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Unearthing the legacy of wildfires: post fire pyrogenic carbon and soil carbon persistence across complex Pacific Northwest watersheds

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Abstract Wildfires have the potential to dramatically alter the carbon (C) storage potential, ecological function, and the fundamental mechanisms that control the C balance of Pacific Northwest (PNW) forested ecosystems. In this study, we explored how wildfire influences processes that control soil C stabilization and the consequent soil C persistence, and the role of previous fire history in determining soil C fire response dynamics. We collected mineral soils at four depth increments from burned (low, moderate, and high soil burn severity classes) and unburned areas and surveyed coarse woody debris (CWD) in sites within the footprint of the 2020 Holiday Farm Fire and in surrounding Willamette National Forest and the H.J. Andrews Experimental Forest. We found few changes in overall soil C pools as a function of fire severity; we instead found that unburned sites contained high levels of pyrogenic C (PyC) that were commensurate with PyC concentrations in the high severity burn sites—pointing to the high background rate of fire in these ecosystems. An analysis of historical fire events lends additional support, where increasing fire count is loosely correlated with increasing PyC concentration. An unexpected finding was that PyC concentration was lower in low soil burn severity sites than in control sites, which we attribute to fundamental ecological differences in regions that repeatedly burn at high severity compared with those that burn at low severity. Our CWD analysis showed that high mean fire return interval (decades between fire events) was strongly correlated with low annual CWD accumulation rate; whereas areas that burn frequently had a high annual CWD accumulation rate. Within the first year postfire, trends in soil density fractions demonstrated no significant response to fire for the mineral-associated organic matter pool but slight increases in the particulate pool with increasing soil burn severity—likely a function of increased charcoal additions. Overall, our results suggest that

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these PNW forest soils display complex responses to wildfire with feedbacks between CWD pools that provide varying fuel loads and a mosaic fire regime across the landscape. Microclimate and historic fire events are likely important determinants of soil C persistence in these systems.

Keywords Soil carbon persistence · Wildfire · Pyrogenic carbon · Forest fire history · Coarse woody debris

Introduction

Wildfires have the potential to dramatically alter the carbon (C) storage potential, ecological function, and the fundamental mechanisms that control the C balance of Pacific Northwest (PNW) forested ecosystems. Forest soils hold vast quantities of C in soil organic matter, and the balance between C stabilization and destabilization influences not only forest C processing, but also atmospheric C and global temperature. Recent years have seen changing fire regimes in PNW “westside” (west of the Cascade crest) forests resulting from hotter and drier conditions that persist longer into the fall as a function of climate change, land use change including human encroachment into forests, and increased fuel loads from decades of management that centered around fire exclusion (Halofsky et al. 2020). And yet, fire is an integral part of PNW landscapes. Reilly et al. (2022) note that the PNW 2020 wildfires closely mirrored historical fire patterns. Their findings, drawing on reports from the early 1900s and evidence from paleo- and dendro-ecological records, suggest a continuity of significant wildfires over the past thousand years. These fires exhibited comparable timing (late August/early September), weather conditions, and often occurred in similar geographical areas. The westside forest region has experienced an estimated fire return interval ranging from ~160 years for the pre-settlement period (1550–1849) to ~500 years for the recent fire-suppression period, estimated using a ratio approach (Weisberg 2009). At the same time, evidence of increasing fire frequency and severity resulting from hotter and drier conditions and fuel loads that have built up over decades of fire exclusion in the PNW is well documented in recent years when compared with 20th century fires (Halofsky et al. 2020), and understanding relationships between forest fuels including coarse woody debris (CWD) and fire severity is important to our understanding of postfire C cycling and ecological functioning. Forest floor fuel loads contribute to fire energy and behavior; surface fuels like duff and CWD create conditions where smoldering may cause greater soil effects than if a fire moves quickly through an area. In fact, smoldering fires can persist belowground for months (Watts and Kobziar 2013). However, the opposite can also be the case: If the surface fuel load is high and a high severity fire moves through an area with plentiful additional energy sources available to consume, soil effects can be similarly severe (Leslie et al. 2014).

To take an ecosystem perspective, it is necessary to address the belowground impacts of wildfire and implications for forest soil C cycling. Although most studies have concluded that fires only significantly impact the top 2–5 cm of soil directly (DeBano 2000), fires of varying severity can burn roots and other organic matter deep into the soil (Leslie et al. 2014), potentially creating channels where fire effects are concentrated into hotspots of pyrogenic carbon (PyC). PyC, produced from the incomplete combustion of biomass and soil organic matter (SOM), is an important constituent of the more persistent soil C pool and is therefore relevant to the global C cycle (Abney and Berhe 2018; Bird et al. 2015; Lehmann et al. 2008; Preston and Schmidt 2006). PyC is a continuum of partially combusted organic material from lightly charred biomass to charcoal and soot that tends to have a much longer mean residence time (centuries to millennia; Bowring et al. 2022; Hammes et al. 2008; Lehmann et al. 2008) than other, non-pyrogenically altered, organic soil constituents (decades to centuries) due to its highly aromatic and condensed chemical structure of individual benzene rings substituted with carboxylic acids (Fig. 1; Abney and Berhe 2018; Schmidt et al. 2019; Torn et al. 1997). This increased resistance to biochemical oxidation makes PyC a comparatively longer term reservoir for terrestrial C than bulk SOM. Across global soils, PyC concentration varies widely—anywhere from 0 to 60% with a mean around 14%, but the PyC fraction is currently not included in global ecosystem models (Reisser et al. 2016), despite its ubiquity and significance as a store of soil C. Other studies (see, e.g., Matosziuk 2017) have quantitatively and

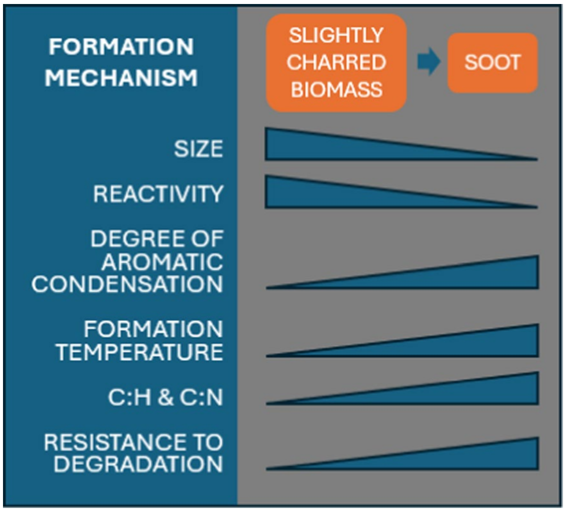


Fig. 1 A visualization of combustion temperature effects on pyrogenic carbon (spanning the continuum from charred biomass to soot) physical and chemical properties. (adapted from Masiello 2004)

qualitatively assessed soil PyC and have found that in general, lower severity prescribed fires produce PyC that tends to be less aromatic and in lower concentrations than do fires that burn with high severity. Between charring temperatures of 250–500 °C, organic matter (OM) becomes increasingly aromatic; above charring temperatures of 500–700 °C, OM becomes increasingly condensed (Masiello 2004; Matosziuk 2017; Schneider et al. 2013). The effects of varying fire severity on soil PyC chemistry and concentration in soils are therefore relevant to short and long-term soil C cycling in PNW forests.

Several decades of studies have attempted to quantify PyC to varying degrees of success and comparability. Methods range from physical separation of charred material based on visual inspection (e.g., Santín et al. 2015) to intensive analytical methods followed by spectroscopy (e.g., Hammes et al. 2007). The benzene polycarboxylic acid (BPCA) method used in the present study is advantageous because it can provide information about PyC chemical structure and PyC concentration (Masiello 2004). However, results from the BPCA method can vary between different laboratories due to variations in specific pre-processing steps, equipment, and chromatographic settings. The present study uses a high-throughput method, discussed further in our "Methods" section, to quantify only the most readily and consistently identified BPCA, B6CA (mellitic acid).

A longstanding paradigm in biogeochemistry is that frequent disturbance leads to loss of SOC, and yet, Pellegrini et al. (2022); see also, Jones et al. (2019) have recently shown that ecosystems can exhibit contrasting and sometimes counterintuitive responses to wildfire. While disturbances such as forest harvest contribute to factors like erosion that lower plant productivity potential, soil C responses to wildfire can be highly variable despite overall declines in biomass inputs (Pellegrini et al. 2022). For example, there can be compensatory gains in stable, pyrogenic SOC that offset some proportion of combustive C losses depending on fire and ecosystem conditions. Wildfires that vary in duration and severity may impact SOC stabilization and destabilization processes and soil density fractions in both the short and long term. Additionally, plant roots and soil microbes play important and sometimes competing roles in soil C stabilization and destabilization, affecting both mineral-associated organic matter (MAOM) and particulate organic matter (POM) pools. Root-derived, microbially processed C compounds make up a substantial portion of MAOM, a fraction of mineral soils that tends to persist in soils as a result of the integrated physical, chemical, and biological mechanisms of organo-mineral complexation (Cotrufo et al. 2019). Events like high severity wildfire that cause major interruptions to C processing, in addition to causing direct tree mortality, may also impede root and rhizosphere function by releasing an influx of dead fine root material while simultaneously arresting root exudation, which would tend to more heavily impact the MAOM fraction. However, the POM soil fraction can also contain longer-lived, more aromatically condensed biomolecules such as PyC (Crow et al. 2007), and this more labile and readily combustible fraction may be more vulnerable to immediate fire effects than the MAOM fraction.

The processes that control the transport and cycling of PyC across complex landscapes that vary in soil burn severity (SBS) and topographic position can impact soil C concentration and composition, resulting in relative differences in PyC, MAOM, and POM pools. While differing fire severity may impact the balance between C losses and gains, site-level differences in landscape features like topographic position, elevation, climatic conditions, and pre-burn vegetation and coarse woody debris (CWD) are also important drivers of SBS and soil C consequences. To investigate the immediate effects of wildfire with variable SBS in a westside forest, we sampled soils and CWD during 2021, 10 months after the 2020 Holiday Farm Fire in Oregon, USA. A significant advantage of our site is that a ~ 500 year fire history has been documented in most locations. Because most studies of fire severity effects on ecosystem properties use the "natural experiment" approach (i.e., multiple fires are not set across a landscape by the researcher for a true experimental design), effects of previous land management or fire history are often unable to be determined. However, management, including harvest and previous wildfire or anthropogenic burns, may have significant effects on fuel loads, resident soil C, and future fire behavior (Harris and Taylor 2017).

In this study, we explore the question: How does a major disturbance like wildfire influence (a) the processes that control soil C stabilization and (b) the consequent soil C persistence in the first year postfire? To address our research question, we formulated several hypotheses: In regions of severely burned forest stands (i.e., high SBS class), pervasive tree mortality would reduce the priming effect of the rhizosphere, but cause a significant influx of dead root material, leading to increases in MAOM-C but decreases in POM-C relative to control soils. We predicted that these changes to soil C processing would be rapid: In a litter bag decomposition study conducted many years previously in our study area (HJA), Chen et al. (2002) found that 40% of fine roots in this ecosystem decompose within the first two years, most of which occur in the first year. Thus, we expected the incorporation of dead root materials into MAOM-C, via a presumed route of microbial biomass within the first year after fire, to produce measurable increases in the MAOM-C pool relative to control soils. Our second hypothesis was that in regions of low to moderate SBS, there would be little immediate or long-term alteration to soil C dynamics or MAOM pools as root growth from surviving large trees should compensate for any fire-derived root loss. Although aboveground litter and CWD may be reduced relative to unburned sites, these matter much less to soil C stabilization than do fine roots. We additionally hypothesized that soils from high SBS sites would exhibit a greater degree of aromatic condensation in their pyrogenic fraction than would soils from low SBS sites because the degree of aromatic condensation tends to follow the combustion temperature (i.e., higher temperature produces more aromatic condensation). We also predicted that the BPCA signature in the light fraction (POM and less dense material) would demonstrate a higher degree of aromatic condensation in the first year in the burn sites relative to the unburned sites. While we expected that the incorporation of dead root materials into MAOM would take place relatively quickly, we expected that the more charred, less dense material of pyrogenic origin would take longer to incorporate into the mineral soil. Finally, we hypothesized that because of the direct combustion of a large proportion of the CWD pool under a high severity fire scenario, SOC would be significantly reduced in the high soil burn class but not in the moderate or low soil burn classes, relative to the control.

We collected mineral soils at four depth increments from burned (low, moderate, and high SBS classes) and unburned areas and surveyed CWD in sites within the footprint of the 2020 Holiday Farm Fire and in surrounding Willamette National Forest and the H.J. Andrews LTER (Long Term Ecological Research site; HJA). To separate mineral-associated and particulate organic matter fractions, we density fractionated composite soil samples by depth increment. Because we expected the most immediate changes to happen in the light fraction within the first year post fire, we further analyzed the light fraction (POM) to determine pyrogenic C content using a high-throughput version of the benzene polycarboxylic acid (BPCA) method followed by quantification by HPLC. Our results relate SOC and PyC content in the light density fraction to SBS class, with implications for post fire soil C persistence.

Methods

Study area

The Holiday Farm Fire ignited in September 2020, likely from downed power lines (Duvernay 2020; USDA Forest Service—Willamette National Forest 2020), and spread rapidly to burn parts of the H.J. Andrews Experimental Forest LTER and into the surrounding Willamette National Forest in the westside Oregon Cascades (Fig. 2). Our selected

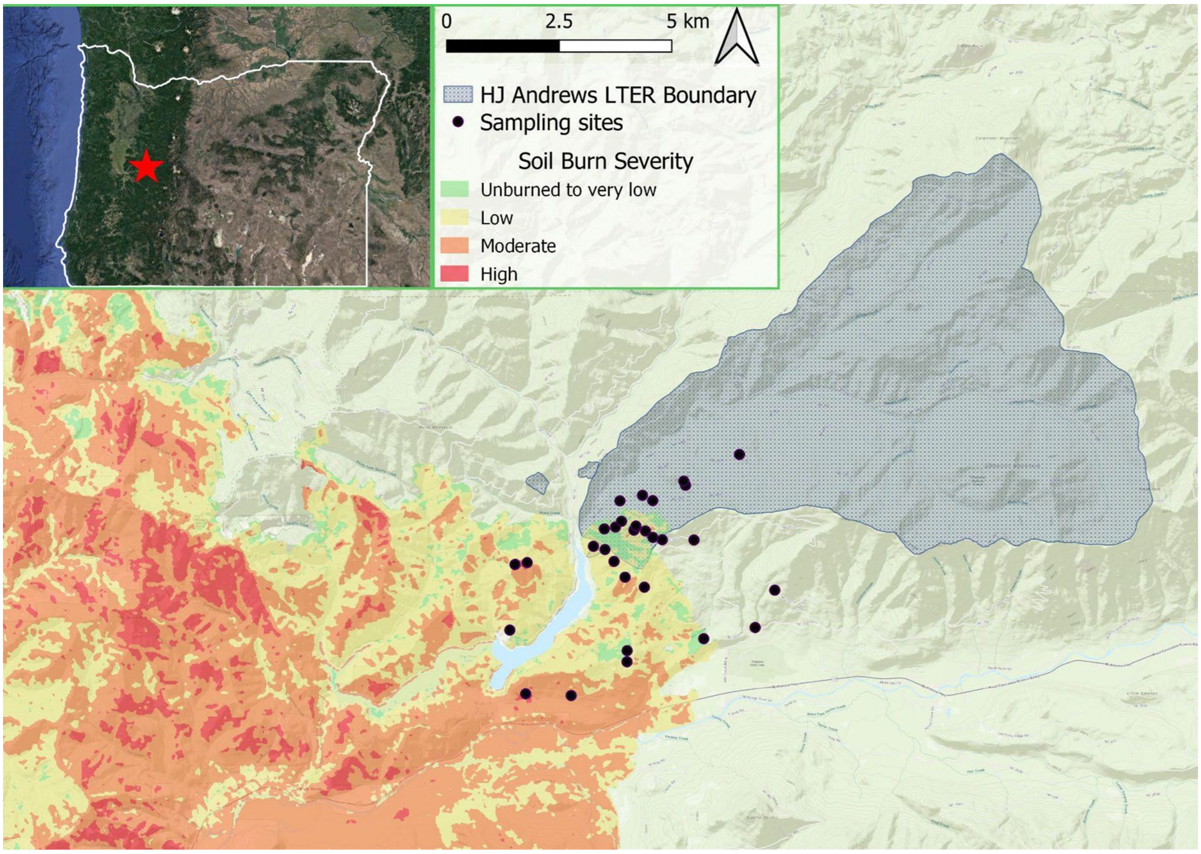


Fig. 2 A map of sampling site locations in burned and unburned areas following the Holiday Farm Fire in Oregon's westside Cascades (Data source: Soil Burn Severity classes from BAER: USDA 2020)

study area comprises old-growth and second-growth coniferous forest with complex, steep topography (study area is within 5 km of 44.19151, -122.24850; see Supplementary Table S2 for site-level elevation and slope) and well-drained soils derived from volcanic, colluvium, and residual materials. Low elevation forests are dominated by Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco), western hemlock (*Tsuga heterophylla* (Raf.) Sarg.), and western redcedar (*Thuja plicata* Donn ex D. Don), while higher elevation forests are dominated by noble fir (*Abies procera* Rehd.), Pacific silver fir (*Abies amabilis* Dougl. ex Forbes), mountain hemlock (*Tsuga mertensiana* (Bong.) Carr.), Douglas-fir, and western hemlock. The climate is maritime Mediterranean, with wet mild winters and dry cool summers. Mean monthly temperatures at elevations within our study area range from 1 °C in January to 18 °C in July and most precipitation falls between November and March, averaging 230 cm yr^{-1} (Zald et al. 2016).

Geospatial analysis and stratification

We used BAER (Burned Area Emergency Response) mapped SBS (USDA Soil burn severity dataset 2020) for site stratification and selection in combination with GIS layers including the 2008 lidar derived products for HJA and some surrounding Willamette National Forest (Andrews Forest 2013) for terrain features and aboveground biomass and the nDSM (normalized digital surface model) derived from 2008 lidar for elevation. We vectorized the BAER SBS map and assigned polygons based on SBS classes, which BAER categorizes as unburned to very low, low, moderate, and high SBS (Parsons et al. 2010). The USFS BAER team began their assessment of burned area on

BLM lands September 30th, 2020–23 days after the initial wildfire ignition and completed their assessment by October 16th, 2020 (USDA Forest Service – Willamette National Forest 2020). For our study, we selected control (unburned) sites based on the unburned to very low class and unburned areas adjacent to the fire, then field-verified and moved sites as needed. We used an HJA research site layer to exclude existing previous or ongoing research plot locations such as permanent vegetation plots from our site selection (HJ Andrews 2019). We also used HJA watersheds, streams, trails, and roads layers to determine site access and placement. HJA watersheds 1, 2, and 9 burned fully or partially and sites were preferentially selected in those watersheds to complement other ongoing biogeochemical and nutrient cycling research. We used OpenTopoMap and Google Earth imagery for additional elevation, slope, and aspect verification, especially outside of the HJA boundary.

We used R and QGIS for GIS analysis and data visualization to produce a stratified random sampling map within BAER-classified SBS polygons. We randomly selected initial sites in each SBS stratum, then systematically narrowed selected sites by accounting for distance from roads, trails, waterways, and previous or ongoing research plots. We clipped the BAER map to the extent of Holiday Farm Fire footprint (for burn plots but not unburned plots), masked out regions outside of 5000 m distance from the HJA perimeter, buffered the waterways layer so that plots were placed at least 50 m from streams, buffered the roads and trails layer so that plots were placed between 50 and 200 m from roads or trails, and buffered the HJA existing research plots map so that sites were chosen at least 30 m from already established ongoing research plots. Our selected sites are 50 m^2 and represent 5 replicate plots of each low, moderate, and high SBS ($n = 15$). We then selected 15 unburned control plots for a total of 30 plots (Fig. 2). Each control plot was within 50 m elevation difference of at least one SBS plot with a similar topographic position (aspect/simple cardinal direction class: N, NE, E, SE, S, SW, W, NW) and same general slope class (gentle 0–5% grade, moderate 5–15%, steep 15%+). Control plots did not burn in the 2020 Holiday Farm Fire, but they have certainly experienced previous fire events.

Field sampling

We conducted field sampling during June-August 2021, about 10 months after the start of the Holiday Farm Fire. Using a handheld Garmin GPS and topographic maps, we surveyed and sampled sites in random order during 3- to 5-day field campaigns. Upon initial site access, we performed field verification of SBS classification based on the methods of Meigs et al. (2009) and USFS BAER SBS field methods (USDA Soil burn severity dataset 2020). Unburned stands typically contained heavy fuel accumulations and high tree and understory vegetation density. Low SBS stands had partial bole scorching, high tree survivorship, and rapid recovery of surface litter, while moderate SBS stands showed increased bole scorch heights, some overstory mortality, and evidence of widespread surface soil and litter burn. High SBS stands exhibited near 100% tree mortality and sometimes, but not always, thick understory vegetation (shrubs and herbs) that had emerged postfire, in addition to complete coverage of soil burn and a noticeable ash layer on the soil surface. If field conditions of a site were different than originally classified or site access proved too difficult, a new site was selected according to previous criteria. Each site was geolocated by recording coordinates in the Garmin GPS unit and photos were taken of the soil surface and surrounding vegetation.

Coarse Woody Debris (CWD) transects were performed to assess the size, position, and amount of burn and decay on forest floor debris following the methods of Meigs et al. (2009) and the USFS Down Woody Debris field guide (Harmon and Sexton 1996). CWD transects consisted of four 15-m transects (radiating in each cardinal direction starting at plot center) and included snags as long as they were >45 degree angle from vertical. Field technicians recorded all CWD greater than 10 cm diameter within 1 m on either side intersecting with the transect, and recorded the location (distance along transect), decay class, length, diameter, and burn class. Decay classes ranged from 1, freshly fallen intact logs to 5, no remaining structural integrity and burned classes ranged from 1, slight/superficial charring but still structurally sound, to 5, fragmented charcoal pieces/ash still recognizable as coarse debris (Supplementary Table S1). Vegetation surveys were performed in each plot and intended to enumerate a census of the tree and understory vegetation present, with plant identification aided using the Seek App. Percent cover of vegetation was also noted.

Three replicate soil samples of each depth increment were taken at random locations within each site and later composited by depth in the laboratory. If an organic horizon was present, we measured its depth and removed 10 cm L × 10 cm W × O horizon depth to access the mineral soil below. If ash was present overlying the mineral soil, it was sampled as part of the topmost horizon as it was never thicker than 1 cm. Sampled depth increments of mineral soil included 0–5, 5–10, 10–20, 20–30 cm. We used a mallet and wood cookie to pound a 10 cm diameter PVC core into the mineral soil, then carefully extracted the intact core for 0–10 cm. A longer PVC core was used to extract the 10–30 cm soils. If soils were too dry or rocky to extract in a PVC core, a small soil pit was excavated with known volumes of soil removed for bulk density calculations.

Lab analyses

Soils were transported in gallon ziplock bags in coolers back to the laboratory in preparation for analysis. Field-moist soil cores were weighed then air-dried for bulk density and water content. To extract soil from each PVC core, we used a reciprocating saw to precisely cut through the PVC and soil to partition the 0–5 and 5–10 cm sections, which were then removed for weighing and sieving.

We sieved soils to < 2 mm and removed large roots and rocks. Rock volumes were assessed by displacement for bulk density correction and rock masses were used for correcting mineral soil mass. Coarse roots were removed and weighed, then dry sieved soil samples were composited by depth for plot-level lab analyses. Soil organic C and Nitrogen (N) content was assessed by dry combustion of pulverized subsamples on an Elementar vario macro cube. We density fractionated composite soils into light (POM) and heavy (MAOM) fractions using 30 g air-dry soil and 1.85 g cm^{-3} Sodium polytungstate (SPT) following the methods described in Pierson et al. (2022). Light and heavy fraction soils were weighed, dried, and pulverized; subsamples of each were analyzed for SOC and N while the remainder was reserved for PyC analysis.

PyC was assessed using a high-throughput version of the BPCA method followed by quantification by HPLC (Glaser et al. 1998; Matosziuk 2017; Wiedemeier et al. 2013). We analyzed the light (POM) fraction soils for pyrogenic carbon content of a single BPCA, B6CA (mellitic acid), which is the first BPCA to elute on the chromatogram and can thus be identified with the highest confidence. Each BPCA run of 24 samples included duplicates and blanks. The BPCA method is both quantitative and qualitative and breaks down the large graphitic sheets of black carbon into individual benzene polycarboxylic acids (BPCAs) that can be separated and quantified by high performance liquid chromatography (HPLC). Standards with known concentrations of B6CA were run alongside samples and were positively identified in the resulting chromatograms of the six-point calibration curves (Supplementary Figure S1). We expected the largest differences between burn severities within the first year post fire to manifest in the light (POM) fraction, since changes in the heavy (MAOM) soil fraction are slower to materialize (Crow et al. 2007). Thus, we analyzed only the light fraction (POM) samples for B6CA concentration in this first year of the study.

CWD analysis

Measured CWD dimensions, decomposition and SBS class were used in combination with parameters from a first-order decay model derived from tree attributes in the same research forest as the present study (Harmon and Sexton 1996) to model CWD input and export rates. The diameter and length of each piece of CWD was used to calculate the volume of each cylindrical piece present within the 120 m^2 transect area. The measured decay class was converted to an estimated percent loss over a given time period, with the time period estimated from the diameter size class of the CWD used in the decay model mentioned above. The above information was used to model the estimated age of each piece of CWD and the estimated mass that had decayed since the woody biomass entered the CWD pool from the aboveground biomass pool, in addition to the mass remaining. A mean wood accumulation rate and wood departure rate from the CWD pool were then calculated as follows:

$$\text{Mass original} = \rho[\pi(d/2)^2 \times l],$$

$$\text{Mass remaining} = \rho[\pi(d/2)^2 \times l] \times c,$$

where ρ = wood density, d = diameter of CWD, l = length of CWD, c = decay class.

Decay rates (*k (d)* from Harmon and Sexton 1996 were related to time (*T*) and used to calculate departure rate (removal from the CWD pool) as follows:

$$Z = k\,(d)$$

$$T = -\left[1/Z\right] \times \ln\left(1 - (c/100)\right)$$

$$\text{Departure rate} = \left[\text{Mass original} - \text{Mass remaining}\right]/T$$

Analysis of historical fire events

To assess the potential contributions of historic fire events to the soil PyC pool, we used a geospatial data layer of reconstructed fire history available for the H.J. Andrews Forest LTER with fire events dating back to the 1800s (Giglia and Swanson 2013). Fire history data were not available for the entirety of our post-Holiday Farm Fire sampling area, so our analysis of fire history was constrained to sites that fell within HJA. We compared the count of fires since 1800 as well as the fire frequency (mean fire return interval) to our measured B6CA concentrations and CWD accumulation and decay rates. Relationships were assessed using simple linear regressions.

Statistical analysis

We calculated the C concentration of each soil fraction (POM and MAOM). SOC stocks were calculated using the bulk density and thickness of each soil depth core as follows:

$$\text{SOC} = \text{C} \times \text{LT} \times \text{BD} \times (1 - \text{R}),$$

where C is the soil organic carbon concentration (%), LT is the layer thickness, BD is the layer bulk density, and R is the volumetric rock content.

We compared soil fraction percent C, C:N ratio, SOC stock, and B6CA concentration in light fraction soils by depth and by SBS class to unburned control soils using unpaired t-tests ($n = 5$ for treatment and $n = 15$ for control groups at alpha = 0.05). To assess differences between each SBS class and control sites, two-way ANOVAs were performed by normalizing each variable to the mean of the control class (observed-expected/expected) and using blocking factors of SBS and soil depth, where the control measurement represented the expected value and SBS measurement represented the observed value. The mean of each variable by SBS ($n = 5$ each) was normalized to the average control set ($n = 5$) for that SBS class prior to running ANOVAs. Pairwise differences were assessed using Tukey's HSD.

Results

Mixed canopy Douglas-fir, western hemlock, and bigleaf maple (*Acer macrophyllum*) dominated unburned sites. Common understory shrubs and trees were red huckleberry (*Vaccinium parvifolium*), rhododendron (*Rhododendron macrophyllum*), salal (*Gaultheria shallon*) and vine maple (*Acer circinatum*). In unburned sites the O horizon ranged from a light duff layer (< 1 cm thick) to a 12-cm thick horizon. High SBS sites had no living canopy and sparse to moderate understory vegetation (vegetation had emerged in the 10 months post fire), while low SBS sites had intact canopies and sparse to occasionally abundant understory vegetation and moderate sites had a partly burned canopy.

There were few statistically significant differences between the C concentration in either of the density fractions or in the bulk soil, but there did appear to be a slight trend of increasing mean percentage carbon with increasing SBS in the POM fraction, relative to control, across depths below 5 cm (Fig. 3). In the 5–10 cm depth increment, mean POM-C was significantly higher in the moderate and high SBS class than the control soils ($p = 0.04$; $p = 0.017$) and in the 10–20 cm depth, POM-C was significantly higher in the high SBS than control POM ($p = 0.011$). The MAOM fraction C concentration was similarly low across depths and SBS classes, while the bulk soil slowed a slight trend of decreasing C concentration with depth, but no statistically significant differences by SBS class.

Trends in C: N ratio across burn severities and depths were not statistically significant for the most part; the only significant differences manifested in

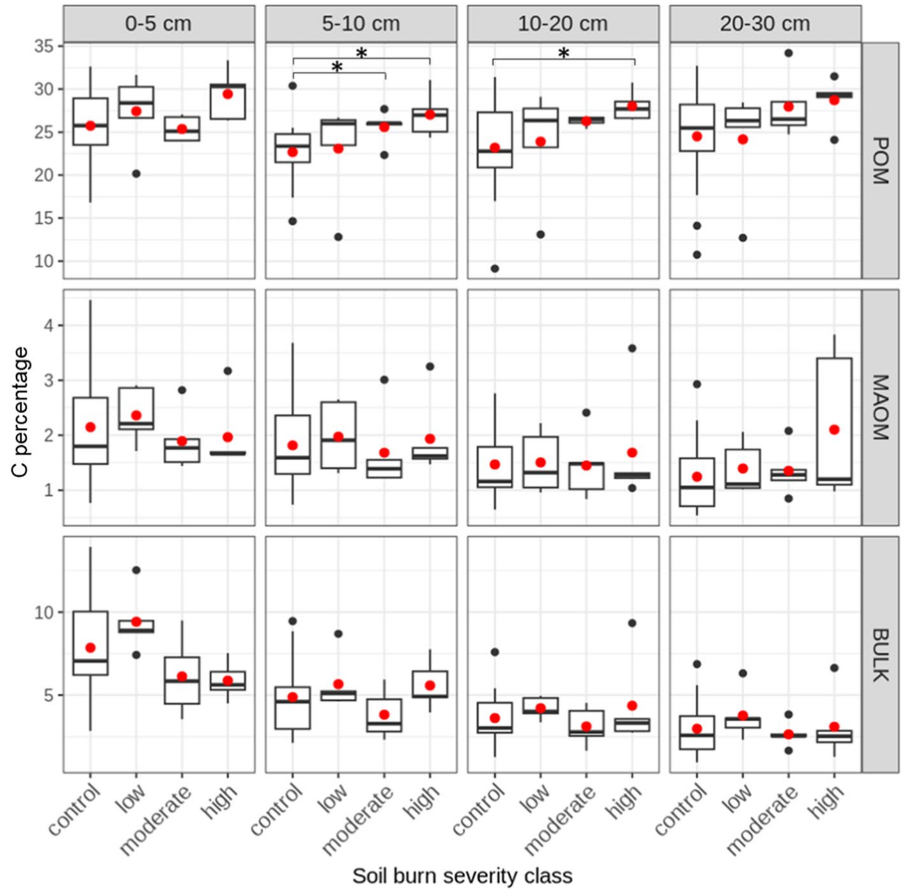


Fig. 3 Percent C in each soil fraction (right side facet; *BULK* whole soil, *MAOM* mineral-associated organic matter, *POM* particulate organic matter) by SBS class (bottom) and soil depth increment (top facet). Means are represented by red points, the midline of each box represents the median, and the tops and bottoms of the boxes represent the third and first quartile of the data, respectively. Statistically significant differences are represented by asterisks at $\alpha = 0.05$

the 0–5 cm depth increment with significantly lower C: N in the low SBS class compared with the control soil in the POM fraction ($p = 0.015$) and significantly lower C: N in the moderate and high SBS compared with the control in the bulk soil ($p = 0.016$; $p = 0.041$, respectively; Fig. 4). POM fraction soils had a wide range (30–65) in C: N that tended to increase with depth. The variation in C: N also increased in the deeper soils and was particularly high in the 10–20 and 20–30 cm depths in the POM fraction of control soils. POM fractions also demonstrated an interesting, but non-statistically significant drop in C: N in the 10–30 depths from control to low SBS, followed by an increase to around the mean C: N of control soil in the moderate and high SBS sites. C: N was quite consistent across all depths and SBS classes in the MAOM fraction (mean C: N ~ 10–15).

In the POM soil fraction and across all depths, mean SOC stock was similar in the control and low SBS, but decreased substantially in the 0–5 cm depth of the moderate SBS class ($p = 0.042$) and showed a similarly large decrease in the high SBS except in the 10–20 cm depth, where variation was high and the mean similar to control and low severity (Fig. 5). In the MAOM fraction, C stock increased slightly with depth but did not have any significant differences by SBS (see also Supplementary Tables S3 and S5).

PyC (B6CA) concentration in the POM fraction was high across unburned control soils with high variation within each depth but a similar mean concentration across all depths (Fig. 6). In all depths except 5–10 cm, mean PyC concentration increases slightly from low to high SBS. Statistically significant differences between the unburned control and burned soils manifest in the 20–30 cm depth, in which PyC concentration was significantly less in low burn severity than in the control ($p = 0.046$).

Historical fire records reconstructed from a combination of burn scars, tree rings, and other management data were available for the HJA region and

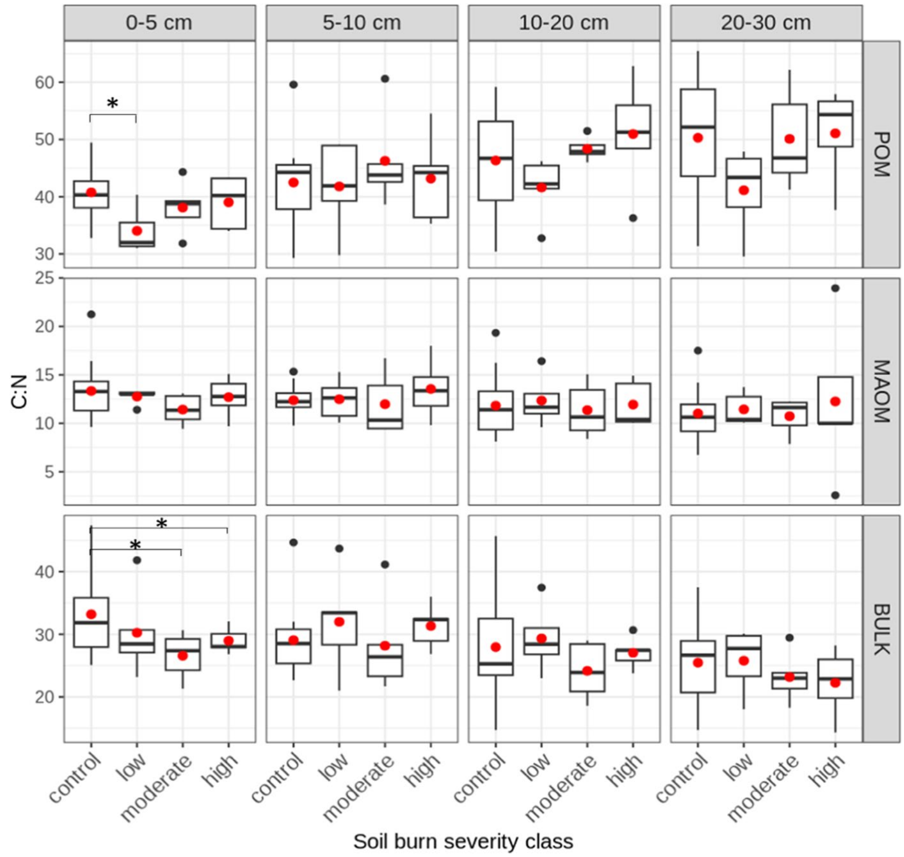


Fig. 4 Soil C: N ratio in each fraction (right side facet; *BULK* whole soil, *MAOM* mineral-associated organic matter, *POM* particulate organic matter) by SBS class (bottom) and soil depth increment (top facet). Means are represented by red points, the midline of each box represents the median, and the tops and bottoms of the boxes represent the third and first quartile of the data, respectively. Statistical significance is represented by the asterisks at $\alpha = 0.05$

slightly southeast into Willamette National Forest (Giglia and Swanson 2013). In the small ~ 2 km^2 area where fire history overlapped the Holiday Farm Fire and up to 2 km further northeast into the HJA where control sites were located, count of historical fires and mean fire return interval were regressed against PyC data to investigate whether legacy fire effects impacted soil PyC concentration. We found a weak linear relationship between fire count and mean PyC concentration of 10–30 cm soils for the plot locations in which there was overlap between the two datasets, with mean PyC concentration increasing with fire count (Fig. 7; $R^2 = 0.21$, $p = 0.075$). The control sites that remained unburned in the Holiday Farm Fire demonstrated high overall PyC concentrations relative to the sites that burned in the 2020 fire.

Loss in CWD as a function of SBS is presented in Table 1. Control sites that did not burn in the Holiday Farm Fire occasionally contained a low background rate of burned debris, resulting in the 2.6% (+/− 1.7% SE) loss in mass due to a previous fire event, while the burned sites ranged from a mean of 47% (+/− 8.7% SE) to 81.2% (+/− 7.8% SE) CWD mass lost due to fire.

A linear regression between CWD accumulation rate (kg m^{-2}) and mean fire return interval (years between fire events) for control plots that were unburned in the Holiday Farm Fire shows a strong negative relationship (Fig. 8; $R^2 = 0.86$, $p = 0.002$) indicating that in areas where fuel accumulation rate is high, more frequent fires occur.

Discussion

This study serves as a baseline assessment of soil C density fractions and of PyC in the POM fraction ~ 10 months after a wildfire event combined with an assessment of CWD, with implications for future C cycling and C stabilization mechanisms. Results indicate that postfire soil C and PyC dynamics are more complex than one might expect from fire-severity

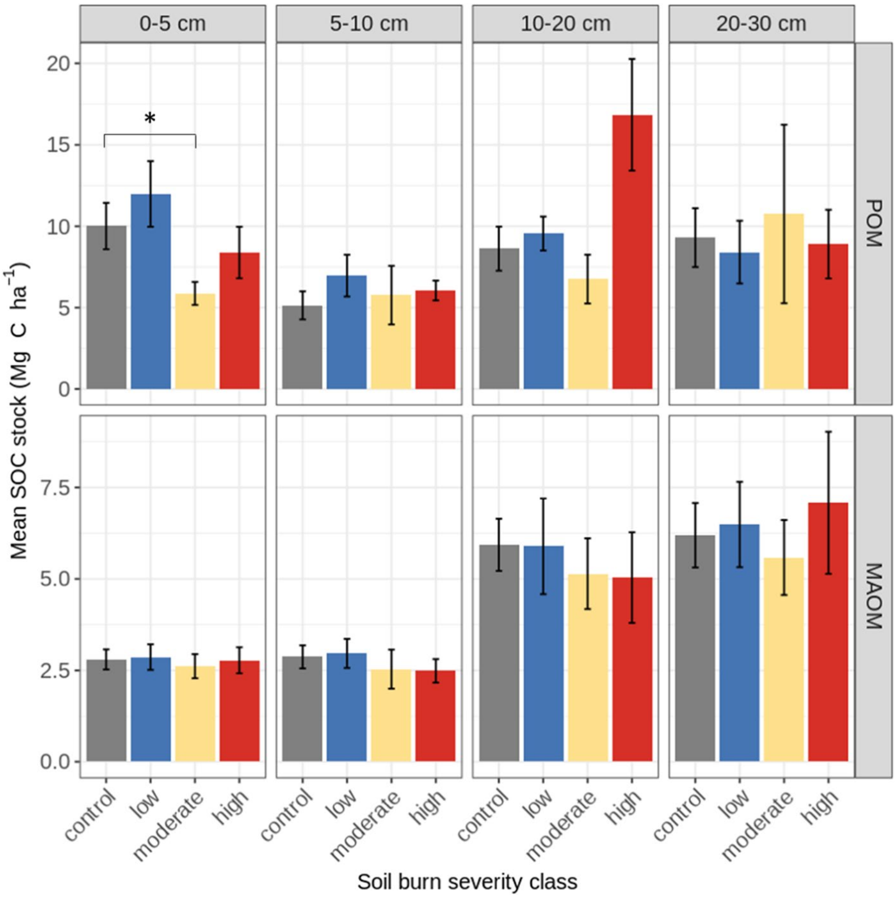
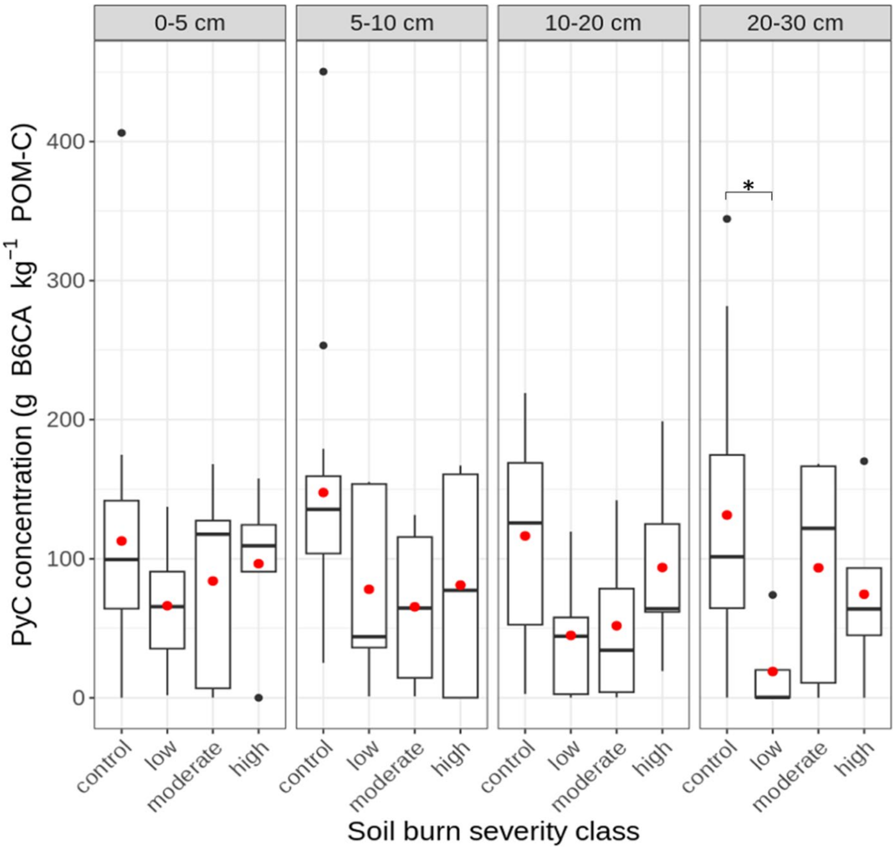


Fig. 5 Mean SOC stocks (error bars represent +/− 1 SE) by soil depth increment and fraction. Statistically significant differences (α = 0.05) between each SBS class and the control group are noted by asterisks

related differences from a single fire event. Our hypothesis that SOC would be reduced under a high severity burn scenario as a function of CWD losses was supported (Table 1), but we acknowledge that this study did not assess the potential for SOC loss through avenues such as erosion. In an ecosystem that is variably undergoing CWD and/or SOM accumulation or erosion, using soils from control sites as we did is preferable to any use of pre-fire soil sampling. We found that regions that burn more frequently tend to have a higher CWD accumulation rate, indicating that they are likely highly productive areas with faster vegetation turnover, and hence a high fuel load. In contrast, regions that burn less frequently have a lower rate of CWD accumulation, indicating that they are lower productivity sites (Fig. 8). While CWD accumulation is not solely a function of fire frequency, we provide evidence of a strong connection between them that likely drives nutrient cycling rates in these fire-adapted environments.

Our results for fire impacts to soil C pools were more complex. We initially hypothesized, based on results from nearby experimental plots (Pierson et al. 2021), that relative to control, high SBS sites would exhibit gains in MAOM relative to POM resulting from a presumed loss of root exudation and an influx of dead root material. We did not find evidence of an increase in MAOM within the first year postfire; we instead found that the proportion of POM increased in burned sites relative to unburned sites, indicating that perhaps a postfire nutrient flush had contributed to the decomposition and fragmentation of plant material, or that dead roots and charred material resulted from fire, but that changes to the MAOM pool take longer than ten months to manifest. The MAOM pool generally represents a longer-lived, more persistent soil C pool that is less likely to experience immediate fire effects compared with the POM pool, which contains more fragmented plant material vulnerable to loss from combustion. MAOM typically

Fig. 6 PyC concentration in the POM-C fraction of soil (g B6CA kg^{-1} POM-C) by SBS class (bottom) and soil depth (top). Means are represented by red points, the midline of each box represents the median, and the tops and bottoms of the boxes represent the third and first quartile of the data, respectively. Statistical significance is represented by the asterisks where α = 0.05



takes longer to form since it is a result of complex interactions between reactive minerals, microbes, and root exudates, among others, and its resulting stability stems from its physical and chemical properties and interactions with the soil matrix (Cotrufo and Lavallee 2022). It may be more resistant to the effects of fire given strong C compound adsorption to clay minerals and metal oxides, physical protection in soil aggregates, higher thermal stability as a function of its advanced decomposition stage, or the greater moisture retention provided by the sorbed clay particles (Pellegrini et al. 2020). Further, the proportion of MAOM increases with depth in the soil profile, with deeper depths not only being less directly exposed to fire effects, but also having reduced oxygen availability and less combustive efficiency.

We found inconclusive evidence for our hypothesis that low and moderate SBS sites would experience little change in C dynamics postfire. Across bulk C, fractional C pools, and the PyC pool, low and moderate SBS sites showed differing C trends to those of the control and SBS sites. While for the most part statistically insignificant, the trends manifested consistently across data types, including CWD, again pointing to fundamental differences in ecological processes in regions that tend to burn with high severity fire compared with regions that tend to burn with low severity fire. It remains possible that in these generally high slope forests (see Supplementary Table S2), some amount of postfire erosion occurred, resulting in losses of surface CWD and/or soil, as has been documented in other studies (e.g., Cotrufo et al. 2016). It is also possible that postfire erosion could have differentially affected more severely burned sites that presumably had less remaining soil structure and fewer plant roots to hold soils in place. It is difficult to assess the amount of erosion that may have taken place in the ten months between the fire and soil sampling, so this should be an avenue of further exploration in future studies in this region.

Our hypothesis that PyC concentration would be greater in the POM fraction of high severity burn sites relative to control sites was not supported and was also confounded by the unexpectedly high PyC

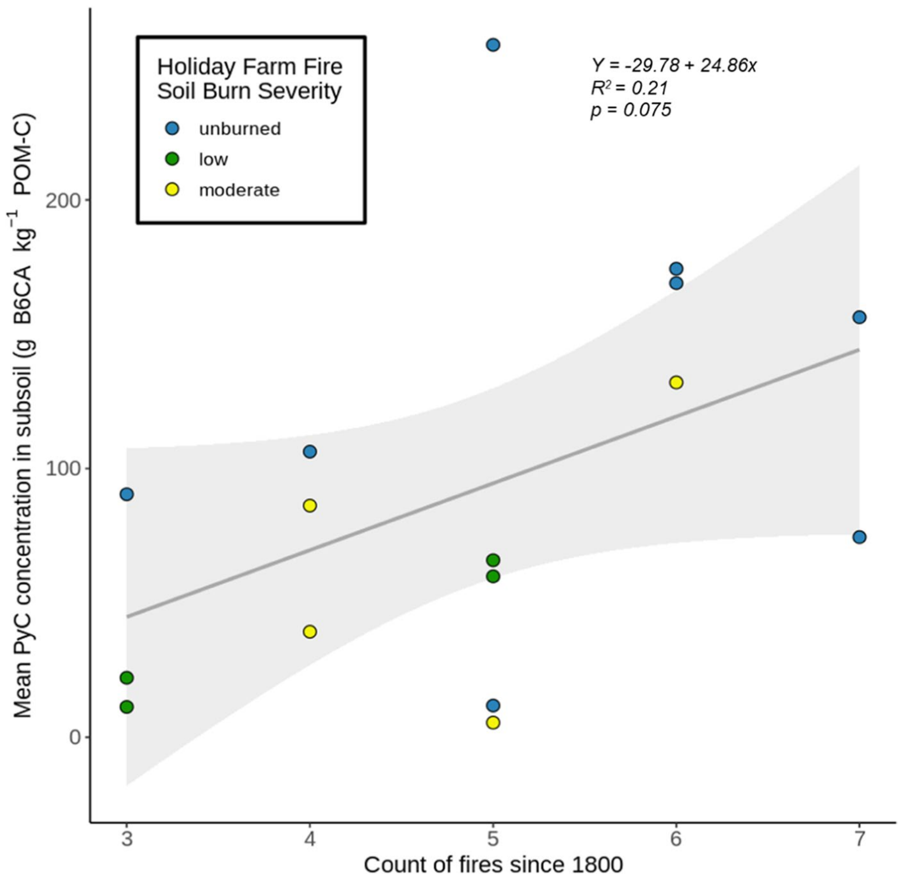


Fig. 7 For the regions where data overlap between historical fires and post-Holiday Farm Fire soils sampled, POM PyC concentration in 10–30 cm depths increases linearly with the number of fire events. There was no overlapping fire history data in the areas represented by high SBS in the Holiday Farm Fire, so only control, low, and moderate SBS sites are shown. The shaded area represents the 95% confidence interval around the linear model mean

Table 1 Percent Coarse Woody Debris (CWD) mass loss by soil burn severity class (+/− 1 SE).

Soil Burn Severity Class	Control	Low	Moderate	High
Mean percent loss in CWD due to fire	2.6% (1.7)	47% (8.7)	59.1% (10.5)	81.2% (7.8)

content in the unburned control sites (Fig. 6). The similar mean PyC content of unburned and high severity sites may be indicative of the longevity of BPCAs in the soil, providing evidence that they do tend to persist as a longer-lived form of soil C, and/or reflect the high frequency of fires in this region. While soil C concentration did not vary widely by SBS class within each fraction, C concentration and C: N ratio both trended upward with soil depth in the POM fraction while decreasing slightly in the bulk soil by SBS and with depth. Other studies have similarly reported postfire increases in fine particulate C (Bird et al. 2000), decreases in overall SOC amount (Bormann et al. 2008; Homann et al. 2015; Nave et al. 2011), and postfire decreases in surface C: N but little change in mineral soil C: N (Nave et al. 2011). We suggest that the slight upward trend in C concentration by SBS and depth while at the same time reduced C: N may be a function of multiple competing nutrient pathways. In the moderate and high severity sites, there had been some regrowth of understory vegetation in the 10 months postfire. Many of these early colonizers were legumes and were likely to have increased the soil N content in the 10-month period. In a meta-analysis of postfire C: N, Nave et al. (2011) report that forest assemblage plays an important role in fire-induced C: N changes, since conifers produce litter that has flammable resinous organic compounds, whereas the litter produced by hardwoods is generally less flammable. In our study area, mixed stands of

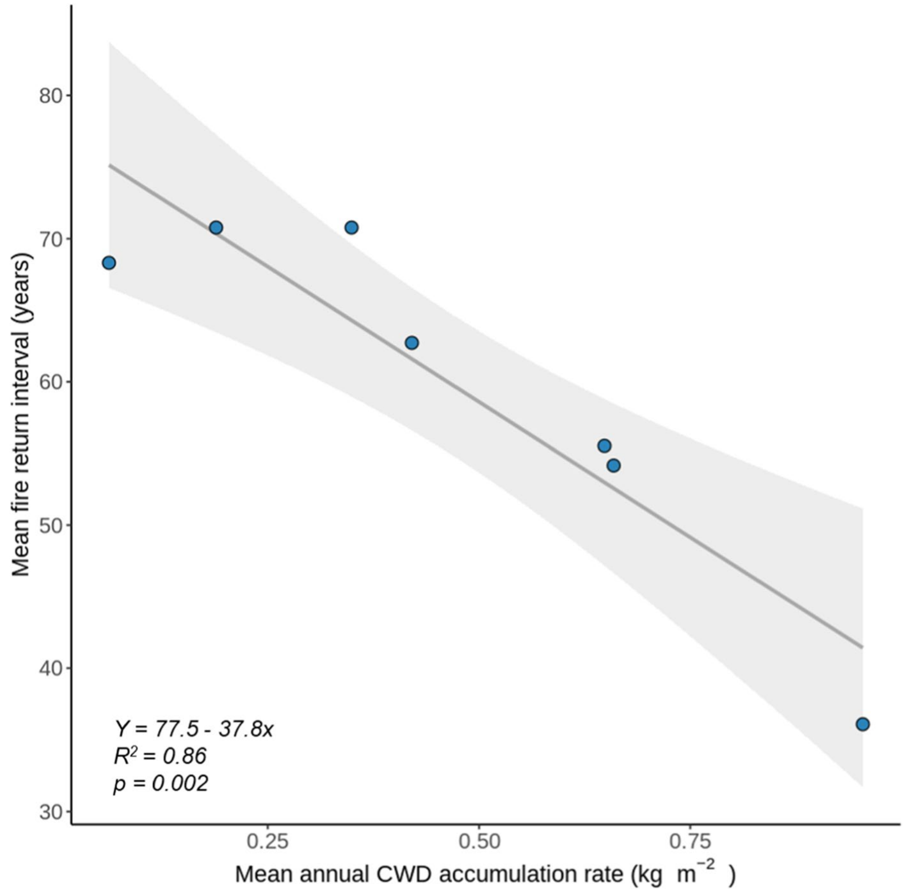


Fig. 8 Mean fire return interval (in years between fire events) as a function of mean annual CWD accumulation rate for control plots (points) that were unburned in the Holiday Farm Fire. The linear model with 95% confidence interval shading shows a strongly decreasing trend where at a high mean fire return interval (decades between fire events), the annual CWD accumulation rate is low whereas in areas that burn frequently, the annual CWD accumulation rate is high

conifers and hardwoods tend to grow at lower elevation in riparian areas (Zald et al. 2016) that should also have a higher moisture status and hence be less susceptible to high severity fire. These stand-level differences represent another manifestation of the patchy nature of SBS, feedbacks between fire severity and vegetation, and their implications for nutrient cycling.

Although most differences between C percent or C: N by SBS class were not statistically significant, the trend of increasing C in the POM fraction with increasing SBS, relative to control, may suggest that PyC in the form of low density charcoal has accumulated in the mineral soil relatively soon after fire. This may be a function of increasing charcoal content with increasing fire severity because the low density of highly charred material separates it into the lighter POM fraction, despite it having other properties more similar to heavy (MAOM) fraction material (Crow et al. 2007). We suggest that even low severity fires will burn along roots, depositing POM in the form of dead and charred roots to a depth of at least 30 cm in the soil profile. Changes in soil structure and collapse of pore spaces that occur postfire are well-documented (Santín and Doerr 2016), as are reports of fires continuing to smolder belowground for months (Watts and Kobziar 2013). Despite burning at lower temperatures, smoldering fires can ultimately transfer more heat to soils than higher severity fires (Kreye et al. 2011; Neary et al. 1999; Watts and Kobziar 2013) and when roots are consumed in this manner, PyC can be expected to be deposited in the root channels. A study of prescribed burn effects on soil macropore formation found that combustion of root material and root decay enhanced soil macropores and serves as one of the few studies to directly measure fire effects on soil pores (Leslie et al. 2014). Abney and Berhe (2018) report that because of its low density, a significant proportion of PyC formed or deposited on the soil surface is laterally transported away from the site by wind and water erosion. However, we found a relatively even distribution of PyC throughout the soil profile (Fig. 6), indicating that a large proportion of the PyC either forms in place through burning roots into the mineral soil profile, or that PyC deposited on the soil surface eventually incorporates into the mineral soil. It is evident that more studies of fire effects on roots are needed, particularly ones which trace root-derived C and PyC through the soil profile and through time.

We found that the highly aromatic B6CA (mellitic acid) tends to increase in concentration with increasing SBS, but that its concentration in unburned control soils remains high across soil depths, likely reflecting the high background rate of B6CA additions to soils in these fire-prone landscapes that have a long history of repeated fire events. Boot et al. 2015 similarly report that unburned and burned soils had equivalent PyC content in the 0–15 cm mineral soil, suggesting a high background rate of PyC additions over time. The surprisingly lower B6CA in low and moderate SBS relative to the unburned control and high severity sites suggests that the signal from legacy fire events outweighs the PyC additions from the Holiday Farm Fire, but also that there may be fundamental differences in the areas that burn at high severity compared with the areas that burn at low severity. At a landscape scale, fire severity shows a patchy, mosaic distribution that reflects landscape topography, elevation, and pre-fire fuel load (Bowring et al. 2022; Reilly et al. 2022). It is possible that the regions that burned at low and moderate severity are areas that have never or rarely experienced high severity fire – perhaps due to their particular topographic position and resulting higher moisture status, or else due to reduced NPP and less organic material available, preventing them from being highly combustible. Another potential explanation of the apparent decrease in PyC concentration from control to low and moderate is the comparative effects of a fast, moving, high-severity fire with a slow-moving, lower severity fire that smolders in the same location for a long time period. These avenues should be explored further in future studies. Within HJA, high and mixed severity fires are the most common fire regimes, with fire returns intervals of 80–200 years (Morrison 1990; Teensma 1987; Tepley et al. 2013). Additionally, non-stand replacing fires have been prevalent, leading to diverse pathways of successional development and considerable variability in stand structure (Tepley et al. 2013).

Legacy fire effects

The relationship between historical fire events (fire count since 1800) and PyC concentration suggests that a greater number of fires correlate with higher PyC concentration and fewer fires with less PyC (Fig. 7). The generally high concentration of PyC in soils that did not burn in the 2020 Holiday Farm Fire suggests that the fire return intervals and propensity for these ecosystems to burn regularly leaves a greater impact on the soil PyC signature than does any single fire event, pointing to the importance of legacy fire effects on this particular pool of more persistent soil C. The westside Cascades are fire-adapted ecosystems and biogeochemical cycling of energy and nutrients may need a much larger perturbation or many repeated disturbance events that remove nutrients from the system (such as forest harvest) to be interrupted or experience a baseline shift. Previous studies based on reconstructed fire histories in the westside Cascades report that early 20th-century fires followed infrequent, high-severity fire regimes (Agee 1993; Reilly et al. 2021, 2022; Spies et al. 2019).

Consideration of microclimatic and geomorphic differences between regions that burn at low or high severity is therefore important. For example, the amount and type of fuel consumed, maximum temperature, and duration that elevated temperatures were maintained are all factors that can be affected by fuel moisture levels, which can differ dramatically within short distances in the highly topographically complex westside Cascades forests. Higher elevation sites (> 750 m) in these forests have tended to follow a less frequent, higher severity fire regime as a function of the cooler, wetter climate and are less likely to start from lightning ignitions. In contrast, low to mid elevations have been more prone to lightning ignitions with a more frequent (35–125 years), mixed severity fire regime attributed to drier conditions (Agee 1993; Walsh et al. 2015). Both in the Cascades and other regions, burned areas tend to be maximized at intermediate moisture status (Archibald et al. 2018; Daniau et al. 2012; Krawchuk and Moritz 2011; Meyn et al. 2007).

Bowring et al. (2022) have pointed to the nonlinearities between SBS and pre-fire fuel conditions that are a function of climatic and vegetative differences. These differences in both SBS and pre-fire conditions result in different rates of PyC inputs, but ultimately high levels of dry fuel accumulation will enable greater combustion and produce higher levels of more aromatically condensed PyC (Bowring et al. 2022). Our finding that regions that remained unburned in the Holiday Farm Fire had similar PyC content to those that burned with high severity (Fig. 6) suggests that these are overall higher NPP areas that produce biomass that accumulates and adds to the CWD fuel load. Our finding that regions that quickly accumulate CWD burn more frequently (Fig. 8) lends further support.

A recent study on the southern end of Willamette National Forest about 80 km south of our study area performed an extensive fire history reconstruction and found distinct mean fire return intervals since the 1500s for differing forest series: Douglas-fir: 6–11 years, grand fir/western hemlock: 19–45 years, silver fir/mountain hemlock: 81–165 years (Johnston et al. 2023). They found that vapor pressure deficit was a strong predictor of mean fire return interval but that historical fire regimes across the western Cascades exhibited stand-level complexities ranging from stands that have been free of fire since experiencing a stand-replacing fire centuries ago, to stands that have been almost free of stand-replacing fires but have experienced persistent non stand-replacing fires for at least a century until fires ceased in the late 1800s (Johnston et al. 2023). This type of complex fire legacy that differs by stand type lends credence to our proposed mechanism for both a high background rate of PyC that overwhelms any recent additions from a single fire event and for the surprising reduction in PyC in low and moderate severity burn sites relative to control and high severity sites. Future studies should continue exploring how differences in soil PyC and CWD manifest at regular intervals following fire events, while accounting for the legacy fire history of a given region.

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Author contributions HPC drafted the manuscript with input from KL and AB. KL envisioned the study broadly, while HPC designed the study stratification and site selection and planned the data analysis. HPC and AB analyzed results with input from KL. HPC and RO performed the field sampling and AM assisted with BPCA laboratory analysis. All authors reviewed and agreed to the final manuscript.

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Data availability The datasets generated during and analyzed during the current study are available in the github repository, [https://github.com/hayleypc/HolidayFarm2020]. Data pertaining to the H.J. Andrews LTER may be accessed at https://andrewsforest.oregonstate.edu/data.

Declarations

Conflict of interest The authors have no relevant financial or non-financial interests to disclose.

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