

THE EFFECTS OF FIRE AND LOGGING ON MONTANE  
FOREST SOILS IN SOUTHERN OREGON

by

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A THESIS

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Climate change is expected to increase the frequency and severity of forest fires and drought across the Pacific Northwest (PNW) of the United States. Due to increasingly variable temperature and precipitation patterns, the effects of fire on forest vegetation can be modeled and predicted with great confidence. However, the effect of fire frequency on soils remains poorly understood. Soils in PNW forests have the potential to sequester large quantities of carbon, which can mitigate the effects of climate change. Furthermore, severely burned forests may be “salvage” logged post-fire in which consequences for carbon storage are uncertain. To quantify the effects of fire on soil properties and carbon content, we measured soil organic carbon (SOC), pH, and texture among a fire severity and post-fire management gradient in a region affected by the Biscuit Fire of 2002. Samples were collected at four sites and two depths for percent SOC, pH, and percent clay analyses. Laboratory analyses showed the low severity ( $8.10 \pm 0.5$ ) had higher levels of SOC than high severity sites ( $7.21 \pm 0.9$ ). However, the unburned site contained  $4.29 \pm 0.4$  % SOC, the lowest percentage of the four sites. There were minimal differences in percent SOC between the salvage logged and non-salvage logged sites. Soil from the high severity non-salvage logged site had a

significantly higher pH than the other sites, and percent clay remained relatively similar across all sites. The results indicate that low severity fires, potentially in the form of prescribed burns, may be optimal for sequestering SOC and could help mitigate the impact of climate change in montane forests in the PNW region.

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## **Introduction**

Anthropogenically induced climate change has increased fire severity through prolonged drought and shifting precipitation regimes (Mote et al., 2019). In the Pacific Northwest (PNW), low severity fires have been a part of forested ecosystems' natural disturbance regimes, promoting nutrient pulses to the soil, seed dispersal, and biodiversity (Halofsky et al., 2011). However, increased fire frequency and severity can adversely affect forested ecosystems. Fire frequency is the number of fire events during a given time period, and severity considers the intensity of the fire event, often using lost biomass as a measurement (Fernández-García et al., 2019). Soil properties such as soil organic carbon (SOC), pH, and texture have the potential to be impacted by forest fires, while forest management to reduce the effects of high severity fires has become an increasingly difficult challenge, as land use and forest fires are strongly correlated due to homogeneity and young age among highly managed forest stands (Zald and Dunn, 2018).

### **A. Research Question and Hypotheses**

Research was focused on nutrient presence in the form of SOC and the physical properties of pH and texture. These soil properties are important to study because SOC storage has the potential to mitigate the adverse effects of climate change, while pH and texture give a representation of the metabolic processes in the soil, which are necessary for retaining carbon and other nutrients (Law et al. 2018; Neina, 2019). This thesis aims to identify soil ecosystem and climate change trends, as well as post-fire policy influences on soil properties to inform land management practices in the Rogue River-



Siskiyou National Forest. The research was guided by the question of: **How does fire severity and post-fire management influence SOC, pH, and texture?**

Because frequent high severity fires cause more belowground carbon to dissipate from the ecosystem (Law et al., 2004), I hypothesized that **(1) percent SOC will decrease in the topsoil along a fire severity gradient**. Salvage logging removes woody debris and organic matter input from the landscape (Slesak et al., 2015); therefore, I hypothesized that **(2) soil in the salvage logged site will contain less carbon content than the non-salvage logged site**.

Because fire inputs alkaline ash after a fire (Fernández-García et al., 2019), I hypothesized that **(3) soil pH will increase with wildfire severity**. As post-fire erosion can increase soil pH (García-Orenes et al., 2017), **(4) pH will be higher in the soils of the salvage logged site than the non-salvage logged site**.

Additionally, **(5) high severity sites will have lower proportions of clay compared to the low severity sites** due to the effects of post-fire erosion after intense wildfires (Butnor et al., 2017). Because long-term weathering and climate conditions have greater influence on texture compared to plant community composition (Granged et al., 2011), **(6) soil texture will not change between the salvage logged and the non-salvage logged sites**.

## **B. Forest Fires and the PNW**

Climate change has produced drastic and irreversible results in the PNW; Oregon will experience temperature increases and precipitation regime shifts, including more drastic summer droughts and increased downpour winter precipitation (Mote et al., 2019). Climate change will extend the fire season, which increases the likelihood of

a fire occurrence (Spies et al., 2014). Research has established that these changes are a result of human activity, and ecosystems around the world will face adversity from transformations in regional and global climates.

The likelihood of increasing fire severity and frequency in the PNW is a multifaceted case with various contributing components. The number of large forest fires on the West Coast has already increased by 300% since the 1980s, and the frequency of wildfires is likely to grow as the climate continues to change (Hanson et al., 2013). The subject of changing fire regimes is complex with direct and indirect effects, positive and negative feedback loops, and delays in response times of different parts of the ecosystem (Liu and Wimberly, 2016). The combination of increasing temperatures and decreasing precipitation will allow forest fires to prevail, and thus the extent of this changing fire regime and its effects on the forest ecosystem need to be studied.

### **C. SOC in PNW Forests**

Soil organic carbon (SOC) is an important biological resource for plant growth, nutrient cycling, and ecosystem services including decomposition and carbon sequestration. SOC has been studied for decades (Isaac & Hopkins, 1937), though its recent importance is due to the carbon sequestration and climate mitigation effects of forests. Stable amounts of SOC are essential because it allows for water retention, cation exchange, reduced leaching, and soil aeration for plants (Gonzalez et al., 2004). SOC, like many ecosystem functions, depends on climate, moisture availability, and disturbances (Butnor et al., 2017). Forest soils help regulate the atmosphere's carbon dioxide content as a part of the global carbon cycle. The largest supply of active terrestrial carbon is found in soils, though significant amounts of SOC are lost each year

due to land use changes from forests and grasslands to agricultural fields (Jackson et al., 2017). SOC in PNW forests is influenced by changes in above ground biomass and species composition, temperature and water conditions, and environmental processes such as erosion and decomposition (Bailey et al. 2018).

The PNW in particular has the possibility to hold large amounts of carbon because of the vast and productive old-growth forests (Goward et al., 2008; Hudiburg et al., 2009). The Rogue River-Siskiyou National Forest in Klamath Mountains region on the California-Oregon border holds almost 12 kg C/m<sup>2</sup> of carbon stocks in the soil and a much lower value of 3 C/m<sup>2</sup> in live biomass, with a potential upper limit of 33 to 44 kg C/m<sup>2</sup> for the region (Hudiburg et al., 2009; Sun et al., 2004). Reaching this upper limit of SOC storage is unlikely because of natural and human-induced disturbances, though management practices in the recent decades have adapted towards increasing carbon sequestration and SOC stocks in forests to reduce the effects of rising atmospheric carbon dioxide levels (Law et al., 2018). The Siskiyou region is about average in terms of SOC stock and high in live biomass carbon compared to other regions in the state, with soil organic carbon values ranging from 2 to 8 percent per sample (Heckman et al., 2013; ISRIC, 2020). This is due to the relatively average mean annual precipitation and widespread old-growth forests (Hudiburg et al., 2009; Sun et al., 2004).

SOC can be measured through soil organic matter (SOM) in the topsoil; SOC is a component of SOM, and the amount of SOC in SOM is dependent on depth, vegetation, and hydrology (Ernest, 2016). SOM, containing SOC, is a part of total ecosystem C, which also includes carbon found in alive and dead plant matter (Jackson

et al., 2017). SOC as a fraction of SOM is a complex structure and would benefit from more research.

#### **D. Fire severity on SOC in Montane Forests**

It is uncertain how much fire severity changes SOC. One study found that low severity fires in a Mediterranean ecosystem did not influence the SOC stock and high severity fires caused a 34.6% decrease in soil organic matter (Granged et al., 2011). Another found that the loss of SOC from a forest fire is not observable after the medium term (defined as 2 to 5 years) as a result of conflicting variables of the fire, such as burning depth, inputs of litter, and varied decomposition rates (Fernández-García et al., 2019). A third study concluded that fire decreased SOC content in the top layer of the litter of Mediterranean ecosystems, while there was an increase in charred carbon in the mineral layer (Cirtini et al., 2012). Wildfire can cause the landscape to be a carbon source rather than a sink, in which more carbon is released than stored in the soil, through the significant reduction in the uptake of carbon (Law et al., 2004). In contrast, Heckman et al. (2013) did not find any significant differences in carbon content after increasing burn severities of a PNW forest fire. Gonzalez et al. (2004) reviewed the literature and explained that there are too many contributing variables to generalize the relationship between fire and SOC. This thesis aims to better quantify the trend specifically for PNW forests in order to contribute to the need for ecosystem-based categorized conclusions.

## **E. Wildfire Effects on Montane Forest Soil pH and Texture**

Soil pH and texture are two prominent characteristics of soil chemistry. Soil pH, the measurement of hydrogen ions of the solution, depends on the mineral composition of the soil's parent material and the degree of weathering (Neina, 2019). Soil pH tends to increase after a wildfire due to the input of ash and organic matter into the soil, though the lasting effects of this change are dependent on the severity of the wildfire and the other physical properties of the soil (Certini et al., 2011; Fernández-García et al., 2019; Granged et al., 2011).

Soil texture is the proportions of different particle sizes and is a scale of largest (sand) to smaller (silt) and smallest (clay). Factors that influence soil texture include sampling depth, weathering, climate, and parent material. Biogeochemical processes such as water holding capacity, root penetration, and nutrient retention depend on texture (Dexter, 2004). Soil texture is not influenced by low severity fires because the fire is unlikely to damage more than the topsoil, but soil may become coarser after a long-lasting high severity wildfire (Butnor et al., 2017; Granged et al., 2011). Researchers noted that this was a result of post-fire erosion following their three-year study period, but the long-term effects of wildfires on soil texture are unclear (Granged et al., 2011).

## **F. Salvage Logging and the Effects on Montane Forest Soil**

Salvage logging, the removal of burned trees from an area after a wildfire to enable forest recovery and regain part of the burned timber profit, is a longstanding controversial post-fire management tool (Cahall and Hayes, 2009; García-Orenes et al., 2017; Lindenmayer and Noss, 2006). This practice has been used extensively for the

last century, and the initial uncertainty about its effects on soil have not changed (Isaac & Hopkins, 1937). Salvage logging has both positive and negative impacts on the burned forests, so public and private land managers do not have a clear choice.

In an extensive literature review, USFS researchers note possible advantages of salvage logging include tree disease prevention, reduced insect outbreaks, improved watershed conditions, and recovered timber sales, while disadvantages include habitat loss, soil degradation, and restricted regrowth (McIver and Starr, 2000). The effect of salvage logging on the environment is highly variable and depends on burn severity, climate, machinery used, topographic conditions, and soil characteristics (Lindenmayer and Noss, 2006; McIver and Starr, 2000).

Salvage-logged areas possess lower carbon stocks due to decreased woody debris and organic matter input into the soil (García-Orenes et al., 2017). By definition, salvage logging removes the biological legacy of trees and has the potential to alter nutrient inputs and cycles by reducing carbon added to the soil and releasing more nutrients into the atmosphere (Law et al., 2004; Lindenmayer and Noss, 2006). Additionally, many nutrients are destabilized from the ecosystem through increased soil erosion after a forest fire, a process exacerbated by salvage logging (García-Orenes et al., 2017; Granged et al., 2011; Slesak et al., 2015).

However, other studies found that while there was a decrease in percent carbon in woody debris, there was no significant difference in forest floor and total ecosystem carbon (Bradford et al., 2012). Salvage logging can be beneficial for the post-fire ecosystem by decreasing the fuel load of the forest, which reduces the chance of future high severity fires by removing excess woody debris, eliminating competition,

stimulating coexistence, and promoting frequent low severity fires (Peterson et al., 2015; Royo et al., 2016). Post-fire logging can increase woody fuels compared to unlogged areas in the short-term, though this difference converges over time and diminish after a decade thereby leaving no apparent long-lasting damage in terms of fuel loading and nutrient cycling (Campbell et al., 2016).

## Methods

### A. Study Site

The Rogue River-Siskiyou National Forest, located in southwest Oregon and northern California, is prone to large and frequent forest fires. Composed of over one million acres of forest land, much of the forest contains Douglas-firs (*Pseudotsuga mensiezii*), incense-cedars (*Calocedrus decurrens*), oaks (*Quercus spp.*), Sitka spruces (*Picea sitchensis*), firs (*Abies spp.*), and pines (*Pinus spp.*) (Joyer, 2019; Sun et al., 2004). The Siskiyou region is one of the most biodiverse and ecologically important forest landscapes on the West Coast (Joyer, 2019). The Rogue River-Siskiyou National Forest experiences hot and dry summers with cool and wet winters (Table 1).

Season	Average High (°C)	Average Low (°C)	Precipitation (mm)
Summer	31.1	9.6	2.4
Fall	20.9	4.4	9.9
Winter	9.6	0.7	23.7
Spring	18.9	3.3	14.7

Table 1. Climate data for the Rogue River-Siskiyou National Forest

Climate data was retrieved from the National Weather Service.

Fire is an important ecological disturbance in the Siskiyou region. Decades of fire suppression have caused more widespread fires to occur, and recent wildfires have driven ecologists and landowners to better understand the effects and implications of forest fires. Historical and recent forest fires, such as the Silver Fire of 1987 and the Chetco Bar Fire of 2017, had biological impacts such as species mortality, habitat loss, and changes to the soil ecology, which can permanently alter the landscape and ecosystem dynamics (Oregon Department of Forestry, 2020).



The 2002 Biscuit Fire – considered Oregon’s most destructive fire in modern history at the time – destroyed half a million acres in the Rogue River-Siskiyou National Forest (LaLande, 2019; Oregon Department of Forestry, 2020). Fire ignition was attributed to a lightning strike July 2002, where fires lasted for four months (LaLande, 2019). The Biscuit Fire burned with varying severity across southwestern Oregon (Figure 1). Burn severity is defined as “the loss of or change in ecosystem biomass, caused by fire” (Fernández-García et al., 2019); low severity fire consumes the litter layer of the forest and singes the bark of trees, while high severity fires eliminate the majority of vegetation and tree species.

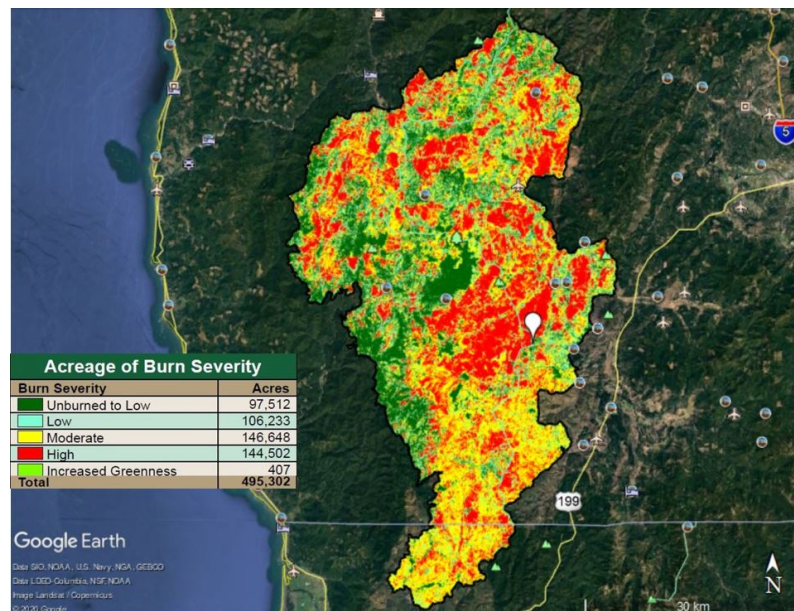


Figure 1. Burn severity map of the Biscuit Fire

The 2002 Biscuit Fire in southern Oregon is a sufficient study region because of the mosaic of burn severities that the fire created (U.S. Geological Survey, 2005). The white marker in the center-right of the landscape is the location of data collection, where unburned, low severity and high severity fire damages are represented.

The sampling region within the Rogue River-Siskiyou National Forest was chosen because it contained all three burn severities within the same area (Table 2). The closeness of the sites ensured constant climate and community composition.

Site	Description	Latitude (N)	Longitude (W)	Elevation (m)
1	Unburned control	42.22210	-123.78989	1364.9
2	Low severity	42.22287	-123.79010	1338.4
3	High severity non-salvage	42.24207	-123.79842	1214.6
4	High severity salvage	42.24037	-123.79615	1232.3

Table 2. Summary of site characteristics

The control site possessed minimal or no evidence of fire damage, where abundant vegetation existed on the forest floor and canopy (Figure 2).



Figure 2. Unburned control site

Control site understory (left) with unharmed trees and lack of burned woody debris; control site canopy (right), where there is a presence of ground, mid-height, and canopy plants, are characteristic of an unburned forest site.

The low severity site had minimal yet present fire damage. The canopy level of the forest was intact, and there was some burned debris on the forest floor. One of the main indications of a forest fire are the burn scars left on the standing trees. In the low

severity site, the fire scars were usually on the bottom half of the trunk or near the base of the tree and did not cause mortality to the species (Figure 3). Site 2 did not have reachable soils past 20 cm, so this site is excluded from analyses at lower depths.



Figure 3. Low severity site

*Left:* The minimally damaged tree on the left in proximity to the scarred tree on the right is common for the low severity site. There is a mixture of burned and unburned trees, with varying amounts of floor level and canopy level vegetation. *Right:* The fire scars on the trees are indications of the severity of the burn. In the low severity site, some trees were damaged with fire scars, while others were left unharmed.

In the high severity non-salvage logged site, snags (standing dead trees) were marked with blacked fire scars and white inner wood remains. There were minimal trees in the area (<10% at the fire-affected areas), and the ground level saplings, primarily manzanita (*Arctostaphylos* spp.), chinquapin (*Chrysolepis chrysophylla*), and buckthorn (*Ceanothus cuneatus*) dominated the vegetation. The high severity salvage had a similar composition but snag stumps instead of snags, a result of the common post-fire practice of salvage logging (Figure 4).





Figure 4. High severity non-salvage vs salvage site

*Left:* There are burned snags, or standing dead trees, present throughout the high severity non-salvage site, and there is minimal ground vegetation. *Right:* The burned tree stumps are indications of a high severity fire in which the snags were logged, and the removal of the snags is the only difference between the high severity non-salvage site and the high severity salvage site.

These four sites represent a burn severity gradient and differing post-fire management strategies. By isolating the change in these variables, analyses can be completed to determine how fire severity and management practice influence soil properties of SOC, pH, and texture.

## **B. Soil Collection**

Soil samples were collected with an auger for carbon data and physical characterization on July 7 and 8, 2020. Three replicate points were established 50 meters apart within each site for a total of twelve locations of samples. At each point, soil samples were taken every 20 cm down to 40 cm or the greatest depth if obstructed by an impenetrable layer or parent material.

## C. SOC, pH, and Texture Data Collection

### I. SOC

Soils were left at room temperature for over 48 hours before sieving to remove particles larger than 2 mm. SOC data was quantified using the Loss-On-Ignition (LOI) method. LOI burns the organic matter of a soil sample and is then used to calculate the mass difference, with the assumption that the mass lost in ignition is solely soil organic matter, consisting of 50% carbon and 50% water (Jensen et al., 2018; Pribyl, 2010). The LOI calculation yields SOC concentration, which is converted to percent for ease of interpretation. In preparation for SOC analysis, samples were placed in ceramic crucibles and the total pre-burning weight was documented. The samples were transferred to a furnace and left for 2 hours at 550 °C, which is a temperature that burns organic carbon and not the inorganic carbon fraction. Once the organic matter burned off, the samples were weighed again. SOC was calculated using Equation 1.

$$\% \text{ SOC} = \frac{((\text{weight}_{\text{pre}} - \text{weight}_{\text{post}}) / \text{weight}_{\text{pre}}) \times 100}{2}$$

Equation 1. SOC calculation

The Loss-On-Ignition method has the potential to volatilize additional compounds other than soil organic matter, and thus the percent SOC values obtained from this method are likely an overestimate (Jensen et al., 2018).

### II. pH

Samples were prepared with 20 g soil and 40 mL deionized water. Samples were shaken for ten minutes and left to sit for fifteen minutes (Maxwell, 2017). The pH

values were obtained using the SevenCompact S220 pH meter by Mettler Toledo (Columbis, Ohio, USA).

### *III. Texture*

Five g of each soil sample was sieved to less than two mm and added to 40 mL 0.5% Sodium Hexametaphosphate. Sodium Hexametaphosphate acts as a dispersing agent, ultimately separating soil particles from each other. After the samples were shaken overnight, 2.5 mL of each sample were pipetted out of the solution after 10.6 seconds to capture sand and again after 110.8 minutes to capture clay. The subsamples were placed in previously-weighed tins and left in a drying oven until the excess moisture samples was evaporated. The samples were weighed, and R studio was used to calculate the percentages of each soil particle for each sample (Maxwell, 2017). Each soil particle size was calculated for the samples, but percent clay was used for the results because this soil particle size is the main indicator of chemical properties relating to soil texture.

### **D. Statistical Analyses**

R Studio and Excel were used to produce graphs and statistically evaluate the data. Tukey tests were used to compare soil physical properties for each pair of sites to determine any significant distinction among treatment types (burn severity, post-fire management). Significance is determined with an alpha of 0.05.

## Results

Table 3 provides the averages of percent SOC, pH, and percent clay for each site per depth.

Site and Depth (cm)	<i>n</i>	% SOC	pH	% Clay
Unburned, 0-20	4	4.29 ± 0.4	5.47 ± 0.05	17.7 ± 3.7
Unburned, 20-40	2	3.26 ± 0.9	5.31 ± 0.03	24.6 ± 13.4
Low Severity, 0-20	4	8.10 ± 0.5	5.49 ± 0.05	13.9 ± 4.7
High Severity Non-Salvage, 0-20	3	7.21 ± 0.9	6.55 ± 0.1	21.5 ± 2.3
High Severity Non-Salvage, 20-40	3	7.63 ± 0.8	6.53 ± 0.08	16.4 ± 6.5
High Severity Salvage, 0-20	3	7.96 ± 0.5	5.28 ± 0.08	35.5 ± 4.5
High Severity Salvage, 20-40	2	8.23 ± 0.4	5.35 ± 0.03	15.9 ± 2.4

Table 3. Average soil properties per site

Values are presented as mean ± standard error.

Changes in soil properties across sites are shown below using box plots. Error bars represent standard errors, and significant differences are denoted by an asterisk.

### A. Effects of Fire and Land Management on SOC Concentration

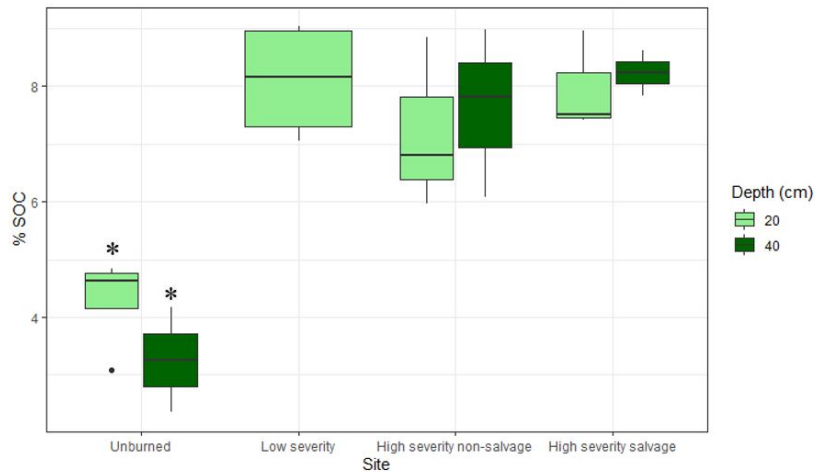


Figure 5. Effects of fire and land management on SOC

There were significant differences between the unburned sites and all others in percent SOC. Percent SOC values are lowest in the unburned control site and increase with the

introduction of fire. The salvage logged sites have percent SOC that are slightly higher than the severity non-salvage logged areas, though the difference is not significant.

## B. Effects of Fire and Land Management on Soil pH

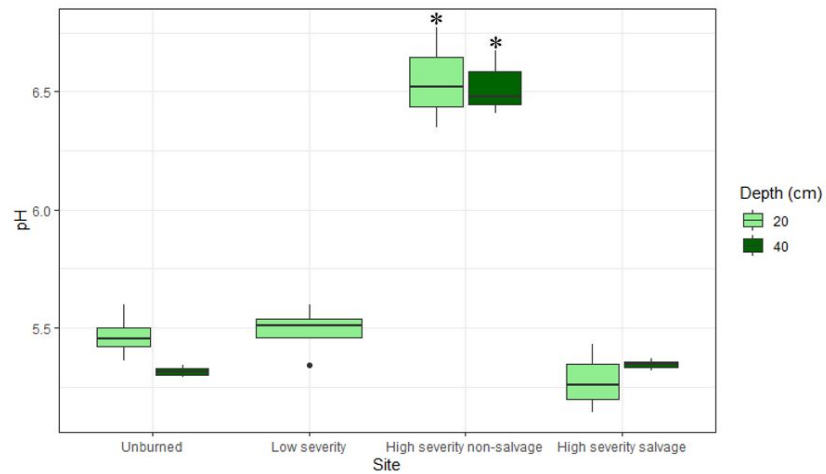


Figure 6. Effects of fire and land management on pH

Soils in the high severity non-salvage logged site had significantly higher pH values than the other sites. The other three sites had similar pH values around 5.5, while the soils of the unlogged site had an increase of one pH unit. There was a general increase in pH from unburned to burned, though the high severity salvage site had the lowest soil pH values.



### C. Effects of Fire and Land Management on Soil Texture

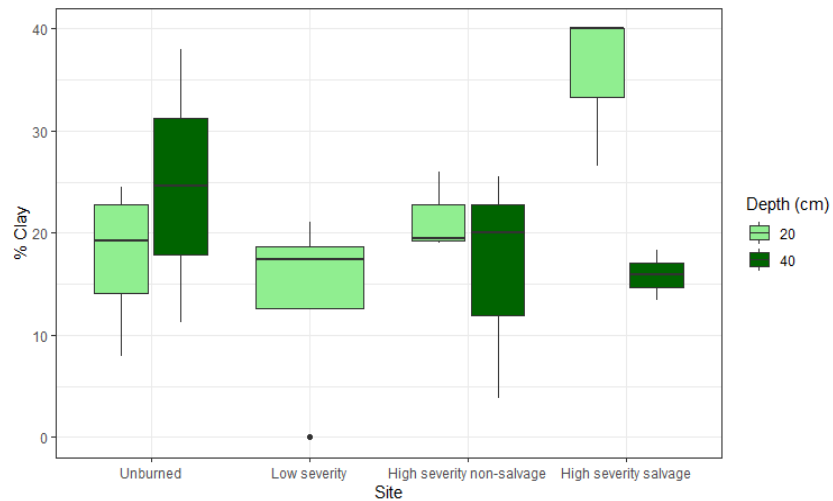


Figure 7. Effects of fire and land management on texture

There were no significant differences in any of the sites with percent clay. There was a decrease in percent clay after fire presence, and there was a meaningful yet not significant difference in the percent clay in the high severity salvage site at 20 cm. The soils at all the sites had high clay content.

The soil texture triangle is utilized to represent the three different proportions of soil particle sizes; soils are placed into different classes that indicate its physical properties (Figure 8).

### Soil Texture Classes

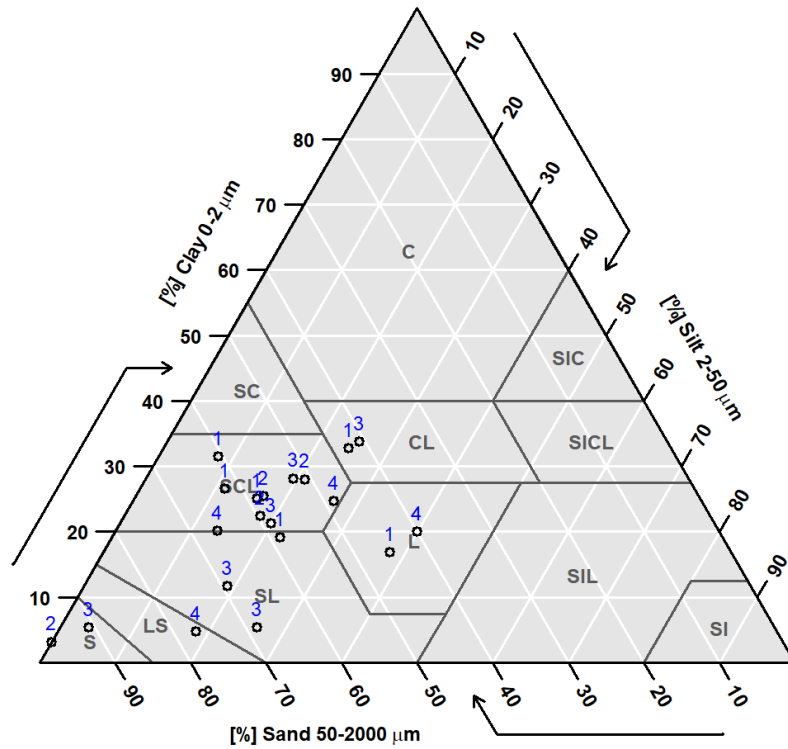


Figure 8. Soil texture classes for each site

Soil classes follow NRCS-USDA guidelines. Texture classes represented by samples include sand (S), loamy sand (LS), sandy loam (SL), loam (L), sandy clay loam (SCL), and clay loam (CL).

There appears to be no pattern among the sites with respect to soil texture classes.

While the samples are concentrated in the bottom left corner indicating sandy loams and clay loams, the texture samples are dispersed among the texture classes, as opposed to grouped together by site.

## Discussion

### A. Effects of Fire on SOC Concentration

The initial hypothesis (1) considered the greater conversion of belowground SOC to ecosystem losses after more severe fires, but analyses of SOC produced results that were in the reverse trend than expected. The amount of carbon in the soil was significantly lower in the unburned sites than the burned sites, and the low severity site had the highest amount of SOC at 20 cm. Most research has concluded that fire decreases the amount of SOC in the forest ecosystem (Granged et al., 2011; Law et al. 2004), but few have found data that show that high severity sites contain a fraction of the belowground carbon of low severity sites (Yocom et al., 2015). The LOI method may have produced SOC results that are a high estimate, but the trends of carbon content among differentially burned and logged soils are worth analyzing.

Rather than carbon being completely lost from the ecosystem, these results indicate that the soil may be sequestering carbon after a wildfire, especially with respect to low severity. There were no significant differences in percent SOC among burn severities, suggesting that SOC is influenced after the presence of burning rather than the degree of intensity of the fire. One current hypothesis that explains these results is the idea that wildfires cause losses to microbial communities, which leads to slowed decomposition rates and increased intact soil organic carbon (Jiménez Esquilín et al., 2008). This hypothesis is in line with the trend of increasing SOC after a forest fire, yet still other research concludes either no change or even a decrease in SOC after a burning (Heckman et al., 2013; Law et al., 2004). Because of the conflicting

conclusions about the effects of fire on SOC, establishing global trends is challenging and problematic. Therefore, it is worthwhile to pursue links between fire severity and SOC for each ecosystem type, with emphasis on changing forest types and typical climate.

### **B. Effects of Land Management on SOC Concentration**

In addition, percent SOC slightly increased but was not significantly different between the non-salvage logged site and the salvage logged site, contrasting hypothesis (2) of decreasing SOC after biomass removal. This preliminary conclusion may require a longer timescale to be confirmed, as the long-term effects of salvage logging remain negligible or unclear (Campbell et al., 2016; Royo et al., 2016). Most studies that observed the effects of salvage logging on SOC consider sites that burned and were logged within the last two decades, and the effects of land management on soil may occur on longer temporal scales. These results show that SOC was relatively unaffected after 18 years post-logging, but research that includes more sites and varying timescales would give insights to the possibility of SOC differences in salvage logged sites after a much longer time period.

### **C. Effects of Fire and Land Management on Soil pH**

In hypothesis (3), Soil pH was expected to increase with burn severity because of the addition of alkaline ash into the soil from burning vegetation (Certini et al., 2011; Jiménez Esquilín et al., 2008). When comparing the unburned site to the burned sites, this trend is consistent with the data collected except for the high severity salvage site. As others have observed, it is possible that during the 18-year period between the

wildfire and data collection, soil pH levels have returned to relatively normal conditions for that region (Fernández-García et al., 2019).

As shown in Figure 6, there is a significant difference in pH between the high severity non-salvage logged site and the other three site conditions. This is likely due to the continuous input of base cations from fallen woody vegetation, mainly calcium and trace elements such as phosphates, manganese, and iron (Granged et al., 2011). In the high severity non-salvage logged site where these cations were removed along with the burned trees, the pH remained similar to the low severity and unburned sites.

Hypothesis (4) predicted a higher pH in the high severity salvage logged site due to post-fire erosion, but these results suggest that cation input has a more significant impact on the non-salvage site than post-fire erosion on the salvage logged site.

#### **D. Effects of Fire and Land Management on Soil Texture**

The four sites contained soil of relatively similar particle sizes, as there is no significant difference in site comparisons. There is no discernable trend in soil texture class by site, shown in Figure 8. Hypothesis (5) of decreasing clay content was verified by the experiment from the unburned control site to the low severity site, but this did not carry through to the high severity sites. The differences in clay percentages concluded by other researchers were more immediate to the fire's aftermath (Granged et al., 2011), and the results from this study may indicate that this difference is not long lasting even after a high severity fire.

Considering hypothesis (6), soil texture increased in clay content in the topsoil after logging, likely as a result of erosion (Heil & Burkle, 2018), though this difference did not persist at the 40 cm depth. The results suggest that pedogenic (soil forming)

processes are minimally affected by disturbances, such as single-event logging, in depths other than the topsoil. Within the same region, where the soil properties are determined by the same climate, weathering, and parent material, long-term soil pedogenic characteristics will be relatively similar across the landscape. Soils observed shortly after a forest fire or after long-term repeated fire events may show differences in soil texture, but these results show that percent clay is potentially meaningfully but not significantly affected by fire severity or post-fire logging in the long term after one fire event.

#### **E. Management Implications and Solutions for PNW Forest Fires**

Researchers and policymakers have attempted to find management solutions that counteract the detrimental impacts of climate change while keeping the ideas of changing fire regimes and the consequential effects on PNW forests in mind. One of the main priorities of governmental agencies and environmental groups is to reverse the negative influences of historic fire suppression. Starting in the early 20th century, the U.S. Forest Service (USFS) and timber companies marketed wildfires to the general public as destructive for the ecosystem. This created a nationwide paradigm of viewing forest fires as harmful and catastrophic (Driscoll et al., 2012). The practice is becoming increasingly expensive to upkeep, as USFS reported a record-high fire suppression budget of \$2 billion in 2017 (U.S. Department of Agriculture, 2017). Fire suppression creates overcrowded litter layers and overgrown canopy levels; the lack of consistent rejuvenation of the forest floor creates higher density forests, which are more at risk for drought and fire (Driscoll et al., 2012). The excess of woody debris and fuel load causes a highly destructive disturbance when a suppressed forest is inevitably struck with

lightning or ignited from human activity (Hatten et al., 2005; Spies et al., 2014; Taylor and Skinner, 2003). Only within the past few decades, the Forest Service has sought to end fire suppression strategies and ecologists have begun to understand the importance of fire as a nutrient cycling and cleansing agent for these environments (Halofsky et al., 2016). Historic fire suppression in the region has created more intense wildfires in recent decades, and West Coast forests continue to face the effects of this insufficient management strategy (Perry et al., 2011).

Restoring a fire-suppressed forest is a complex task. Successful management plans in southern Oregon require a high degree of cooperation between government agencies, scientists, landowners, and resource managers, as well as a variety of communication and education methods (Halofsky et al., 2016). Furthermore, the public must change how it views wildfires, as many people still believe the 20th century ideology and are in favor of fire suppression. Forest managers must find a balance between maintaining the ecosystems for social value while restoring the fire suppressed habitats (Kline et al., 2013). Prescribed burning is a pre-fire management tool that has been used to safely promote fire in a forest ecosystem, particularly in pre-colonial American by indigenous groups (Diver, 2016). This approach involves purposefully burning the ground level of a forest under the close watch of experts to decrease the likelihood of a high severity fire; although it requires extensive ecological planning and collaboration between stakeholders, this is a promising and accepted solution in the forestry community (Law et al., 2018).

Different species respond in contrasting ways to salvage logging. In the Biscuit Fire, complex compounding factors such as increased amounts of past timber harvest,

salvage logging, and high severity burns all collectively contributed to the possible decline in northern spotted owls (Clark et al., 2013), although other birds became more abundant (Cahall and Hayes, 2009; Woodall et al., 2009). In contrast, post-fire logging benefits bee species and their floral communities by removing canopy layers and generating landscapes of primary succession (Heil and Burkle, 2018). Overall, species that are typically saproxylic (live in dead wood) decrease in abundance after salvage logging and species that prefer open habitats increase in abundance because they are better suited for post-fire logged areas (Thorn et al., 2017).

The results of this study found that there were no significant differences in SOC and texture after logging, but SOC was highest after a low severity fire. This data supports prescribed burning for maximizing the carbon sequestration effects of low severity fires. The pH values of the soils in the logged sites were more similar to the low severity and unburned sites, and this may be a benefit if the goal of land managers is to restore a forest affected by wildfire to pre-fire ecosystem conditions. Texture was minimally affected by logging, though the long-term effects are unclear and should be considered in the future. In determining the post-fire management practice after a given fire, it is best to survey the effects of the fire on SOC content in each ecosystem in promoting prescribed burning or salvage logging.

Potentially the optimal system after a wildfire includes a combination of logged, unlogged, and pre-burned areas to accommodate the habitat needs of animal species and to sequester more carbon after a fire event (Heil and Burkle, 2018). Salvage logging is a practice that has been used by USFS and private landowners for decades (García-



Orenes et al., 2017), and it continues to be a management solution that needs more research and holistic understandings of consequences and implications.

## Conclusion

As the West Coast climate experiences increasingly severe abnormalities, wildfire severity will increase at alarming rates. California, Oregon, and Washington have already seen year after year of record-breaking burn detections, acres burned, and costs of damages as a result of climate change-induced wildfires (Migliozzi et al., 2020). Global government action against climate change is slow to combat rising emissions, and we near the point of being unable to return to pre-industrial age temperatures (Driscoll et al., 2012; Mote et al., 2019).

This study indicated that carbon is most sequestered in soils after a low severity fire and there were no measured differences between the salvage logged and the non-salvage logged sites in terms of SOC. These two conclusions support prescribed burning, in which frequent low severity fire can prevent high severity fires. Salvage logging is controversial, with foresters finding difficulty in balancing economic recovery with maintaining structural diversity of the forest ecosystem (Woodall et al., 2009). Land managers should weigh the advantages and disadvantages in terms of carbon and other soil properties when implementing pre- and post-fire adaptation strategies.

The results of this study may show that the differences in carbon sequestration between post-fire management strategies, but longer-term effects need to be studied. Future research could include longer temporal scales, other climate and forest types, and a more direct study of prescribed burning in order to have a more holistic understanding of how fire and human influence affect forest soils. Going forward, this study may indicate the effects of low and high severity fires on carbon sequestration, rather than

the conversion of forests to carbon sources as previously researched. As researchers and land managers seek to adapt to increasingly severe wildfires on the West Coast, it will be important to observe forest soils to identify geophysical trends and best practices for fire adaptation.

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