Soil Fire Ecology: Assessing Wildfire Severity Impacts on Pacific Northwest Forest Soil Carbon

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Abstract

Pacific Northwest temperate rainforests are anticipated to experience increasingly frequent and severe wildfires in the foreseeable future due to climate change, increased fuel loads, and deforestation. Soil, underlying these forests, is the largest terrestrial carbon ("C") reservoir. Fire disturbance influences soil C persistence, the timeframe and magnitude of which remain unclear. Understanding post-fire soil C dynamics may prove helpful for creating predictive models that incorporate the role of terrestrial ecosystems in climate change mitigation. In this study, we measured mean soil C content in density-separated soil fractions in HJ Andrews Experimental Forest one year after the 2020 Holiday Farm Fire. These include light fractions ("LF", representing particulate organic matter) and heavy fractions ("HF", representing mineral-associated organic matter). Four burn severity classes were investigated: high, moderate, low, and no burn. Significant differences between unburned and burned mean soil C content were determined through Welch's t-Tests. We identified that the LF mean soil C content in the high severity burn class significantly increased, which is likely due to the fire-induced influx of low-density charcoal. HF post-fire mean soil C content was not significantly different in any burn class. These findings offer insight into the timeframe of soil C fluctuations following natural disturbances in PNW forest ecosystems. This may inform the creation of predictive models that incorporate the role of terrestrial ecosystems in climate change mitigation.

Introduction

Temperate Pacific Northwest ("PNW") forests, the rare ecosystems residing in the coastal Northwest United States and Canada, fuel life. They harbor biodiversity, cultivate taxa richness, provide habitat for wildlife, drive nutrient cycling, filter watersheds, and enhance carbon sequestration (Brandt et al. 2014). In addition to providing ecosystem services, these forests hold cultural significance and provide natural spaces for recreational opportunities.

Yet, temperate PNW forests would not be able to play these roles if not for their belowground component: soil. Soil organic matter ("SOM") supports agricultural production and water filtration and storage, impacting food security, water access, and climate change (Plaza et al. 2019). SOM is also the largest terrestrial carbon ("C") storage mechanism (Pellegrini et al., 2021), forest soils, in particular, storing approximately 40% of global soil C (Janzen, 2004). The soil C pool is approximately 3.1 times greater than the atmospheric C pool; thus, any perturbations to soil C cycling have the potential to influence global climate (Sulzman et al. 2005; Ontl & Schulte 2012).

Pacific Northwest forests are expected to experience wildfires of increasingly high intensity and frequency due to global warming, exploitative timber harvest, and increased fuel loads due to fire suppression (Hurteau & Brooks, 2011; Halofsky et al. 2020). Rising global temperatures are anticipated to induce warm, dry summers, increasing evaporative demand and decreasing soil moisture (Halofsky et al. 2020; Pellegrini et al. 2021). They are highly vulnerable to fire disturbance due to the exploitative harvest of fire-tolerant, old-growth trees and other damaging anthropogenic activity (Hessburg et al. 2022).

While wildfire impacts on aboveground biomass have been well-researched, there has been little research investigating the timeframe and magnitude of belowground soil C fluctuation following fire disturbance (Lajtha 2021). Understanding soil C fluctuations following wildfires and similar natural disturbances may inform the creation of predictive models that incorporate the role of terrestrial ecosystems in climate change mitigation.

The objective of this study is to assess the impacts of fire severity on soil C persistence. “Fire severity” is defined as the percent mortality of overstory vegetation (Hurteau & Brooks 2011). Soil C persistence describes the We will compare mean C content between unburned (control) and burned sites of high, moderate, and low fire severity to assess post-fire C fluctuations in a PNW forest system: Horace James Andrews Experimental Forest (“HJA”).

HJA is a 16,000-acre National Science Foundation Long Term Ecological Research Network (“NSF LTER”) located in the Western Cascades Mountain Range of Oregon (*H.J. Andrews Experimental Forest,* n.d.; Long-Term Ecological Research (LTER) | National Science Foundation, n.d.). It is designated as the “Pacific Northwest Research Station”, providing long-term data for soil C stabilization and storage, forest ecology, watershed processes, and more since 1980. LTER sites geomorphologically represent major ecosystems and natural biomes, fueling multidisciplinary research of long-term ecological phenomena to provide knowledge of intricate ecosystem interactions and patterns between populations, communities, and ecosystems. The publicized research conducted in HJA may be used to inform future management of PNW forests.

Soil Organic Matter Fractions

To simplify the understanding of its response to disturbance, the complex, heterogeneous pool of SOM can be physically separated into discrete fractions of varying densities (Sollins et al. 2006; Crow et al. 2007; Kramer et al. 2017; Cotrufo et al. 2019; Plaza et al. 2019; Lajtha 2021). Different biochemical SOM components experience varying turnover times and microbial activity, performing diverse functions (Crow et al. 2007; Cotrufo et al. 2019; Plaza et al. 2019). Thus, it is highly difficult to study SOM dynamics as one pool. This separation is accomplished through centrifugal treatment with a high-density liquid, separating the soil into fractions of light and heavy density that have different processes of formation, persistence, and function (Sollins et al. 2006; Crow et al. 2007; Kramer et al. 2017; Cotrufo et al. 2019; Plaza et al. 2019).

Soil scientists have elected to research SOM in two fundamentally diverse pools: particulate organic matter (“POM”) and mineral-associated organic matter (“MAOM”) (Sollins et al. 2006; Crow et al. 2007; Kramer et al. 2017; Cotrufo et al. 2019; Plaza et al. 2019; Lajtha 2021).

POM consists of free organic fragments comprised of dead microbial, animal, and plant materials that are not associated with minerals in the soil, such as clays (Cotrufo et al. 2019). The POM component is less stabilized due to this lack of chemical interactions with minerals (Cotrufo et al. 2019). This fast-cycling SOM component has a short lifetime (1-50 years) (Cotrufo et al. 2019). POM persists in soil through biochemical recalcitrance, aggregation, and/or microbial inhibition, and it is more susceptible to external disturbance and microbial decomposition due to its lack of stabilization (Cotrufo et al. 2019). Soil microbes can solubilize more carbon in POM. POM possesses faster nutrient turnover/cycling rates than MAOM (Cotrufo et al. 2019).

MAOM, composed of microbes, root exudates, and fine, dissolved organic matter, is a highly stabilized pool of carbon undergoing strong chemical and physical binding to minerals (Cotrufo et al. 2019). This high mineral affinity protects MAOM from significant microbial attack (Cotrufo et al. 2019). Therefore, the MAOM boasts longer lifetimes with slower turnover cycles (Cotrufo et al. 2019).

Light fractions represent POM while heavy fractions represent MAOM (Sollins et al. 2006; Crow et al. 2007; Kramer et al. 2017; Cotrufo et al. 2019; Plaza et al. 2019; Lajtha 2021).

Hypotheses

1. We expect that the high severity burn class is more likely to induce significant mean soil C content differences compared to the moderate and low severity classes. The more intense the burn, the more drastic the fluctuations.

2. We hypothesize that POM mean soil C content will decrease post-fire due to the high disturbance vulnerability and lower structural stability observed in POM (Cotrufo et al. 2019, Pierson et al. 2021 in review). Due to its high susceptibility to microbial decomposition, POM generally responds quickly to changing conditions and disturbances. The main C sources for POM (litter and root detritus entering the soil) will burn away, decreasing POM soil C content.

3. In contrast, MAOM mean soil C content is hypothesized to experience little to no significant fluctuation due to its high mineral stabilization and structural durability against disturbance.

Methods

Site Descriptions

Soil was collected in June-August 2021 from HJA (Fig. 1) and the broader Willamette National Forest within the footprint of the Holiday Farm Fire (Fig. 2). HJA watersheds 1, 2, and 9 (Fig. 3) were impacted by the fire; we were given permission by the HJ Andrews Headquarters team to collect in these areas. Watershed 1 contains forested land that was 100% clearcut in 1962-66 followed by a wildfire in 1967, and Watersheds 2 and 9 contains undisturbed reference old-growth land (*Experimental Watersheds and Gauging Stations*, 2017).

Complex, mountainous topography and steep slopes in this location perpetuate vulnerability to strong winds, increasing the potential for rapid fire spread (Halofsky et al. 2020) . This coniferous region is dominated by old-growth Douglas-fir (*Pseudotsuga menziesii*) and Western Hemlock (*Tsuga heterophylla*) at lower elevations and Pacific Silver Fir (*Abies amabilis*) at higher elevations (Crow et al. 2007). The Mediterranean climate in this region induces warm, dry summers and cool, wet winters; the wet season typically occurs from October to May (Sollins et al. 1980). The recorded 1999–2014 mean annual temperature is 9.4℃ with an annual rainfall of 2080 mm (Pierson et al. 2021 in review).

Classified as intermediates between Andisols and Inceptisols, soils in this region are a mixture of several alluvial and colluvial flows of similar age and andesite volcanic bedrock parent material (Crow et al. 2007, *H.J. Andrews Experimental Forest | Pacific Northwest Research Station | PNW - US Forest Service*, n.d.). The forest floor is enclosed with coarse woody debris and moss layering, the magnitude of which are site-specific.

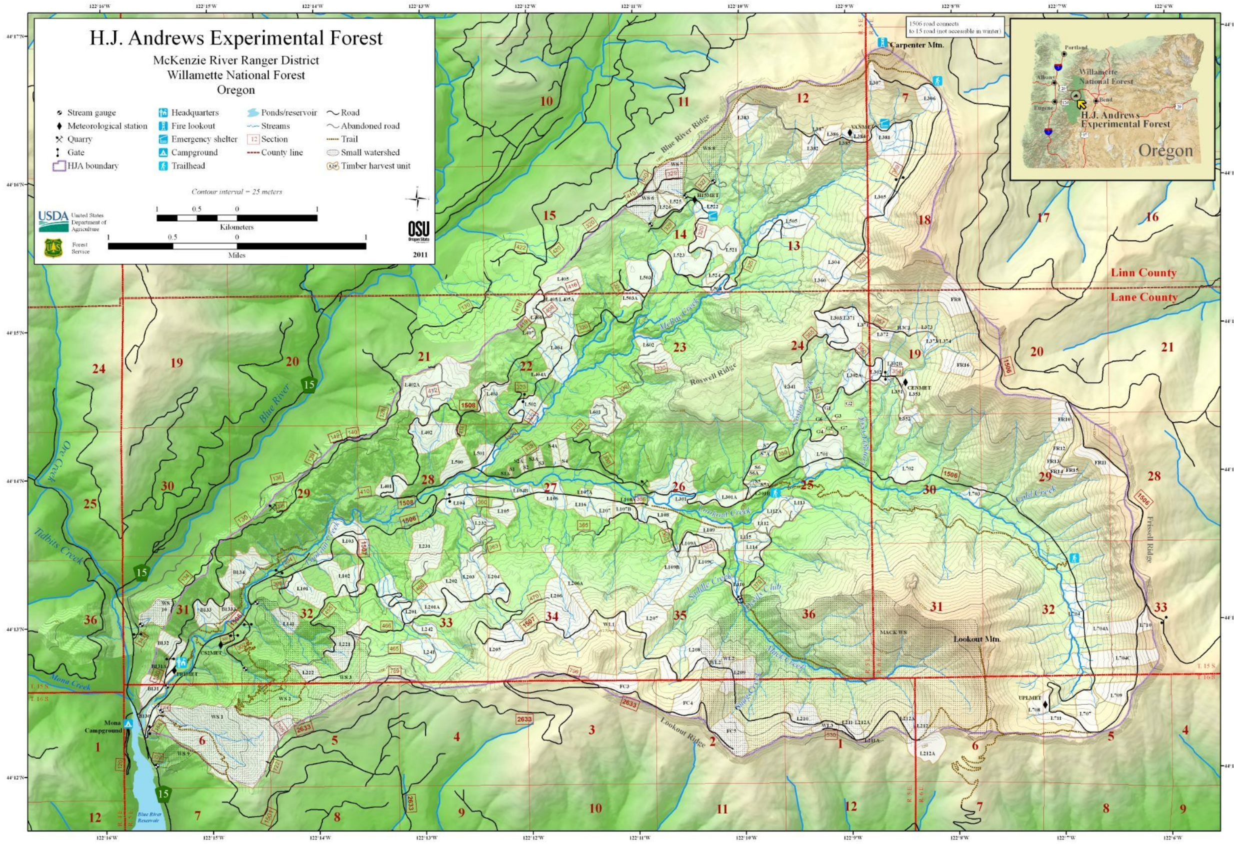

Fig. 1 2011 HJ Andrews map depicting major roads, fire lookouts, streams, and related entities with inset of Oregon (Maps | HJ Andrews Experimental Forest - Oregon State University, 2017).

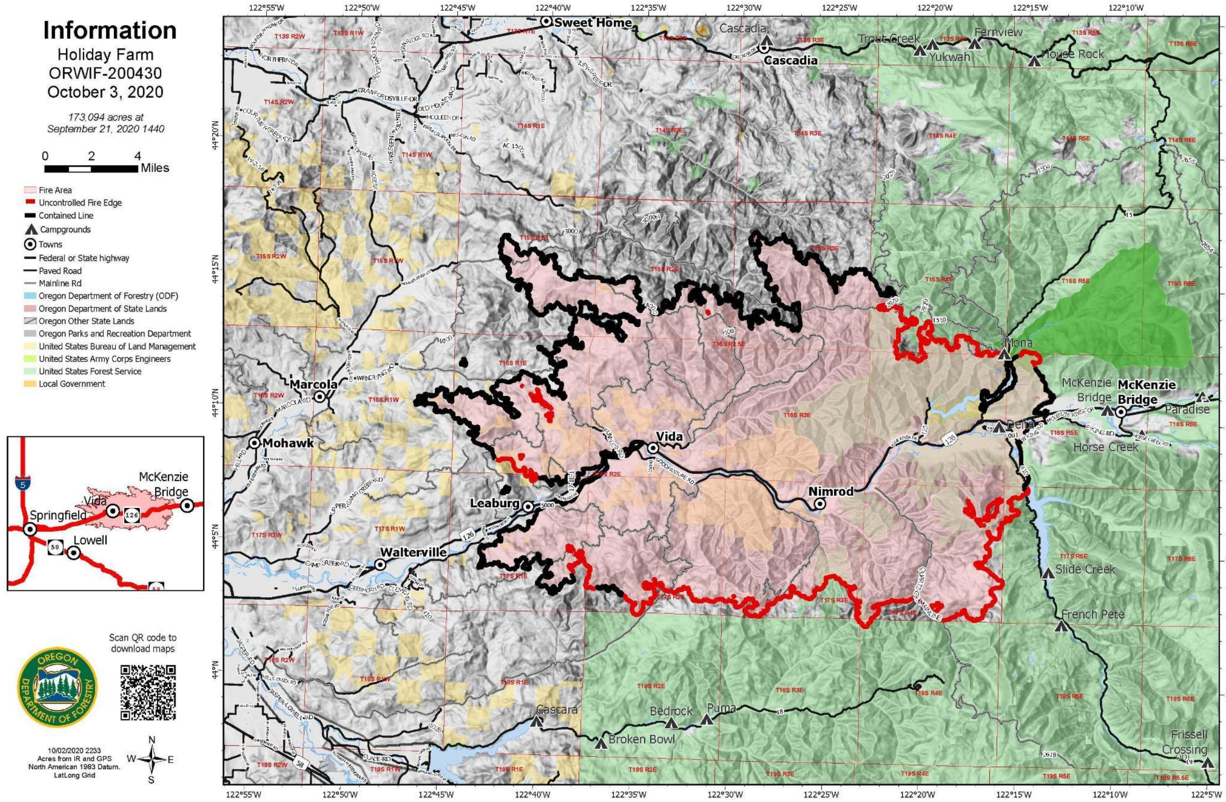

Fig. 2 10/3/2020 Holiday Farm Fire depicting fire area, uncontrolled fire edge, and related parameters in scale of HJ Andrews and Willamette National Forest (Holiday Farm Fire Map - InciWeb the Incident Information System. Oregon Department of Forestry, 2020).

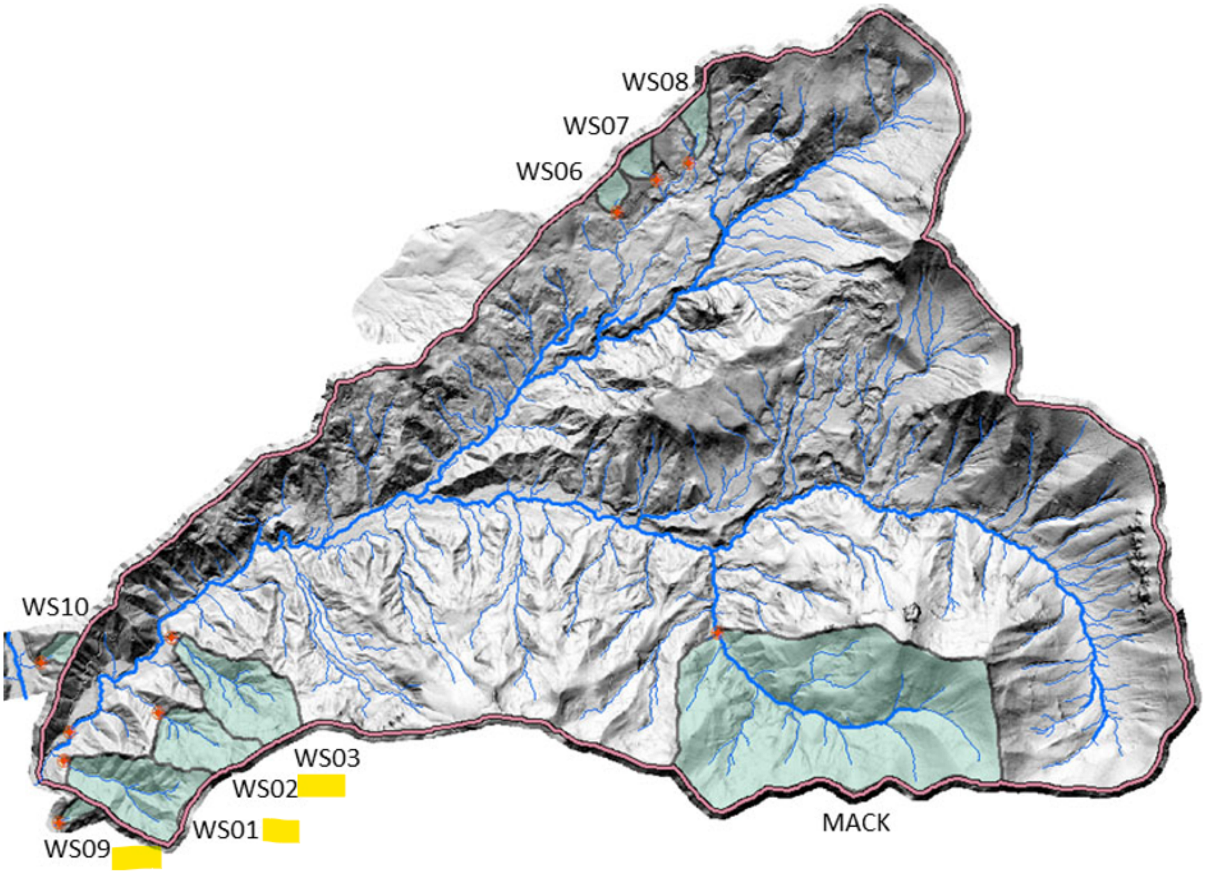

Fig. 3 2017 HJ Andrews watershed map highlighting Watersheds ("WS") 1, 2, and 9. These were the watersheds impacted by the Holiday Farm Fire (*Experimental Watersheds and Gauging Stations*, 2017).

Site Selection

A Burned Area Emergency Response ("BAER") soil burn severity GIS layer was used for initial categorization and stratification of burn severity across sites within the footprint of 2020 Holiday Farm Fire (Resources | Burned Area Emergency Response (BAER) Imagery Support, n.d.). Burn severity classes were low severity, moderate severity, and high severity. Satellite layers of topographic variables were also employed to facilitate site selection. Garmin geolocation technology guided us to sites with precise GPS coordinates.

Field confirmation and relocation was occasionally executed as BAER did not always yield accurate classification. We observed that unburned sites possessed high tree, canopy, and understory vegetation density. Low severity sites retained high tree survivorship and thick overstory with some surface organic layer charring. Medium severity sites depicted strong tree scorching and charred soil with light overstory mortality. High severity sites experienced near 100% tree mortality, retaining little understory vegetation and nearly no overstory.

A paired sampling approach was designed. Each burned site was paired with an unburned control site by similar elevation, slope, and aspect. Five replicate sites were selected per burn severity group (15 total burned), and five replicate sites were selected per unburned control group (15 total control), establishing a total of 30 plots at 50 m^2 (Fig. 4). To minimize potential confounding effects of spatial and temporal autocorrelation, plots were chosen at least 200 m apart and at least 40 m from streams and 50 m from roads.

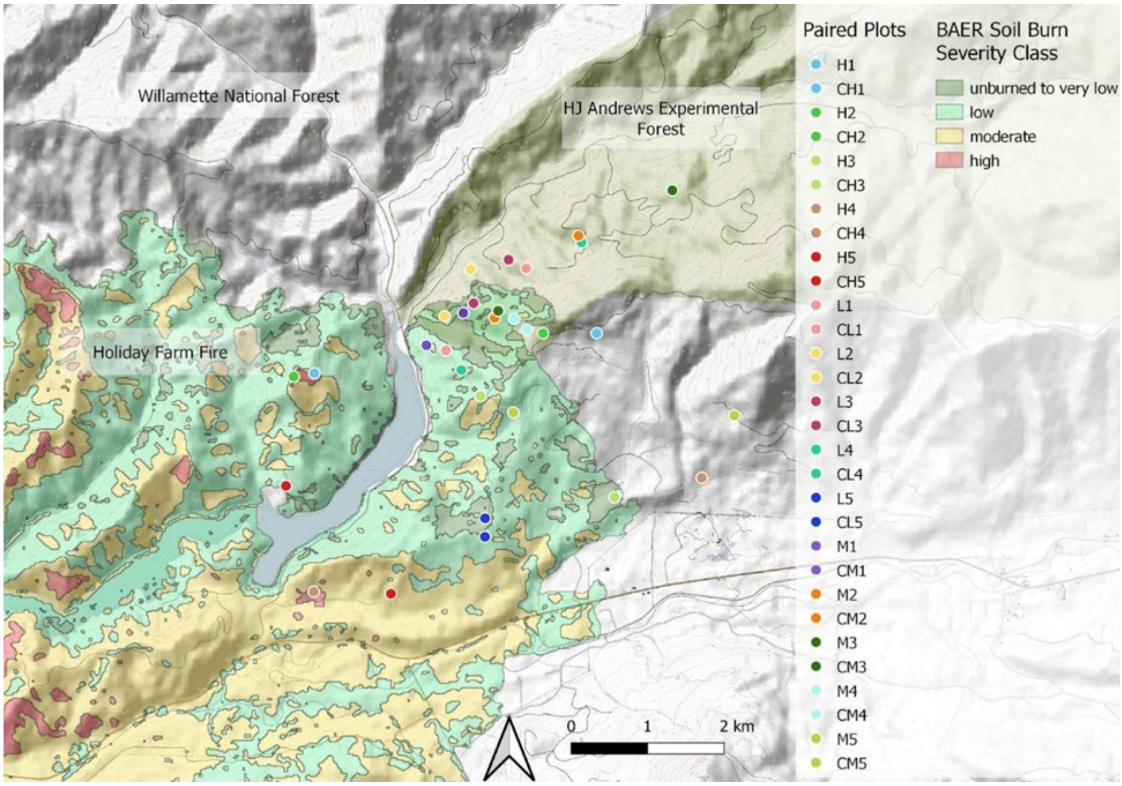

Fig. 4 2021 HJ Andrews map displaying plot locations in footprint of Holiday Farm Fire and Willamette National Forest. Legend depicts burn severity classification: high severity “H”, moderate severity “M”, low severity “L”. “C” indicates the corresponding control plot (e.g. CL1 is the control site for L1). Burned Area Emergency Response (“BAER”) Soil Burn Severity Class shows initial categorization of burn severity across sites. Field confirmation and relocation was occasionally executed as BAER did not consistently yield accurate classification.

Soil Collection

To access mineral soil, 10 cm (length) x 10 cm (width) x organic horizon depth was removed. Different mineral soil depths were sampled by hand-hammering polyvinyl chloride (PVC) cores into the ground and collecting soil at 0–5 cm, 5–10 cm, 10–20 cm, and 20-30 cm. At each site, we subsampled each depth at three locations within each plot, which were later composited by depth in the lab.

Soils were transported back to the lab in intact PVC tubes, which were then carefully sectioned into 0-5, 5-10,10-20 and 20-30 depth increments using a jigsaw. Field-moist soil masses were taken before air drying. Soils were then sieved to separate roots, rock, and other material >2 mm. Mineral soil <2 mm were weighed and stored at room temperature in paper bags for multiple weeks before density fractionation. Roots, charcoal, and associated organic material >2 mm were placed into separate paper bags labeled with corresponding sample site information and “OM”. Roots from all samples were isolated for root biomass analysis in future research projects. Rock masses and volumes were taken to correct for bulk density and volumetric water content in the mineral soil samples (Poeplau et al. 2017). Soils extracted from PVC cores were then taken for density fractionation following current protocols (Sollins et al. 2006; Crow et al. 2007; Kramer et al. 2017).

Soil Density Fractionation

To quantify C content in soil samples, the complicated matrix of soil organic matter (SOM) was physically separated into discrete fractions of varying densities (Sollins et al. 2006; Crow et al. 2007; Kramer et al. 2017; Cotrufo et al. 2019; Plaza et al. 2019; Lajtha 2021). This was accomplished through centrifugal treatment with a commonly used high-density liquid: sodium polytungstate (SPT, density 1.85 g cm^{-3} .) (Sollins et al. 2006; Conceição et al. 2007; Crow et al. 2007; Kramer et al. 2017; Plaza et al. 2019).

Approximately 30 g of one soil sample and 60 mL of SPT were added to one 250 mL conical polypropylene centrifuge tube. Eight centrifuge tubes were processed at a time. The eight centrifuge tubes were secured on a shaking platform for two hours, then loaded into the two Beckman Coulter Allegra-14R swinging bucket centrifuge machines for ten minutes at 3,000 x g relative centrifugal force (Fig. 5).

Fig. 5 Beckman Coulter Allegra-14R swinging bucket centrifuge machine in ALS Room 3119.

Following the 10-minute centrifuge spin, centrifuge tubes typically displayed distinct layers of liquid versus solid separation. Some soils required additional centrifuge spinning to yield this separation. The liquid (SPT) and visible POM (roots, plant material) were aspirated through a tube connected to a 1000 mL Erlenmeyer filter flask connected to a bench vacuum (Fig. 6). MAOM remained in the centrifuge tube (Fig. 7).

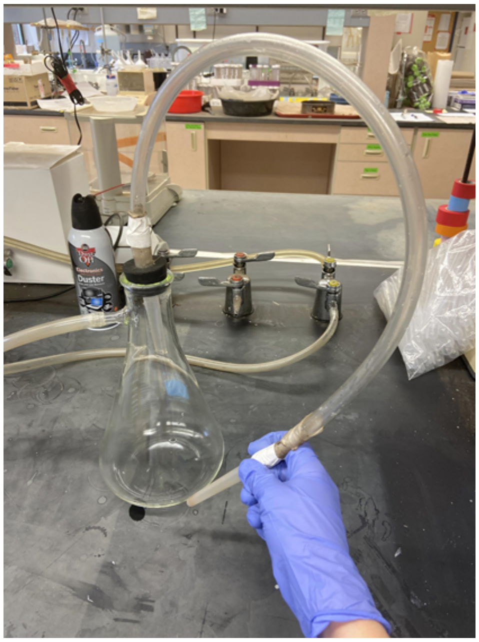

Fig. 6 Aspirating materials: aspiration tube and 1000 mL Erlenmeyer sidearm flask connected to bench vaccuum.

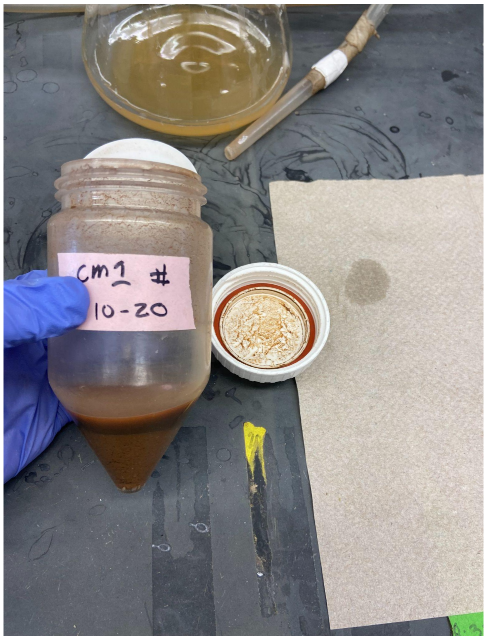

Fig. 7 Centrifuge tube containing example HF from paired control soil sample for moderate burn severity, replicate 1 ("CM1").

The contents in the 1000 mL Erlenmeyer flask were transferred into a 12 cm ID porcelain Buchner funnel containing a 110 mm glass fiber filter seated atop a 1000 mL Erlenmeyer sidearm flask connected to a vacuum. This allowed the SPT to filter into the flask and the light fraction material (POM) to be collected by the filter (Fig. 8)

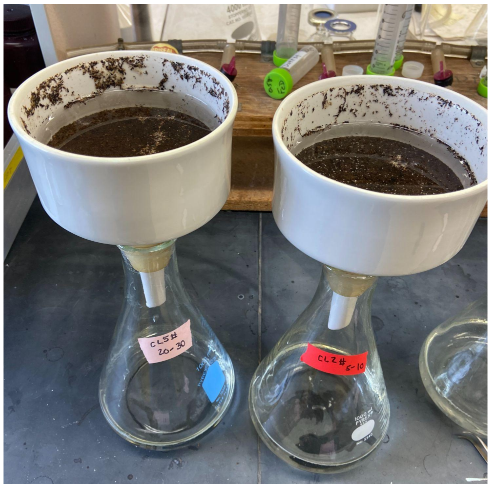

Fig. 8 Twelve cm ID porcelain Buchner funnel containing a 110 mm glass fiber filter seated atop a 1000 mL Erlenmeyer sidearm flask connected to a vacuum funnel. This contained LF of the control sample for low burn severity, replicate 5 ("CL5", left) and paired control soil sample for low burn severity, replicate 2 ("CL2", right).

The centrifuge procedure for SPT was repeated three times, which was followed by three additional centrifuge-aspiration rounds with distilled deionized (DDI) water . Following the third DDI round, the density of the centrifuge tube liquid content was determined with a 25mL volumetric flask and a mass balance machine. If the density was greater than 1, additional rounds of water washing were performed until density of 1 was reached to ensure that all SPT was entirely removed from sample.

The LF material in the filtration funnel HF material remaining in the centrifuge tube following the density check were transferred into individually labeled mason jars with metal scraping utensils and DDI water. Heat ovens were utilized at 60℃ to dry the labeled mason jar contents. Dried mason jar contents were weighed and then ground for C analysis.

Elemental Analysis

Total organic C quantities (ppm) in fractionated, ground soil samples were determined through Elementar C analysis in the Soil Health Lab at Oregon State University. The CNS Elementar Vario Macro Cube, which can analyze approximately 100 mg of solid, dried, and ground soil sample at a time, was used to yield total organic C quantities (Methods and Equipment - Soil Health Lab Oregon State University, 2020). These values were converted into soil C content using soil bulk density values.

Statistical Analysis

Mean soil C content (mg C per g soil) of burned and control (unburned) groups were compared through Welch's t-Tests conducted in R Studio (RStudio Team 2020). This t-Test adjusts the number of degrees of freedom when the variances are expected to be different values. We compared mean C content of burned HF and LF fractions to their controls in each burn severity class.

- Null hypothesis: the true difference between the burned mean soil C content and control mean soil C content is equal to zero.
- Alternative hypothesis: the true difference between the two means is not equal to zero.

At a significance level of $\boldsymbol{\alpha}=0.05$, mean soil C content values in burned groups were statistically different from mean soil C content values in control groups when the resulting p-value was less than 0.05 (Table 1).

Results

The t-Test for LF in high severity burn areas versus its control at all soil depths yielded a statistically significant difference in mean soil C content (p=0.003). The mean soil C content for high severity LF at all soil depths (283.0 g C per g soil) was significantly higher than that of its control at all depths (221.89 g C per g soil).

There were no additional statistically significant t-Test results for mean soil C content differences (Table 1).

Table 1 t-Test p-values determining significant mean soil C content differences between burned groups and control groups.

t-Test Comparison Category	p-value	Control mean soil C content (mg C per g soil)	Burned mean soil C content (mg C per g soil)	Significantly Different?
Low Severity HF vs. control HF at all depths:	0.5072	16.0	18.1	No
Low Severity LF vs. control LF at all depths:	0.9519	247.1	248.0	No
Moderate Severity HF vs. control HF at all depths:	0.9465	15.8	15.9	No
Moderate Severity LF vs. control LF at all depths:	0.3422	252.1	263.0	No
High Severity HF vs. control HF at all depths:	0.754	18.2	19.2	No
High Severity LF vs. control LF at all depths:	**0.003404**	**221.9**	**283.0**	**Yes**

As observed in Fig. 9-12, the mean C content for the high severity LF group was significantly higher than that of the control. This is supported by the fact that the control standard error bars do not overlap with the burned standard error bars, signifying that the confidence intervals do not align.

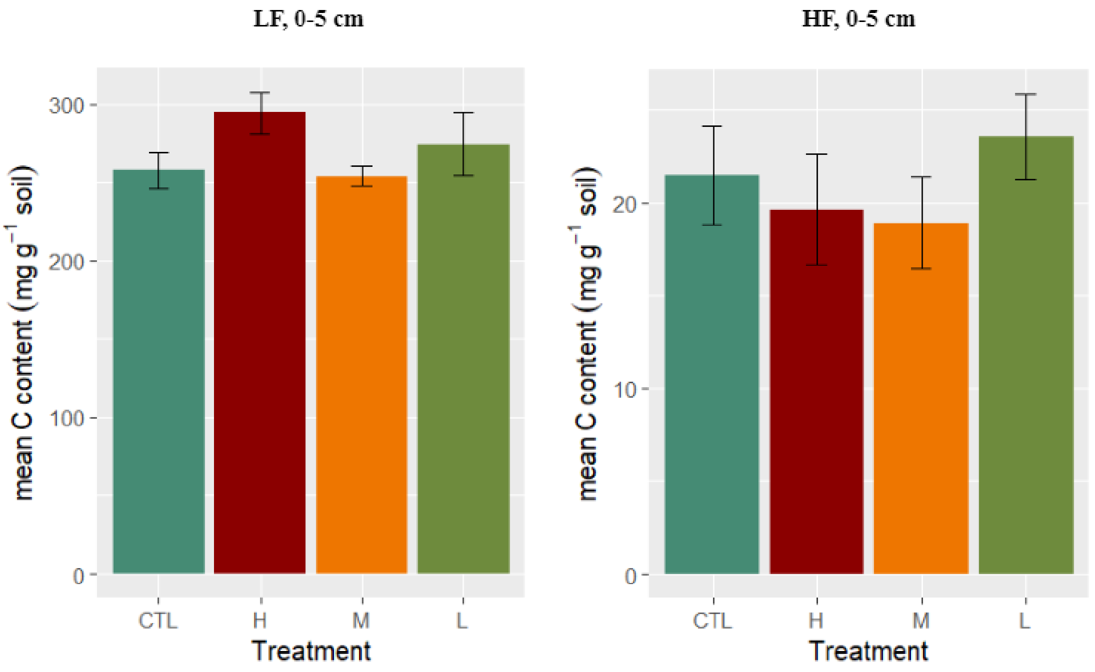

Fig. 9 Mean C content for LF and HF at a depth of 0-5 cm separated by control (unburned, "CTL") and treatment groups (high severity "H", moderate severity "M", low severity "L"). Error bars represent standard error.

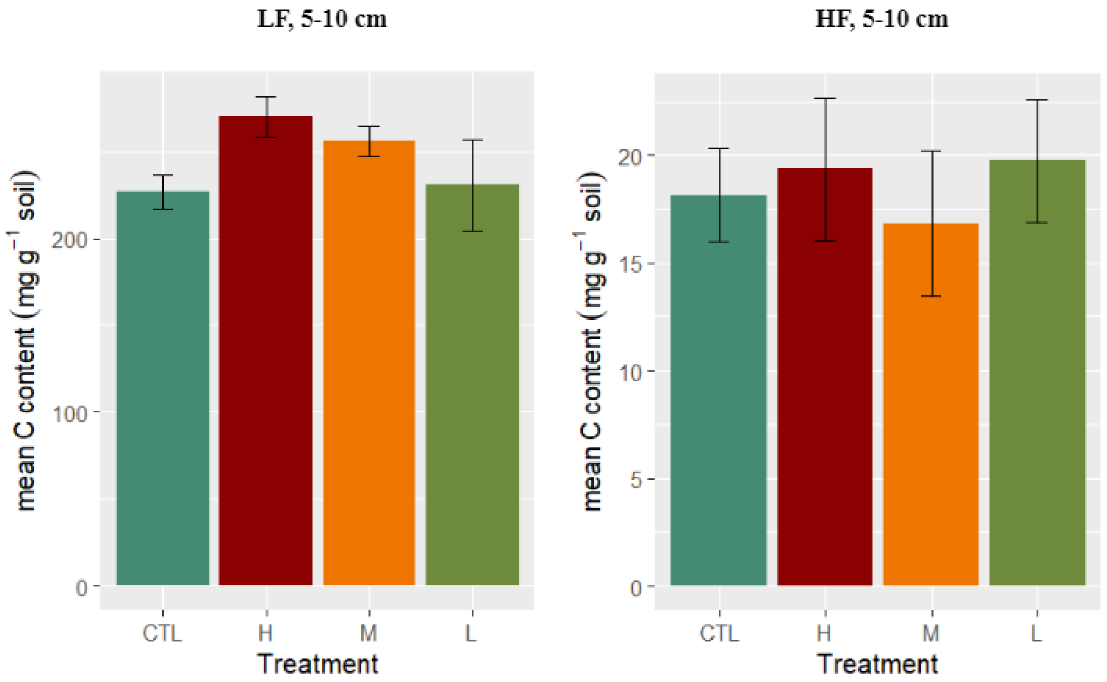

Fig. 10 Mean C content for LF and HF at a depth of 5-10 cm separated by control (unburned, "CTL") and treatment groups (high severity "H", moderate severity "M", low severity "L"). Error bars represent standard error.

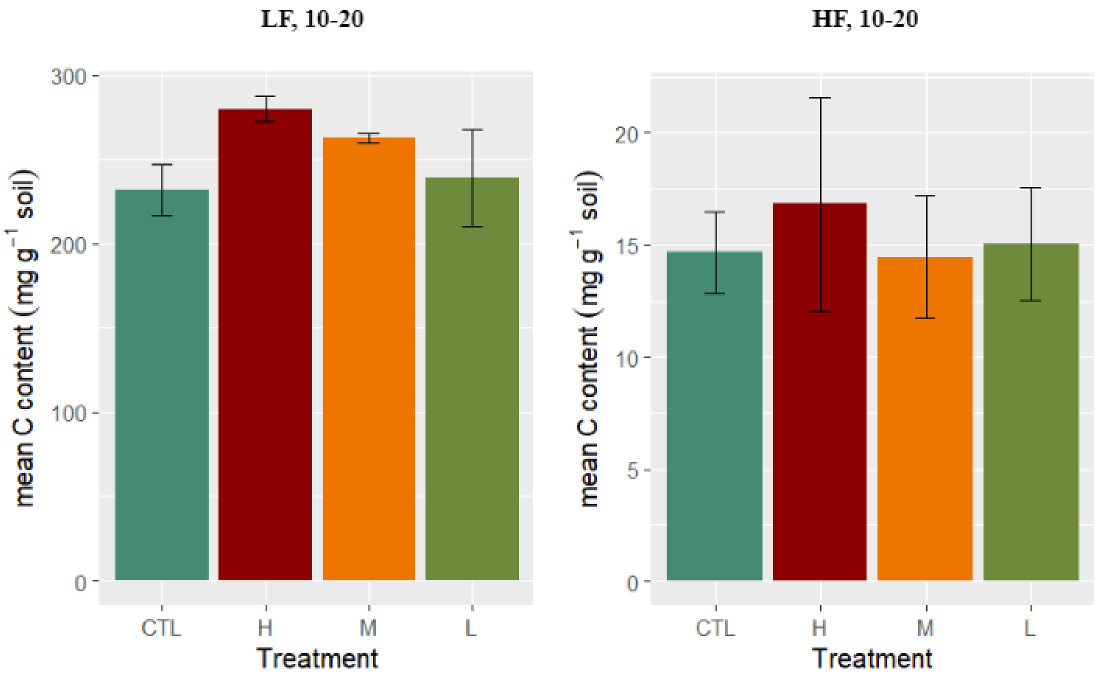

Fig. 11 Mean C content for LF and HF at a depth of 10-20 cm separated by control (unburned, “CTL”) and treatment groups (high severity “H”, moderate severity “M”, low severity “L”). Error bars represent standard error.

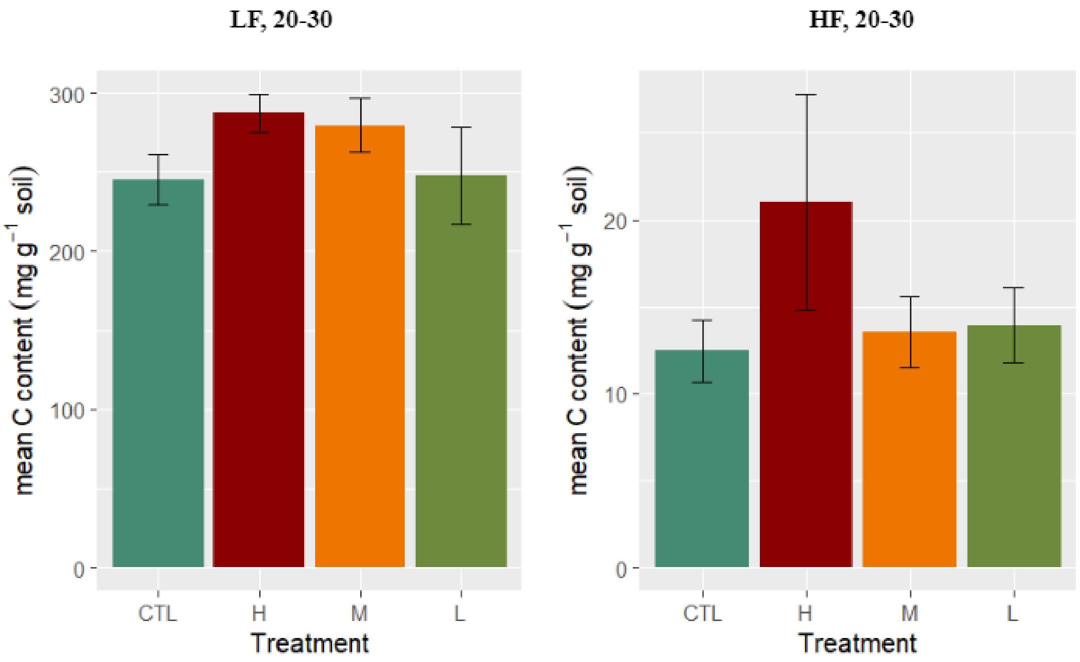

Fig. 12 Mean C content for LF and HF at a depth of 20-30 cm separated by control (unburned, “CTL”) and treatment groups (high severity “H”, moderate severity “M”, low severity “L”). Error bars represent standard error.

Discussion

Burn Severity Influence on Mean Soil C Content

We predicted that the high severity burn class was more likely to induce, if any, significant post-fire mean soil C content fluctuations compared to the moderate and low severity burn classes. This was consistent with our results, but only in the POM category. Moderate and low severity fires did not inflict significant post-fire mean C content differences in either soil fraction.

Significant Increase in Post-Fire Mean Soil C Content for POM

Further, we hypothesized that POM post-fire mean soil C content would decrease due to the fire-induced loss of POM C sources, such as tree needles and detritus entering the soil. Contrarily, there was a significant post-fire increase in the mean soil C content for the high severity POM category.

There are multiple viable explanations for this. When fire consumes vegetation and detrital matter, nutrients are introduced to the soil, potentially boosting post-fire vegetation and increasing soil C (Halofsky et al. 2020). This would support an increase in POM mean soil C content, as the C sources for POM are plant materials.

Alternatively, there is the possibility of charcoal increasing POM soil C. Following pyrogenic C analyses in a different project in the Lajtha lab, it was discovered that there is a high concentration of charcoal appearing specifically in the burned POM. Charcoal is introduced into the soil through fire disturbance (Bruun et al. 2008). This persistent, low-density material is protected from environmental degradation through mineral stabilization, resisting microbial attack and external disturbances, and boasting a long turnover time (Bruun et al. 2008; Egli et al. 2012). These biochemical characteristics align more closely with MAOM, but due to its low density, charcoal persists in POM. POM dynamics may change with significant additions of charcoal. Post-fire POM pools may thus serve as a slow-cycling C system. Our findings suggest that in fire-prone systems, POM will increase and contain a greater proportion of slowly-cycling biochar.

No Significant Change in Post-Fire Mean Soil C Content for MAOM

Lastly, we expected MAOM to experience little to no significant fluctuation in post-fire mean soil C content due to its high mineral stabilization and structural durability against disturbance. MAOM soil C content was not significantly different one year post-fire, though it is possible that any fluctuations in MAOM soil C content may require a longer time to materialize due to the buffered responses to disturbances observed in MAOM compared to the labile POM (Cotrufo et al. 2019; Pierson et al. 2021 in review).

Study Limitations and Future Research

One summer was required to procure all soil samples, and yet we could only sample thirty plots total with the time allotted. The topography in HJA, while magnificent, is not designed for effortless human travel. Further replication may be necessary to draw accurate conclusions regarding post-fire soil C content fluctuations at a larger scale in the future.

This study was conducted one year after the Holiday Farm Fire. We do not know if these effects are short or long-term. Future studies should investigate the effects of soil C content after two, five, ten, and more years post-fire. That is, however, under the assumption that there will be no future wildfires in the same area, which is unlikely given our climate change trajectory (Hurteau & Brooks, 2011; Halofsky et al. 2020; Pellegrini et al. 2021). As long as efforts are safe and approved by fire experts and HJ Andrews administration, this goal should still be attempted.

Moreover, the Holiday Farm Fire was one wildfire event. The data collected may not provide conclusions that can be accurately generalized to global wildfires, or even to all wildfires occurring across Oregon. As depicted in Figure 12, there were multiple wildfires that inflamed Oregon during the summer of 2020. Different regions vary by climate, vegetation, topography, and other related parameters; thus, it would be ideal to procure data with the same methodology used in this project in these other burn locations. We may be able to extrapolate to other regions and climates with this increased understanding.

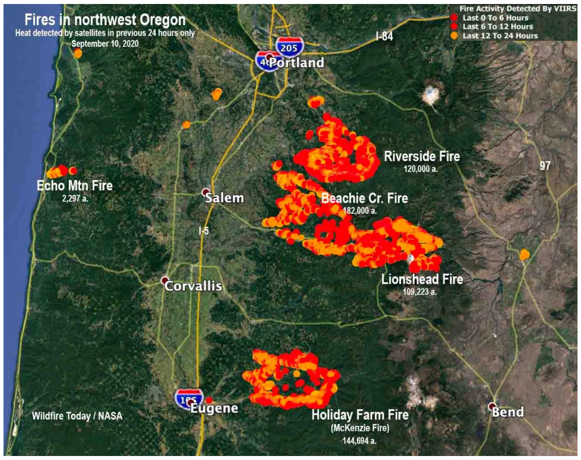

Fig. 13 Map of Oregon Summer 2020 Wildfires (Holiday Farm Fire Archives, 2020).

Future research in this discipline should prioritize pyrogenic C analysis; that is, we must understand the implications of charcoal in soil. What are the implications of slower cycling POM pools due to high concentrations of charcoal? Is charcoal a viable carbon sink? How does charcoal impact soil health?

Wildfire Management Options

To reduce fire severity and resulting fluctuations in soil C, controlled burning may be necessary to systematically reduce fuel loads (Hurteau & Brooks 2011; Halofsky et al. 2020; Pellegrini et al. 2021; Hessburg et al. 2022). Fuel reductions decrease fire severity and improve forest resilience to fire, insects, and drought, all of which are projected to increase with climate change (Halofsky et al. 2020). When combined with reforestation, fuel treatment has been shown to greatly reduce the intensity of future reburns and allow most new trees to survive (Lyons-Tinsley & Peterson 2012, Halofsky et al. 2020).

To enhance soil health and resilience upon disturbance, soil restoration and woodland regeneration techniques may be beneficial. Employing no-till farming, cover crop cultivation, nutrient management, manuring application, regulated grazing, water conservation and enhanced storage techniques, and agroforestry practices are some examples (Lal, 2004).

Concluding Remarks

As wildfires and other natural disturbances increase in frequency and severity, we must develop a deeper understanding of how the ecosystems we rely on respond. Conceptualizing the post-fire C fluctuations in the heterogeneous, complex nature of SOM in two fractions is one step towards that knowledge. Charcoal-rich POM pools may become more stabilized with longer turnover times, changing SOM C dynamics---and potentially global C cycling, given the significant amount of C stored by SOM compared to the atmosphere. These findings offer insight into the timeframe of soil C fluctuations following natural disturbances in PNW forest ecosystems. This may inform the creation of predictive models that incorporate the role of terrestrial ecosystems in climate change mitigation.

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