior evidence in the field (Varela et al., 2005). Through the results from the Green Ridge Fire, we know that patterns of SWR cannot simply be inferred by categories of burn severity (canopy or soil) due to the dissimilarity of soil-water relations over short distances. This would support the expansion of BAER protocol to include both large-scale interspersed measurements in addition to fine scale observations to gain a clearer understanding of the variance within the mapped classes. Improved protocols will allow managers to identify the extent of fine scale SWR variation within burn classes and perhaps alter the prescribed treatments to reflect a more heterogeneous system. Areas of high burn severity are proportionally more often selected for treatment efforts compared to moderate and low burn severity classes (Robichaud, 2000). The degree and variation in SWR may be similar throughout the different soil severity classes in forests with naturally-occurring hydrophobicity; management prescriptions applied to reduce or prevent SWR related erosion may be biased toward highly burned soils while moderate and low soil burn severity classes may receive less preventative action. Federal funds may be best applied for erosion management based on general loss of soil structure from organic matter loss and other environmental factors.

Soil burn severity is the management applicable variable used by BAER teams to translate hydrophobic soil patterns to local management (Parson et al., 2010). Still an essential piece to the puzzle, soil burn severity is just a single factor in the tangled web of environmental conditions driving SWR (Doerr et al., 2009). We found a number of environmental factors in the Green Ridge Fire that significantly associate both positively and negatively with SWR in the Deschutes National Forest. In this system, finer soil textures were associated with the presence of SWR which, though it exists in stark contrast to the post-fire assessment protocols which connect coarser soils to post-fire hydrophobicity, often occurs under soil conditions with volcanic influences like in the Deschutes National Forest (Parson et al., 2010). Our study sites also had a positive association between high levels of organic matter content and SWR. Higher levels of organic material in a soil, which is the primary source of hydrophobic compounds, contributes to the ability for the larger surface area of finer soil textures to become water repellent (Doerr et al., 1996; de Jonge et al., 1999). Organic matter has even been suggested as a vital piece in an updated calculation for critical water content, the amount of water needed to remove a SWR layer, further supporting the importance of this variable in future research efforts (Täumer et al., 2005). In addition to these relationships, more basic soils and those with higher moisture contents were negatively associated with SWR at our sampling locations. The responses from these two variables were anticipated as they are synonymous with prior field observations (Zheng et al., 2016; Jordán et al., 2013; Dekker et al., 2001). In some cases, soils with a higher water content (0.08 g g^{-1}) did not exhibit SWR regardless of the temperature applied in a lab while dry soils from the same region did exhibit hydrophobicity (de Jonge et al., 1999). The influence of water content adds to the list of physical soil qualities that impact SWR. These results indicate that there may be significant spatial and temporal variability in SWR development in area with naturally occurring SWR as relatively constant soil characteristics, like texture, interact with fluctuating conditions (e.g., climate). Assessment of SWR with the available mapping pixel size of soil burn severity can be improved through the production of additional raster maps of other environmental conditions to compare with or overlay onto the BARC, providing the additional context necessary for informed predictions. We hope that remote sensing specialists and ecosystem modelers take this study as a call to action to create fine-scale (raster) mapping products which incorporate diverse datasets for both pre- and post-fire environments to best identify areas at risk for increased erosion from SWR impacts.

3.6 Conclusions

As the importance of soil health in post-fire research is increasingly highlighted, a more fine-scale observation of SWR patterns across burn severity classes must be conducted to give insight to below-ground fire effects. The dynamic interactions between soil and fire are closely tied with viable succession and ecosystem recovery. Increased erosion risk will affect not only reestablishing plant communities but also the communities living within the wildland urban interface. It is essential to develop a framework of SWR prediction for wide-scale erosion management to maximize safety in land use decisions and promote ecosystem resilience to fire.

The capacity of this dataset to effectively inform managers is limited due to the inherent variation found in field conditions. While rising above the scope of this paper, the future of research in this field will heavily rely on satellite-derived products to identify fine-scale variation in soil properties and relevant ecosystem conditions which should include a field-based assessment of existing SWR conditions in PNW forests. An effective method in SWR prediction in forests with natural SWR is still far from reach, yet the understanding of soils as an essential natural resource is taking hold in forest management decisions and post-fire strategies.

Figures

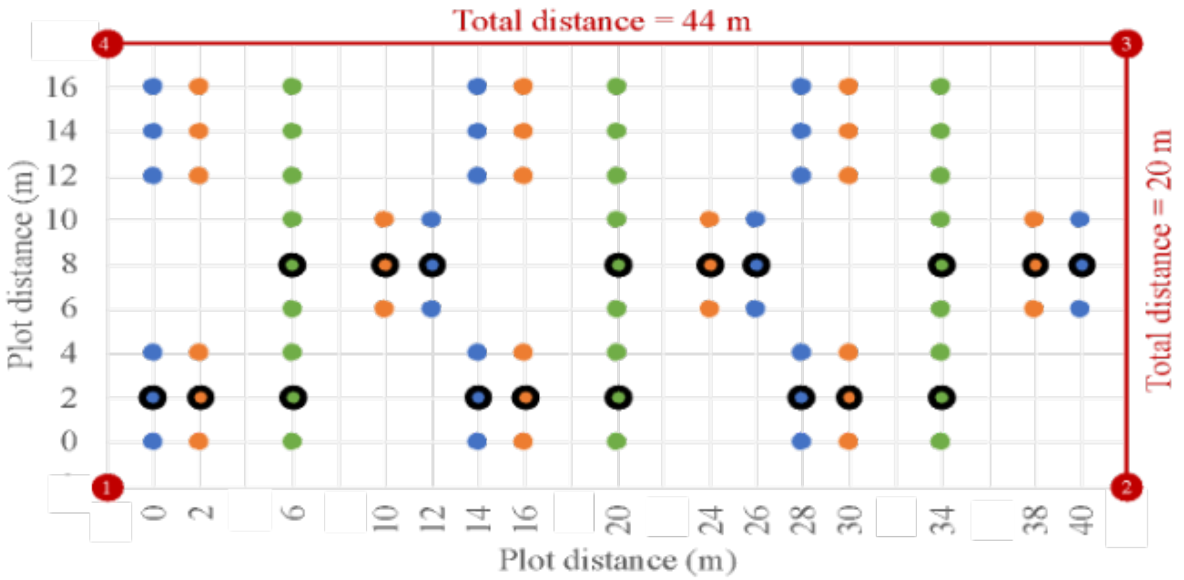

Figure 4. The 44x20 m plot encompassing a cyclic design of sampling points (N=81). A small subset of points (n=18), identified with a dark border, were sampled for additional water repellency and general soil information.

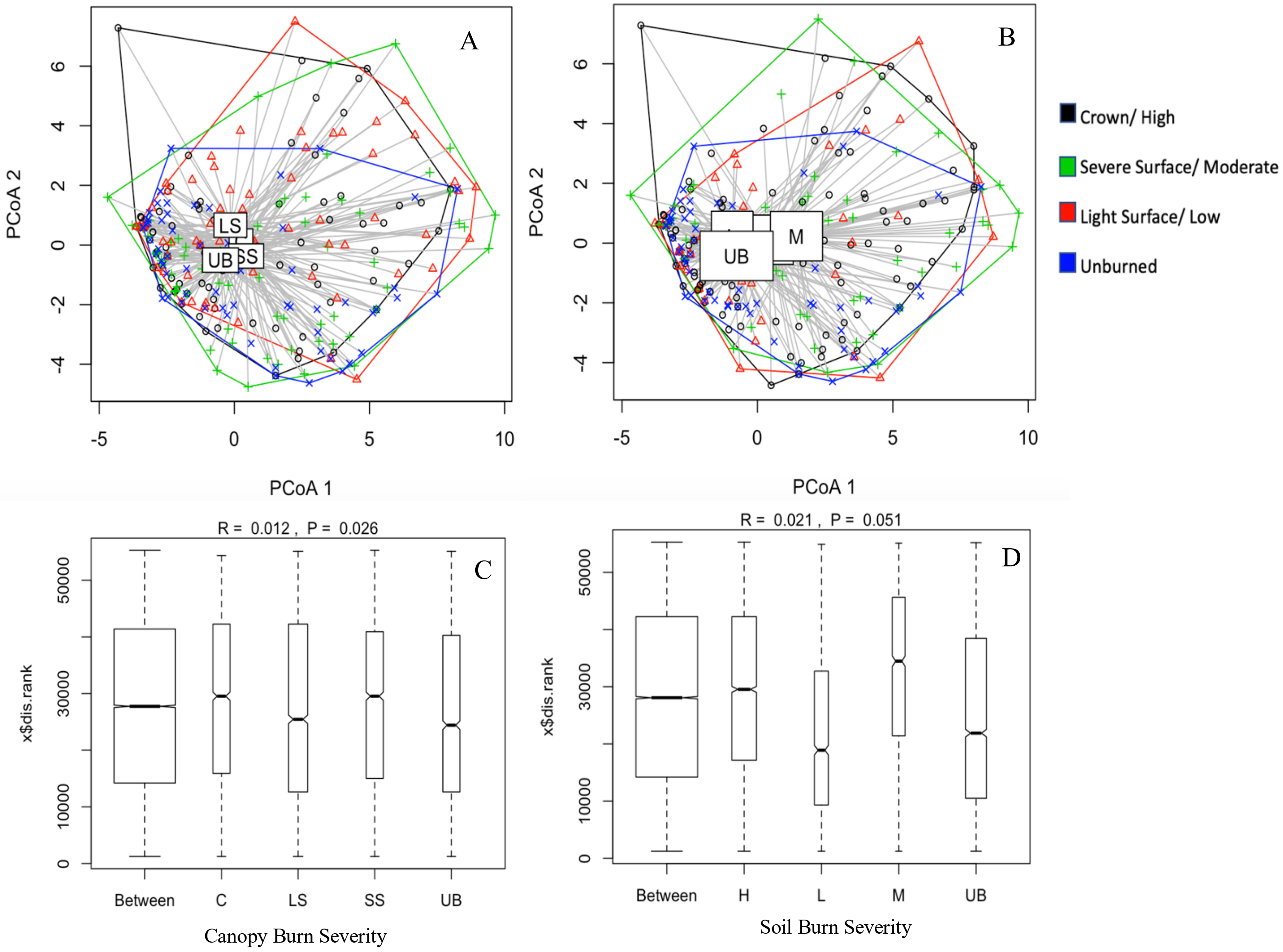

Figure 5. The dispersion of SWR responses when grouped by canopy burn severity class (A) and soil burn severity class (B). Group categories are outlined with the color assigned to show the spread of data. Analysis of similarity box and whisker plots are grouped by the same two grouping variables, canopy burn severity (C) and soil burn severity (D). The R statistic and p values are listed above the panel C and D plot borders.

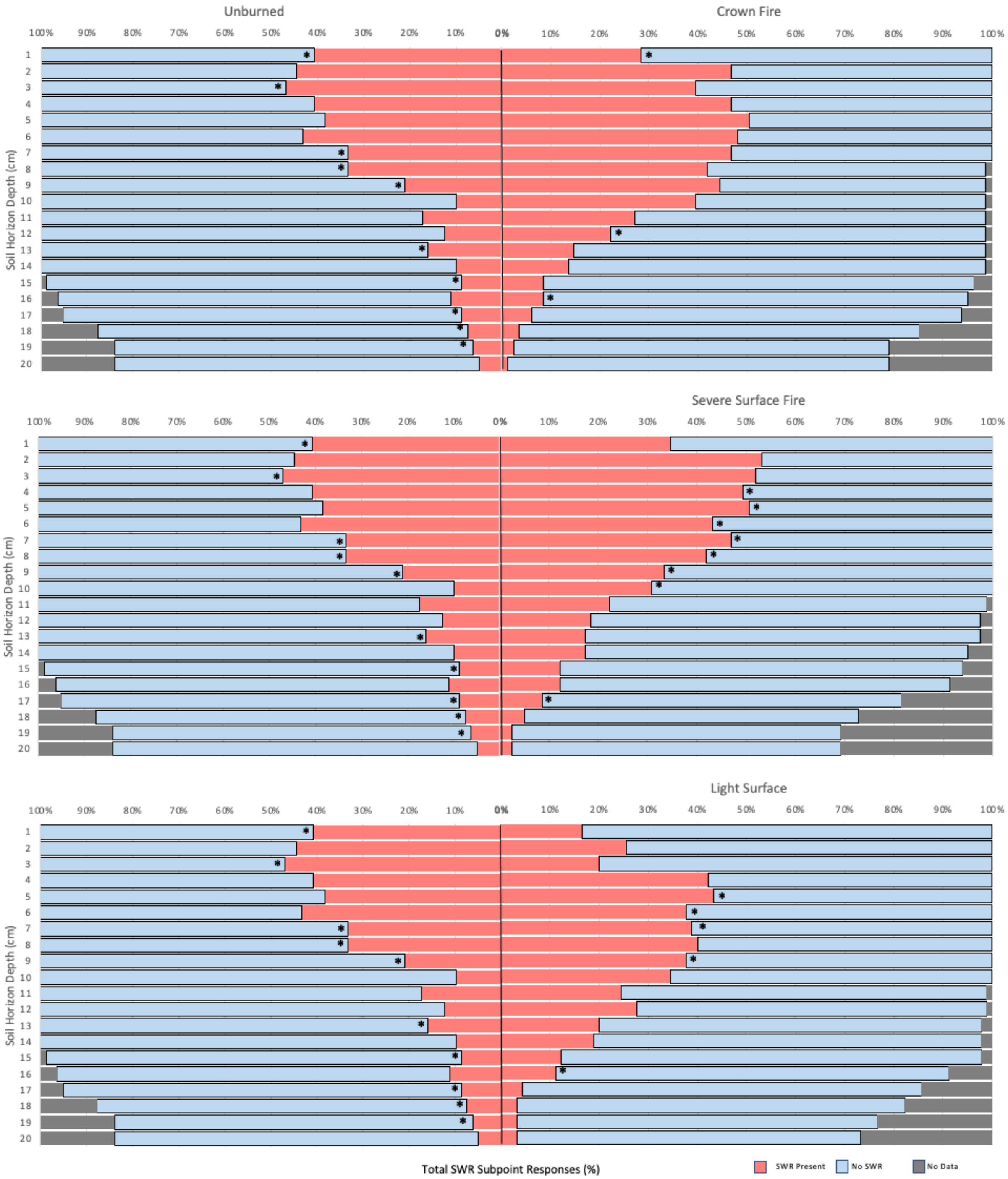

Figure 6. Percent of SWR presence and absence found at each centimeter depth down to 20 cm of all plot subpoints. Depths with gray signify a percent of the subsites that could not be sampled beyond a certain depth due to an obstruction of the auger. Each canopy burn severity response plot is mirrored across from the unburned control response. Depths noted with an * signify locations of a significant Moran's I statistic for spatial autocorrelation.

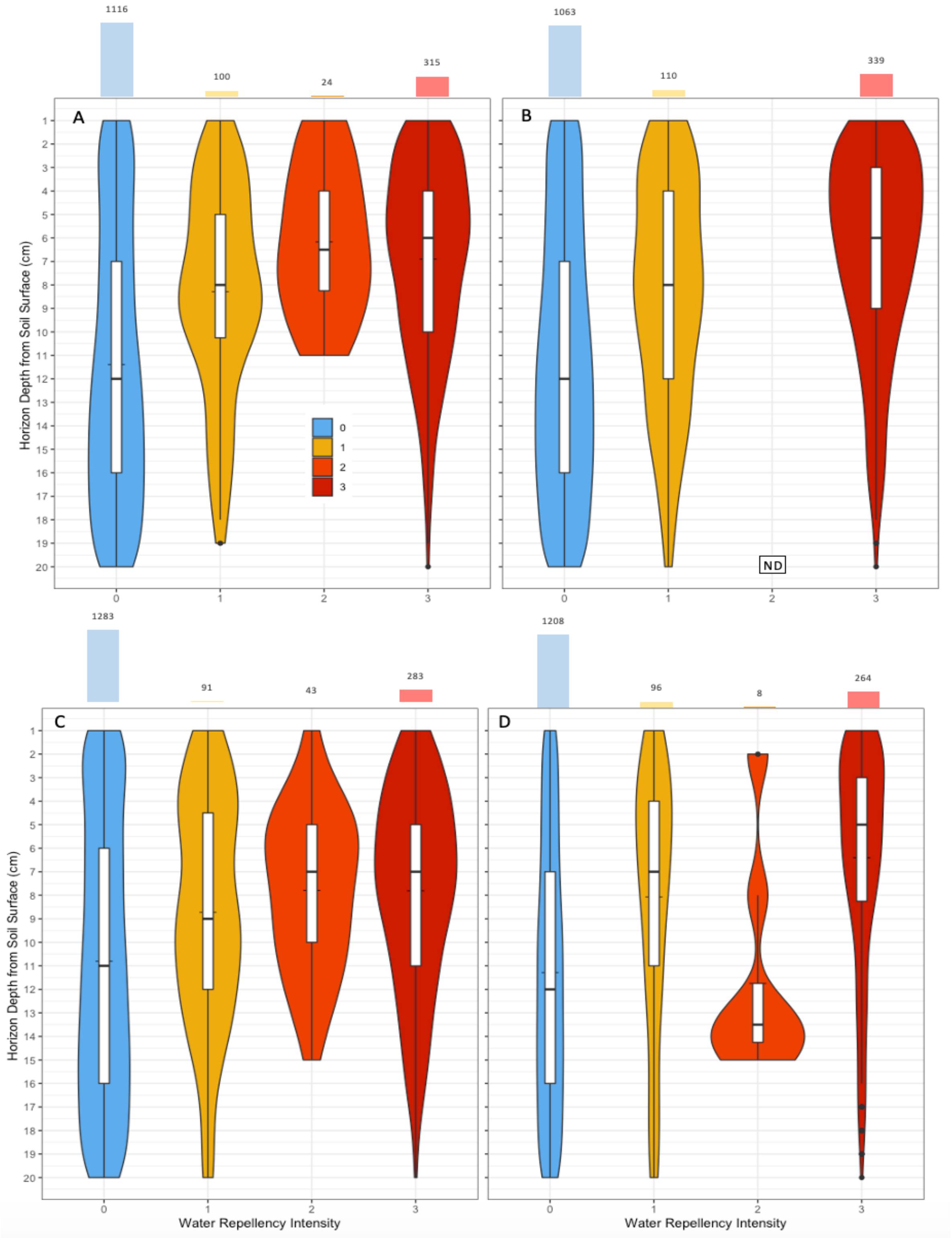

Figure 7. Probability distributions of each SWR class (0: <5 seconds, 1: 5-15 seconds, 2: 16-30 seconds, 3: >30 seconds until infiltration) at each plot of canopy burn severity where A= crown, B= severe surface, C= light surface, and D= unburned. The count of points at each class across all depths is shown above each violin plot distribution. Individual violins are scaled to contain the same area within their range as all others SWR classes of that plot.

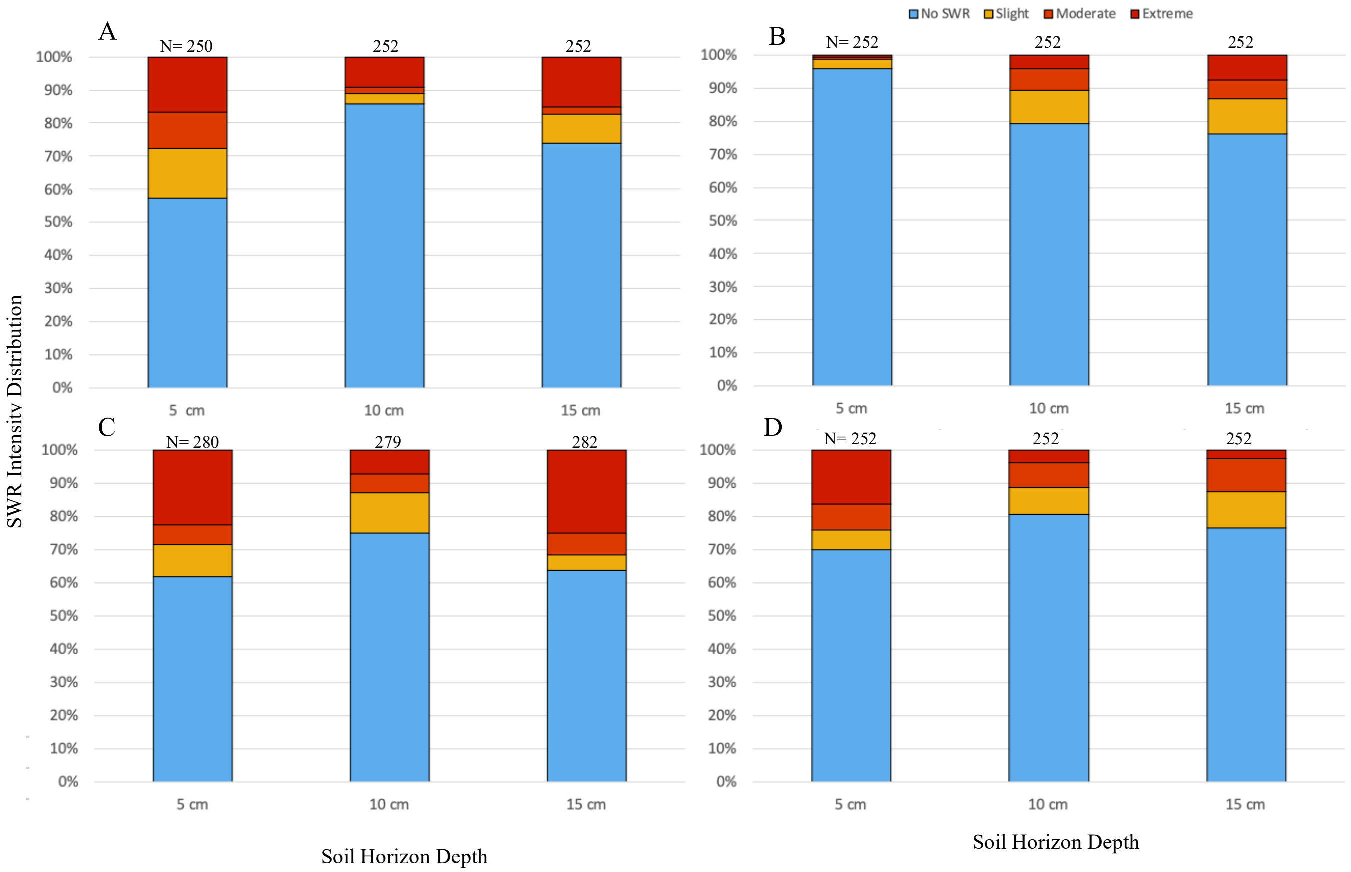

Figure 8. The distribution of SWR responses on the small horizontal scale from each water droplet placed at 5, 10, and 15 cm depths of the additional sampling subsites where vertical soil core responses were shown not to be hydrophobic (A= Crown, B= Severe Surface, C= Light Surface, D= Unburned; N= number of droplets from the horizontal plane).

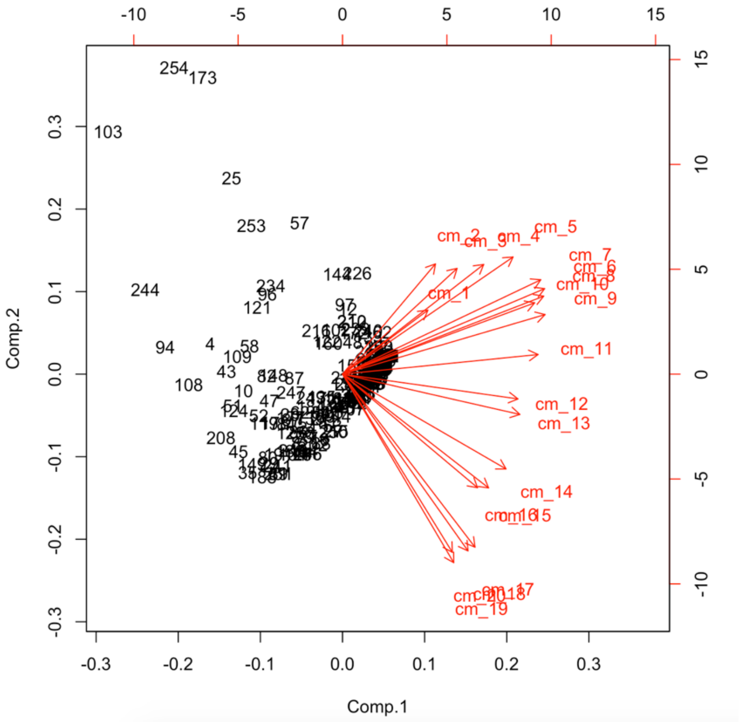

Figure 9. The first two principal components from a principal components analysis of SWR measured at each centimeter depth of the soil core taken at all 81 sampling points across all four plots.

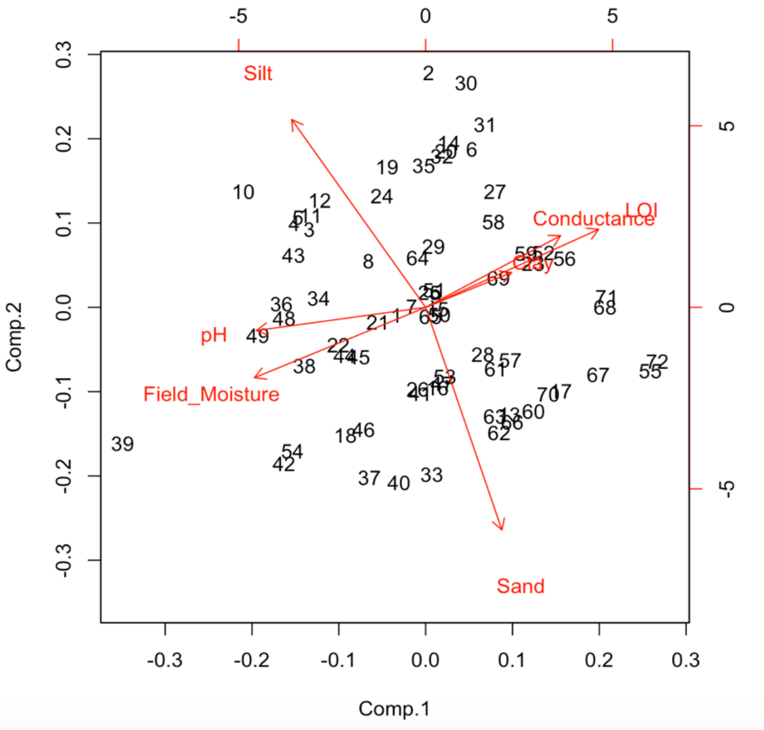

Figure 10. The first two principal components from a principal components analysis of the relationship between environmental variables and SWR conditions at the additional sampling points of all four plots.

Tables

Table 7. Permanova outputs of the first four principal components comparing SWR response and depth across all four plots are given above the specific weightings and Principal component results from the principal components analysis). Principal component significance of <0.05 is marked with **.

Permanova Results	PC1	PC2	PC3	PC4
Sum of Squares	271029	89958	87178	42617
R^2	0.38	0.13	0.12	0.060
F	301.99	100.23	97.14	47.49
p	*0.001***	*0.001***	*0.001***	*0.001***
PCA Results and Weightings				
Standard Deviation	2.66	1.87	1.49	1.20
Proportion of Variance	0.35	0.17	0.11	0.072
Cumulative Proportion	0.35	0.53	0.64	0.71
1 cm	0.12	0.13	0.37	0.13
2 cm	0.13	0.22	0.37	0.27
3 cm	0.16	0.21	0.34	0.24
4 cm	0.20	0.22	0.27	-
5 cm	0.24	0.234	0.13	-
6 cm	0.29	0.17	-	-0.16
7 cm	0.28	0.19	-	-0.20
8 cm	0.28	0.16	-0.10	-0.27
9 cm	0.29	0.12	-0.17	-0.25
10 cm	0.27	0.14	-0.25	-
11 cm	0.28	-	-0.25	-
12 cm	0.25	-	-0.28	-
13 cm	0.25	-	-0.21	0.17
14 cm	0.23	-0.19	-0.17	0.37
15 cm	0.21	-0.23	-0.14	0.39
16 cm	0.19	-0.23	-	0.34
17 cm	0.19	-0.35	0.18	-
18 cm	0.18	-0.35	0.22	-0.18
19 cm	0.16	-0.38	0.24	-0.27
20 cm	0.16	-0.36	0.21	-0.29

Table 8. Outputs from Moran’s I analysis of observed vs expected spatial responses and the associated p values are given . The rage of spatial dependence found from semivariogram analysis is shown in meters; ranges with a dash only produced a pure nugget semivariogram without a definitive range. Significant Moran’s I tests <0.05 are marked with ** while significant <0.1 are marked with *.

	Crown			Severe Surface			Light Surface			Unburned		
Depth	**Observed/Expected**	**p**	**Range (m)**	**Observed/expected**	**p**	**Range (m)**	**Observed/expected**	**p**	**Range (m)**	**Observed/expected**	**p**	**Range (m)**
1 cm	0.034 / -0.013	0.0054**	-	0.0020 / -0.013	0.38	-	-0.00041 / -0.011	0.45	-	0.036 / -0.013	0.0036**	-
2 cm	-0.0076 / -0.013	0.77	-	-0.016 / -0.013	0.83	-	0.010 / -0.011	0.14	-	0.0099 / -0.013	0.18	-
3 cm	-0.019 / -0.013	0.68	-	0.0083 / -0.013	0.21	4.22	-0.0047 / -0.011	0.65	3.77	0.053 / -0.013	<0.001**	-
4 cm	-0.021 / -0.013	0.61	-	0.023 / -0.013	0.0367**	4.94	-0.00016 / -0.011	0.45	-	0.009 / -0.013	0.19	-
5 cm	-0.012 / -0.013	0.98	-	0.028/ -0.013	0.015**	7.67	0.030/ -0.011	0.0051**	-	-0.00093 / -0.013	0.49	-
6 cm	-0.019 / -0.013	0.71	-	0.040 / -0.013	0.0017**	14.96	0.037/ -0.011	0.0010**	-	0.0045 / -0.013	0.31	-
7 cm	-0.0058 /-0.013	0.69	3.90	0.046 / -0.013	0.00046**	-	0.033 / -0.011	0.0021**	48.42	0.024 / -0.013	0.030**	-
8 cm	-0.033 / -0.013	0.23	-	0.041 / -0.013	0.0014**	5.06	0.018 / -0.011	0.049**	10.04	0.031 / -0.013	0.0089**	-
9 cm	-0.019 / -0.013	0.70	3.09	0.029 / -0.013	0.023**	1.06	0.026 / -0.011	0.011**	3.04	0.034 / -0.013	0.0049**	11.79
10 cm	0.017 / 0.013	0.081*	5.15	0.035/ -0.013	0.0038**	5.15	0.0030 / -0.011	0.33	-	0.0034 / 0.016	0.313	-
11 cm	0.014 / -0.013	0.11	-	0.019 / -0.013	0.059*	8.89	-0.016 / -0.011	0.73	-	-0.0089 / -0.013	0.82	-
12 cm	0.036 / -0.013	0.0033**	-	-0.0077 / -0.013	0.76	-	-0.0032/ -0.011	0.58	-	-0.0054/ -0.013	0.65	-
13 cm	0.0090 / -0.013	0.18	-	-0.00076/ -0.013	0.46	9.92	-0.0066 / -0.011	0.74	-	0.036 / -0.013	0.0028**	-
14 cm	-0.0058 / -0.013	0.67	-	0.012 / -0.013	0.13	-	-0.0012/ -0.011	0.49	-	0.011 / -0.013	0.12	-
15 cm	0.014 / -0.013	0.085*	2.77	0.011 / -0.013	0.15	-	0.0064/ -0.011	0.21	4.26	0.028 / -0.013	0.011**	-
16 cm	0.035 / -0.013	0.0020**	7.08	0.00021 / -0.014	0.42	-	0.028 / -0.012	0.0076**	-	0.018/ -0.013	0.055*	-
17 cm	-0.018 / -0.013	0.78	-	0.024 / -0.015	0.036**	6.90	-0.013 / -0.013	0.99	1.69	0.026 / -0.013	0.013**	-
18 cm	-0.021 / -0.015	0.57	-	-0.013 / -0.017	0.79	-	-0.011 / -0.014	0.82	-	0.031 / -0.014	0.0070	-
19 cm	-0.020 / -0.016	0.61	-	-0.012 / -0.018	0.50	-	-0.017 / -0.015	0.80	1.81	0.078 / -0.015	<0.001**	-
20 cm	-0.016 / -0.016	0.84	-	-0.012/ -0.018	0.50	-	-0.022 / -0.015	0.55	2.20	-0.0087 / -0.015	0.60	-

Table 9. Permanova results and weightings from the principal components analysis of environmental factors as they relate to levels of SWR. The first explanatory variable on the permanova, not shown below, is the canopy burn severity included in this permanova to remove the stand-level noise across plots (R^2=0.12, p=0.003). Principal component significance of <0.05 is marked with ** while significant <0.1 are marked with *.

Permanova Results	PC1	PC2	PC3	PC4
Sum of Squares	10141	5671	1262	2094
R^2	0.063	0.035	0.0079	0.013
F	5.35	2.99	0.67	1.10
p	*0.002***	*0.003***	*0.032**	*0.57*
PCA Results and Weightings				
Standard Deviation	1.44	1.30	1.15	1.02
Proportion of Variance	0.30	0.24	0.19	0.15
Cumulative Proportion	0.30	0.54	0.73	0.87
Organic Matter	0.47	0.24	0.24	0.44
pH	-0.45	-	-0.50	-0.24
Field Moisture	-0.43	-0.25	-	0.48
Conductance	0.37	0.23	-0.26	-0.55
Sand (%)	0.21	-0.69	0.19	-0.20
Silt (%)	-0.38	0.58	0.31	-
Clay (%)	0.25	0.12	-0.70	-0.41

4 Supplemental Work: Predictive Power of BAER Soil Burn Severity Mapping: A Pacific Northwest Case Study Ground-Truthing BARC Maps

4.1 Abstract

Following larger wildfires, Burn Area Emergency Response (BAER) teams are tasked with the assessment of landscape impacts and the mapping of post-fire soil burn severity. Managers rely on soil burn severity maps, referred to as the Burn Area Reflectance Classification (BARC) maps, for general predictions of areas within the burn perimeter most vulnerable to degradation. Post-fire mapping data is derived from Landsat satellite spectral signatures that are validated in the field by members of the BAER team. This case study examines the accuracy of BARC maps across six Pacific Northwest (PNW) wildfires burned in 2017 through comparisons of mapped soil burn severity to observations gathered in the field. Severity levels were generally underreported by BARC maps with the majority of this discrepancy occurring in moderate and low burn classes. Additional time and resources must be allotted for BAER work to obtain more robust validation data to train BARC maps effectively.

4.2 Brief Introduction to Remote Sensing and Wildfire

The primary objective of Burn Area Emergency Response (BAER) teams is to assuage risk to human life, property, and ecosystem health as a result of weakened forest soils and vegetative structures from fire (USDA, 2020). The post-fire mapping products developed by BAER teams are crucial for assessing the extent of ecosystem change and vulnerability to allocate monetary resources to protect the system from further damage. The USFS Remote Sensing Applications Center (RSAC) produces Burn Area Reflectance Classification (BARC) maps from the Normalized Burn Ratio (NBR) spectral signature outputs following wildfire containment. The base layer NBR is derived from the difference over the sum of the fourth and seventh band of the Landsat 5 TM satellite (Key and Benson, 2006). Of the spectral manipulations assessed for use in post-fire mapping, NBR has been identified as the most proficient satellite derived imagery presenting general patterns of immediate burn severity (Hudak et al., 2007). NBR has been shown to correlate with vegetative spectral signatures in addition to ground-based factors (Hudak et al., 2004a) and requires additional training data to represent the true soil conditions. For this reason, the BAER post-fire analysis team will often include a soil scientist and geologist to assess soil-water relations and erosion risk. BAER teams collect varying quantities of field data at the fire incident to train the BARC map outputs so they best reflect soil burn severity conditions for management purposes (Hudak et al., 2004b; Safford et al., 2008). This is done by isolating ground-related signatures and removing differences in the vegetative signatures from satellite imagery (Bobbe et al., 2001).The time and resources available for this map calibration relative to wildfire area may vary across incidents as map production must be carried out quickly to prescribe treatments as close to fire containment as possible (USDA, 2020).

Fire characteristics, and the response of soil burn severity, are a result of environmental and climatic conditions (e.g., fuel moisture content, humidity, wind speed during fuel consumption, vegetation density before ignition, and topography), which often vary widely within a fire perimeter (Birch et al., 2015). This heterogeneity results in a complex mosaic of burn severity (Dyrness and Norum, 2011; Miyanishi and Johnson, 2002) and, in combination with the varying quality and resolution of available remotely sensed data, contributes to the challenge of mapping fine scale variations in soil conditions for management assessment (Clark et al., 2003). For federal expenses designated for post-fire management to effectively prevent significant damage of natural resources and local communities from post-fire erosion, it is imperative that land managers are informed accurately of the influence of wildfire disturbance on soils. BAER teams work tirelessly onsite to create soil burn severity maps with the ability to provide a visual representation of the general trends of complex soil burn patterns across the landscape immediately post-fire. However, as burn acreage increases annually as a result of changes in climate, human activity, and the effects of past management, BAER team personnel are tasked with evaluating larger swaths of land with limited resources. The fundamental objective of this case study is to assess how closely calibrated BARC maps are to the conditions present on the ground in the Pacific Northwest (PNW) through plot-level measurements from six 2017 PNW fires to compare map evaluations to field data. The PNW is characterized by some of the most diverse and productive ecosystems across the globe all encompassed within a relatively small geographic area (Nelson et al., 2006), making this the perfect ecoregion to investigate the efficacy of mapping products.

4.3 Methods

4.3.1 Site Descriptions and Data

Six 2017 lightning-ignited fires in the PNW were evaluated one year following containment: Lolo Peak, Liberty, Milli, Norse Peak, Rice Ridge, and Jolly Mountain (Table 11). Sampling was conducted within uniform 30x30 m plots (matching standard BARC pixel sizes) within each canopy burn severity class (crown, severe surface, light surface, and unburned control; Table 2) using the Composite Burn Index (Key and Benson, 2003). Plots were located at least 400 meters from all roads and other plots to avoid potential pseudo-replication and effects from the forest road system (Harvey et al., 2013). GPS coordinates at the plot center were documented (TRIUMPH-2, Javad GNSS Inc., San Jose, CA) and soil burn severity at 4, 8, 22, and 26 m along the east-west and north-south axes (n=8 per plot) was assessed using the established US Forest Service field protocol based on measurements of surface soil color, mineral soil color, depth of the remaining ash layer, effect on soil structure, condition of roots, and mineral soil burn condition (Table 2; Parson et al., 2010). BARC maps for each incident were obtained through the *USFS Geospatial Technology and Applications Center* (USDA, 2019).

4.3.2 Data Analysis

ArcGIS was used to overlay BARC maps with plot center GPS points and a 30x30 m square buffer. Plots containing more than a single BARC severity class within the plot buffer (89 out of 120 total plots) were removed from the analysis dataset to streamline the comparison and obtain more clear results. Classes of soil burn severity at each plot point were converted to numeric values (0=unburned, 1=low, 2=moderate, 3=high, Table 2) and the average soil burn severity calculated for the plot. These ordinal values were also assigned to the BARC plot severity categories. BARC plot values were compared with the plot average soil burn severity using a paired sample t-test.

Additionally, a simple linear regression was used to examine the relationship between field- and remote-based soil burn severity values. Finally, amassed field measurements of each individual subsite location were compared to the overall plot BARC map identifier across all sampled fires. The distributions of BARC burn intensity reported were separated by the class identified in the field and plotted in a histogram. All statistical analyses were completed in R (R Core Team, 2020).

4.4 Results

According to paired t-test results, field-recorded and BARC predictions of soil burn severity were not statistically different in the Lolo and Liberty fires and only marginally different in the Jolly Mountain and Rice Ridge fires (Table 12). However, soil burn severity values between the field and remote data were significantly different in the Norse Peak and Milli wildfires (Table 12).

Despite these results, all fires excluding Lolo Peak demonstrated a significant, positive linear relationship between the field and BARC classifications though slopes were always less than 1 (0.42-0.84) (Figure 10; Table 12). Higher soil burn severity measures are recorded across field values compared to the corresponding area in BARC maps. While soils classified as high burn severity in the field were largely accurate in BARC map reporting (Figure 11), some soils reported as unburned were found to have been burned at varying intensities in the Jolly Mountain, Norse Peak, and Milli fires (Figure 10). Burn severity in map areas categorized as moderate and low soil burn severity were more often underestimated when compared to field data with the largest range of difference in the low severity subsites. Intercept values were close to the plot origin in significant linear regression lines, further offsetting the severity measurement methods with a small slope; Norse Peak was found to have a negative intercept in concurrence with a lower slope value (Table 12).

4.5 Discussion

The use of BAER soil burn severity in BARC maps is a vital component of post-fire assessment. Landsat satellite use over other aerial and field methods for BARC map creation is attributed to a $35 million in federal savings over just a five year period (Bernknopf et al., 2019), making it a pillar in post-fire management. This study has aimed to provide additional context above the current level of technological advancements and financial benefits of BARC mapping for why these images must be translated to managers as a general representation of soils rather than a mirrored image of burn severity conditions. Average soil burn severity values for five of the 2017 fires deduced from the BARC map, excluding Lolo Peak which did not show a significant relationship, underestimated the conditions found in the field. Lolo Peak was likely an outlier due to the small sample size. Satellite technology and BAER field assessments have resulted in a successful, general representation of ground level measurements; however, none of the fires exhibited 1:1 linear slope that would be assumed by local management indicating that sub-pixel variation is substantial and should be considered when devising management plans. Our comparisons track similarly with another study of 183 plot locations in a Colorado wildfire that found just 69% accuracy in BARC map reporting (Lewis et al., 2006). We initially hypothesized that field measurements would reflect a lower soil burn severity than BARC maps after a year of recovery; however, this was not the case. If sampling was conducted immediately following containment rather than a year post-fire, the difference between the higher intensity found in the field over BARC levels may have been even more dramatic.

The complexity of soil burn severity across a landscape creates issues of scale for the application of management practices. Moderate and low soil burn severities are more prone to high levels of variation in BARC with poorer correlation to commonly measured field variables like vegetation from wildfires across Montana, California, and Alaska (Hudak et al., 2007). The six PNW wildfires sampled in this study were no exception to this observed pattern. Moderate, low, and unburned soils were found to be more often misrepresented in the map while highly burned soils were generally well represented. As wildfire perimeters have grown larger, matched with a higher average burn intensity due to climate change conditions and historic management (Rogers et al., 2011), the most vulnerable highly burned soils are also the most reliably mapped of all soil burn levels. The variable representation of mid-range severity classes may become increasingly detrimental to management as prescribed burning efforts to reduce burn intensity gain traction in the wake of recent megafires (Fernandes, 2015). Future research efforts must focus on improving the quality of mid-range severity mapping as the push for prescribed burning permeates wildfire management practices.

Although the most highly sampled fires, Norse Peak and Milli, were also those with the most discrepancy between measurements, data presented here are at least hopeful, as simple linear models do show a significant relationship between field and BARC derived soil burn severity values. Our regression model findings for most of these fires support the continued use of BARC mapping by managers. The significant difference between pairwise comparisons of field and BARC maps in the majority of sampled fires, excluding Lolo and Liberty, is a cause for concern as managers rely heavily on these maps for management decisions. Discrepancies between field and BARC data are not a deterrent for managers to rely on BAER team reports, but rather should act as a call for continued improvements to satellite data products and for increased time and resources to be allotted toward on-site sampling and model validation.

4.6 Conclusions

While managers are informed of the heterogeneity that will be present on the ground compared to what is reported in a satellite derived map, the true degree of burn severity underestimation identified in this regional case study must be acknowledged. Further analysis of the spectral signatures and canopy-soil relations is beyond the scope of this case study, but it remains an area in need of continued research. An accurate soil burn severity is crucial for the effective deployment of restoration efforts in high-risk areas. With, lower soil burn intensities reported following a fire to managers, vulnerable soils may be overlooked and land use actions and could increase time of ecosystem recovery. The findings of this study do not reduce the importance and applicability of BAER maps in post-fire land management, but rather are presented here to advocate for increased funding and resources to allow additional map calibration of field conditions in BARC model training. Elevated fire activity in the Western US has concurrently increased the demand for BAER team deployment, severely limiting the collection of extensive field observations throughout the burn perimeters before creating the final report and soil burn severity map. Future efforts should focus on increased time and resources for strategic ground-truthing to train the outputs of satellite data essential to producing these management tools.

Figures

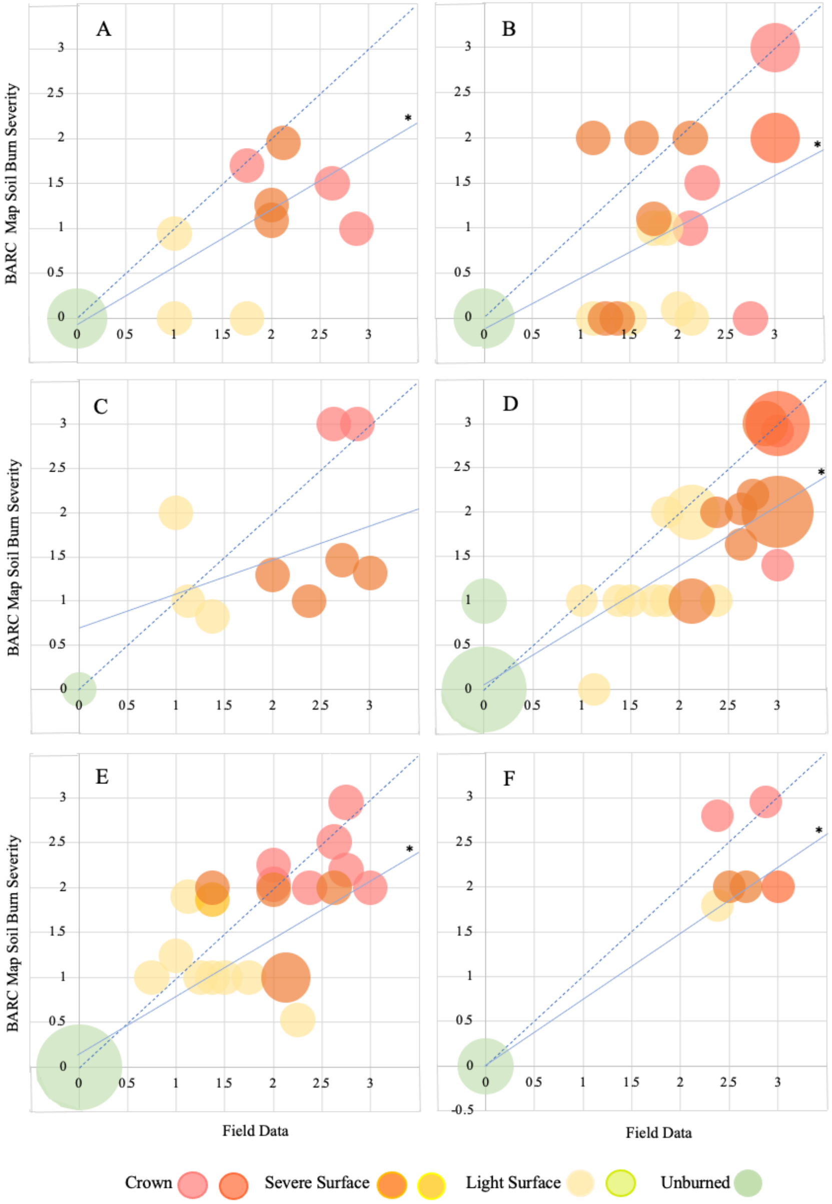

Figure 10: Relationships between field and remotely sensed measurements of soil burn severity for the six fires sampled (A: Jolly Mountain, B: Norse Peak, C: Lolo Peak, D: Milli, E: Rice Ridge, F: Liberty Fire). Plotted values of soil burn severity correspond to the ordinal values assigned to each severity class (high, 3; moderate, 2; low, 1; unburned, 0). Data point size indicates the frequency of relationship occurrence and color the canopy burn severity class represented by that point. Points represented by two canopy burn severity classes are given their own color identifier. The dashed line indicates a 1:1 relationship between predicted and measured values while projected linear relationships are shown as solid lines (* = significant linear regression).

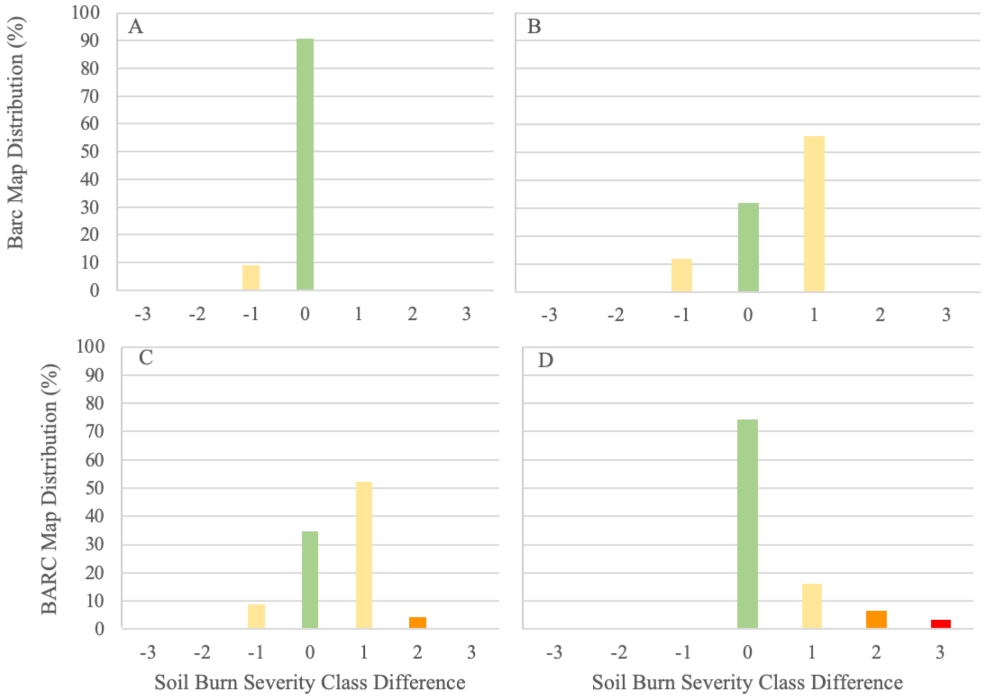

Figure 11. Variation (expressed as % of plot subsites) between field and remote data soil burn severity classifications. Here, a value of "0" indicates that the classifications were a match. If a value is positive, the BARC map underestimated the soil burn severity by x categories and if negative, the BARC map overestimated severity. For example, if soil classified as "low" in the remote data but the field assessment yielded "high", that soil would be given a value of "2" indicating that the map has underestimated the severity by two categories of burn severity. BARC map distribution is separated by high soil burn severity = A, moderate= B, low=C, and unburned= D.

Tables

Table 11. Fire information. Data courtesy of the EcoWest Interactive Wildfire mapping tool (EcoWest, 2021).

Fire	**National Forest(s) (State)**	**Size (Hectares)**	**Ignition Date**	**Control Date**
Liberty	Flathead (MT)	11,661	7/22/2017	09/18/2017
Lolo Peak	Lolo Bitterroot Nez Pierce-Clearwater (MT)	21,951	7/17/2017	09/17/2017
Milli	Deschutes (OR)	9,744	8/11/2017	09/24/2017
Norse Peak	Mt. Baker-Snoqualmie Okanogan-Wenatchee (WA)	24,112	8/12/2017	11/1/2017
Rice Ridge	Flathead Lolo (MT)	66,695	7/18/2017	9/27/2017
Jolly Mountain	Okanogan-Wenatchee (WA)	14,996	8/12/2017	9/16/2017

Table 12. Results of linear regressions and paired t-test comparisons between field observations and BARC-derived observations of soil burn severity.

Fire	**Linear Regression**				**Paired T-Test**
	n	**Intercept**	**Slope**	**P-Value**	**P-Value**
All Plots	87	0.04	0.73	<0.01 **	< 0.01**
Norse Peak	18	-0.23	0.69	<0.01 **	< 0.01**
Jolly Mountain	10	0.02	0.54	< 0.01 **	0.088*
Milli	21	0.099	0.74	< 0.01 **	0.0043**
Lolo Peak	10	0.76	0.42	0.29	0.15
Liberty	7	0.027	0.84	<0.01 **	0.14
Rice Ridge	21	0.17	0.74	< 0.01 **	0.07*

References

Agee, J. 1998. The landscape ecology of western forest fire regimes. Northwest Science 72. *Northwest Science*. 72.

Agee, J.K. 1996. Fire Ecology of Pacific Northwest Forests. Island Press. 513 pp.

Agee, J.K. 1994. Fire and weather disturbances in terrestrial ecosystems of the eastern Cascades. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 52 p. (Everett, Richard L., assessment team leader; Eastside forest ecosystem health assessment; Hessburg, Paul F., science team leader and tech. ed., Volume III: assessment.). 320. doi:10.2737/PNW-GTR-320.

Arabas, K.B., K.S. Hadley, and E.R. Larson. 2006. Fire history of a naturally fragmented landscape in central Oregon. *Can. J. For. Res.* 36:1108–1120. doi:10.1139/x06-004.

Barrett, S.W. 1998. Riparian fire history and fire regimes Upper Swan Valley, Flathead National Forest.

Bernknopf, R., Y. Kuwayama, R. Gibson, J. Blakely, B. Mabee, T.J. Clifford, B. Quayle, J. Epting, T. Hardy, and D. Goodrich. 2019. The Cost-Effectiveness of Satellite Earth Observations to Inform a Post-Wildfire Response. 28.

Birch, D.S., P. Morgan, C.A. Kolden, J.T. Abatzoglou, G.K. Dillon, A.T. Hudak, and A.M.S. Smith. 2015. Vegetation, topography and daily weather influenced burn severity in central Idaho and western Montana forests. *Ecosphere*. 6:art17. doi:10.1890/ES14-00213.1.

Bisdom, E.B.A., L.W. Dekker, and J.F.Th. Schoute. 1993. Water repellency of sieve fractions from sandy soils and relationships with organic material and soil structure. *In* Soil Structure/Soil Biota Interrelationships. L. Brussaard and M.J. Kooistra, editors. Elsevier, Amsterdam. 105–118.

Bivand, R.S., Pebesma, E., Goméz-Rubio, V. 2013. Applied Spatial Data. https://link.springer.com/book/10.1007%2F978-1-4614-7618-4

Bobbe, T., H. Lachowski, P. Maus, J. Greer, and C. Dull. 2001. A primer on mapping vegetation using remote sensing. *Int. J. Wildland Fire*. 10:277–287. doi:10.1071/wf01029.

Bodí, M.B., I. Muñoz-Santa, C. Armero, S.H. Doerr, J. Mataix-Solera, and A. Cerdà. 2013. Spatial and temporal variations of water repellency and probability of its occurrence in calcareous Mediterranean rangeland soils affected by fires. *CATENA*. 108:14–25. doi:10.1016/j.catena.2012.04.002.

Booth, D.B., D. Hartley, and R. Jackson. 2002. Forest Cover, Impervious-Surface Area, and the Mitigation of Stormwater Impacts1. *JAWRA Journal of the American Water Resources Association*. 38:835–845. doi:10.1111/j.1752-1688.2002.tb01000.x.

Bouchard, M.B., D.P. Pothier, and S.G. Gauthier. 2008. Fire return intervals and tree species succession in the North Shore region of eastern Quebec. *Canadian Journal of Forest Research*. doi:10.1139/X07-201.

Boyer, D.E., and J.D. Dell. 1980. Fire effects on Pacific Northwest forest soils.

Burrows, S.N., S.T. Gower, M.K. Clayton, D.S. Mackay, D.E. Ahl, J.M. Norman, and G. Diak. 2002. Application of Geostatistics to Characterize Leaf Area Index (LAI) from Flux Tower to Landscape Scales Using a Cyclic Sampling Design. *Ecosystems*. 5:0667–0679. doi:10.1007/s10021-002-0110-z.

Calkin, D.E., M.P. Thompson, and M.A. Finney. 2015. Negative consequences of positive feedbacks in US wildfire management. *For. Ecosyst.* 2:9. doi:10.1186/s40663-015-0033-8.

Campbell, S.E., Morris, S.E. 1988. Hydrologic Response of the Pack River ,ldaho, to the Sundance Fire. 6.

Chas-Amil, M.L., J. Touza, and E. García-Martínez. 2013. Forest fires in the wildland–urban interface: A spatial analysis of forest fragmentation and human impacts. *Applied Geography*. 43:127–137. doi:10.1016/j.apgeog.2013.06.010.

Clark, J., Parsons, A., Zajkowski, T., Lannom, K. 2003. Operations Burned Area Emergency Response Team.

Crockford, H., S. Topalidis, and D.P. Richardson. 1991. Water repellency in a dry sclerophyll eucalypt forest — measurements and processes. *Hydrological Processes*. 5:405–420. doi:10.1002/hyp.3360050408.

DeBano, L.F. 1981. Water repellent soils: a state-of-the-art. U.S. Department of Agriculture, Forest Service, Pacific Southwest Forest and Range Experiment Station, Berkeley, CA.

Debano, L.F., and J.S. Krammes. 1966. Water Repellent Soils and Their Relation to Wildfire Temperatures. *International Association of Scientific Hydrology. Bulletin*. 11:14–19. doi:10.1080/02626666609493457.

DeBano, L.F., L.D. Mann, and D.A. Hamilton. 1970. Translocation of Hydrophobic Substances into Soil by Burning Organic Litter 1. *Soil Science Society of America Journal*. 34:130–133. doi:10.2136/sssaj1970.03615995003400010035x.

DeBano, L.F., R.M. Rice, and C.C. Eugene. 1979. Soil heating in chaparral fires: effects on soil properties, plant nutrients, erosion, and runoff. *Res. Paper PSW-RP-145. Berkeley, CA: U.S. Department of Agriculture, Forest Service, Pacific Southwest Forest and Range Experiment Station. 21 p*. 145.

Debano, L.F., S.M. Savage, and D.A. Hamilton. 1976. The Transfer of Heat and Hydrophobic Substances During Burning 1. *Soil Science Society of America Journal*. 40:779–782. doi:10.2136/sssaj1976.03615995004000050043x.

de Jonge, L.W., O.H. Jacobsen, and P. Moldrup. 1999. Soil Water Repellency: Effects of Water Content, Temperature, and Particle Size. *Soil Science Society of America Journal*. 63:437–442. doi:10.2136/sssaj1999.03615995006300030003x.

Dekker, L.W., S.H. Doerr, K. Oostindie, A.K. Ziogas, and C.J. Ritsema. 2001. Water Repellency and Critical Soil Water Content in a Dune Sand. *Soil Science Society of America Journal*. 65:1667–1674. doi:10.2136/sssaj2001.1667.

Doerr, S.H., W.H. Blake, R.A. Shakesby, F. Stagnitti, S.H. Vuurens, G.S. Humphreys, P. Wallbrink, S.H. Doerr, W.H. Blake, R.A. Shakesby, F. Stagnitti, S.H. Vuurens, G.S. Humphreys, and P. Wallbrink. 2004. Heating effects on water repellency in Australian eucalypt forest soils and their value in estimating wildfire soil temperatures. *Int. J. Wildland Fire*. 13:157–163. doi:10.1071/WF03051.

Doerr, S.H., R.A. Shakesby, L.W. Dekker, and C.J. Ritsema. 2006. Occurrence, prediction and hydrological effects of water repellency amongst major soil and land-use types in a humid temperate climate. *European Journal of Soil Science*. 57:741–754. doi:https://doi.org/10.1111/j.1365-2389.2006.00818.x.

Doerr, S.H., R.A. Shakesby, and L.H. Macdonald. 2009. Chapter I.7. Soil Water Repellency: A Key Factor in Post-Fire Erosion? pp. 197-224

Doerr, S.H., R.A. Shakesby, and R.P.D. Walsh. 1996. Soil hydrophobicity variations with depth and particle size fraction in burned and unburned Eucalyptus globulus and Pinus pinaster forest terrain in the Águeda Basin, Portugal. *CATENA*. 27:25–47. doi:10.1016/0341-8162(96)00007-0.

Doerr, S.H., R.A. Shakesby, and R.P.D. Walsh. 2000. Soil water repellency: its causes, characteristics and hydro-geomorphological significance. *Earth-Science Reviews*. 51:33–65. doi:10.1016/S0012-8252(00)00011-8.

Dyrness, C.T. 1976. Effect of wildfire on soil wettability in the high Cascades of Oregon.

Dyrness, C.T., and R.A. Norum. 2011. The effects of experimental fires on black spruce forest floors in interior Alaska. *Canadian Journal of Forest Research*. doi:10.1139/x83-118.

EcoWest.Visualizing Environmental Trends. EcoWest.org. Accessed 12/02/2020.

Ebel, B.A. 2012. Wildfire impacts on soil-water retention in the Colorado Front Range, United States. *Water Resources Research*. 48. doi:https://doi.org/10.1029/2012WR012362.

Eckert, B.E. 2005. The Story of the Deschutes National Forest. ir.library.oregonstate.edu.

Eckstein, D.M. Winges, Künzel,V., Schäfer, L., and Germanwatch. 2019. Global Climate Risk Index 2020 Who Suffers Most from Extreme Weather Events? Wether-Related Loss Events in 2018 and 1999 to 2018.

Fernandes, P.M. 2015. Empirical Support for the Use of Prescribed Burning as a Fuel Treatment. 10.

Fry, T. 2016. US Forest Service. *West. Water Threat. Wildfire*. https://www.fs.fed.us/features/western-water-threatened-wildfire.

García, F.J.M., L.W. Dekker, K. Oostindie, and C.J. Ritsema. 2005. Water repellency under natural conditions in sandy soils of southern Spain. *Soil Res.* 43:291–296. doi:10.1071/SR04089.

Gräler, B., E. Pebesma, and G. Heuvelink. 2016. Spatio-Temporal Interpolation using gstat. *The R Journal*. 8:204–218.

Harvey, B.J., D.C. Donato, W.H. Romme, and M.G. Turner. 2013. Influence of recent bark beetle outbreak on fire severity and postfire tree regeneration in montane Douglas-fir forests. *Ecology*. 94:2475–2486. doi:10.1890/13-0188.1.

Helvey, J.D. 1980. Effects of a North Central Washington Wildfire on Runoff and Sediment Production. *Journal of the American Water Resources Association*. 16:627–634. doi:10.1111/j.1752-1688.1980.tb02441.x.

Hemstrom, M.A., and J.F. Franklin. 1982. Fire and Other Disturbances of the Forests in Mount Rainier National Park. *Quat. res.* 18:32–51. doi:10.1016/0033-5894(82)90020-5.

Hessl, A.E., D. McKenzie, and R. Schellhaas. 2004. Drought and Pacific Decadal Oscillation Linked to Fire Occurrence in the Inland Pacific Northwest. *Ecological Applications*. 14:425–442. doi:10.1890/03-5019.

Higuera, P.E., and J.T. Abatzoglou. 2021. Record-setting climate enabled the extraordinary 2020 fire season in the western United States. *Global Change Biology*. 27:1–2. doi:https://doi.org/10.1111/gcb.15388.

Hoover, K., and L.A. Hanson. 2019. Wildfire Statistics. Congressional Research Service.

Hudak, A., R. Forester, P. Robichaud, T. Jain, and R. Forester. 2004a. The relationship of field burn severity measures to satellite-derived Burned Area Reflectance Classification (BARC) maps. 9.

Hudak, A.T., P. Morgan, M.J. Bobbitt, A.M.S. Smith, S.A. Lewis, L.B. Lentile, P.R. Robichaud, J.T. Clark, and R.A. McKinley. 2007. The Relationship of Multispectral Satellite Imagery to Immediate Fire Effects. *fire ecol*. 3:64–90. doi:10.4996/fireecology.0301064.

Hudak, A.T., P. Robichaud, J. Evans, J. Clark, K. Lannom, P. Morgan, and C. Stone. 2004b. Field validation of Burned Area Reflectance Classification (BARC) products for post fire assessment. *USDA Forest Service / UNL Faculty Publications*.

Huddleston, J.H., and G.F. Kling. 1996. *Manual for Judging Oregon Soils.* Extension Service, Oregon State University. https://ir.library.oregonstate.edu/concern/open_educational_resources/3197xm437

Huebner, K., Z. Lindo, and M.J. Lechowicz. 2012. Post-fire succession of collembolan communities in a northern hardwood forest. *European Journal of Soil Biology*. 48:59–65. doi:10.1016/j.ejsobi.2011.10.004.

Huffman, E.L., L.H. MacDonald, and J.D. Stednick. 2001. Strength and persistence of fire-induced soil hydrophobicity under ponderosa and lodgepole pine, Colorado Front Range. *Hydrological Processes*. 15:2877–2892. doi:10.1002/hyp.379.

Incident Information System. 2021. https://inciweb.nwcg.gov/.

Jordán, A., L.M. Zavala, J. Mataix-Solera, and S.H. Doerr. 2013. Soil water repellency: Origin, assessment and geomorphological consequences. *CATENA*. 108:1–5. doi:10.1016/j.catena.2013.05.005.

Kane, V.R., C.A. Cansler, N.A. Povak, J.T. Kane, R.J. McGaughey, J.A. Lutz, D.J. Churchill, and M.P. North. 2015. Mixed severity fire effects within the Rim fire: Relative importance of local climate, fire weather, topography, and forest structure. *Forest Ecology and Management*. 358:62–79. doi:10.1016/j.foreco.2015.09.001.

Key, C.H., and N.C. Benson. 2006. Landscape Assessment (LA). *In: Lutes, Duncan C.; Keane, Robert E.; Caratti, John F.; Key, Carl H.; Benson, Nathan C.; Sutherland, Steve; Gangi, Larry J. 2006. FIREMON: Fire effects monitoring and inventory system. Gen. Tech. Rep. RMRS-GTR-164-CD. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. p. LA-1-55*. 164.

King, P.M. 1981. Comparison of methods for measuring severity of water repellence of sandy soils and assessment of some factors that affect its measurement. *Soil Res.* 19:275–285. doi:10.1071/sr9810275.

Landfire. 2016. Disturbance. https://landfire.gov/. Accessed 02/28/2019.

Lakshmanan, V., G. Selvaraj, and H.P. Bais. 2014. Functional Soil Microbiome: Belowground Solutions to an Aboveground Problem. *Plant Physiology*. 166:689–700. doi:10.1104/pp.114.245811.

Lemmnitz, C., M. Kuhnert, O. Bens, A. Güntner, B. Merz, and R.F. Hüttl. 2008. Spatial and temporal variations of actual soil water repellency and their influence on surface runoff. *Hydrological Processes*. 22:1976–1984. doi:https://doi.org/10.1002/hyp.6782.

Letey, J. 1969. Measurement of contact angle, water drop penetration time, and critical surface tensions. Proc. Symp. Water Rep. Soils, Univ. Calif., Riverside.

Lewis, S.A., J.Q. Wu, and P.R. Robichaud. 2006. Assessing burn severity and comparing soil water repellency, Hayman Fire, Colorado. *Hydrological Processes*. 20:1–16. doi:10.1002/hyp.5880.

Lowe, M.-A., G. McGrath, and M. Leopold. 2021. The Impact of Soil Water Repellency and Slope upon Runoff and Erosion. *Soil and Tillage Research*. 205:104756. doi:10.1016/j.still.2020.104756.

Lynch, D.L. 2004. What Do Forest Fires Really Cost? *Journal of Forestry*. 102:42–49. doi:10.1093/jof/102.6.42.

Mainwaring, K., I.L. Hallin, P. Douglas, S.H. Doerr, and C.P. Morley. 2013. The role of naturally occurring organic compounds in causing soil water repellency: Soil water repellency from organic compounds. *Eur J Soil Sci*. 64:667–680. doi:10.1111/ejss.12078.

Mataix-Solera, J., I. Gómez, J. Navarro-Pedreño, C. Guerrero, and R. Moral. 2002. Soil organic matter and aggregates affected by wildfire in a Pinus halepensis forest in a Mediterranean environment. *Int. J. Wildland Fire*. 11:107–114. doi:10.1071/wf02020.

Miyanishi, K., and E.A. Johnson. 2002. Process and patterns of duff consumption in the mixedwood boreal forest. 32:11.

Moritz, M.A., E. Batllori, R.A. Bradstock, A.M. Gill, J. Handmer, P.F. Hessburg, J. Leonard, S. McCaffrey, D.C. Odion, T. Schoennagel, and A.D. Syphard. 2014. Learning to coexist with wildfire. *Nature*. 515:58–66. doi:10.1038/nature13946.

Moritz, M.A., M.E. Morais, L.A. Summerell, J.M. Carlson, and J. Doyle. 2005. Wildfires, complexity, and highly optimized tolerance. *PNAS*. 102:17912–17917. doi:10.1073/pnas.0508985102.

Mutch, L. 2018. Lolo Peak Fire 2017: From the wilderness to the wildland urban interface. Northern Rockies Fire Science Network.

Napper, C. 2006. Burned Area Emergency Response Treatments Catalog. Watershed, Soil, Air Management 0625 1801—SDTDC. https://www.fs.fed.us/td/pubs/pdf/BAERCAT/lo_res/TOContents.pdf

Neary, D.G., K.C. Ryan, and L.F. DeBano. 2005. Wildland fire in ecosystems: effects of fire on soils and water. U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Ft. Collins, CO.

Nelson, P., R. White, and R. Molina. 2006. The Pacific Northwest Research Station's Biodiversity Initiative: Collaborating for Biodiversity Management. 40.

NIFC. 2020. Suppression Costs. https://www.nifc.gov/fire-information/statistics/suppression-costs. Accessed 01/04/2021

O’Brien, R. 1999. Forest Resources of the Flathead National Forest. U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 16 pp.

Odion, D.C., and D.A. Sarr. 2007. Managing disturbance regimes to maintain biological diversity in forested ecosystems of the Pacific Northwest. *Forest Ecology and Management*. 246:57–65. doi:10.1016/j.foreco.2007.03.050.

Oksanen, J.Guillaume F.B., Friendly, M., Kindt, R., Legendre, P., McGlinn, D., Minchin, P.R., O'Hara, R. B., Simpson, G.L., Solymos, P., Stevens, M.H.H., Szoecs, E., Wagne, H. 2020. Package ‘vegan’. https://cran.ism.ac.jp/web/packages/vegan/vegan.pdf.

Osborn, J., J. Letey, F. DeBano, and E. Terry. 1967. Seed Germination and Establishment as Affected by Non-Wettable Soils and Wetting Agents. *Ecology*. 48:494–497. doi:10.2307/1932685.

Paradis, E., and K. Schliep. 2019. ape 5.0: an environment for modern phylogenetics and evolutionary analyses in R. *Bioinformatics*. 35:526–528. doi:10.1093/bioinformatics/bty633.

Parson, A., P.R. Robichaud, S.A. Lewis, C. Napper, and J.T. Clark. 2010. Field guide for mapping post-fire soil burn severity. U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Ft. Collins, CO.

Passialis, C.N., and E.V. Voulgaridis. 1999. Water Repellent Efficiency of Organic Solvent Extractives from Aleppo Pine Leaves and Bark Applied to Wood. *Holzforschung*. 53:151–155. doi:10.1515/HF.1999.025.

Perry, D.A., H. Jing, A. Youngblood, and D.R. Oetter. 2004. Forest Structure and Fire Susceptibility in Volcanic Landscapes of the Eastern High Cascades, Oregon. *Conservation Biology*. 18:913–926. doi:https://doi.org/10.1111/j.1523-1739.2004.00530.x.

Radeloff, V.C., D.P. Helmers, H.A. Kramer, M.H. Mockrin, P.M. Alexandre, A. Bar-Massada, V. Butsic, T.J. Hawbaker, S. Martinuzzi, A.D. Syphard, and S.I. Stewart. 2018. Rapid growth of the US wildland-urban interface raises wildfire risk. *PNAS*. 115:3314–3319. doi:10.1073/pnas.1718850115.

Rillig, M.C., N.F. Mardatin, E.F. Leifheit, and P.M. Antunes. 2010. Mycelium of arbuscular mycorrhizal fungi increases soil water repellency and is sufficient to maintain water-stable soil aggregates. *Soil Biology and Biochemistry*. 42:1189–1191. doi:10.1016/j.soilbio.2010.03.027.

Robichaud, P.R. 2000. Evaluating the Effectiveness of Postfire Rehabilitation Treatments. U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 92 pp.

Robichaud, P.R., S.A. Lewis, and L.E. Ashmun. 2008. New procedure for sampling infiltration to assess post-fire soil water repellency. U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Ft. Collins, CO.

Rogers, B.M., R.P. Neilson, R. Drapek, J.M. Lenihan, J.R. Wells, D. Bachelet, and B.E. Law. 2011. Impacts of climate change on fire regimes and carbon stocks of the U.S. Pacific Northwest. *Journal of Geophysical Research: Biogeosciences*. 116. doi:10.1029/2011JG001695.

RStudio Team (2020). RStudio: Integrated Development for R. RStudio, PBC, Boston, MA URL http://www.rstudio.com/.

Safford, H.D., J. Miller, D. Schmidt, B. Roath, and A. Parsons. 2008. BAER Soil Burn Severity Maps Do Not Measure Fire Effects to Vegetation: A Comment on Odion and Hanson (2006). *Ecosystems*. 11:1–11. doi:10.1007/s10021-007-9094-z.

Schoenholtz, S.H., H.V. Miegroet, and J.A. Burger. 2000. A review of chemical and physical properties as indicators of forest soil quality: challenges and opportunities. *Forest Ecology and Management*. 138:335–356. doi:10.1016/S0378-1127(00)00423-0.

Schoennagel, T., M.G. Turner, and W.H. Romme. 2003. The Influence of Fire Interval and Serotiny on Postfire Lodgepole Pine Density in Yellowstone National Park. *Ecology*. 84:2967–2978. doi:https://doi.org/10.1890/02-0277.

Schoennagel, T., T.T. Veblen, and W.H. Romme. 2004. The Interaction of Fire, Fuels, and Climate across Rocky Mountain Forests. *BioScience*. 54:661–676. doi:10.1641/0006-3568(2004)054[0661:TIOFFA]2.0.CO;2.

Seaton, F.M., D.L. Jones, S. Creer, P.B.L. George, S.M. Smart, I. Lebron, G. Barrett, B.A. Emmett, and D.A. Robinson. 2019. Plant and soil communities are associated with the response of soil water repellency to environmental stress. *Science of The Total Environment*. 687:929–938. doi:10.1016/j.scitotenv.2019.06.052.

Service, O.S.U.E., Huddleston, J.H., and Kling, G.F. Manual for judging Oregon soils.

Shakesby, R.A., S.H. Doerr, and R.P.D. Walsh. 2000. The erosional impact of soil hydrophobicity: current problems and future research directions. *Journal of Hydrology*. 231–232:178–191. doi:10.1016/S0022-1694(00)00193-1.

Simkovic, I., P. Dlapa, S.H. Doerr, J. Mataix-Solera, and V. Sasinkova. 2008. Thermal destruction of soil water repellency and associated changes to soil organic matter as observed by FTIR spectroscopy. *CATENA*. 74:205–211. doi:10.1016/j.catena.2008.03.003.

Soil Survey Staff. 2021. https://www.nrcs.usda.gov/wps/portal/nrcs/main/soils/survey/. Accessed 02/14/2021.

Täumer, K., H. Stoffregen, and G. Wessolek. 2005. Determination of repellency distribution using soil organic matter and water content. *Geoderma*. 125:107–115. doi:10.1016/j.geoderma.2004.07.004.

Tolhurst, K.G., and G. McCarthy. 2016. Effect of prescribed burning on wildfire severity: a landscape-scale case study from the 2003 fires in Victoria. *Australian Forestry*. 79:1–14. doi:10.1080/00049158.2015.1127197.

Turner, M.G., W.L. Baker, C.J. Peterson, and R.K. Peet. 1998. Factors Influencing Succession: Lessons from Large, Infrequent Natural Disturbances. *Ecosystems*. 1:511–523. doi:10.1007/s100219900047.

Urness, Z. Oregon's 2020 wildfire season brought a new level of destruction. It could be just the beginning. *Statesman Journal*.

USDA. 2020. Burned Area Emergency Response-BAER. https://www.fs.fed.us/naturalresources/watershed/burnedareas.shtml

USFS. 2020. Forest Service Manual FSM 2500-Watershed and Air Management Chapter 2520-Watershed Protection and Management 2523-Emergency Stabilization- Burned-Area Emergency Response (BAER). https://www.fs.fed.us/naturalresources/watershed/pubs/wo_2520_Amend-20-1.pdf. Accessed 12/05/2020.

USFS. 2017.BAER Imagery Support Data Download. https://fsapps.nwcg.gov/baer/baer-imagery-support-data-download Accessed 03/10/2018.

Vacchiano, G., S. Stanchi, G. Marinari, D. Ascoli, E. Zanini, and R. Motta. 2014. Fire severity, residuals and soil legacies affect regeneration of Scots pine in the Southern Alps. *Science of The Total Environment*. 472:778–788. doi:10.1016/j.scitotenv.2013.11.101.

Van Wagtendonk. 1985. General Technical Report INT. Intermountain Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture. 836 pp.

Varela, M.E., E. Benito, and E. de Blas. 2005. Impact of wildfires on surface water repellency in soils of northwest Spain. *Hydrological Processes*. 19:3649–3657. doi:https://doi.org/10.1002/hyp.5850

Westerling, A.L., H.G. Hidalgo, D.R. Cayan, and T.W. Swetnam. 2006. Warming and Earlier Spring Increase Western U.S. Forest Wildfire Activity. *Science*. 313:940–943. doi:10.1126/science.1128834.

Wei, T., Simko,V., Levy, M., Xie, Y., Jin, Y., and J., Zemla,. 2017. Package 'corrplot'. https://peerj.com/articles/9945/Supplemental_Data_S10.pdf

Wieting, C., B.A. Ebel, and K. Singha. 2017. Quantifying the effects of wildfire on changes in soil properties by surface burning of soils from the Boulder Creek Critical Zone

Observatory. *Journal of Hydrology: Regional Studies*. 13:43–57. doi:10.1016/j.ejrh.2017.07.006.

Woods, S.W., A. Birkas, and R. Ahl. 2007. Spatial variability of soil hydrophobicity after wildfires in Montana and Colorado. *Geomorphology*. 86:465–479. doi:10.1016/j.geomorph.2006.09.015.

Woudt, B.D. van't. 1959. Particle coatings affecting the wettability of soils. *Journal of Geophysical Research*. 64:263–267. doi:10.1029/JZ064i002p00263.

Zavala, L.M., A.J.P. Granged, A. Jordán, and G. Bárcenas-Moreno. 2010. Effect of burning temperature on water repellency and aggregate stability in forest soils under laboratory conditions. *Geoderma*. 158:366–374. doi:10.1016/j.geoderma.2010.06.004.

Zheng, W., E.K. Morris, A. Lehmann, and M.C. Rillig. 2016. Interplay of soil water repellency, soil aggregation and organic carbon. A meta-analysis. *Geoderma*. 283:39–47. doi:10.1016/j.geoderma.2016.07.025.

5 Thesis Conclusions

This investigation into SWR both throughout the PNW and within the Green Ridge Fire of the Deschutes National Forest can be recapitulated through key findings observed in the field from the relationship of soil-water relations to its post-fire environment. Our initial project protocol in Chapter 1 highlighted both the need for a finer scale method of data collection as well as a research gap in the impacts of fire on systems with naturally occurring SWR pre-disturbance. The second chapter looking closer into the conditions present in the Deschutes National Forest allowed us to answer three main questions: i) How does soil water repellency vary across burn severity classes in soils with pre-existing repellency? We found that the standard metric of burn severity does not entirely capture the patterns of soil water repellency at this scale in the Green Ridge Fire. Additional factors may play a larger role in soils with SWR as an inherent quality of the system. ii) Is there an appropriate spatial scale on which to evaluate properties of soil water repellent layers? Hydrophobic compounds move deeper into the soil profile following wildfire, as was anticipated; however, small scale variation over the landscape in repellency does not easily scale up to the fire-level. Actual field conditions of soil water repellency may be lost through single point measurements. iii) Variation of SWR found both as a factor of burn severity and with spatial dependence requires an intent focus on environment characteristics; do environmental factors drive patterns in soil water repellency? Soil water repellency was found most often with acidic soils, low moisture content, smaller particle fractions, high organic matter content, and high soil conductance in the Green Ridge Fire. Knowledge of these conditions in a forest can guide areas to sample for soil water repellency post-fire. Key findings from the study may be applicable to forested areas across the US but will be particularly significant in Pacific Northwest systems of similar ecotypes and soil classifications.

We have deduced three major management recommendations from these key takeaways: i) Update landscape inventory protocols to include baseline soil water repellency characteristic reporting. A baseline report of SWR conditions does not currently exist in US forest sampling protocols. This simple addition would save time and resources in post-fire assessment as areas with pre-existing hydrophobic conditions may be less reliant on burn severity metrics that those found without. ii) Locate areas most at risk for soil water repellency through environmental characteristics in addition to burn severity. SWR was found to be more closely linked to ecosystem variables than solely soil burn severity, providing an increase in predictive power for managers. ii) Post-fire sampling would benefit from continued research to define the most effective sampling densities for different baseline repellency levels. Efficient sampling of SWR would greatly benefit BAER data collection in conjunction with baseline information of SWR availability prior to their arrival. These action points are the final product of this thesis research developed over three years of data collection and assessment. Any questions or comments regarding these key takeaways and managements recommendations can be directed to jaleneweatherholt@gmail.com.

6 Appendix

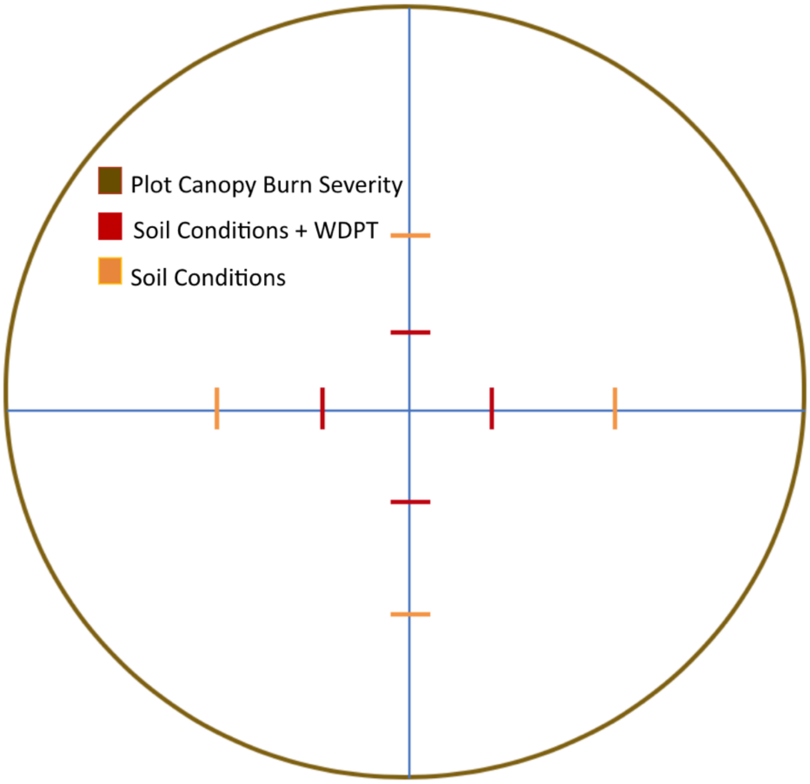

Figure A1: Plot design. Sampling points for soil burn severity and soil water repellency (SWR) are noted (n=8).

7 Data Files

“GrandDataSheet_BurnSeverityData:Analysis.xlsx”- a data file with additional analysis sheets containing the master dataset of the Pacific Northwest fires burned in 2017 and sampled in 2018 utilized in Ch1 and in the Supplemental work Sections (Norse Peak, Milli, Lolo Peak, and Liberty). Fire name, plot name, GPS location, canopy burn severity, soil burn severity, surface soil color, ash depth, soil structure, root condition, SWR condition from 1-10 cm depths, and BARC map soil burn severity and other collected location metadata are reported and manipulated in subsequent sheets.

“total_subpoint_responsematrix.csv”- a data file (333 rows x 24 columns) containing all information from each of the 81 (Light surface plot has 9 additional sampling points taken at the 18 m column of the plot) sampling points from each plot. They include the soil water repellency (SWR) responses at each depth, x coordinate of the plot, y coordinate of the plot, canopy burn severity class, and soil burn severity class.

“Permanova_Format_alldata.csv”- a data file (72 rows x 33 columns) containing information from the additional sampling subset of plot point. They include the SWR responses at each depth, x coordinate of the plot, y coordinate of the plot, pH, field moisture, conductance, organic matter content (loss on ignition/LOI), sand percent, silt percent, clay percent, stand basal area, percent mortality by basal area, canopy burn severity class, and soil burn severity class.

“horizonvert_compare.csv”- a data file (72 rows x 7 columns) containing information of SWR response at 5, 10, and 15 centimeters of the average SWR response from measurements on the horizontal plane and from the point measurements at those depths from the vertical soil core.

“total_WHOLECOREpoint_responsematrix.csv” - a data file (254 rows x 24 columns) containing all information from each of the 81 (Light surface plot has 9 additional sampling points taken at the 18 m column of the plot) sampling points from each plot where any location not measured to the whole 20 cm depth was removed. Variables include the soil water repellency (SWR) responses at each depth, x coordinate of the plot, y coordinate of the plot, canopy burn severity class, and soil burn severity class.