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Soil C storage following salvage logging and residue management in bark beetle-infested lodgepole pine forests

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ABSTRACT

Bark beetle outbreaks have altered carbon (C) dynamics in lodgepole pine (*Pinus contorta* var. *latifolia* Engelm. ex Wats.) forests across western North America. The sensitivity of soil C to post-beetle management operations remains unknown in these forests. We quantified total C stocks in the O horizon and upper mineral soil (0–10 cm) 6–7 years after salvage logging in lodgepole pine forests of northern Colorado and compared biomass retention or removal residue management to uncut beetle-infested forests. We evaluated the quantity and chemical composition of C in physical fractions of the O horizon and upper mineral soil layers to better understand how management impacts the quality of C with implications for soil C persistence. Post-harvest residue retention increased O horizon C storage compared to the removal treatment and uncut stands. Total soil C (O horizon and upper 0–10 cm mineral soil) was an average of 11.4 (± 5.6) Mg C ha^{-1} higher in salvage logged plots compared to uncut forests and the increase was primarily in particulate organic matter. Salvage logging did not alter the chemical composition of the soil C fractions analyzed. The C:N ratios, Fourier-transform mid-infrared spectra, and ^{13}C values analyses each showed that the C composition of the organic and upper mineral soil layers were distinct. This indicates that physical transfer of fresh or decomposed O horizon material may not be the primary source of particulate C, and we suggest that belowground inputs are likely to be an important contributor to these mineral soils. Our finding that logging residue removal did not reduce post-harvest upper mineral soil C stocks has implications for biomass harvesting in these forests, though the long-term impacts of post-bark beetle management on C storage in these ecosystems depend on understory dynamics, tree regeneration and forest recovery that will progress over the course of decades. This work suggests that greater understanding of post-logging organic matter inputs and C dynamics in O horizon and mineral SOM fractions can help inform forest management aimed at sustaining soil C.

1. Introduction

Widespread mortality of lodgepole pine (*Pinus contorta* var. *latifolia* Engelm. ex Wats.) in the Rocky Mountain region of western North America due to a climate-driven outbreak of the endemic mountain pine beetle (MPB; *Dendroctonus ponderosae* Hopkins) has significantly altered ecosystem carbon (C) dynamics (Edburg et al., 2011; Hansen, 2014). During the most recent outbreak, bark beetles killed 70% or more of the lodgepole pine overstory basal area in many Colorado forests (Collins et al., 2011; Klutsch et al., 2009). Clear cut salvage logging of MPB-infested lodgepole pine stands has taken place in Colorado (Collins et al., 2010) and across western North America to reduce fuel loads and wildfire risk, reduce treefall hazards, recover the economic value of the timber, and regenerate new forests. Post-beetle salvage has the potential to increase C captured within rapidly growing young forests and store it in timber and other wood products (Malmsheimer et al., 2011). Yet, a recent systematic map of primary studies evaluating post-disturbance salvage logging cited 51 publications on post-wildfire salvage, 26 publications on post-wind salvage and only 13 publications on post-insect salvage, less than a quarter of the cited studies (Leverkus et al., 2018). Studies following this most recent MPB outbreak are starting to fill this gap in understanding and have found that salvage logging reduces canopy fuels and wildfire risk, and regenerates new trees without negatively effecting plant diversity or

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soil nitrogen availability (Collins et al., 2011, 2012; Fornwalt et al., 2018; Griffin et al., 2013; Hood et al., 2017; Rhoades et al., 2018, 2020a); however, none of the aforementioned studies directly evaluated changes to forest soil C.

Soils store half of the C in forest ecosystems of the conterminous U.S. (Turner et al., 1995), totaling approximately 13–28 Pg of soil organic C (Lajtha et al., 2018). Following the MPB-outbreak in Colorado, upper mineral soil (0–5 cm) % C declined by 38–49% under beetle-killed lodgepole pine compared to live, green trees at Niwot Ridge Long-Term Ecological Research site, which the authors attributed to declines in C inputs to the rhizosphere (Xiong et al., 2011). This finding supported initial model-based predictions that decreases in net primary production (NPP) due to tree mortality would convert infested stands into net sources of atmospheric C due to reduced new C inputs, respiration during decomposition and salvage logging (Kurz et al., 2008). However, other studies have documented the recovery of NPP and net ecosystem production within 4–7 years following MPB (Brown et al., 2010, 2012) due to the increased photosynthetic activity and C uptake of residual vegetation (Bowler et al., 2012; Romme et al., 1986). Compensatory increases in C uptake by understory vegetation, new recruits or residual trees were not accounted for in the Kurz et al. (2008) model. Salvage logging increases new seedling establishment and growth of residual trees, though it reduces understory plant cover in beetle-killed Colorado forests (Collins et al., 2012; Fornwalt et al., 2018). Changes in soil C quality have also been detected in Colorado in MPB-infested stands. Brouillard et al. (2017) reported lower soil C to nitrogen (N) ratios and increased aromaticity under MPB-killed lodgepole compared to green trees. The quality and distribution of soil C among soil organic matter (SOM) fractions may also be vulnerable to post-bark beetle salvage logging or other management (Lajtha et al., 2018) with implications for function, mechanisms of C persistence and turnover times (Christensen, 2001; von Lützow et al., 2007, 2008).

Forest soil C is distributed vertically with an accumulation of surface organic inputs forming the O horizon above the mineral soil. While C concentrations are highest in the O horizon, the majority of C in temperate forest systems is stored in the upper 100 cm of the mineral profile as a component of soil organic matter (SOM) (Nave et al., 2010; Shaw et al., 2008). SOM can be separated based on size and/or density into particulate (POM) and mineral-associated organic matter (MAOM) fractions with different chemical properties and potential turnover times (Christensen, 2001; Lavallee et al., 2020; Sollins et al., 2006). Forest soils typically store a high proportion of soil C (i.e., $\geq 60\%$) as light POM (< 1.85 g cm^{-3}) (Cotrufo et al., 2019; Denef et al., 2013; Sollins et al., 2006), characterized by structural plant residues with a high C:N ratio that have undergone little decomposition (Golchin et al., 1994; Gregorich et al., 2006). Light POM is formed through fragmentation and physical transfer of above or belowground plant C inputs (Cotrufo et al., 2015; Haddix et al., 2016). Microbial processing of plant residues and light POM mineralizes much of the C, with some of the residual C forming sand-sized heavy POM (> 1.85 g cm^{-3} and $>$ 53 µm) (Grandy and Neff, 2008). In contrast to the POM fractions, MAOM (> 1.85 g cm^{-3} and $<$ 53 µm) is thought to form from soluble compounds entering the mineral soil through root exudation, leaching from plant residues or from products of microbial transformation (Cotrufo et al., 2015; Liang et al., 2017; Sokol et al., 2019). The efficiency of SOM formation and distribution of C among SOM fractions is controlled by the chemistry and physical structure of the plant C inputs (Cotrufo et al., 2015, 2013; Haddix et al., 2016). While the chemical recalcitrance of the POM fractions may slow their decomposition, inaccessibility to microorganisms through protection within aggregates or mineral association are the most important mechanisms for stabilizing soil C (Lehmann and Kleber, 2015; Mikutta et al., 2006; Sollins et al., 2006). Formation of MAOM requires silt and clay particles and may be limited in forest soils with coarse texture and recalcitrant litter (Cotrufo et al., 2013).

Clear cut salvage logging and residue management may alter forest soil C through changing the microclimate and the quantity and type of plant C inputs contributing to the O horizon and available for mineral POM and MAOM formation. Changes in microclimate and microbial controls on decomposition—temperature, moisture and nitrogen availability—have been well studied (e.g., Prescott, 2010, 1997; Smolander et al., 2008). Overall, long-term changes in soil C stocks in response to logging and residue management depend on the balance of soil C loss due to logging and the formation of new SOM, particularly MAOM, from the decaying residues and live plant inputs. A global meta-analysis found that forest harvesting decreased C storage in the O horizons of coniferous and mixed coniferous and broadleaf forests by 20% on average, but that changes within mineral soils were relatively minor (Nave et al., 2010). Site conditions, post-harvest site preparation, logging residue (e.g. slash) prescriptions influence whether O horizon C increases, decreases, or is unchanged (Johnson and Curtis, 2001). Many factors influence the amount of surface detritus contributing to the O horizon in both the uncut and salvage logged stands. In uncut stands, needles are shed 3–5 years following MPB-infestation, slowly contributing fine residues to the O horizon (Hicke et al., 2012; Schoennagel et al., 2012; Simard et al., 2011). In salvage logged stands, shatter of dry, MPB-killed tree crowns during felling increases foliage and branch residue inputs within the harvest unit, regardless of slash prescription. Soil C stocks might be most responsive to changes in the inputs of smaller residues in the first few decades following MPB infestation and salvage logging. Less than 20% of snags have fallen in the first decade following the beetle outbreak in Colorado (Rhoades et al., 2020b) and large diameter woody material decompose on the order of a century (Brown et al., 1998; Busse, 1994; Fahey, 1983), thus C inputs from snags and large woody residues are likely to have small contributions to soil C stocks early in the decomposition process.

This study documents changes in forest soil C following salvage logging and residue management of MPB-infested lodgepole pine forests. We sought to characterize how forest harvest and residue management impacted (1) forest soil C stocks, (2) its distribution, between the O horizon and the upper 10 cm of mineral soil, and among light and heavy POM and MAOM fractions, and (3) forest soil C chemistry. To address these objectives, we studied three management treatments: (1) uncut beetle-infested lodgepole pine forest and, adjacent areas that were clear cut salvage logged with either woody residue (2) retention or (3) removal. We quantified C stocks in the O horizon, bulk mineral soil and mineral SOM fractions and characterized C chemistry using Fourier transformed mid-infrared spectroscopy (FTIR) and stable isotope analysis. We expected the O horizon and light POM to be the most responsive to surface residue manipulations (Bowden et al., 2014; Crow et al., 2009a; Lajtha et al., 2014), increasing in proportion to the woody residue load. Further, we expected that the O horizon and the light POM would be more chemically recalcitrant due to the contribution from woody inputs.

2. Materials and methods

2.1. Experimental management area description and design

This study was conducted at four MPB management areas in northern Colorado on the Arapaho-Roosevelt National Forest (Fraser Experimental Forest; 'Fraser' hereafter), the Medicine Bow-Routt National Forest (Gore Pass and Willow Creek), and the Colorado State Forest State Park (State Forest). At all sites, lodgepole pine is dominant on lower elevations and drier, southern aspects (Alexander and Watkins, 1977), comprising 70 to > 90% of the overstory cover (Collins et al., 2012, 2011). Other species include Engelmann spruce (*Picea engelmanni*), subalpine fir (*Abies lasiocarpa*), and Quaking aspen (*Populus tremuloides*). Bark beetle activity began in the region between 1998 and 2002, peaked between 2006 and 2009 and caused 79–91% mortality of lodgepole pine basal area (Collins et al., 2012). The management areas have a mean elevation range of 2750 to 2850 m

(Fornwalt et al., 2018) and a continental climate with mean annual precipitation ranging from 544 to 687 mm and mean annual temperature ranging from 1.8 to 2.7 °C (PRISM Climate Group, 2017).

The respective management agency at each of the four management areas determined where the harvest units were located. Three replicate blocks were established at each of the four management areas during summer 2009. Pre-harvest stand exams (USFS Region 2 and Colorado State Forest Service, unpublished records) and stand inventories of uncut areas (Collins et al., 2012, 2011) were used to identify paired uncut and salvage logged areas within each management area to establish the block locations to minimize differences between treatments due to location of the harvested areas. Further, the uncut and salvage logged areas were located $\leq$ 400 m from each other on similar aspects and slopes (Collins et al., 2012) to achieve this goal. The three treatments were (1) uncut control, (2) clear cut salvage-logged with logging residue retention ('retention' hereafter), and (3) clear cut salvage-logged with logging residue removal ('removal' hereafter) (Fornwalt et al., 2018). Salvage-logged treatments were randomly assigned to treatment plots located adjacent to each other with a 10 m buffer between plots (Fornwalt et al., 2018) to reduce the variability between the salvage logged plots as much as possible so that the main difference was the application of the logging residues. Clear cut salvage logging coincided with the peak of the outbreak in northern Colorado (Fraser: winter 2007–2008; Other Areas: winter 2008–2009). Logging operations were restricted to times with dry or frozen soils or > 1 m of snow to minimize soil disturbance (Collins et al., 2011). Each treatment was applied to a 30 × 30 m (900 m^2) area containing a 20 × 20 m (400 m^2) sampling plot. Logged areas were first whole-tree harvested (i.e., removal) and then experimental logging residue treatments (e.g., retention) were established in in 2009 by returning slash to the plots (Fornwalt et al., 2018).

2.2. O horizon and mineral soil sampling and processing

The O horizon and upper mineral soil (0–10 cm) were sampled in fall 2015. For this sampling each research plot was divided into four 10 × 10 m quadrants then the O horizon and upper mineral soil were sampled from the center of three quadrants. O horizon samples were collected from a 15 × 15 cm sample frame. A knife was used to separate the O horizon and a plastic scoop was used to collect the sample. All three O horizon samples from each plot were composited in the field and were transported on ice and stored at 4 °C until processing. The composited samples were air-dried and sieved into three size classes: large residues (> 8 mm), fine residues (2–8 mm), and organic material (< 2 mm). Large residues were comprised of identifiable plant tissues including twigs, cones and needles and most closely resembled the litter or Oi horizon. The fine residues consisted of decomposing wood, needle fragments and portions of cones and resembled the Oe horizon. The organic material resembled the Oa horizon and contained uniform, highly decomposed matter. The O horizon size classes were oven dried to a constant mass at 60 °C, dry weight was recorded, and a representative subsample was finely ground on a Wiley-Mill (Model No. 3, Arthur H. Thomas Co., Philadelphia, USA) prior to further analysis.

After O horizon sampling, two, 10 cm deep mineral soil samples were collected from each of the three quadrants from the same location where the O horizon was sampled using a 5 cm diameter core (Giddings Machine Company, Windsor, CO, USA) for a total of 216 soil cores which were composited in the field at the plot level. Mineral soils were then transported on ice and stored at 4 °C until processing. Mineral soils were sieved to 2 mm and air-dried. One subsample of the mineral soil was used for SOM physical fractionation and another was ground to a fine powder using a roller-mill, dried at 105 °C and used for total soil C and $\delta^{13}C$ (Mosier et al., 2019).

Soil bulk density was measured by pit excavation due to the rockiness of the soils (Page-Dumroese et al., 1999). Three pits were dug within the uncut and salvage logged areas of each block, outside of the sampling plots, then the total volume of the excavated soil pit was measured using millet (Boot et al., 2015). The soil excavated from each pit was brought back to the lab, air-dried and 2 mm sieved to separate the coarse fraction (> 2 mm) from the soil fraction (< 2 mm). The mass of the soil fraction was weighed after sieving and a ~5 g subsample was dried at 105 °C to apply an air-dry to oven-dry moisture correction. Bulk density for each pit was calculated using the hybrid approach of Throop et al. (2012) using the oven-dry mass of the soil fraction divided by the volume of the entire pit. Soil texture was analyzed using the hydrometer method (Gee and Bauder, 1986).

We utilized a physical fractionation scheme to separate the SOM into two uncomplexed POM fractions: light (< 1.85 g cm^{-3}) and sand-sized heavy POM (> 1.85 g cm^{-3} and > 53 µm); and fine MAOM (> 1.85 g cm^{-3} and < 53 µm) (Christensen, 2001; Lavallee et al., 2020; Mosier et al., 2019). A 5 g oven-dry subsample of each bulk soil sample was shaken for 18 h with 25 mL of 0.5% sodium hexametaphosphate (Na-HMP) and glass beads to disperse aggregates. After dispersion, centrifuge tubes were filled to 30 mL with 1.85 g cm^{-3} sodium polytungstate (SPT) (~25 mL SPT) and samples were centrifuged for 60 min at 2500 rpm to separate the light POM. Light POM was aspirated and filtered using a 20 µm Millipore glass filter, rinsed clean of SPT, and dried at 60 °C. The remaining fractions were rinsed 3 times with DI water to remove SPT, then wet sieved through a 53 µm sieve to separate heavy POM from silt and clay sized MAOM. Fractions were rinsed into pre-weighed aluminum pans, dried at 60 °C for two days, and weighed. Mass recovery was calculated by the difference between the starting soil weight and the combined weight of all fractions, with an accepted recovery of 100 ± 5%. All dried fractions were ground to a fine powder using a mortar and pestle.

2.3. O horizon and mineral soil analyses

A subsample of each of the O horizon size classes, bulk mineral soil and mineral SOM fractions (light and heavy POM and MAOM) were analyzed for %C, %N, and $\delta^{13}C$ on an elemental analyzer (Costech ECS 4010, Costech Analytical Technologies, Valencia, CA, USA) coupled to an isotope ratio mass spectrometer (Delta V Advantage IRMS, Thermo-Fisher, Bremen, Germany). The analytical precision of the internal laboratory standards was < 0.2‰ for $\delta^{13}C$. Additionally, the O horizon size classes and mineral SOM fractions were scanned for Fourier-transform infrared spectroscopy analysis (FTIR) on a Digilab FTS 700 Fourier transform spectrometer (Varian, Inc., Palo Alto, CA) with a deuterated, Peltier-cooled, triglycine sulfate detector and potassium bromide beam splitter and fitted with a Pike AutoDiFF diffuse reflectance accessory (Pike Technologies, Madison, WI). Potassium bromide was used as background. Spectra were collected at 4 cm^{-1} resolution, with 64 co-added scans per spectrum from 4000 to 400 cm^{-1}. Spectra were obtained as pseudo-absorbance (log[1/Reflectance]) in the method of Calderón et al. (2011). Two subsamples were scanned separately then averaged before statistical analyses and subtractions.

2.4. Data analyses

Linear mixed models using *lmer* and the R packages *lme4*, lmerTEST, and lsmeans (Bates et al., 2015; R Core Team, 2019) were used to test for the effect of treatment on the C stocks, C:N ratio, and $\delta^{13}C$ of the O horizon size classes and SOM fractions, and bulk density, % C, and C stocks of the bulk mineral soil. For all models, treatment was classified as a fixed effect. Management area and blocks nested within management area were classified as random effects. For bulk density there were just two treatments, uncut and salvage logged, while the other variables had all three treatments of uncut control and logged with residue retention and removal. For C:N ratio and $\delta^{13}C$, fraction (in this case the O horizon size classes and SOM fractions) was also included as a fixed effect. The interaction of treatment and fraction was not of interest for either variable, so it was dropped from both models due to nonsignificance. Data that were not normally distributed were first log transformed. Models were evaluated using analysis of variance using a significant alpha level at $p = 0.10$ (Crow et al., 2009b) followed by Tukey-adjusted pairwise comparisons.

Principle component analysis (PCA) of the FTIR spectra was used to visualize differences between the forest management treatments, O horizon size classes, and SOM fractions in Unscrambler® X version 10.4 (CAMO, Oslo, Norway). Statistical assessment of differences among FTIR spectra as a function of fraction and treatment were tested with the permutational multivariate analysis of variance (PERMANOVA) ADONIS method in R using the vegan package using a Euclidean distance metric and 999 permutations (Oksanen et al., 2019) and pairwise comparisons were evaluated in PAST with Bonferroni adjustment (Hammer et al., 2001). All FTIR spectra were mean-centered prior to statistical analysis. Spectral averages and subtractions were carried out using Grams A/I version 9.3 (Thermo Fischer Scientific, Massachusetts, USA), using the default autoscale, optimal factor, and tolerance values suggested by the program.

We calculated minimum detectable differences (MDD) between our uncut and logged treatments for the C fractions contained in the O horizon and upper mineral soil using the following paired sample equation (Schöning et al., 2006):

$$MDD \geq \sqrt{\frac{s^2}{n}(t_{\alpha(2),v} + t_{\beta(1),v})^2}$$

where the variables were the pooled variance (s^2), sample size (n) and degrees of freedom (v). We assigned a significance level (α) of 0.10, consistent with the rest of our study, and a statistical power ($1-\beta$) of 0.80 to the t-statistic (t). We calculated the percentage change needed to conclude that logged and uncut C stocks differed as follows:

$$MDD\% = \frac{MDD}{\bar{x}} \times 100\%$$

where $\bar{x}$ is the mean value of the uncut treatment for a specific C stock.

3. Results

3.1. O horizon carbon stocks

The C stock of the large residues (> 8 mm) differed with treatment ($F(2, 22) = 4.27$, $p = 0.03$). The C stock in the large residues of the retention treatment was more than double that of the uncut control (Tukey's pairwise comparison, $p = 0.02$) but not different than the residue removal treatment (Tukey's pairwise comparison, $p = 0.14$; Fig. 1). There was a non-significant trend of highest C in the retention treatment for the fine residues (2–8 mm) ($F(2, 22) = 1.19$, $p = 0.32$) and no differences in the organic material (< 2 mm) ($F(2, 22) = 0.24$, $p = 0.79$; Fig. 1). The MDD % needed to conclude treatment differences for fine residues and organic material were ≥ 95% and ≥102%, yet we measured 55% and 38% differences respectively. The mean total Mg C ha^{-1} (± 1 standard error) in the three O horizon size classes was 12.1 (1.80) for the uncut, 20.6 (3.83) for the retention and 14.8 (4.44) for the removal with no treatment effect ($F(2, 22) = 1.44$, $p = 0.26$). The MDD % for the total O horizon was ≥90% and the measured difference was ~71%.

3.2. Mineral soil C stocks and distribution among physically-defined SOM fractions

Both soil bulk density and bulk soil C concentration (%C) had a non-significant trend of increase with salvage logging and residue removal (Table 1), resulting in differences in bulk soil C stocks between treatments ($F(2, 22) = 3.10$, $p = 0.07$; Fig. 1). Pairwise comparisons showed that removal had the most upper mineral soil C (0–10 cm) with a mean increase of 8.5 (4.1) Mg ha^{-1} (± 1 standard error) more C than the uncut control, a 34% difference (Tukey's pairwise comparison,

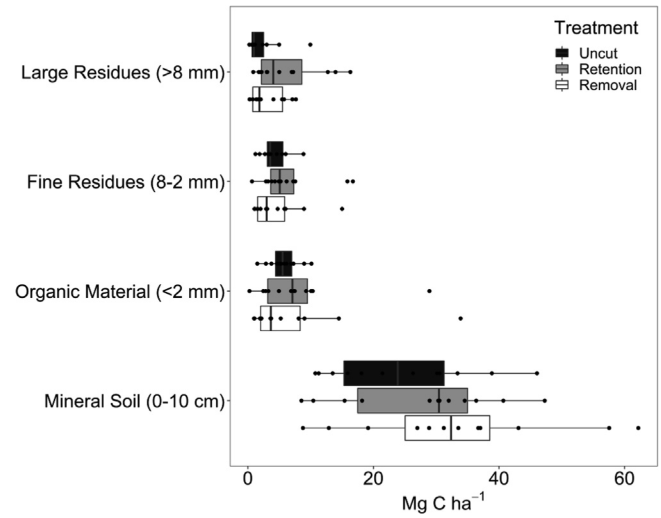

Fig. 1. Carbon stocks (Mg C ha^{-1}) on the soil surface in the large and fine O horizon size classes, organic material, and in the bulk mineral soil for the uncut control and salvage logged plots with residue retention or removal. Black dots represent the individual raw data points (n = 12).

$p = 0.05$; Fig. 1). This analysis had a power (1-β) of 0.42 and the MDD calculations showed that a ≥59% difference was required to have 0.80 power or higher. Larger post-harvest upper mineral soil C stocks were driven by larger POM fractions relative to the uncut control (Fig. 2). However, only the heavy POM C stocks differed with treatment ($F(2, 22) = 4.63$, $p = 0.02$) and pairwise comparison showed that the removal treatment more C in heavy POM than the other two treatments (Tukey's pairwise comparison, $p = 0.02$; Fig. 2). The measured difference in light POM between the uncut and removal treatments was 39%; to detect differences in that fraction our MDD analysis indicated that differences ≥75% would have been required. Independent of treatment, light POM was the largest soil C pool with approximately seven times more C than heavy POM, three times more C than MAOM and ~63% of total upper mineral soil C.

3.3. Soil C:N ratios, C chemistry, and ^{13}C

Overall, C:N ratios ranged from an average of 96.1 in large residues to an average of 14.2 in MAOM (Table 2). C:N ratios differed among fractions but not treatments (Table 3). The C:N ratio of each fraction was different from all others (Tukey's pairwise comparison, $p < 0.0001$) except for the fine residues and light POM (Tukey's pairwise comparison, $p = 0.44$). C:N ratio did not differ with treatment for the bulk soil ($F(2, 22) = 0.08$, $p = 0.93$) and across all plots the mean C:N ratio (± 1 standard error) was 26.37 (0.55).

The $\delta^{13}C$ signature differed among fractions and treatments (Table 3). The large residues and mineral SOM fractions were significantly less depleted in ^{13}C than fine residues and organic material (Tukey's pairwise comparison, $p < 0.0001$) and the organic material was also depleted relative to the fine residues (Tukey's pairwise comparison, $p = 0.08$; Fig. 3). The MAOM fraction had the highest ^{13}C enrichment (Tukey's pairwise comparison, $p \leq 0.01$). The retention treatment was depleted in ^{13}C in all fractions relative to the uncut (Tukey's pairwise comparison, $p < 0.004$). Across fractions the removal treatment was not consistently enriched or depleted in ^{13}C relative to the retention or uncut treatment and thus the $\delta^{13}C$ of the removal did not differ from either treatment (removal-uncut Tukey's pairwise comparison, $p = 0.24$; removal-retention Tukey's pairwise comparison, $p = 0.23$).

PCA analysis of the FTIR spectra showed compositional differences among the O horizon and mineral SOM fractions. PERMANOVA showed that the spectra differed by fraction ($F(7, 244) = 261.52$, $p = 0.001$) as

Table 1
Bulk mineral soil characteristics (0–10 cm) of the four management areas of the study including soil texture, bulk density, and soil C concentration (%C), and the C stock of the woody residues (> 7.62 cm) on the surface after treatment application. Data are means followed by the standard error (± 1 S.E.) in parentheses (n = 3). Linear mixed model results for bulk density, soil C concentration and woody residue C stocks using the predictor effect treatment. Effects with p < 0.05 are emphasized in bold (n = 12).

Management Area	Treatment	Soil Texture (% sand, % silt, % clay)	Bulk Density (g cm^{-3})	Soil C Concentration (%C)	Woody Residue C Stocks (Mg C ha^{-1})*
Fraser	Uncut	43, 40, 17	0.65 (0.06)	4.04 (0.88)	3.48 (1.82)
	Retention	52, 34, 14	0.73 (0.02)	3.63 (0.64)	21.88 (2.20)
	Removal	48, 38, 14		4.80 (0.42)	7.72 (0.52)
Gore Pass	Uncut	57, 33, 10	0.94 (0.07)	3.34 (0.54)	4.16 (2.48)
	Retention	60, 29, 11	0.77 (0.02)	4.60 (0.46)	16.28 (1.00)
	Removal	58, 32, 10		5.03 (1.25)	3.57 (1.32)
State Forest	Uncut	56, 36, 8	0.75 (0.03)	4.06 (0.96)	0.48 (0.27)
	Retention	47, 43, 10	0.93 (0.09)	4.28 (0.63)	27.54 (3.00)
	Removal	51, 39, 10		5.54 (2.05)	3.68 (0.78)
Willow Creek	Uncut	68, 24, 8	0.67 (0.03)	1.81 (0.26)	3.71 (1.79)
	Retention	72, 22, 6	0.79 (0.07)	1.53 (0.32)	23.76 (1.70)
	Removal	74, 21, 5		1.72 (0.22)	1.26 (0.39)
Model results					
		Num DF	1	2	2
		Den DF	11	22	22
		F value	0.56	1.466	97.514
		Pr > F	0.47	0.25	**< 0.0001**

*The values were calculated by multiplying the loads (Mg ha^{-1}) of large diameter (> 7.62 cm) downed wood and logging residues by 0.5 to convert to C stock (Mg C ha^{-1}). The loads of woody residues were estimated in 2010 along two, 20-m planar intercept transects in each plot and summed across decay classes and are derived from Collins et al. (2012).

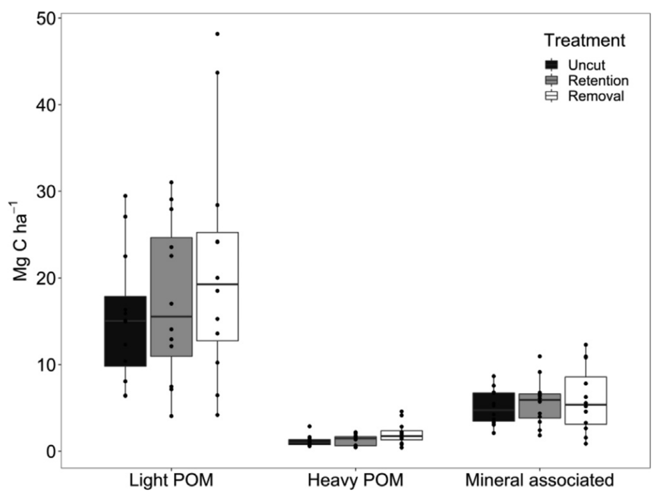

Fig. 2. Carbon stocks (Mg C ha^{-1}) in the measured SOM fractions, light particulate organic matter (POM; < 1.85 g cm^{-3}), heavy POM (> 1.85 g cm^{-3}, > 53 µm) and mineral-associated organic matter (> 1.85 g cm^{-3}, < 53 µm), for the uncut control and salvage logged plots with residue retention or removal. Black dots represent the individual raw data points (n = 12).

Table 2
C:N ratio of the O horizon size classes and mineral SOM fractions for the uncut control and salvage logged plots with residue retention or removal. Data are means followed by the standard error (± 1 S.E.) in parentheses (n = 12). The C:N ratio did not differ with treatment for any of the fractions.

	O Horizon C:N		
	Uncut	Retention	Removal
Large residues (> 8 mm)	100.10 (11. 5)	89.01 (6.8)	99.15 (10.1)
Fine residues (2–8 mm)	41.86 (2.0)	44.33 (3.0)	46.10 (2.7)
Organic material (< 2mm)	28.31 (0.9)	29.05 (1.7)	28.97 (1.0)
	Mineral Soil (0–10 cm) C:N		
Light POM (< 1.85 g cm^{-3})	41.15 (2.0)	40.09 (1.9)	37.97 (0.8)
Heavy POM (> 53 µm)	18.86 (1.5)	19.72 (1.7)	22.35 (1.3)
MAOM (< 53 µm)	13.72 (0.6)	13.93 (0.5)	14.49 (0.7)

all O horizon size classes and mineral SOM fractions were different from one another (Bonferroni corrected $p = 0.002$), except for the large and fine residues (Bonferroni corrected $p = 0.48$). There were no treatment effects ($F(2, 249) = 0.05$, $p = 0.996$), therefore, we averaged all FTIR spectra of the organic material and light POM and used spectral subtraction to help elucidate the unexpected C:N and $\delta^{13}C$ differences between these two fractions. The spectral subtraction showed that the organic material had different features than the light POM, in particular more amines and O-H functional groups (3400 cm^{-1}), aliphatics (2920–2850 cm^{-1}), esters (1750 cm^{-1}), amides (1750 cm^{-1}), and aromatic C=C (1515 cm^{-1}) (Fig. 4).

4. Discussion

Salvage logging MPB-killed lodgepole pine forests has the potential to alter forest soil C by removing C as tree biomass, transferring residue C to the soil surface where it may be more readily decomposed and altering root inputs and decomposition dynamics. Six to seven years following harvest, C stored in the O horizon and upper mineral soil was 11.4 (5.6) Mg C ha^{-1} higher on average in salvage-logged areas compared to uncut stands. Retention of large diameter woody residues (> 7.62 cm) added 8.6 Mg C ha^{-1} to the O horizon compared to the uncut, equivalent to 41% more C (Table 1). But surprisingly, differences in upper mineral soil C did not parallel the treatment effects on C in woody residues or the O horizon and it was the residue removal treatment that had more upper mineral soil C compared to the uncut, a difference of 8.5 (4.1) Mg C ha^{-1} (Fig. 1; Table 1).

Studies of the effects of salvage logging on soil C following pest infestations are limited. The findings of this study are notable because they suggest that the MPB-infested lodgepole pine forests of Colorado can be salvage logged with a low risk of significant soil C loss. The differences in upper mineral soil C we measured were the result of modest differences in both soil bulk density and C concentration with salvage logging (Fig. 1; Table 1) and fell short of the 59% MDD needed to maintain power of 0.80. We suggest that the higher upper mineral soil C with post-beetle salvage logging can be attributed to direct inputs from surface organic matter in the cut areas through mixing of O horizon and harvest residues into the upper mineral soil by tracked equipment during logging operations (Rhoades et al., 2020a; Yanai et al., 2003). Mixing in of the surface organic matter during logging is

Table 3
Linear mixed model results for C:N ratio and $\delta^{13}C$ using the predictor effects treatment and fraction. In this analysis fraction included all the O horizon size classes and SOM fractions. Effects with $p < 0.05$ are emphasized in bold ($n = 12$).

Effect	C:N				$\delta^{13}C$			
	Num DF	Den DF	F value	Pr > F	Num DF	Den DF	F value	Pr > F
Fraction	5	197	326.15	**< 0.0001**	5	196.02	80.94	**< 0.0001**
Treatment	2	197	0.97	0.38	2	196.02	5.25	**0.006**

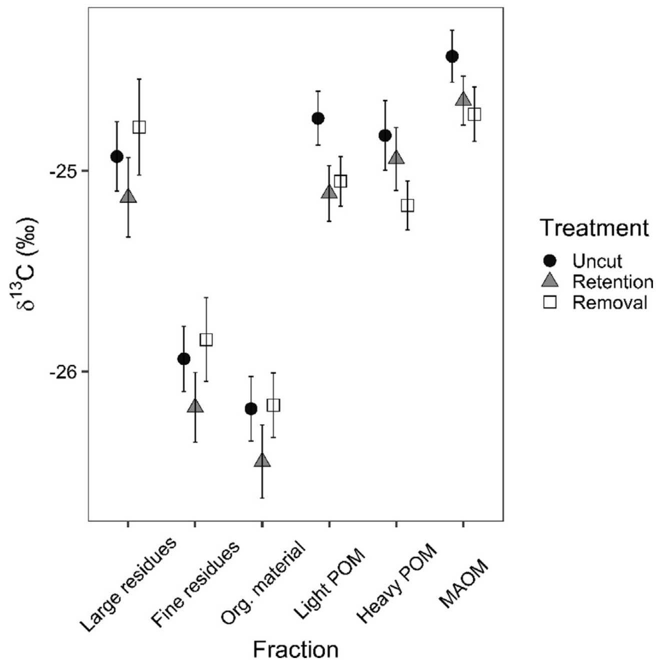

Fig. 3. $\delta^{13}C$ of each O horizon size class and mineral SOM fraction by treatment for the uncut control and salvage logged plots with residue retention or removal. Data are means with standard errors ($n = 12$).

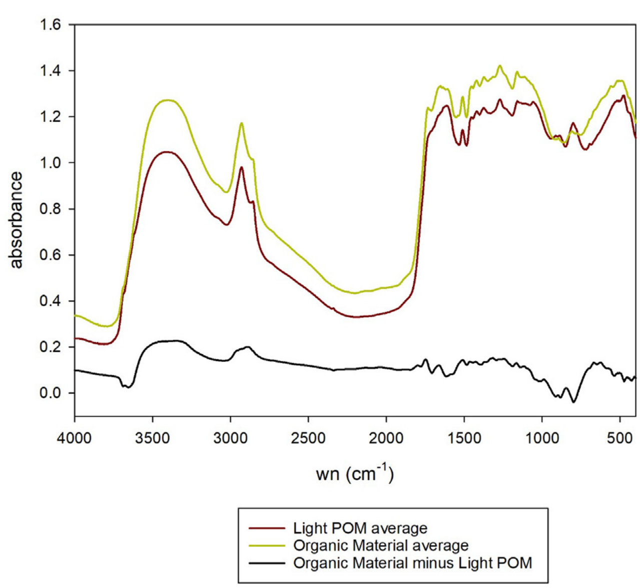

Fig. 4. Mid-infrared FTIR spectra averaged across management area and treatment of the organic material of the O horizon and light particulate organic matter (POM) fraction of the mineral SOM and the spectral subtraction of the organic material minus the light POM. Absorbance is unitless and upward peaks in the subtraction denote bands that were more abundant in the organic material.

supported by reduced O horizon cover and increased mineral soil exposure reported at these sites and nearby comparisons of cut and uncut beetle-killed lodgepole stands (Fornwalt et al., 2018; Rhoades et al., 2018; Rhoades, 2019). Mayer et al. (2020) concluded that soil C losses following clear cut harvesting are most closely tied to reduced litter C inputs and/or increased decomposition. Despite reduced cover of O horizon, the O horizon C stock was unchanged or increased in these dry, high elevation salvage logged areas and our data did not indicate that there was a net increase in decomposition.

The chemical composition and $\delta^{13}C$ results show a decoupling of O horizon C from upper mineral soil C and supports the idea that belowground C inputs are a dominant source of mineral soil C and in particular to POM (Bird et al., 2008; Fulton-Smith and Cotrufo, 2019; Puget and Drinkwater, 2001). The C:N of the light POM (39.7 ± 0.9) was higher than the organic material (28.8 ± 0.7) across all treatments, indicating that the light POM is less decomposed than the organic material (Table 2). Additionally, ^{13}C became ~1‰ more depleted moving from large residue litter to organic material (Fig. 3). In pine forests, needles and woody residues are high in lignin and lipids, which are 2–3‰ and ~4‰ depleted in ^{13}C, respectively, relative to bulk leaf tissue due to positional isotope effects (Bowling et al., 2008; Gleixner et al., 1993). Accumulation of lignin-derived C in fine residues and organic material would explain why the O horizon became depleted in ^{13}C with decomposition, and is consistent with higher abundance (e.g., absorbance) of aromatic C=C compounds on the mid-IR FTIR spectra of the organic material compared to the light POM (Fig. 4). Additionally, the spectral subtraction of the organic material and light POM FTIR spectra showed that the organic material had more microbial products with higher absorbance of aliphatic C–H and amide functional groups than the light POM (Fig. 4).

Chemical recalcitrance of the structural inputs contributing to light POM, results in POM decomposition and transformation on a yearly to decadal time frame. In these medium- to coarse-textured soils the two POM fractions together accounted for 76.7% of the C in the upper mineral soil (ranging from 65 to 95%) (Fig. 2), with the most C stored in the light POM fraction (63%). This finding is not surprising as coarse-textured forest soils with poor litter quality inputs will inherently have limited capacity to accumulate MAOM (Cotrufo et al., 2013). Yet, the importance of the POM fractions to maintaining the total soil C stock in this system, highlights the need to better understand what the dominant C inputs contributing to POM are and what management practices help build and preserve POM.

5. Conclusions and management implications

A better mechanistic understanding of how salvage logging and residue management alter SOM fractions will help guide management aimed at maintaining soil C stocks. We found that salvage logging with slash removal did not reduce soil C, instead upper mineral soil C was highest in this treatment. The C:N ratio, $\delta^{13}C$ and FTIR analyses of O horizon and upper mineral soil layers indicate that these two C stocks are likely derived from distinct organic matter sources. These results show the utility of separating SOM into POM and MAOM to identify differences in soil C stocks and chemical composition (Lavallee et al., 2020). Future studies that aim to link the manipulation of C inputs to changes in forest soil C stocks should attempt to quantify the contribution of various types of C inputs (e.g., aboveground litter, root residues, rhizodeposition) to each forest soil C pool. Within forest types that store a high percentage of the total soil C as POM, this pool should be the area of focus and further evaluation of the sensitivity of POM to disturbance and the ecosystem response will better inform system response to forest management.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.foreco.2020.118251.

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