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ORIGINAL ARTICLE

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Quantifying impacts of forest fire on soil carbon in a young, intensively managed tree farm in the western Oregon Cascades

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Abstract

Forest soils of the Pacific Northwest contain immense amounts of carbon (C). Increasing acreage burned by severe wildfire in the western Oregon Cascades threatens belowground C stocks. The objective of this research was to quantify the changes in soil C stocks, nitrogen (N) stocks, and relevant chemical and physical parameters after a severe wildfire in a young, intensively managed *Pseudotsuga menziesii* (Douglas-fir) tree farm in the western Oregon Cascades. This longitudinal study was originally established to detect soil C changes after a harvest; therefore, it offers insight into long-term soil C dynamics after compounding disturbances. Forest floor and 0–30 cm depth soil samples were collected for comparison before and after the fire and were then split into size fractions to assess the fire's effect on different grain sizes and forest floor compositions. Overall, soil C was approximately 40 Mg C ha^{-1} lower after the fire, equivalent to approximately 30% of soil C stocks. Of these decreases, two-thirds were in the forest floor and one-third were in the mineral soil. C stock losses were driven by changes in mass in every composite level. C concentration was unchanged in most levels while N concentration increased in certain levels. Losses extended further belowground than most previously studied soil C decreases from severe wildfire. The effects of wildfire on soil C stocks in industrial tree farms should be further explored to determine long-term trajectories of soil C and N.

1 | INTRODUCTION

Approximately 500 gigatons of carbon (C) held in temperate forest soils, equivalent to 25% of the world's total forested land, is at risk of acute loss from an increasing frequency of severe wildfire (Janowiak et al., 2017). The Pacific Northwest is a particularly C-rich region of vegetation and soils, with an area approximating 8% of United States forests but 12% of its C storage (Nave et al., 2022). The changing C stocks, cycling, and potential losses in western Cascades forests are therefore paramount to the global C budget.

The previous several decades of western US drought combined with over a century of fuels accumulation have increased both the frequency of wildfire and the acreage burned by large wildfires (Abatzoglou & Williams, 2016; Flannigan et al., 2009; Halofsky et al., 2020; Rogers et al., 2011; Steel et al., 2015; Westerling, 2016). Severe wildfire on forested landscapes directly threatens the aboveground biomass of trees, shrubs, and legacy wood as well as the forest floor and belowground mineral soil. Indirect effects, like C released to the atmosphere due to wildfire, exacerbates warming and further adds to climate trends that point to magnified impacts on C cycling (González-Pérez et al., 2004). Western Cascades forests are more susceptible to high severity wildfire in periods of drought compared to other western forest types due to a low fire frequency and accumulation of understory fuels (Reilly et al., 2017). Thus, climatic and land use factors concurrently influence fire risk in western Cascades forests.

The 2020 Labor Day fires in Oregon were driven by a combination of historic fire suppression, a warming climate, and strong eastern winds following drought that led to rapid spreading of fire downhill (Abatzoglou et al., 2021; Reilly et al., 2022). One such event was the Holiday Farm fire, which was one of the state's largest historical fires. The Holiday Farm fire's location in the western Cascades led to intense impacts on federal land, urban areas, and private timberland (Evers et al., 2022). The lack of recent fire from suppression has inflated effects on vegetation and soils, particularly in landscapes with high loads of existing dry fuels (Haugo et al., 2019; Reilly et al., 2017; Scott et al., 2018).

Especially in managed tree farms, the presence of harvest residues, compaction, and thinner, younger trees that act as fine, flammable fuels in periods of hazardous fire weather may lead to compounding consequences on soil C during severe wildfire (Lindenmayer et al., 2011). Assessing soil C changes in an industrial tree farm offers insight into post-disturbance soil C dynamics and opportunities for future management guidance. Live fuel has been modeled as the most significant driver of high-severity fire in the western Cascades (Parks et al., 2018) due to fire suppression transferring fires to canopy levels (Bowman et al., 2013). Low canopy height and private land ownership were modeled as two of the largest drivers of high-severity fire in the 2020 Labor Day fires, indicating that industrial tree farm management may result in higher burn severity and more extreme effects on the ecosystem (Evers et al., 2022). Weighing the risks of wildfire associated with high tree densities and low rotation periods (Zald & Dunn, 2018) is crucial for industrial tree farm managers to understand the impacts of fire on soil C.

The Pacific Northwest is a productive ecosystem due in part to high levels of soil organic matter occurring from long-term C accumulations in the forest floor and mineral soil; these associations in the mineral soil are likely a product of high moisture content (Heckman et al., 2023). Soil C further increases water holding capacity because of its high surface area of organic particles, which can be vital during the drier summer growing months in the western Cascades (Berryman et al., 2020). High mineral soil nitrogen (N) has been found to correlate with high net primary productivity of Oregon conifer forests (Myrold et al., 1989). Nutrient fluxes within the soil, therefore, have broad influences on aboveground growth.

Core Ideas

- Highly productive western Cascades forest soils are at risk of carbon (C) and nitrogen losses from severe wildfire.
- We found significant changes in forest floor and soil carbon stocks after wildfire.
- C stocks were approximately 40 Mg C ha^{-1} lower in the post-fire period.
- Two-thirds of C decreases were in the forest floor and one-third were in the mineral soil.

Aboveground assessments of post-fire effects are often explored due to ease of sampling and comparison, while belowground ecosystems are investigated less often after severe wildfire. The unpredictability and danger of fire complicates pre-fire comparisons in unestablished soil plots (Adkins et al., 2018). The existence of this long-term soil C study that burned in a high-severity wildfire provides a rare opportunity for direct pre- and post-fire comparison.

Soil C is typically only considered significant in the smallest size fraction, defined by a diameter of <2 mm (Corti et al., 2002). However, previous studies have demonstrated that up to 25% of soil C can be stored in larger size fractions that are not typically analyzed (Busse et al., 2019). This study's inclusion of larger soil particles and splitting of soil into fractions is essential to assess total C changes after a wildfire and disparate effects of fire on mineral soil particles. Similarly, fire may impact the forest floor in a variety of severities based on woody biomass composition, which can lead to increases in forest floor C due to pyrogenic C formation (Pellegrini et al., 2022). The analysis of forest floor in both woody and nonwoody litter categories, therefore, demonstrates how fire interacts with different forest floor compositions.

The goal of this research paper is to quantify changes in soil parameters that occurred after a fire burned at high severity in a young, intensively managed tree farm. Geochemical soil parameters measured are C stock, soil mass, C concentration (%C), N concentration (%N), C:N ratio, N stock, and dry bulk density. These parameters are indicators of overall forest health and may influence site productivity after disturbances (Page-Dumroese et al., 2000). The findings from this paper directly inform industrial tree farm managers of potential impacts on soil health after severe wildfire that may lead to future effects on aboveground productivity.

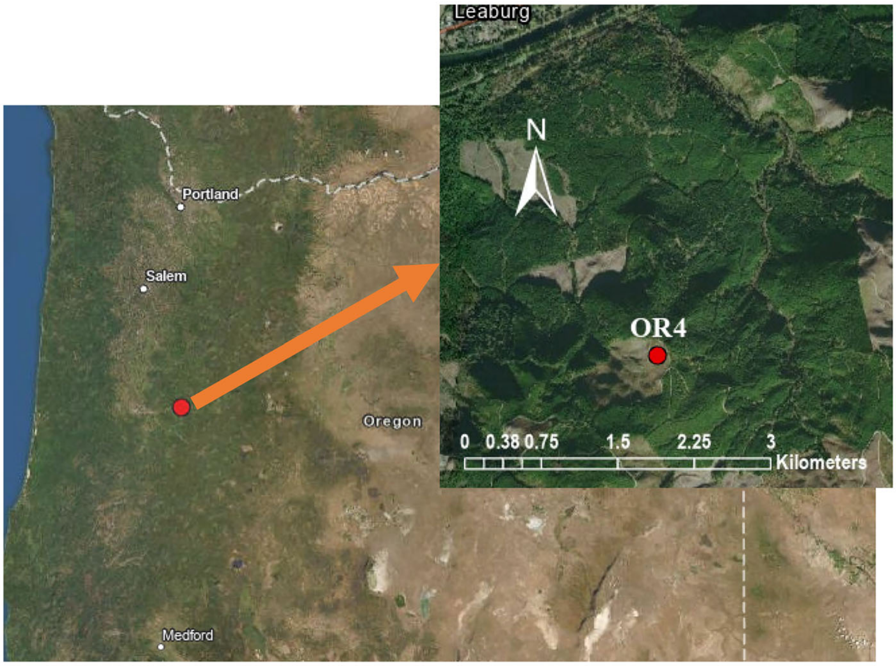

FIGURE 1 Map of Oregon with site map inset. Site is located in industrial Douglas-fir timberland in the western Oregon Cascades, south of the town of Leaburg (located in the northwest corner of the inset map).

2 | MATERIALS AND METHODS

2.1 | Site description

The study site was established as part of a nine-site soil C study in 2010 (see Holub & Hatten, 2019 for details). The sites were created to observe long-term trends in soil C dynamics in the western Cascades after a harvest. The random selection process required sites to be 5 ha in size, predominately Douglas-fir, in western Oregon and Washington, and scheduled for harvest in the 2012 season. Sites were selected from low rock content soils based on National Resources Conservation Service (NRCS) soil classification to allow for the soil sampling procedure.

This site, named "OR4" as the fourth Oregon site selected for the original soil C study, is located near Leaburg in the western Oregon Cascades at 44.085˚N, 122.662˚W (Figure 1). The site had a mean elevation of 628 m, a mean slope of 33%, and a mean west-facing aspect of 262˚. The sampled area was 5.5 ha, with a mean spacing of 12.2 m between the original 300 sampling points.

Soils were derived from colluvium and residuum from basaltic lava flows and were classified as Inceptisols. The site was mapped as 90% McCully clay loam (fine, isotic, mesic Typic Humudepts) and 10% Blachly–McCully clay loam (fine, isotic, mesic Humic Dystrudepts) soil series (Soil Survey, 2023). Both series featured well-drained, strongly acidic soils with high available water capacity and O horizons defined by moderately decomposed plant material. McCully soils contained 15–30 cm of A and AB horizons with loam to clay-loam textures. Subsoil horizons were Bw horizons with silty clay to clay textures. Many very fine, fine, medium, and coarse roots were present to a depth of approximately 65 cm, with a decreasing frequency of roots with depth. Soils had no inherent hydrophobicity except in the case of extreme seasonal (summer) dryness. Post-fire soil had fire-induced hydrophobicity at varying depths of approximately 5–10 cm.

Within the sampling period of 2010–2020, the site received an average of 2213 mm of rain per year, 1900 of which fell in the wet season (October–April) months (PRISM, 2023). Due to the site's position on the warmer and sunnier western slopes of the Oregon Cascades, most precipitation fell as rain, though occasional snow fell in the winter. The average mean temperature was 10.7˚C (51.3˚F), with a mean minimum of 5.7˚C (42.3˚F) and a mean maximum of 15.6˚C (60.1˚F). Precipitation and temperature trends were stable throughout the 10-year period. The Köppen Climate Classification defines the site as warm-summer Mediterranean climate (Csb), with dry summers, wet winters, and mild temperatures.

2.2 | Site history

Prior to industrial management of the forest, the presence of Indigenous land managers is known in the western Cascades. The area of study is the homeland of several Indigenous Peoples, including the Winefelly, Mohawk, and Yoncalla Bands of the Kalapuya Tribe, who are now represented by the Confederated Tribes of Siletz Indians and the Confederated Tribes of Grand Ronde (Confederated Tribes of Grande Ronde, 2023; Confederated Tribes of the Siletz Indians, 2023; Native Land Digital, 2023). Cultural fire practices prioritized frequent land burning for management, which reduced fuel loads and fire severity (Lake & Christianson, 2019); by the 20th century, these activities were prohibited by colonizing Euro-Americans (Kimmerer & Lake, 2001).

The site was originally harvested in 1948 and naturally regenerated. The stand was commercially thinned in 1999. The site was fertilized in 1986, 1999, and 2003, over respective areas of 5.2, 5.2, and 0.12 ha, with 206 kg N ha^{-1} applied in each period. The study harvest, which occurred in December 2011, was a clear-cut with methods of ground-based mechanical cutting and shovel yarding. Some harvest residues were placed into piles, but most residues remained in place on site (Figure 2).

The site burned at high severity from the Holiday Farm Fire, one of several large fires in Oregon's 2020 fire season named the Labor Day Fires. In soil, wildfire severity is characterized by organic matter consumption, with partial scorching corresponding to low severity and total consumption defined as high severity (Neary et al., 1999). Because this site had full consumption of organic matter, the effect of the wildfire was classified as high severity.

The Holiday Farm Fire started on August 16, 2020, in Vida, OR (Griggs, 2020), and was first reported for rapid westward growth on September 7, 2020 at 8:20 PST (Borsum & Plouffe, 2020). Dry, hot conditions, and extreme westward winds combined to expand the fire to over 100,000 acres less than 36 h after the growth was reported. The site was located in the southwestern portion of the fire perimeter and is estimated to have burned during the morning of September 9 (Trout Creek RAWS Station, 2023). At this time, relative humidity was estimated to be less than 10% and winds were westward with gusts around 20 mph. The fire was determined entirely contained on October 29, 2020.

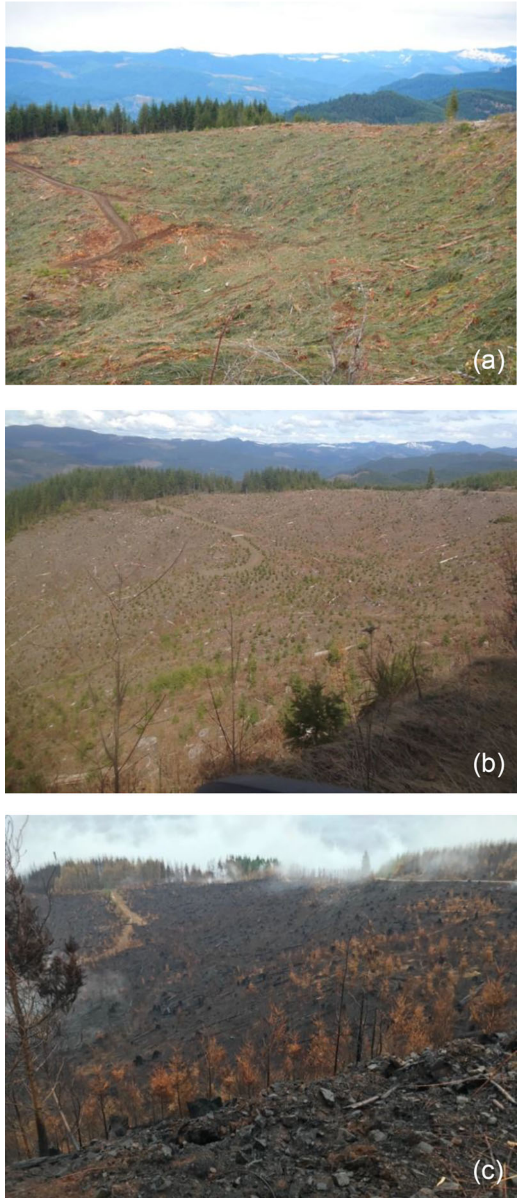

FIGURE 2 Photos of the site looking northeast. (a) is 4 months post-harvest in March 2012, (b) is 6 years post-harvest in March 2018, and (c) is immediately post-fire in September 2020.

2.3 | Field processes

Initial pre-harvest sampling occurred in the summer of 2010 (Figure 3). All nine sites were established with 300 points located on a fixed grid. Points were split into 25 blocks of 12 points for composited chemical analyses; blocks were labeled A–Y, with A occurring at the northernmost point of the site and Y at the southernmost (full site map available in the Supporting Information). Points were sampled at established positions unless obstructed. Points were marked with PVC pipe and corresponding metal marker with point number to ensure points were sampled at identical locations in all sampling periods.

Post-harvest sampling occurred 3.5 years after the harvest and 2 years after the planting of 2-year-old nursery-grown Douglas-fir seedlings at 320 trees per acre, which occurred in spring 2013.

Post-fire sampling of the site began on December 8, 2020. Due to the severity of the fire, the majority of PVC point markers and flags were buried in topsoil or combusted. PVC markers that were still in the soil were utilized as exact locations for points, while points that could not be located

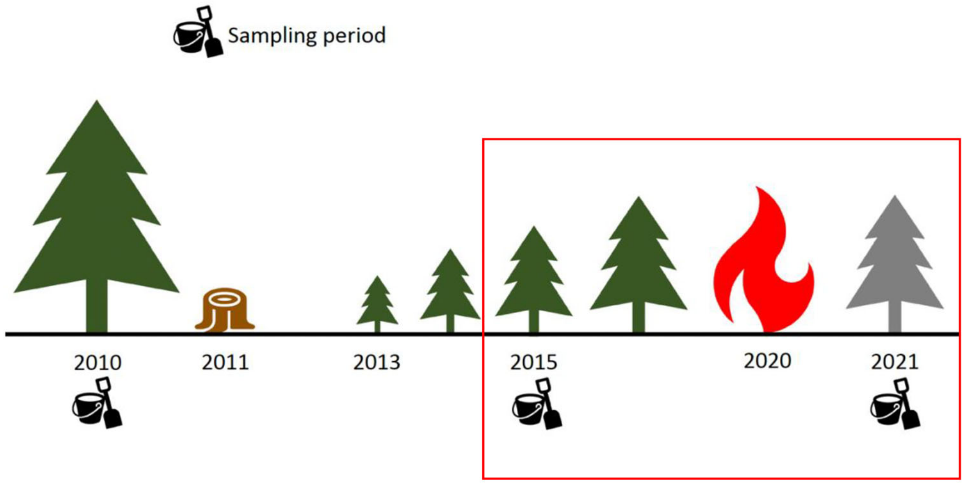

FIGURE 3 Diagram of site history with the focus of this paper outlined in red. Sampling occurred in three periods: pre-harvest in summer 2010, 3.5 years post-harvest in summer 2015, and 4 months post-fire in winter 2021. Harvest occurred in December 2011. In September 2020, the site burned at high severity in the Holiday Farm fire. Post-fire samples were collected between December 2020 and April 2021.

were determined from the grid design and 12.2 m inter-point spacing.

The study area was sampled post-fire from December 2020 to April 2021. The site was replanted with 2-year-old Douglas-fir seedlings at a density of 225 trees per acre in March 2021.

Soil samples were collected at three depths: forest floor, 0–15, and 15–30 cm. The forest floor collection was carried out using a ring of 500 cm^2 (0.05 m^2) area located directly above the sampling location. "Forest floor" encompassed all aboveground live or dead biomass including char, sticks, pieces of wood (<5 cm diameter), live or dead plants, micro-invertebrates, and any organic layer (O horizon) material. All forest floor material was collected by gloved hand and placed in a labeled bag.

The 0–15 and 15–30 cm depths were collected with a metal core of 7.62 cm (3 inch) diameter, forming a total volume of 870.97 cm^3 (0.00087 m^3) that included mineral soil, rocks, roots, and pore space over the 15 cm depth. The core was placed over the center of the forest floor ring and driven to 15 cm depth using a dead blow sledgehammer. Once the soil was collected, the process was repeated for the 15–30 cm sample by placing the core into the hole created by the 0–15 cm sample.

The sampling process was repeated 5 years later in summer 2015 and was designated as the post-harvest period. Post-harvest samples were collected using the same methods as pre-harvest samples in the same point locations.

In the post-fire period, speed of sampling was prioritized due to the possibility of immediate post-fire runoff impacting C results (Johnson et al., 2007). Available personnel were also limited; previous sampling periods involved hired summer crews, while post-fire sampling occurred in the winter and was

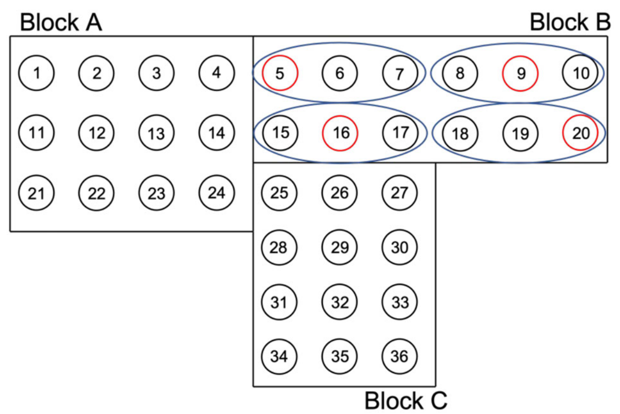

FIGURE 4 Diagram of site layout with post-fire sampling scheme in Block B. Blue ellipses represent numerical clusters of three, while red circles are randomly selected points. Random selections within groups were made of points 1, 2, 2, and 3, respectively. This process was replicated at each block throughout the entire site (see Supporting Information for a full site map).

limited to individuals trained in post-fire safety. Due to these limitations, sampling was confined to four points per block, with random selection of one point from each consecutive cluster of three points (Figure 4).

Forest floor and soil samples were collected using the same methods as the pre-harvest and post-harvest samples. After the post-fire sampling period, samples were stored in a refrigerated room less than 12 h after collection at 4°C (39.2°F) until processing began in June 2021. Pre- and post-harvest samples were also held in refrigerated rooms for approximately 90 days before processing.

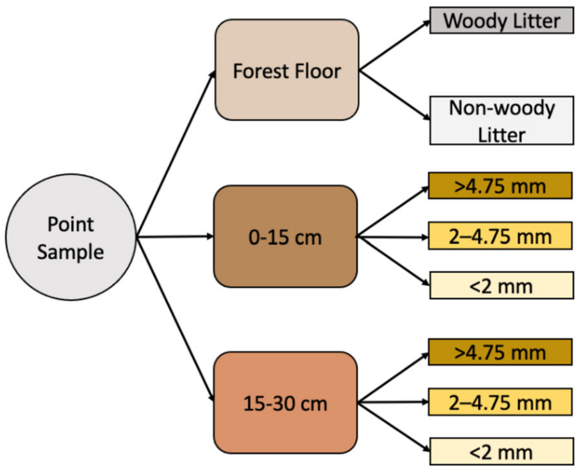

FIGURE 5 Breakdown of resulting size and composition fractions from each depth of each point sample.

2.4 | Lab processes

Each point sample, consisting of a forest floor sample, 0–15 and 15–30 cm depth sample, was further split into size fractions based on diameter (for soil) or composition (for forest floor) to assess individual size contributions to soil C and N. A total of 300 post-harvest samples were collected at each of the eight levels outlined in Figure 5 and a total of 100 post-fire samples were collected based on strategies outlined in the previous section.

The forest floor was processed first by block order (A, B, C,…,Y). The entire wet sample was separated by gloved hand into woody litter and nonwoody litter categories, with woody litter consisting of branch pieces with associated bark and nonwoody litter consisting of moss, needles, char, and any recolonizing plants and herbs. Material with a diameter over 5 cm was not included. Woody pieces less than 3 cm in length were placed in the nonwoody litter category.

Woody and nonwoody litter were combined as composited (averaged) samples of the four points in each block. Samples were dried in a forced air mechanical drying oven at 60˚C for 36–48 h based on drying curves conducted; up to 60 h, if needed, was acceptable. Once dried, samples were recorded for weight with a toploading balance with 0.01 g sensitivity. Samples were then placed into sealable plastic bags and stored in boxes at room temperature.

After forest floor processing was completed, 0–15 cm samples were processed, followed by 15–30 cm samples. Individual point samples were spread onto a metal tin and assessed for wetness. If the sample was too wet, judged by stickiness when spread out, it was allowed to air dry for 1–24 h. Air-dried contents were emptied into stacked sieves consisting of a base, 2 mm (No. 10) sieve, and 4.75 mm (No. 4) sieve from bottom up, resulting in soil fractions of <2, 2–4.75, and >4.75 mm. These separations were utilized to incorporate measurements of typical soil sizes (<2 mm) for chemical analyses as well as larger fractions (2–4.75 mm).

The mineral soil sample was shaken vigorously in the stack of sieves for multiple minutes. Dirt clumps were broken up by any means necessary, including hands, rulers, and wooden handles. This step, as well as the wet sieving, was undertaken due to clumping, as the dried soil was significantly too hard to break up and pass through the sieve (Holub & Hatten, 2019). Soil particles that did not pass through the 4.75-mm sieve (the largest fraction) mainly consisted of roots and rocks and are referred to as the rock fraction in this paper. Rock fraction samples were returned to bags and restored in the freezer. They were later dried for 7 days to obtain mass in December 2021.

The coarse soil fraction, consisting of particles with a diameter of 2–4.75 mm, was processed next and placed in a pre-weighed tin. This process was repeated for the fine soil fraction, consisting of particles with a diameter of <2 mm. Once an entire block was prepared for processing, the samples were dried for 2–5 days based on drying curves conducted; up to 7 days, if needed, was acceptable. Soil was stirred with a fork every day to ensure all particles were being dried.

After drying, tins were weighed on the toploading scale and 90 ± 1 g of each individual sample was added to a composite tin, with four points in a block comprising the composite tin. Samples were placed into labeled bags and stored in boxes at room temperature.

Dried composite samples of all fractions were analyzed for C and N percentages. Composite samples consisted of the four points per block for 25 blocks, leading to 25 samples each for forest floor woody litter, forest floor nonwoody litter, 0–15 cm < 2 mm, 0–15 cm 2–4.75 mm, 15–30 cm < 2 mm, and 15–30 cm 2–4.75 mm. A random selection of each composite was taken for analyses. Soils were composited to limit high costs of chemical analyses. The largest size fraction (<4.75 mm) was not analyzed for concentrations under the assumption that the C concentration was not large enough to contribute to the whole soil C and N pool (Harrington et al., 2017).

C and N were analyzed by Soiltest Farm Consultants lab in Moses Lake, WA, an independent company that was utilized in previous sampling periods. Samples were ground and processed by the lab. The analyses were conducted using Dumas combustion (LECO CN, model 628. Method P-2.20) (Gavlak et al., 2005). The laboratory was blind to total soil masses.

2.5 | Data processes

C and N stocks were calculated as the product of C or N concentration (%C or %N) and soil or forest floor mass. Concentration values were obtained from composite soil samples (see Supporting Information for equations).

Comparisons were drawn between post-harvest and post-fire means of C stock, soil mass, %C, %N, C:N ratio, N stock, and bulk density. In the post-harvest period, the mean of 12 points was used as the block-level mean, while four points were used as the block-level mean in the post-fire period. To ensure this comparison was valid, equivalence tests were conducted on the mass values in each block ($n = 25$) between 12 points and the same selected four points in the post-harvest period. The same tests were conducted on two blocks (K and U) in the post-fire period, where all 12 points were sampled. Tests were conducted using one-sample tests in the equivUMP function in R (Wellek, 2010). One sample Kolmogorov–Smirnov tests were also conducted to ensure distributions were the same. In all depths and fractions, the four-point and 12-point samples were found to be equivalent with equal distributions.

To compare the fire's effect on the seven outlined parameters (C stock, soil mass, %C, %N, C:N ratio, N stock, and bulk density), linear mixed-effects models were conducted with the restricted maximum likelihood method. Values in the forest floor and mineral soil were separated, equating to two models per parameter with the parameter in question as the response variable. Fire occurrence and slope of the block center were fixed effects throughout all the models and block was a random effect (Pellegrini et al., 2021). Slope and block were included in the model to account for spatial differences between blocks.

In forest floor models, composition (woody or nonwoody) was also a fixed effect; in mineral soil models, fraction (<2, 2–4.75, and >4.75 mm in only the soil mass model) and depth (0-15 and 15–30 cm) were also fixed effects. Interactions were found in all mineral soil models except the bulk density model and were included as interactions between depth and fraction, depth and fire, and fraction and fire. Interactions were found in the forest floor models in the %C, C:N ratio, and N stock models, where a significant interaction between fire and fraction was found and included. The lack of interaction otherwise indicates that fire's effect on woody and nonwoody forest floor was equal, or, in the case of bulk density, the depth of soil; forest floor and bulk density statistical summaries are therefore reported as the overall forest floor, except for the %C, C:N ratio, and N stock parameters.

In the C stock and mass models, forest floor response variables were log-transformed to fit normality for residuals. In the %C, %N, and N stock models, mineral soil response variables were log-transformed to satisfy the assumption of homoscedasticity. Bulk density and C:N ratio models were not transformed. All models satisfied assumptions of residual normality, independence, and homoscedasticity after corrections.

Comparisons over the treatment, depth, and fraction level were conducted using the emmeans function in R. Tukey's method for multiple comparisons was applied for adjustments.

All analyses were performed in R. Models were fit with function lme in the nlme package (Lindstrom & Bates, 1988).

3 | RESULTS

Post-fire mineral soil C stocks showed significant changes from post-harvest stocks in the forest floor and mineral soil fine fraction. There was an overall mean decrease of 3.8 ± 0.6 Mg C ha^{-1} ($p < 0.001$) across all fractions in the 0–30 cm mineral soil (Table 1).

Forest floor C had the most marked decrease, with median post-harvest forest floor 26.6 ± 2.8 times higher than median post-fire forest floor ($p < 0.001$) (Table 2). These changes resulted in a 96% decrease in forest floor C (Figure 6). The total changes in C stocks across mineral soil fractions equate to approximately 15 Mg C ha^{-1} (Table 1). The mean post-fire forest floor C stocks are approximately 1 Mg C ha^{-1} (see Supporting Information for full data table); multiplying this value by the median ratio results in approximately 25 Mg C ha^{-1} lower floor C stocks after the fire. Therefore, total decreases are approximately 40 Mg C ha^{-1}, with two-thirds of C stocks lost in the forest floor and one-third in the mineral soil.

Mineral C stocks showed lower values post-fire across both the 0–15 and the 15–30 cm depths (Table 1). Across fine (<2 mm) and coarse (2–4.75 mm) sizes, post-fire 0–15 cm C had a mean decrease of 5.4 ± 0.9 Mg C ha^{-1} ($p < 0.001$) from post-harvest to post-fire while the 15–30 cm depth decrease was 5.3 ± 0.9 Mg C ha^{-1} ($p = 0.01$).

Fine fractions at depths of both 0–15 and 15–30 cm were also lower post-fire (Table 1). The 0–15 cm fine fraction C decreased 9.1 ± 1.1 Mg C ha^{-1} compared to post-harvest C stocks ($p < 0.001$), while the 15–30 cm fraction C decreased 6.0 ± 1.1 Mg C ha^{-1} compared to post-harvest C stocks ($p < 0.001$). Coarse fractions did not have changes in soil C stocks.

The mass of the soil was lower across all depths and size fractions except for the rock fraction, equating to an overall decrease of 45 ± 7 Mg (Table 1). In the forest floor, median post-harvest mass was 25.4 ± 3.4 times greater than median post-fire mass ($p < 0.001$). Fine (<2 mm) size fractions at both soil depths had significant changes in mass from post-harvest to post-fire. The fine fraction in the 0–15 cm depth decreased by 124 ± 14 Mg ha^{-1} from the mean post-harvest mass ($p < 0.001$). The fine fraction in the 15–30 cm depth decreased by 121 ± 14 Mg ha^{-1} from the mean post-harvest mass ($p < 0.001$). The change in mass was also significant in both coarse (2–4.75 mm) fractions. For the 0–15 cm depth, the mean post-fire mass decreased 49 ± 14 Mg ha^{-1} from the post-harvest mean ($p < 0.001$). In the 15–30 cm depth, the mean post-fire mass decreased 47 ± 14 Mg ha^{-1} ($p < 0.001$). Rock size fraction masses at both depths were higher post-fire. For the 0–15 cm depth, the mean post-fire

TABLE 1 Results of linear mixed-effects models for mineral soil.

Depth			0–15 cm			15–30 cm		
Parameter	**Unit**	**Comparison**	**<2 mm**	**2–4.75 mm**	**>4.75 mm**	**<2 mm**	**2–4.75 mm**	**>4.75 mm**
C stock	Mg ha^{-1}	Overall	−3.8 ± 0.6***					
		Depth	−5.4 ± 0.9***			−5.3 ± 0.9*		
		Fraction	−9.1 ± 1.1***	−1.7 ± 1.1	–	−6.0 ± 1.1***	1.4 ± 1.1	–
Mass	Mg ha^{-1}	Overall	−45 ± 7***					
		Depth	−47 ± 10***			−44 ± 10***		
		Fraction	−124 ± 14***	−49 ± 14***	33 ± 14*	−121 ± 14***	−47 ± 14***	35 ± 14*
%C	Post-harvest to post-fire ratio	Overall	1 ± 0.03					
		Depth	1.04 ± 0.04			0.96 ± 0.04		–
		Fraction	1.13 ± 0.05**	0.96 ± 0.04	–	1.06 ± 0.05	0.88 ± 0.04**	–
%N	Post-harvest to post-fire ratio	Overall	0.91 ± 0.02***					
		Depth	0.92 ± 0.02***			0.90 ± 0.02***		–
		Fraction	0.99 ± 0.03	0.86 ± 0.03***	–	0.97 ± 0.03	0.84 ± 0.02***	–
C:N ratio	Ratio	Overall	−2.1 ± 0.4***					
		Depth	−2.8 ± 0.5***		–	−1.4 ± 0.5**		–
		Fraction	−3.3 ± 0.6***	−2.3 ± 0.6***		−1.8 ± 0.6**	−0.9 ± 0.6	
N stock	Post-harvest to post-fire ratio	Overall	1.07 ± 0.02**					
		Depth	1.10 ± 0.03**			01.04 ± 0.03		
		Fraction	1.23 ± 0.05***	0.96 ± 0.04	–	1.19 ± 0.04***	0.90 ± 0.03**	–
bulk density	g cm^{-3}	Overall	−0.091 ± 0.014***					

Note: Results are given in unit change from post-harvest to post-fire (mass, carbon (C) stock, carbon to nitrogen (C:N) ratio, and bulk density) or post-harvest to post-fire ratio (%C, %N, N stock) for log-transformed models. The “Comparison” category refers to the method of statistical comparison: “Overall” includes values for the parameter across all depths and fractions, “Depth” includes values for the parameter across all fractions within a depth (0-15 cm or 15–30 cm), and “Fraction” includes values for the parameter within a single size fraction in a single depth. Negative values and ratios over 1 represent lower values post-fire.
***, **, and * represent significance at the $p < 0.001$, $p < 0.01$, and $p < 0.05$ levels, respectively.

TABLE 2 Results of linear mixed-effects models for forest floor.

Depth Size	Unit	Comparison	Forest floor Woody	Forest floor Nonwoody
Carbon stock	Post-harvest to post-fire ratio	Overall	26.6 ± 2.8***	
Mass	Post-harvest to post-fire ratio	Overall	25.4 ± 3.4***	
%C	%	Overall	−3.1 ± 1.0**	
		Composition	2.3 ± 1.4	−8.4 ± 1.4***
%N	%	Overall	0.24 ± 0.04***	
C:N ratio	Ratio	Overall	−36 ± 6***	
		Composition	−48 ± 8***	−25 ± 8**
Nitrogen stock	Post-harvest to post-fire ratio	Overall	17.3 ± 2.1***	
		Composition	15.4 ± 2.6***	19.3 ± 3.3***

Note: Results are given in percentage change (%C, %N) or percent change (Mass, C stock, N stock) for log-transformed models. The "Comparison" category refers to the method of statistical comparison: "Overall" includes values for the parameter across both categories (woody and nonwoody) and "Category" includes values for the parameter within a category. Negative values and ratios over 1 represent lower values post-fire.
*** and ** represent significance at the $p < 0.001$ and $p < 0.01$ levels, respectively.

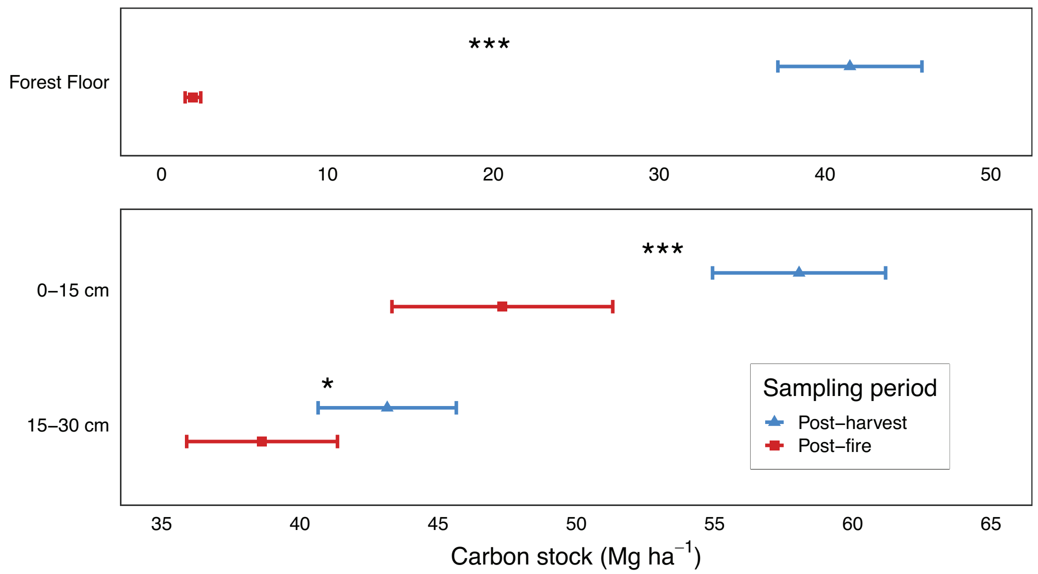

FIGURE 6 Mean soil carbon stock (Mg ha^{-1}) by depth and sampling period. Error bars are standard errors at 95% confidence level. *indicates statistical differences based on linear mixed-effects models at $p < 0.05$ and *** at $p < 0.001$. Note different x-axes for forest floor and mineral soil depths.

mass increased 33 ± 14 Mg ha^{-1} from the mean post-harvest mass ($p = 0.019$). In the 15–30 cm depth, the mean post-fire mass increased 35 ± 14 Mg ha^{-1} from the mean post-harvest mass ($p = 0.012$).

Changes in C concentration (%C) before and after the fire were statistically significant in only the forest floor nonwoody fraction, the 0–15 cm fine soil, and the 15–30 cm coarse soil (Figure 7). Overall, %C did not change over either of the mineral soil depths or the whole mineral soil (Table 1). In the forest floor, overall %C across fractions was 3.1 ± 1.1 percentage points lower post-fire ($p = 0.01$) (Table 2). %C was lower in the 0–15 cm fine fraction and did not change in the coarse fraction. The median post-harvest %C was 1.13 ± 0.05 times higher than the median post-fire %C ($p = 0.008$). In the 15–30 cm depth, the coarse fraction %C was higher in the post-fire period than the post-harvest period; the median post-harvest %C was 0.88 ± 0.04 times higher than the median post-fire %C ($p = 0.007$).

The forest floor N concentration (%N) was higher post-fire by 0.24 ± 0.04 percentage points ($p < 0.001$) (Figure 8). %N was unchanged in fine fractions at both depths, while higher post-fire values were evident in both coarse fractions (Table 1). The median 0–15 cm coarse fraction %N in the post-harvest period was 0.86 ± 0.03 times the median of the

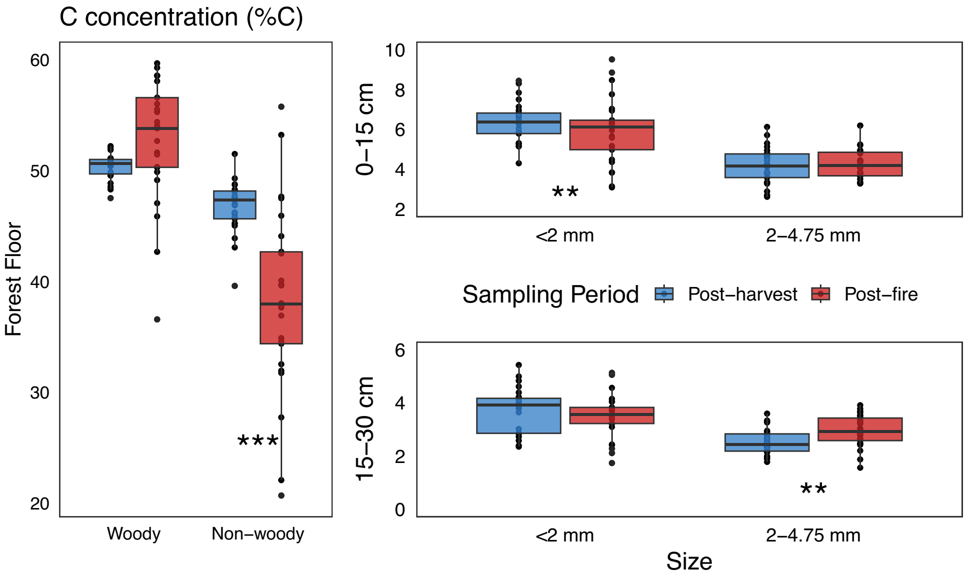

FIGURE 7 Carbon concentration data values (%C) by depth and sampling period. Each point is the mean block ($n = 25$) value. **indicates statistical differences based on linear mixed-effects models at $p < 0.01$ and *** at $p < 0.001$. Note different y-axes for forest floor and mineral soil depths.

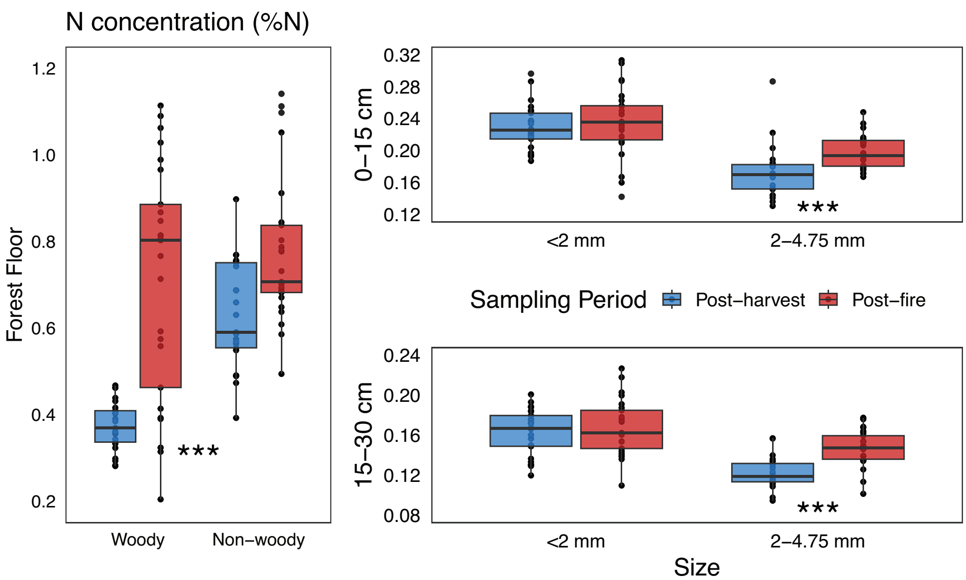

FIGURE 8 Nitrogen concentration data values (%N) by depth and sampling period. ***indicates statistical differences based on linear mixed-effects models at $p < 0.001$. Significant differences are shown for overall forest floor. Note different y-axes for forest floor and mineral soil depths.

post-fire period ($p < 0.001$), and the coarse fraction at the 15–30 cm depth in the post-harvest period was 0.84 ± 0.02 times the median of the post-fire period ($p < 0.001$). Overall, the %N in the post-harvest period was 0.91 ± 0.02 times the post-fire period ($p < 0.001$).

The increase in %N in the post-fire period combined with the lack of change of %C led to lower C:N ratios (Figure 9). In the woody forest floor, the post-fire C:N change was −48 ± 8 compared to post-harvest ($p < 0.001$) and −25 ± 8 in the non-woody forest floor ($p = 0.003$). The change across the forest floor was −36 ± 6 ($p < 0.001$).

There were also lower C:N values in the 0–15 cm depth (Table 1), with the fine fraction post-fire C:N ratio changing by −3.3 ± 0.6 ($p < 0.001$) and the coarse fraction post-fire C:N ratio changing by −2.3 ± 0.6 ($p < 0.001$), equating to a mean change of −2.8 ± 0.5 ($p < 0.001$) in the 0–15 cm depth.

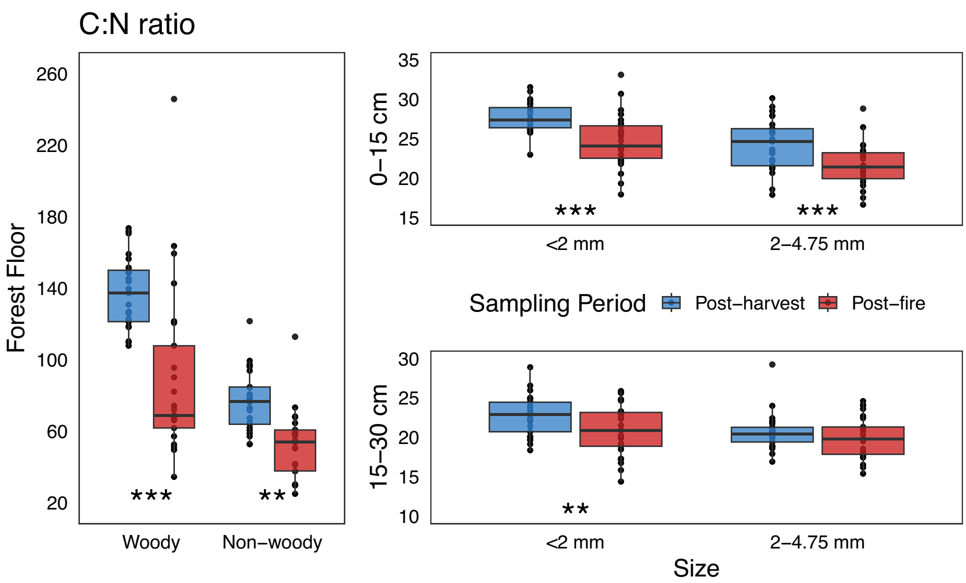

FIGURE 9 Carbon to nitrogen (C:N) ratio data values by depth and sampling period. ***indicates statistical differences based on linear mixed-effects models at $p < 0.001$, and **at $p < 0.01$. Note different *y*-axes for forest floor and mineral soil depths.

Only the fine fraction significantly decreased in the 15–30 cm depth, with a post-fire C:N change of −1.8 ± 0.6 ($p = 0.004$) and a mean change of −1.4 ± 0.5 ($p = 0.009$) over the 15–30 cm depth. The overall change across the mineral soil was −2.1 ± 0.4 ($p < 0.001$).

Though %N increased in the forest floor, mass decreases were so large that N stocks still decreased significantly (Table 2). In the 0–15 cm depth, the median post-harvest to post-fire N stock ratio was 1.10 ± 0.03 ($p = 0.003$) due to decreases in the fine fraction; N stocks did not change in the coarse fraction. Overall N stocks were lower across the mineral soil after the fire, with post-harvest median N stocks 1.07 ± 0.03 times post-fire N stocks ($p = 0.004$). N stocks in the forest floor were much lower after the fire because of the large mass decrease. Overall, median post-harvest N forest floor stocks were 17.3 ± 2.1 times greater than post-fire mass N stock ($p < 0.001$).

The mineral soil bulk density decreased significantly from the post-harvest to post-fire sampling period at both soil depths (Table 2). A different effect of fire was not found for the 0–15 cm depth and the 15–30 cm depth. Therefore, the overall change across both depths was a decrease of 0.091 ± 0.014 g cm^{-3} ($p < 0.001$) (Figure 10).

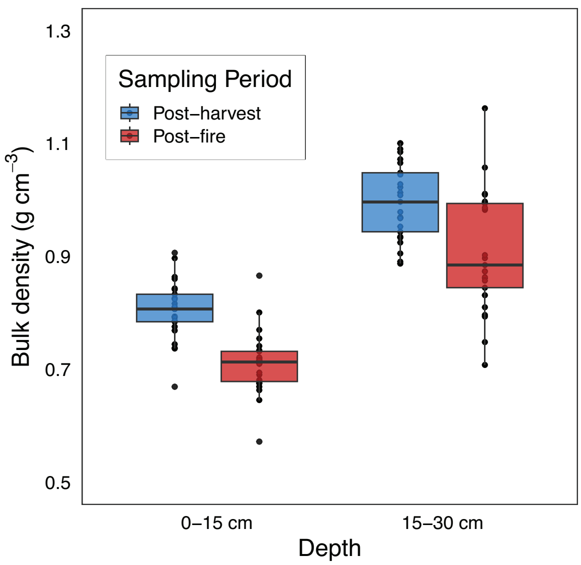

FIGURE 10 Bulk density values between soil depths and periods. In both periods, bulk density was calculated as the sum of all soil fractions (fine, coarse, and rock) divided by the volume of the collection core. The overall difference between post-harvest and post-fire bulk density is significant at $p < 0.001$.

4 | DISCUSSION

4.1 | Soil carbon stocks

Soil C stock changes from fire were primarily driven by lower soil mass values. In most previously studied high-severity fires, only the forest floor was impacted, mostly through combustion of organic matter (Bormann et al., 2008; Hatten & Zabowski, 2009). However, significant changes in soil C stocks were found down to 30 cm in this study (Table 1), indicating the potentially impactful combination of novel compounding disturbances in an area where high-severity wildfire is uncommon (Dove et al., 2020; Reilly et al., 2017). The amount of C removed in the fire was also unusual;

typical findings in other wildfire studies resulted in losses of approximately 20% of soil C, while this site experienced 30% at similar depths (Miesel et al., 2018). C stock changes were most pronounced in the fine mineral soil fractions and in the forest floor, while the change in coarse fractions at both depths was insignificant.

C concentration (%C) overall did not change between the post-harvest and post-fire sampling periods. This may be due to the high temperature of the rapidly moving, wind-driven fire and subsequent soil heating, which was hot enough to combust soil and forest floor mass but not so hot as to destabilize soil C, which would result in lower %C. The presence of hydrophobicity suggests temperatures between 176˚C and 288˚C in the subsurface (Neary et al., 1999); oxidation of N and organic matter, and evaporation of waxy plant residues, typically occurs at a minimum of 200˚C. Based on observations of in situ hydrophobicity, temperatures were therefore likely high enough to cause severe physical changes but short of the high temperatures (approximately 500˚C) needed to alter the C associated with mineral soil (Certini, 2005).

There was a significant change in %C in the coarse (2–4.75 mm) soil fraction at the 15–30 cm depth that led to higher post-fire values. This change could be a product of increasing aggregation as an effect of soil heating, leading to conversion of previously C-rich fine-grained particles to coarse, soil organic matter-rich aggregates. Increasing porosity of larger aggregates, potentially indicated by the decrease in post-fire bulk density, could also contain more C than the fine (<2 mm) fraction because of a higher percentage of air space (Corti et al., 2002). The additional C could also be due to combustion of fine roots that became incorporated after fire-driven seedling mortality. This may have occurred in the coarse fraction because particles had not yet decomposed to fine (<2 mm) diameters and in the 15–30 cm depth because it was less affected by combustion than the upper soil layers. Increases of %C at this depth and size are unusual post-fire; this change warrants further research investigating deep soil C dynamics post-fire.

There was lower %C in the forest floor litter, which can be expected based on the differing compositions between the post-harvest and post-fire forest floors. After the harvest, nonwoody forest floor accounted for needles, plants, soil organic matter, grasses, and leaves, which increased due to remaining harvest residues. The removal of most of the forest floor between the post-harvest and post-fire sampling periods nearly negated C contributions to the forest floor, with only bare mineral soil or combusted, low C material existing in place of previously observed vegetation.

In the forest floor, it is evident that loss of mass was the primary driving factor behind C stock changes due to the almost total eradication of the organic layer. These losses are expected, as the forest floor is typically the most impacted by fire due to proximity to heat and combustion (Elliot et al., 1999). Mineral soil is usually only slightly affected by wildfire due to the insular capacity of soil that often reduces deeper soil heating (Neary et al., 2005). The components driving C decrease in the mineral soil are likely more complex than solely combustion and could be a combination of soil mass changes, erosion, or combustion of soil organic material, all of which warrant further investigation.

C stock changes could be partially driven by post-harvest soil C trends. Though the impacts of forest harvesting in the western Cascades typically have little short-term effect on soil organic content (Holub & Hatten, 2019; Nave et al., 2022), full site soil C trajectories can span decades after a harvest. A meta-analysis by James and Harrison (2016) found that total average soil C stocks decreased by over 10% after harvesting. Thus, the reduction in mineral soil C observed in this study may be partially a product of time since harvest. It is possible that the change of mineral soil C, and related bulk density decrease, was due to a combination of reduced C inputs after harvest, the combustion-driven losses from the fire, and soil erosion. Though fire is often expected to increase bulk density, when compared to a landscape of post-harvest compaction, a lower bulk density may be expected.

4.2 | Nitrogen

N stocks overall are expected to decrease after a fire. N begins to oxidize at 200˚C, a range well within the possibility of the Holiday Farm fire based on the presence of the hydrophobic layer (Neary et al., 1999). The combustion of N is the presumed leading driver of site-wide N losses (Johnson et al., 2007). A review by Johnson and Turner (2014) found that the mean loss of N in fires that consumed both forest floor and foliage was 0.8 Mg ha^{-1}, with ranges between 0.2 and 2.6 Mg ha^{-1}. This site's total loss was approximately 0.7 Mg N ha^{-1}.

While site-wide N decreased, changes differed within the various depths and size fractions. Both forest floor categories and depths of fine soil sizes had lower N stocks post-fire. The N stocks of the 15–30 cm coarse mineral soil, however, were higher after the fire. Consideration of these larger grain sizes is vital to calculating both the N and C total stocks because they can contain up to 37% of total site N (Whitney & Zabowski, 2004) and 25% of total site C across the 12 major soil orders (Zabowski et al., 2011). At this location, the >2 mm size fraction accounted for 45% of mineral soil C stocks, an increase from 40% in the post-harvest period, while 50% of post-fire N was in the coarse fraction compared to 43% of post-harvest N. The increase in N stocks at the 2–4.75 mm level is an indicator of the potential resilience of N through conversion to inorganic forms during fire (Corti et al., 2002).

Forest floor N stocks were lower due to the almost complete eradication of forest floor mass, while the %N was higher post-fire. These concentration changes are likely a factor of different forest floor compositions, with a higher %N expected in Douglas-fir needles, which were a primary component of the post-harvest composition, than in woody biomass. Temperature of oxidation could also be significant driver of increased N since N is oxidized at a higher temperature than soil organic matter, leading to a higher %N relative to %C in the severely burned forest floor (Neary et al., 2005). The increase in woody litter %N post-fire indicates that compounding effects of both chemical and physical alterations may have occurred to increase %N in the forest floor level and coarse mineral soil.

Reductions in the C:N ratio are expected after a fire based on increases in %N (Figure 7). Potential N increases from leaching (Matosziuk et al., 2020) can also lead to a lower C:N in mineral soil.

4.3 | Implications

The risk emerging from the compounding disturbance of harvest followed by fire has not been extensively studied in the fire-infrequent western Cascades forests. The high commercial and C value of these forests makes further investigation warranted to determine soil C changes in industrially harvested landscapes. Understanding the interactions between recurring disturbances like wildfire and harvest in the C-rich soils of the western Cascades is crucial for land management planning to prevent further C losses.

Through an analysis of the driving factors of burn severity in the 2020 Labor Day fires, Evers et al. (2022) determined that canopy height was the strongest indicator of high severity fire, with lower canopy heights (<10 m) having over 80% high severity designation. High severity in this study was defined by over 75% tree mortality; the site investigated in this article (OR4) had 100% mortality. The low canopy height of 8-year-old trees and abundant harvest residues combined with extremely dry fuels and westward winds may have created ideal conditions for widespread high-severity fire on site. Zald and Dunn (2018) observed similar causes in their research determining the driving factors of fire severity in the southwestern Oregon 2013 Douglas Complex. Private timberland structures of homogenized trees were found to have burned more severely than mixed-age managed stands due to both the higher flammability of younger seedlings and the dense layout of stands. Low, homogenous canopy height therefore may be possible contributors to increased fire outcomes on vegetation and soil.

The deficit created by recent fire suppression has allowed the prevalence of forest structures that differ from historical stands in the western Cascades forests that couple to form conditions suitable for high-severity fire in areas without recent high-severity fire experience (Haugo et al., 2019; Parks et al., 2018). Areas burned in high severity have demonstrated more likelihood of high-severity reburn, indicating the possibility of an ecosystem transformation to high-severity fire tendencies (Bowman et al., 2013; Halofsky et al., 2020; Lindenmayer et al., 2011; Thompson et al., 2007). The young age structure of many western Cascades stands and the post-harvest downed woody debris should be further explored to understand potential effects on soil C in a reburn.

This novel western Cascades wildfire leaves many pieces of future site resiliency to be determined. Therefore, it is vital that long-term soil C projects such as this one are maintained and expanded in order to separate soil C changes into fire-induced, harvest-induced, and interactive causes. Effects on a variety of management landscapes, like beetle-killed (Stephens et al., 2022) and non-clearcut harvested, will provide further direction for tangible actions to take to preserve soil C after a severe wildfire. Soil C cycles on the order of years to millennia (Lehmann & Kleber, 2015), making impacts on belowground cycles even more vital to understand. Further investigation into the drivers of post-fire soil C changes is fundamental for supporting adaptive landscapes that can withstand climate change and increasing fire frequency while maintaining some of the most valuable belowground C resources.

5 | CONCLUSION

After a wildfire burned at high severity through a stand of industrially planted 8-year-old Douglas-firs, forest floor and soil C stocks to 30 cm decreased by approximately 30%, corresponding to a loss of 40 Mg C ha^{-1}. Two-thirds of these losses were in the forest floor, which had an overall mass decrease of 95%. Mineral soil C stock decreases were driven by losses of soil mass.

C concentration did not change and N concentration was higher overall after the fire. These characteristics point to the potential resilience of western Cascades forests when confronting hotter and drier temperatures that may spur more fires in the coming decades. Future research should investigate the compounding effects of harvest and fire and their potential impacts on soil C and N storage.

AUTHOR CONTRIBUTIONS

Katherine D. McCool: Data curation; investigating; writing—original draft; writing—review and editing. **Jeff A. Hatten**: Conceptualization; funding acquisition; methodology; supervision; writing—review and editing. **Scott M. Holub**: Conceptualization; funding acquisition; methodology; writing—review and editing. **Si Gao and Jessica E.**

Blunn: Data curation; writing—review and editing. **Brett A. Morrissette**: Data curation; methodology; writing–review and editing. **Adrian C. Gallo**: writing—review and editing.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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