MAPPING SOIL CARBON IN WILDFIRE-AFFECTED AREAS OF THE MCKENZIE RIVER BASIN, OREGON, USA

by

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THESIS ABSTRACT

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Title: Mapping Soil Carbon in Wildfire-Affected Areas of the McKenzie River Basin, Oregon, USA

Large-scale wildfires are increasing in frequency and are likely to become more severe under future Pacific Northwest climate scenarios. The effects of wildfires on soil organic carbon (SOC) remain difficult to estimate because soil heterogeneity limits generalizations. We sampled a burn severity gradient (unburned, low, high) of the Holiday Farm Fire (McKenzie River, Oregon, 2020) in a detailed scheme to account for intra-site variation. We measured total SOC, mineral-associated organic carbon (MAOC, stable), particulate organic carbon (POC, unstable), and pyrogenic carbon (PyC, fire-derived). Compared to unburned, the low severity site had higher MAOC and significantly lower POC. We found lower PyC in burned sites, indicating combustion of this pool. There was remarkable variation within each site, but the consistent high levels of MAOC in low severity areas support prescribed burning as a technique to mitigate wildfire risk while limiting losses or increasing SOC compared to high severity fires.

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TABLE OF CONTENTS

LIST OF FIGURES

CHAPTER I

INTRODUCTION

The Pacific Northwest (PNW) of the United States is experiencing increases in fire frequency due to changes in temperature and precipitation patterns (Halofsky et al., 2020). Wildfires are an integral part of forest ecosystem dynamics in the PNW, but catastrophic fires have become increasingly frequent and severe, especially in working landscapes where intensive forest management can amplify climatic stress (Zald & Dunn, 2018). In recent years, the record-breaking effects of climate change and fire disturbance on PNW forests also impacted people's livelihoods near and far from fire-affected landscapes (Higuera & Abatzoglou, 2021; Weisberg, 2009), in some cases, releasing carbon to the atmosphere at rates that could offset the benefits of management for carbon sequestration (Jerrett et al., 2022). As carbon sequestration projects continue to be incentivized in landscapes, fire seasons are becoming longer and warmer, and rainy winters are becoming shorter and drier; new research is needed to inform conservation and management plans for PNW "forests of the future" (Case et al., 2021).

It is well known that PNW forests hold large quantities of soil organic carbon (SOC), and the response of SOC to wildfire is expected to have major implications for carbon sources and carbon sinks throughout the region (Nave et al., 2011; Pellegrini et al., 2022). However, fire severity and carbon sequestration are still assessed primarily from the perspective of impacts on vegetation. Soils and SOC are variable at the landscape level even under the homogeneous vegetation cover; therefore, site-specific and geographically-focused research is needed to understand how climate change and wildfires affect ecosystem carbon balance across landscapes (Loescher et al., 2014). To this end, we designed a spatially explicit approach to quantify fire effects on SOC at the landscape level, which could be replicated across the PNW to determine climate change effects on a regional scale to inform policy and management. The goal of this project is to map the spatial distribution of SOC in unburned, low severity, and high severity sites from a recent catastrophic wildfire in a typical PNW working landscape, in the McKenzie River basin. By combining field sampling techniques with GIS mapping and quantification of fire severity impacts on carbon pools across the soil profile, we infer the transformation and movement of SOC across the landscape influenced by fire severity. Our objectives for this post-fire McKenzie River landscape study can be summarized in the following research questions:

(Q1): What are the percentages and stocks of different soil organic carbon pools at the varying burn severities in one-year post-fire conditions?

(Q2): What is the spatial and depth variation of the effects of wildfire on soil organic carbon?

To answer these questions, we partitioned SOC into three pools: mineral-associated organic carbon (MAOC), particulate organic carbon (POC), and pyrogenic carbon (PyC). MAOC is the organic matter that has been adsorbed onto mineral surfaces, such as clays, or in physically protected structures, such as soil micro-aggregates (Kögel-Knabner et al., 2008). It is characterized by its long-term persistence in the soil and heavy fraction density (Lehmann & Kleber, 2015), compared to more labile forms of light fraction POC (Lavallee et al., 2020). Mapping the distributions of unstable POC and stable MAOC is crucial for understanding the persistence of carbon in the soil on both short and long timescales. Recent studies estimated that the MAOC fraction of total SOC has turnover times up to 1000 times longer than POC. Thus, enhancing MAOC formation may be a key to lasting soil carbon sequestration (Georgiou et al., 2022.). However, severe fires can cause major losses of MAOC and POC to the atmosphere, or transform large fractions of those pools into PyC, which is the carbon that is found in charred biomass, charcoal, and soot (Santín et al., 2016).

PyC does not have physical or chemical characteristics that can be grouped with POC or MAOC (Lavallee et al., 2020) and is less predictable than the other pools of SOC in terms of persistence and stability. In some cases, PyC formation can be derived mostly from POC and occasionally from MAOC (Bowring et al., 2022). In all cases, regardless of its source, PyC is expected to represent a significant fraction of the total SOC carbon pool after wildfires, and therefore it is important to include PyC, as well as MAOC and POC, in the analysis carbon losses following fire disturbance (Santín et al., 2016). This is particularly important when SOC is considered as a form of climate change mitigation. As a problem of pattern and scale, enhancing SOC as a mitigation tool requires more research because the risk and severity of fire disturbance on SOC stocks are difficult to generalize, even when the impacts on vegetation are obvious. For example, one current hypothesis for the PNW is that increasing wildland fire would significantly decrease soil carbon storage, but low severity burns could minimize the risk and severity of fire impacts on SOC (Nave et al., 2022), with the production of PyC through pyrolysis, which can increase relative to baseline levels (Pingree & DeLuca, 2018), or be consumed and released back to the atmosphere after catastrophic fires (Miesel et al., 2018; Reisser et al., 2016).

CHAPTER II

METHODS

2.1 Study sites

Our study site is the McKenzie River basin of the Willamette Valley, Oregon, USA. The study region encompasses typical working landscapes of the PNW, where different types of conservation and management strategies co-exist across steep topographic gradients. The McKenzie River basin is dominated by Douglas-fir (*Pseudotsuga menziesii*) forests - with other common species including western hemlock (*Tsuga heterophylla*), incense cedar (*Calocedrus decurrens*), and red alder (*Alnus rubra*) - under a natural fire rotation that is estimated to range between ~160 years for the pre-settlement period (1550–1849) to ~500 years for the recent fire-suppression period (Weisberg, 2009). In September 2020, this region experienced the Holiday Farm Fire, a catastrophic wildfire and at over 170,000 acres, one of the largest forest fires in Oregon's history (InciWeb, 2020). The burn severities in terms of canopy cover mortality of the sampling sites are shown in Figure 1. The site locations for our soil severity assessments are also depicted on the map on the western side of the McKenzie River region. The study sites occur at elevation between 300 and 400 meters, annual precipitation around 1700 mm, winter temperatures averaging 4 °C, and summer temperatures averaging 18 °C (Sproles et al., 2013).

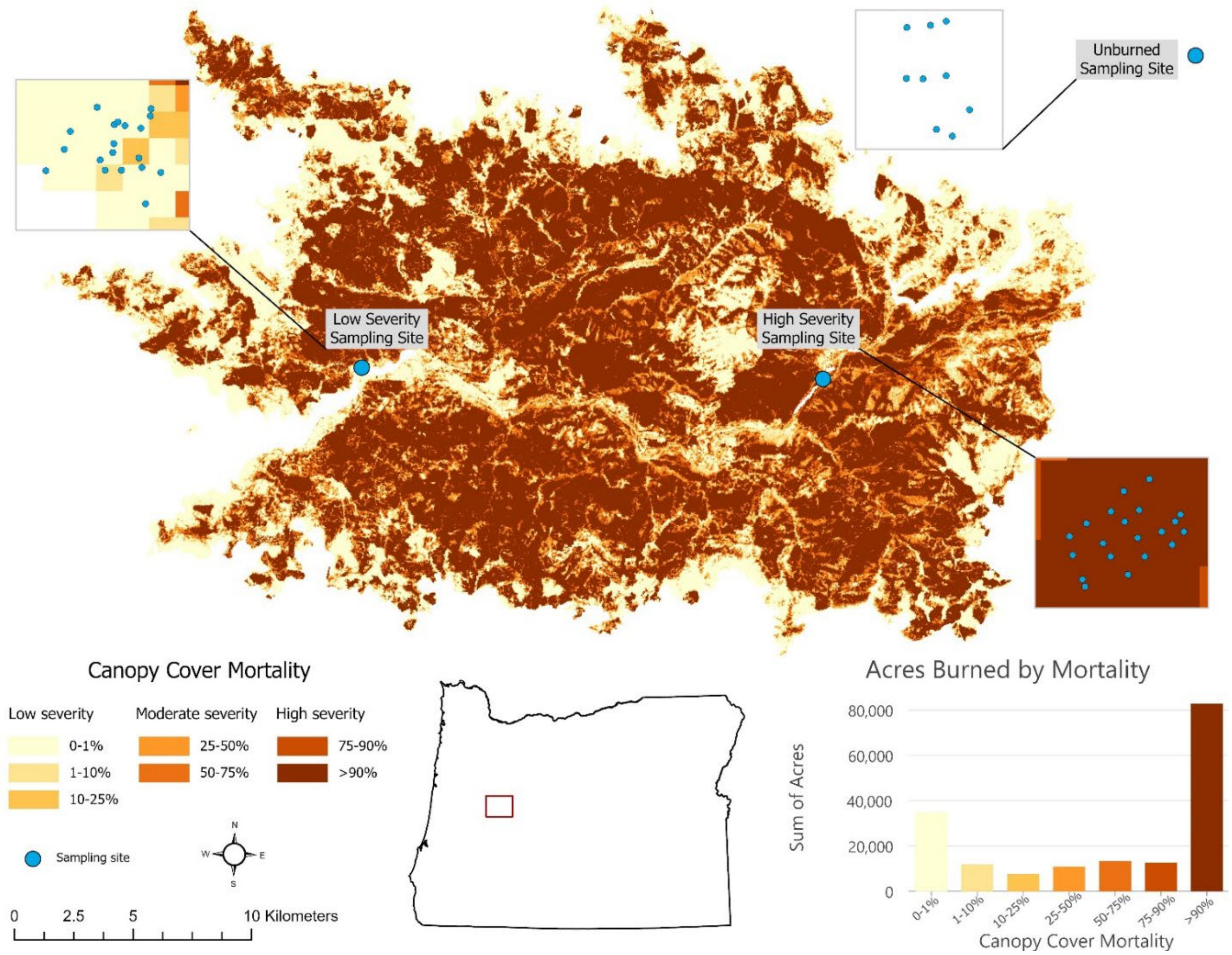


Figure 1. Map of burn severities from the Holiday Farm Fire based on Basal Area Mortality from Rapid Assessment of Vegetation Condition after Wildfire. This method uses change detection analysis from Landsat and similar satellite imagery, wherein a Relative Differenced Normalized Burn Ratio (RdNBR) image is created by subtracting post-fire imagery from pre-fire imagery (USDA Forest Service & Geospatial Technology and Applications Center, 2020). Most of the wildfire was high severity, where more than 75 percent of biomass was burned.

2.2 Sampling Design

We collected soil samples in September 2021, one year after the fire occurred. We estimated severity based on biomass loss (canopy cover mortality), wherein the low severity site had canopy cover loss of 0-25 percent and the high severity site had canopy cover loss of 75-100 percent. We used a gridded approach to take soil samples from one low severity site and one high severity site. The low severity site is located at the

McKenzie River Discovery Center (44.142562, -122.607505), and the high severity site is near Finn Rock Landing (44.142265, -122.36458), owned by the McKenzie River Trust. As a baseline control, we used samples collected in 2018 using similar methods from an unburned old-growth forest site at the HJ Andrews Experimental Forest (44.26706, -122.17198) (Farinacci, 2020).

At the three sampling locations, soils are categorized as Inceptisols with predominantly silty and sandy loam properties. The sampling landscapes have a gentle slope ranging from ~3 to ~5 percent inclination. Previous studies have estimated SOC stocks for the McKenzie River basin between 8 and 25 kg/m^2 (Nave et al., 2022; Walkinshaw et al., 2021).

At the low and high severity sites, we sampled a total of 20 profiles per 0.5 hectare. After removing the litter layer, we sampled three soils per profile at depths 0-2 cm, 0-20 cm, and 20-40 cm depth. In addition to soil samples for carbon content analysis, we collected plant litter in 25 by 25 cm^2 around each of the soil profiles before soil collection and determined bulk density at each soil depths using three profiles per site, where the average was used to estimate SOC stocks. For bulk density, we collected soil samples by pressing 100 cm^3 rings into each layer of a sequentially dug soil layer, preventing soil compaction. At the unburned reference site, we took samples in a three-by-three grid, where each row spanned 100 meters, for a total of nine profiles per hectare. We sampled soils at depths 0-20 centimeters and 20-40 cm and bulk density for each row, using the same approach explained above for litter and soil collection from the 0-2 cm depth (2022).

2.3 SOC Processing

In the laboratory, we dried soil samples at room temperature after which the fine roots were separated by hand and samples were ground and homogenized. We measured total SOC and SOC pools (MAOC, POC, and PyC) through combustion using a Thermo Scientific FlashSmart Elemental Analyzer (Waltham, MA, USA). In all cases, we determined percent concentration and estimated total stocks for each SOC fraction on a mass basis using standard methods and international units (see SI for full dataset).

To separate the heavy density fraction (MAOC) and the light density fraction (POC), we used methods developed in previous density separation studies (Pierson et al., 2021; Sollins et al., 2006), where 10 g of each sample and 10 mL of sodium polytungstate (density of 1.85 g/cm^3) were shaken for 2 hours and centrifuged for 10 minutes at 3000 revolutions per minute.

We filtered each sample three times with sodium polytunstate and three times with distilled deionized water. We verified that the sum of the MAOC and POC values were close to the separately measured total SOC.

We measured SOC concentrations (% mass) using the equation 1 for the MAOC and POC pools and equation 2 for the PyC pool:

$$C_{\text{fraction}}\ (\%\ C) = \frac{\text{weight of fraction (g)}}{\text{weight of total sample (g)}} * \%\ C \tag{1}$$

$$C_{\text{PyC}}\ (\%\ C) = \frac{\text{post-digestion mass (g)}}{\text{pre-digestion mass (g)}} * \%\ C \tag{2}$$

where % C is the measured percent carbon from the elemental analyzer before correction. We calculated stocks (kg/m^2) using the equation 3 (Villarino et al., 2017):

$$\text{C stocks (kg/m}^2) = [\text{soil depth (m)}] * [\text{bulk density (g/cm}^3)] * [\%\ C * 10\ (\text{g/kg})] \tag{3}$$

We used a weak acid-peroxide digestion to separate pyrogenic carbon from the total sample (Kurth et al., 2006). We added 5 mL 1 M HNO_3 and 10 mL 30% H_2O_2 to 0.4 g soil sample, which we then covered with aluminum foil, placed in 90° C heat bath for 16 hours, and filtered the remaining soil in each sample to isolate pyrogenic carbon.

We calculated stocks at the 0-20 cm and 20-40 cm depths because bulk density samples were collected at these depths; we added stocks from the 0-2 cm and 2-20 cm depths to yield the 0-20 cm depth. The >2 mm fraction of the soil sample was small enough to ignore in the C stocks calculation. No carbonates are present in regional bedrock; therefore, hydrolysis of carbonate minerals and inorganic carbon inputs are not a plausible source of variation in total carbon across our sites, which we verified with soil pH values (values for the three sites ranged between 5.08 and 6.4) (Swanson & James, 1975). For bulk density, we weighed the soil samples after drying them in an oven at 70 °C for 2 days and divided by the volume of the collection cylinder. Litter stocks were calculated by dividing litter biomass (g/cm^2) by 2, under the assumption that biomass is composed of 50 percent carbon, and converted to units (kg/m^2) matching the SOC stocks (Houghton et al., 2009).

2.4 Spatial Data Analysis and Interpolation

Interpolated maps of the four pools of SOC for each site were created using ArcGIS Pro 2.7.0 by Esri (Redlands, CA, USA). For each SOC pool, site, and depth, the inverse distance weight spatial interpolation technique was used to visualize the variation of SOC data (Almasi et al., 2014; Robinson & Metternicht, 2006). Standard parameters were used, wherein power = 2, minimum neighbors = 10, and maximum neighbors = 15.

2.5 Statistical Analysis

Due to the non-normal distribution of the data, we log transformed SOC percents and stocks to meet the assumptions of statistical analysis. We used planned contrast ANOVA tests of means to determine significant differences between carbon percentage and stock of each burn severity class within the same SOC pool and depth (Huang et al., 2023). We used p-values of less than 0.05 to determine significance and noted values between 0.05 and 0.10.

2.6 Data Availability

The data used for all tables and figures shown below can be found in the SI.

CHAPTER III

RESULTS

3.1 SOC Concentrations and Stocks

To demonstrate the importance of a gridded sampling scheme for sampling soil properties, where high variation is common, Figure 2 shows histograms of each SOC pool. In all the SOC pools, the high severity site has the highest frequency of lower values. The unburned and low severity sites show similar frequency distributions.

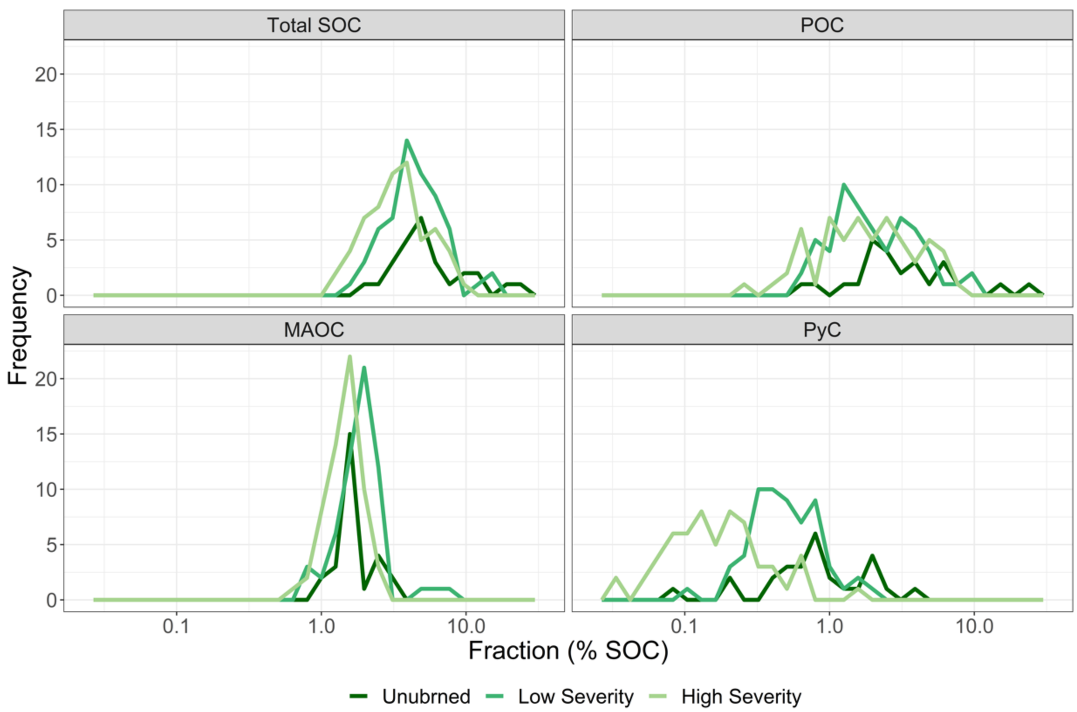


Figure 2. Distribution of the frequency of percent SOC data. Note the log scale on the x-axis. N = 27 for unburned, n = 60 or low severity, and n = 60 for high severity.

We found significant differences between total SOC concentrations and stocks in response to fire intensity and soil depth. Figure 3 shows the median percents of SOC pools along the fire severity and depth gradient, and values discussed below are in mean differences. Total SOC percent decreased significantly along the burn severity gradient, from ~10% to 5% on average, in the topsoil of unburned and high severity fire-affected profiles, respectively. The percent SOC in the unburned and low severity sites were statistically similar across more than half of the comparisons across carbon pools and depths, and we found a similar pattern, although with lower SOC losses, up to 40 cm depth.

The effects of burning on the individual pools were more variable than on SOC. MAOC was significantly lower in the low severity site than the high severity site (-1.08% MAOC at 0-2 cm, 40% change; -0.44% MAOC at 2-20 cm, 22% change) and increased in the top two depths between the unburned site and the low severity site (+0.48% MAOC at 0-2 cm, 22% change; +0.28% MAOC at 2-20 cm, 17% change). The unburned MAOC and low severity MAOC were statistically similar at each depth. POC decreased significantly in the 0-2 cm (-5.12% POC, 54% change) and 2-20 cm (-1.73% POC, 48% change) depths between unburned and low severity but was otherwise minimally changed between treatments.

PyC decreased along the burn gradient and by depth. The unburned and low severity sites showed similarity in the topsoil and 20-40 cm depth and were both significantly higher than the high severity site at every depth. In the 2-20 cm depth, each site was statistically different from one another, with decreases compared to the unburned site of 0.61% PyC (58% change) in the low severity fire and 0.91% PyC (85% change) in the high severity fire.

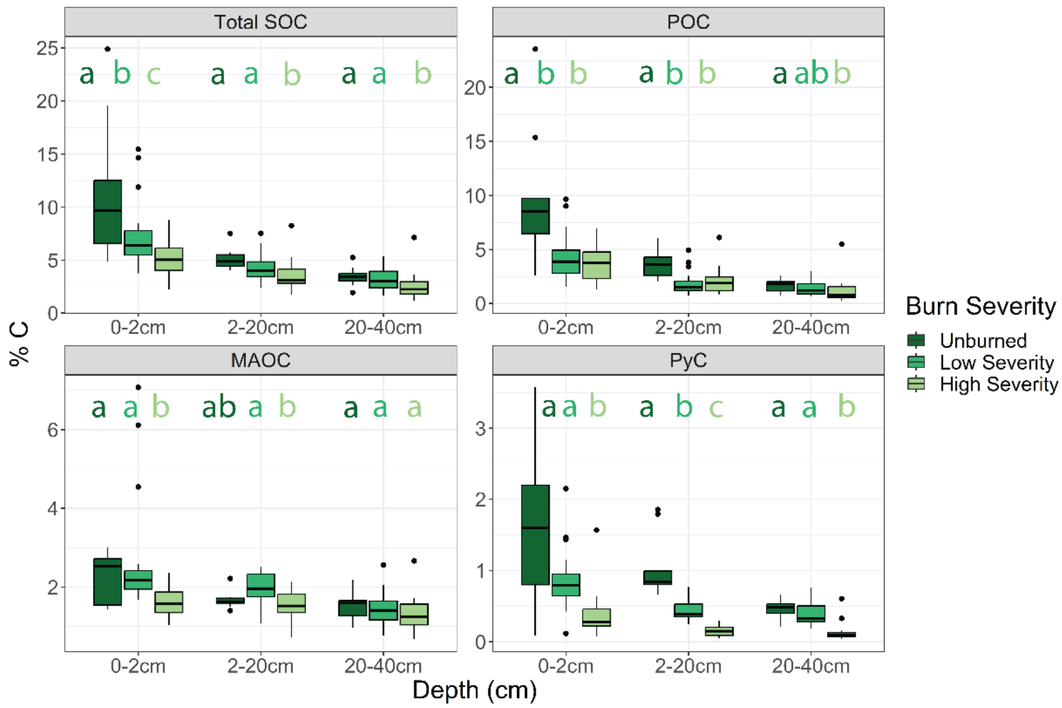


Figure 3. Boxplots of SOC percent. Letters above plots correspond to significant differences between sites (i.e. fire severity treatments) at any given depth. Note the differences in scale for each organic carbon pool. N = 9 for each depth of unburned (27 total), n = 20 for each depth of low severity (60 total), and n = 20 for each depth of high severity (60 total). See Table 1 in SI for corresponding values.

Figure 4 shows the breakdown of total SOC as proportions of MAOC and POC. In the unburned site, POC holds a larger percentage than MAOC in all depths, though the differences become smaller by the 20-40 cm depth. The low severity and high severity sites show smaller differences in MAOC and POC proportions and converging at shallower depths than the unburned site. In the high severity 20-40 cm depth, MAOC holds a larger percentage of total SOC than POC.

In the topsoil, POC proportion is significantly higher in the unburned and high severity sites than the low severity site, while MAOC proportion is significantly higher in the burned sites than the unburned site. PyC is significantly lower in the high severity site than the unburned and low severity sites. For the 2-20 cm depth, POC proportion is significantly highest in the unburned site and significantly lowest in the low severity site, both of which are statistically significant from the high severity site. Proportion of MAOC is significantly lowest in the unburned site than the low and high severity sites, and PyC proportion decreases significantly along the burn severity gradient. In the lowest depth, proportions of POC decreased with increasing burn severity. MAOC proportions were similar between unburned and low severity and was significantly higher in the high severity site. PyC proportions were similar between unburned and low severity and was significantly lower in the high severity site.

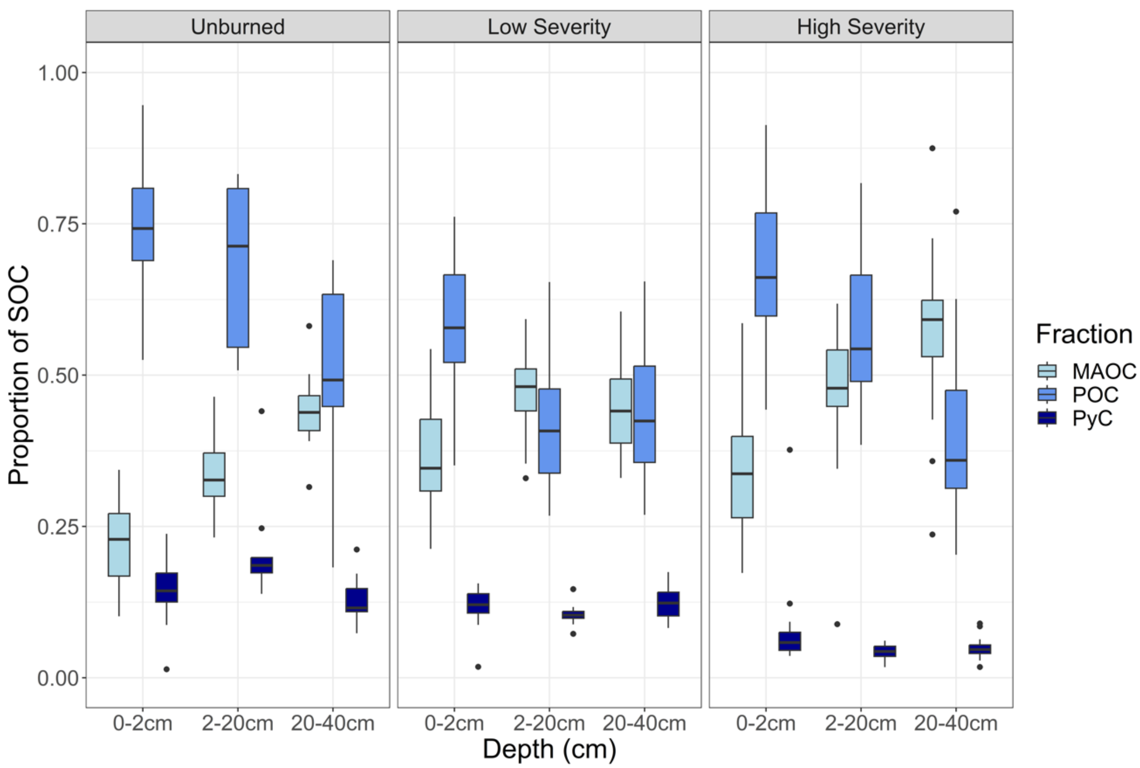


Figure 4. Proportion of total SOC that is composed of each fraction (MAOC, POC, and PyC). Note that the proportions of the three fractions added together for each site and depth exceed 100 percent due to the overlap between PyC and its foundational components of mainly POC and some MAOC. N = 9 for each depth of unburned (27 total), n = 20 for each depth of low severity (60 total), and n = 20 for each depth of high severity (60 total). See Table 1 in SI for corresponding values.

Median SOC stocks by burn treatment and depth are shown in Figure 5, and the values discussed are mean differences. Litter was significantly lower after the high severity burn (-0.03 kg/m^2, 70% change) and remained similar after the low severity burn (-0.01 kg/m^2, 22% change). At the 0-20 cm depth, total SOC stocks were significantly higher in the low severity fire (+7.45 kg/m^2, 71% change) and higher in the high severity fire (+3.25 kg/m^2, 31% change) compared to the unburned site. We found that stocks were higher in the low severity fire in the 20-40 cm depth (+0.87 kg/m^2, 8.4% change) and lower in the high severity fire (-1.79 kg/m^2, 17% change). The difference in stocks between the low severity site and the high severity site (-2.66 kg/m^2, 23% change) at the 20-40 cm depth is statistically significant.

POC stock was higher in the 0-20 cm depth and lower in the 20-40 cm depth along the burn severity gradient, with significantly lower POC stock in the high severity site compared to the unburned in the deeper soils (-1.03 kg/m^2, 21% change).

There was statistically higher MAOC stock in the low severity site in the 0-20 cm depth than in the unburned site (+4.81 kg/m^2, 153% change) and the high severity site (+2.52 kg/m^2, 80% change). The 20-40 cm depth had similar MAOC stock. Compared to the unburned site, PyC was significantly lower in the high severity burn at both the 0-20 cm depth (-1.37 kg/m^2, 68% change) and the 20-40 cm depth (-0.90 kg/m^2, 66% change) while remaining similar between the unburned and low severity sites.

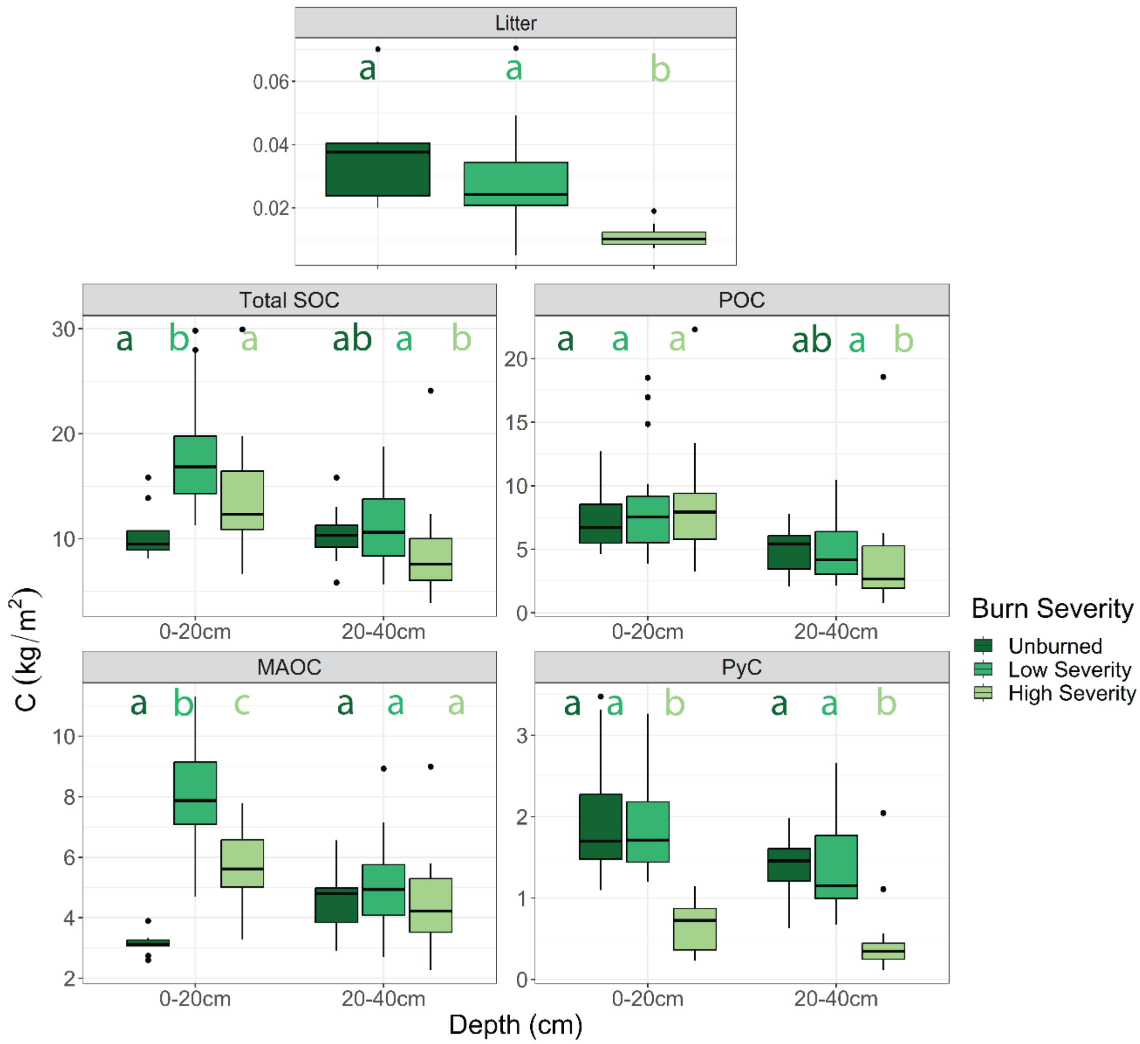


Figure 5. Boxplots of SOC stock along the burn severity gradient. Stocks used the 0-20 cm and 20-40 cm depths because we collected bulk density samples at these depths; we calculated stocks for the 0-20 cm depth by adding the stocks from the 0-2 cm and 2-20 cm depths. Note the differences in scale for each organic carbon pool. Letters indicate significant differences at any given depth between sites along the fire severity gradient. Bulk density values used for total SOC and PyC stock calculations are as follows: unburned (0-20 cm: 0.91±0.36 g/cm^3; 20-40 cm: 1.51±0.08 g/cm^3), low severity (0-20 cm: 1.95±0.24 g/cm^3; 20-40 cm: 1.75±0.31 g/cm^3), high severity (0-20 cm: 1.85±0.16 g/cm^3; 20-40 cm: 1.69±0.07 g/cm^3). For bulk density samples, n = 3 for each site. For soil samples, n = 9 for each depth of unburned (27 total), n = 20 for each depth of low severity (60 total), and n = 20 for each depth of high severity (60 total). See Table 2 in SI for corresponding values.

3.2 SOC Interpolations

Interpolation maps for each site of the burn severity gradient and SOC pool are shown in Figure 6.. When observing the hotspots of SOC in these sites, note that total SOC is composed of the other three carbon fractions (PyC, MAOC, and POC); thus, the total SOC interpolation maps incorporate variation and accumulation in hotspots for the MAOC and POC carbon fractions combined.

The unburned site shows hotspots of POC and PyC in the west section of the site, with minimal MAOC spatial variability. In the topsoil of the low severity region, there were hotspots of MAOC in the north-central and north-east parts of the site, as well as higher percentages of POC in the north-central and central sections. These hotspots persisted throughout the soil profile even as overall SOC percentages decreased. The areas of high accumulation for POC, MAOC, and PyC generally matched in the low severity site. In the high severity site, there was minimal spatial variability in MAOC. There were small hotspots of POC in the eastern parts of the site in the 0-2 cm and 2-20 cm depths, that line up with areas of accumulation of PyC in the topsoil, and in the south-central section of the 20-40 cm depth.

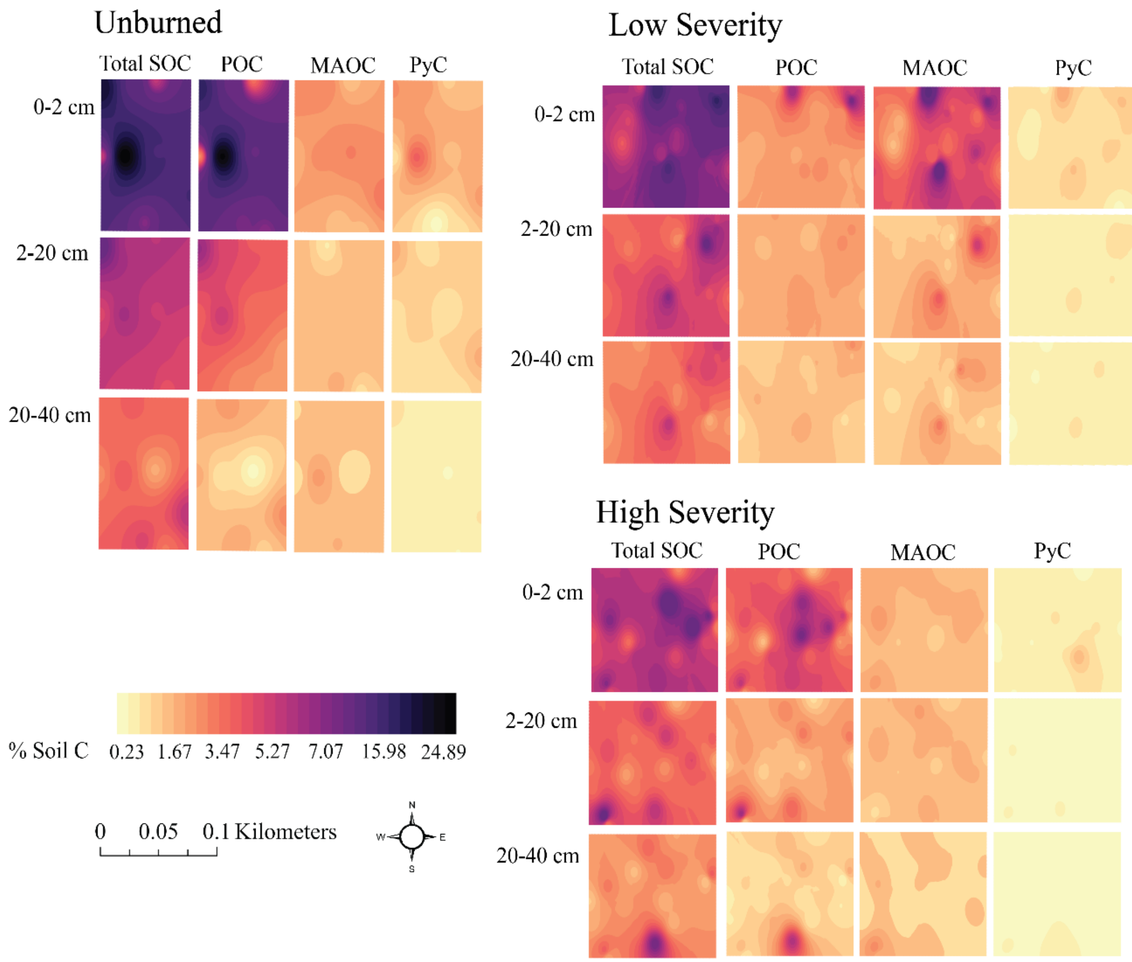


Figure 6. Spatially interpolated SOC types for the unburned, low severity, and high severity sites. Note the same color ramp is used across all plots. Number of soil cores in each plot upon which the interpolation is based varied by burn severity (9 in unburned, 20 in low severity, and 20 in high severity). See Table 1 in SI for corresponding values.

CHAPTER IV

DISCUSSION

Percent SOC decreased after burning in the majority of pools in most depths (Figure 3). The high severity site showed the lowest SOC in all pools for most depths, with the exception of POC in the 2-20 cm depth. This is consistent with other findings, where wildfire causes a decrease in SOC quantity in Pacific Northwest and temperate forests (Bormann et al., 2008; Homann et al., 2015; Nave et al., 2011). The low severity fire was similar to the unburned site in most carbon pools and depths, pointing to the resiliency of the soil after low severity burns, which were once common in this ecosystem.

As an aboveground process, fire rarely directly affects soil C at depths lower than 20 cm as there is little heating of mineral soils deeper than 20 cm (Brady et al., 2022; Heckman et al., 2013). Indeed, we did not find major changes in the 20-40 cm depth. We also note that % C at 20-40 cm depth in the unburned site was comparable to that of the burned plots at 2-20 cm depth, which is consistent with loss of most of the surface-soil POC and subsequent soil compaction. The effect of burn severity on soil C will likely manifest over longer timescales due to processes such as plant succession, pedogenesis, microbial activity, and soil leaching (Nave et al., 2011; Pierson et al., 2021). Future studies that focus on the effects of fire severity on soil carbon pools over longer periods of time than one-year post-fire in the McKenzie River basin could attempt to answer these phenomena.

While the total amount of MAOC was similar across unburned and burned at all depths (Fig. 3), the proportion of SOC occurring as MAOC was significantly higher in the burned plots than the unburned control plots (Fig. 4), suggesting that mineral-association can protect the soil carbon pool through fire. As partially decomposed plant material, POC is more susceptible to burning than MAOC, especially during high severity fires. In PNW ecosystems where the O horizon is thick and active, forest fires cause greater losses to POC than MAOC, leading to shifts in the pool makeup of SOC (Pierson et al., 2021).

Bulk density was higher in the low severity site than the unburned and high severity sites at each corresponding depth, as is found in other systems (Agbeshie et al., 2022). The shift from higher proportions of POC (light fraction) to equal proportions or higher MAOC (heavy fraction) can explain the higher bulk density in the low severity site (Figure 4). Total SOC stock and MAOC stock in the 0-20 cm depth increased after a low severity burn, driven by bulk density differences rather than concentration. With soil compaction occurring, this may point to evidence of soil organic carbon sequestration through low severity fires in the McKenzie River landscape, which supports other findings where in some cases low severity or prescribed burns mitigates the loss of SOC as compared to a high severity fire (Homann et al., 2011; Pellegrini et al., 2021).

The finding of low PyC in the high severity site is somewhat consistent with other findings, where PyC either remained consistent across burn severities or can be consumed by fires (Doerr et al., 2018; Miesel et al., 2018; Reisser et al., 2016). The high severity fire more thoroughly consumed the woody debris and mineral-associated carbon that may have been converted to PyC. In the unburned site, the central-western location of high accumulation of PyC could be understood through the methods. Samples that included high levels of organic material and POC also may contain high levels of recalcitrant carbon that is not pyrogenic in origin, and thus survive the acid-peroxide treatment (Schmidt & Noack, 2000). Additionally, historical fires that occurred in the 20^{th} century in nearby areas, while not directly impacting the unburned site, may have dispersed PyC onto the unburned study site (as was common after the 2020 fires), thus affecting PyC at that site.

The spatial variation of SOC is unique to each site (Figure 6). There are locations of high accumulation of SOC at each of the variably burned sites, especially in the unburned site. These are potentially due to minute topographic variations in the landscape that could be both relatively long-term, such as minor slope changes, or short-term, such as woody debris or fallen snags in the burned areas. Using a gridded sampling scheme of 20 soil cores in the burned areas and 9 in the unburned site helped to account for the large variation in soil carbon within one site, and these concepts should be considered when working towards generalizing the effects of phenomena, such as wildfire, on a landscape's variable soil properties (Pellegrini et al., 2022).

CHAPTER V

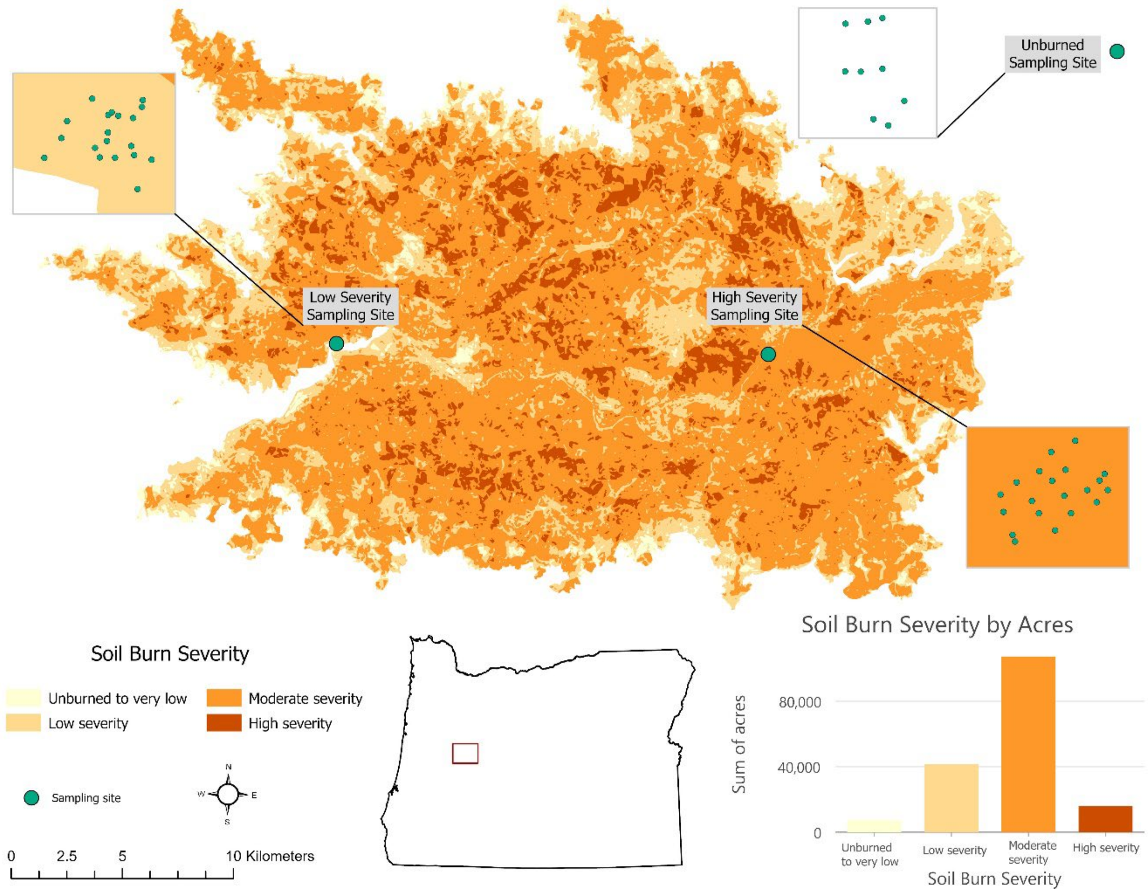
CONCLUSION

Wildfire, at both the low and high severity levels, affects soil organic carbon in the McKenzie River landscape. In the case of this landscape, wildfire decreased SOC in most SOC pools and depths. Because of the variability of soils even within a single landscape, generalizations about the effects of wildfire on soil are difficult to make. Rather, site-specific and localized research is needed to understand connections between soil and disturbance.

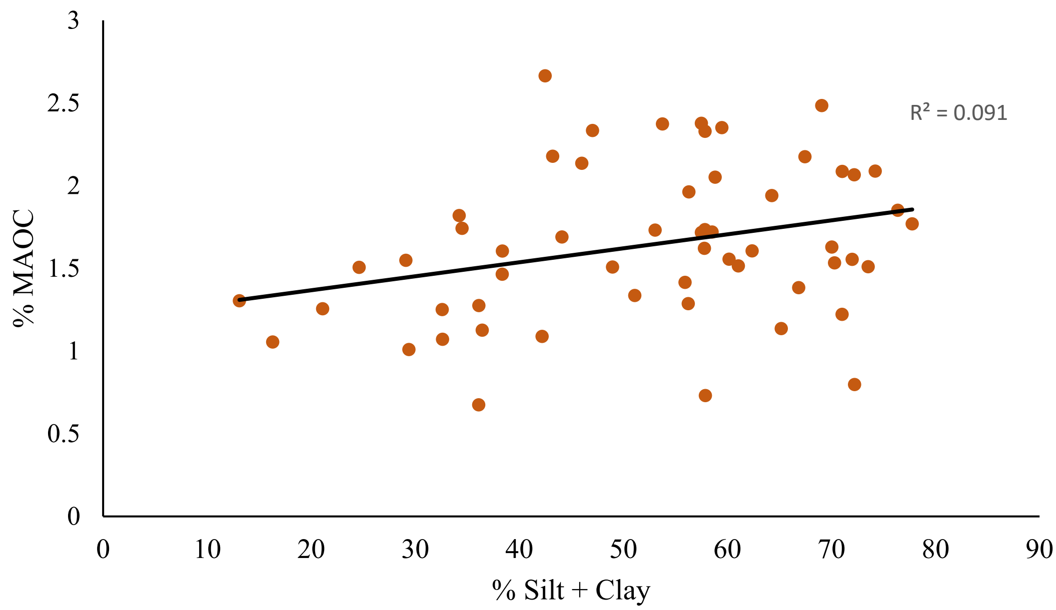
We found evidence that low severity fire has the potential to mitigate the loss of SOC as compared to a high severity fire and, in some cases, as compared with undisturbed landscapes. Specifically, we found that mineral-associated C persisted or even increased through low-severity fire, indicating that MAOC can protect soil C stocks from fire. This may point to the soil advantages of prescribed burning in the McKenzie River Basin and other similar montane forest landscapes, where fire suppression and intensive management can lead to catastrophic disturbance and major carbon losses that can offset carbon gains from biomass accumulation. This fire management strategy could prevent the buildup of fuels, reduce the loss of SOC that would occur in a stand-replacing fire, and increase soil carbon stock in some SOC pools. With wildfires increasing in frequency under climate change in the PNW, land managers and policy makers would benefit from considering how fires affect belowground carbon and what conservation and management strategies can preserve or increase SOC storage going forward.

APPENDIX A

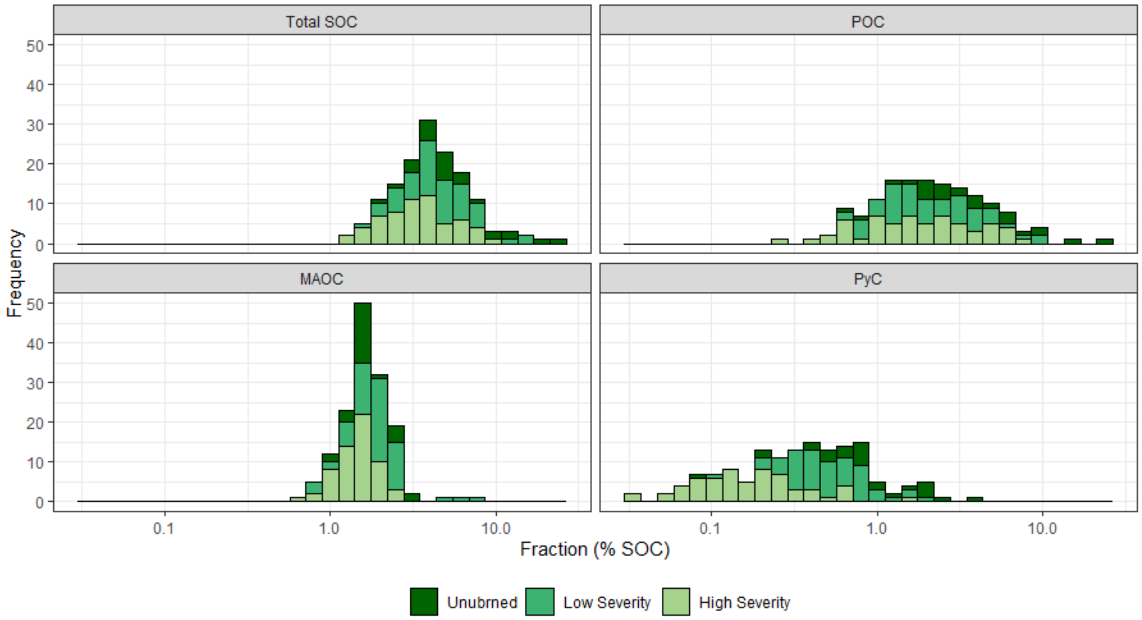
SUPPLEMENTARY FIGURES



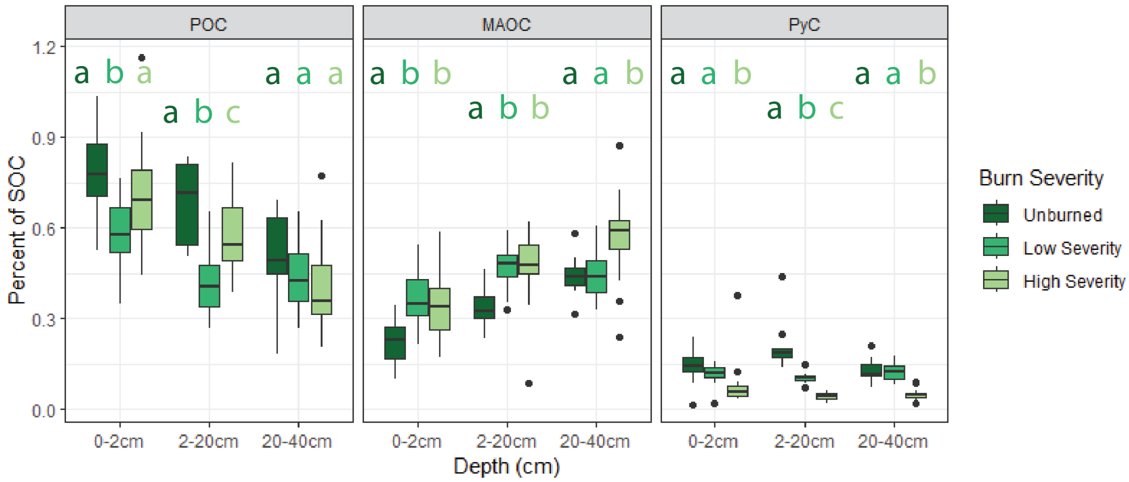
S1. Map showing the soil burn severities of the Holiday Farm Fire based on Sentinel 2 satellite imagery data, where pre- and post-fire images were compared to create a differenced Normalized Burn Ratio (dNMR) dataset (USDA Forest Service et al., 2020). The majority of the wildfire was of moderate soil burn severity, in which moderate but not significant effects of the fire were detected in the soil.



S2. Percent silt and clay compared to percent MAOC for a subset of samples across a range of depths and burn severities.



S3. Distribution of the frequency of percent SOC data as stacked histograms. Values are logged to show normal distributions of each SOC fraction. N = 27 for unburned, n = 60 or low severity, and n = 60 for high severity. Corresponds to the lined histogram shown in Figure 2.



S4. Proportion of total SOC that is composed of each fraction (MAOC and POC), organized by SOC pool. The proportions of the two fractions were divided by the measured total SOC. Note that the proportions of the three fractions added together for each site and depth may exceed 100 percent due to the overlap between PyC and its foundational components of mainly POC and some MAOC elements. N = 9 for each depth of unburned (27 total), n = 20 for each depth of low severity (60 total), and n = 20 for each depth of high severity (60 total). See Table 1 in SI for corresponding values. Corresponds to Figure 4, which is organized by site.

APPENDIX B

SUPPLEMENTARY TABLES

Table 1. Summary of Percent Carbon Values for Each Burn Severity Site and Depth

SOC Pool	n	0-2 cm	2-20 cm	20-40 cm
SOC				
Unburned	20	11.63 ± 6.74 [a]	5.14 ± 1.07 [a]	3.45 ± 0.96 [a]
Low Severity	20	7.32 ± 3.19 [b]	4.29 ± 1.33 [a]	3.22 ± 1.06 [a]
High Severity	9	5.15 ± 1.78 [c]	3.56 ± 1.47 [b]	2.55 ± 1.32 [b]
POC				
Unburned	20	9.44 ± 6.88 [a]	3.61 ± 1.31 [a]	1.67 ± 0.64 [a]
Low Severity	20	4.32 ± 2.17 [b]	1.88 ± 1.06 [b]	1.42 ± 0.70 [ab]
High Severity	9	3.72 ± 1.72 [b]	2.09± 1.22 [b]	1.17 ± 1.14 [b]
MAOC				
Unburned	20	2.21 ± 0.65 [a]	1.68 ± 0.23 [ab]	1.48 ± 0.37 [a]
Low Severity	20	2.69 ± 1.47 [a]	1.96 ± 0.38 [a]	1.43 ± 0.44 [a]
High Severity	9	1.61 ± 0.36 [b]	1.52 ± 0.37 [b]	1.34 ± 0.44 [a]
PyC				
Unburned	20	1.65 ± 1.07 [a]	1.06 ± 0.44 [a]	0.45 ± 0.15 [a]
Low Severity	20	0.87 ± 0.44 [a]	0.45 ± 0.16 [b]	0.40 ± 0.17 [a]
High Severity	9	0.39 ± 0.32 [b]	0.15 ± 0.07 [c]	0.14 ± 0.13 [b]

Values are means ± 1σ. Letters indicate significant differences at any given depth between sites along the fire severity gradient.

Table 2. Summary of Carbon Stocks ± standard deviation (kg/m^2) for Each Burn Severity Site and Depth

SOC Pool	n	0-20 cm	20-40 cm
Total SOC			
Unburned	20	10.50 ± 2.75 ^{a}	10.40 ± 2.90 ^{ab}
Low Severity	20	17.95 ± 2.58 ^{b}	11.27 ± 3.72 ^{a}
High Severity	9	13.75 ± 5.30 ^{a}	8.61 ± 4.44 ^{b}
POC			
Unburned	20	7.61 ± 2.98 ^{a}	5.04 ± 1.75 ^{ab}
Low Severity	20	8.32 ± 4.02 ^{a}	4.96 ± 2.47 ^{a}
High Severity	9	8.35 ± 4.33 ^{a}	3.93 ± 3.84 ^{b}
MAOC			
Unburned	20	3.15 ± 0.39 ^{a}	4.47 ± 1.17 ^{a}
Low Severity	20	7.96 ± 1.87 ^{b}	4.98 ± 1.49 ^{a}
High Severity	9	5.67 ± 1.28 ^{c}	4.52 ± 1.47 ^{a}
PyC			
Unburned	20	2.03 ± 0.73 ^{a}	1.36 ± 0.46 ^{a}
Low Severity	20	1.91 ± 0.68 ^{a}	1.39 ± 0.58 ^{a}
High Severity	9	0.66 ± 0.28 ^{b}	0.46 ± 0.43 ^{b}
Litter			
Unburned	20	0.036 ± 0.015 ^{a}	
Low Severity	20	0.028 ± 0.015 ^{a}	
High Severity	9	0.011 ± 0.003 ^{b}	

Values are means ± 1σ. Letters indicate significant differences at any given depth between sites along the fire severity gradient.

Table 3. Summary of bulk density along the burn severity at each depth, in units g/cm^3

Site	n	0-20 cm	20-40 cm
Unburned	3	0.91 ± 0.36^{a}	1.51 ± 0.08^{a}
Low Severity	3	1.95 ± 0.24^{b}	1.75 ± 0.31^{ab}
High Severity	3	1.85 ± 0.16^{b}	1.69 ± 0.07^{b}

Values are means ± 1σ. Letters indicate significant differences at any given depth between sites along the fire severity gradient.

Table 4. Summary of ANOVA planned contrast tests for SOC percent across the burn severity gradient by soil profile depth

			Total SOC	**POC**	**MAOC**	**PyC**
Depth	Comparison	*df*	*p*	*p*	*p*	*p*
0-2 cm	Unburned - High Severity	46	**< 0.001**	**< 0.001**	**0.025**	**< 0.001**
	Low Severity - High Severity	46	**0.012**	0.352	**< 0.001**	**< 0.001**
	Unburned - Low Severity	46	**0.021**	**0.002**	0.265	0.142
2-20 cm	Unburned - High Severity	46	**0.002**	**0.002**	0.184	**< 0.001**
	Low Severity - High Severity	46	**0.037**	0.525	**0.001**	**< 0.001**
	Unburned - Low Severity	46	0.111	**0.001**	0.128	**< 0.001**
20-40 cm	Unburned - High Severity	46	**0.018**	**0.021**	0.324	**< 0.001**
	Low Severity - High Severity	46	**0.021**	*0.054*	0.511	**< 0.001**
	Unburned - Low Severity	46	0.574	0.415	0.637	0.520

*Bold value indicates significant difference of $p < 0.05$, italicized value indicates significant difference of $p < 0.1$

Table 5. Summary of ANOVA planned contrast tests for ratio of SOC fraction to total SOC across the burn severity gradient by soil profile depth

			POC	**MAOC**	**PyC**
Depth	Comparison	*df*	*p*	*p*	*p*
0-2 cm	Unburned - High Severity	46	0.179	**0.003**	**0.008**
	Low Severity - High Severity	46	**0.015**	0.300	**0.031**
	Unburned - Low Severity	46	**0.002**	**< 0.001**	0.303
2-20 cm	Unburned - High Severity	46	**0.012**	**0.001**	**< 0.001**
	Low Severity - High Severity	46	**< 0.001**	0.864	**< 0.001**
	Unburned - Low Severity	46	**< 0.001**	**< 0.001**	**< 0.001**
20-40 cm	Unburned - High Severity	46	*0.090*	**0.003**	**< 0.001**
	Low Severity - High Severity	46	0.522	**0.001**	**< 0.001**
	Unburned - Low Severity	46	0.228	0.783	0.425

*Bold value indicates significant difference of $p < 0.05$, italicized value indicates significant difference of $p < 0.1$

Table 6. Summary of ANOVA planned contrast tests for SOC stock across the burn severity gradient by soil profile depth

			Total SOC	**POC**	**MAOC**	**PyC**
Depth	Comparison	*df*	*p*	*p*	*p*	*p*
Litter	Unburned - High Severity	46	**< 0.001**			
	Low Severity - High Severity	46	**< 0.001**			
	Unburned - Low Severity	46	0.147			
0-20 cm	Unburned - High Severity	46	*0.064*	0.803	**< 0.001**	**< 0.001**
	Low Severity - High Severity	46	**0.004**	0.934	**< 0.001**	**< 0.001**
	Unburned - Low Severity	46	**< 0.001**	0.753	**< 0.001**	0.810
20-40 cm	Unburned - High Severity	46	*0.099*	*0.065*	0.948	**< 0.001**
	Low Severity - High Severity	46	**0.010**	**0.035**	0.314	**< 0.001**
	Unburned - Low Severity	46	0.666	0.854	0.465	0.964

*Bold value indicates significant difference of p < 0.05, italicized value indicates significant difference of p < 0.1

Table 7. Summary of ANOVA planned contrast tests for bulk density across the burn severity gradient by soil profile depth

Depth	Comparison	*df*	**Bulk Density** *p*
0-20 cm	Unburned - High Severity	6	**0.014**
	Low Severity - High Severity	6	0.5688
	Unburned - Low Severity	6	**0.014**
20-40 cm	Unburned - High Severity	6	**0.0472**
	Low Severity - High Severity	6	0.7646
	Unburned - Low Severity	6	0.2626

*Bold value indicates significant difference of $p < 0.05$, italicized value indicates significant difference of $p < 0.1$

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