

# Changes in Soil Organic Matter Pools and Carbon Mineralization as Influenced by Fire Severity

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Fire transforms soil organic matter (SOM) to recalcitrant forms of C. The degree to which SOM is altered is dependent on fire severity. This study investigated changes in SOM composition and mineralization by controlling the fire severity of laboratory burns on reconstructed soil profiles (O, A1 [0–1 cm], and A2 [1–2 cm] horizons). Burning simulated low-, moderate-, and high-severity fires. Organic and mineral soils were incubated for 180 d and CO<sub>2</sub> production was measured with soda lime traps. Soils were analyzed for SOM composition pre- and post-incubation using an alkaline extraction. Higher severity burning resulted in lower O horizon decomposition rates on a C basis. Fulvic acid C in the control and low-severity O horizons was reduced by 13% by incubation, which was negatively correlated with cumulative C mineralized ( $r = -0.564$ ). After incubation, the SOM composition of the burned O horizons remained different from the control. Higher severity burning caused mineral soil to initially have higher C mineralization rates, which disappeared by the end of the incubation. Fulvic acid concentration was reduced by 61 and 38% during incubation of the A1 and A2 horizons, respectively, returning the SOM composition to control levels. The sum of alkaline insoluble forms (e.g., humin) of SOM accounted for 74 and 61% of total soil C and N, respectively, which was not significantly different between treatments. The fire severities examined show that the major impacts to SOM occurred to the O horizon and any fire-related changes to the mineral soil were not persistent.

Abbreviations: BC, black carbon; FA, fulvic acid; HA, humic acid; HO, other hydrophobic materials; LOI, loss-on-ignition; NH, nonhumic; IS, insoluble; SOM, soil organic matter.

Soil organic matter is one of the largest pools of C on the Earth's surface, accounting for 2344 Pg of global C (Jobbagy and Jackson, 2000). Fire is a naturally occurring process that alters terrestrial C cycling. The direct effect of fire on the soil is a loss of C as combustion products. A portion of the SOM remaining after fire is often transformed to forms that are chemically and biologically recalcitrant, e.g., black carbon (BC), and may contribute to long-term C storage in soils (Kuhlbusch and Crutzen, 1995). The magnitude of transformations occurring to SOM is dependent on fire severity.

Fire severity has been broadly defined as the comprehensive qualitative impact of fire on the soil and water system, atmosphere, and society and is controlled by fire behavior, including fire intensity and duration (Simard, 1991; Agee, 1993; Neary et al., 1999). Fire intensity has been defined as the rate of energy released by an individual fire or the temperature of the burning environment (White and Pickett, 1985; Neary et al., 1999). The amount of organic material consumed and transformed is dependent on temperature, which is contingent

on the amount of heat transferred into the soil (Raison et al., 1984). Heat transfer into soil relies on a soil's heat capacitance and thermal conductivity, as well as fire intensity and duration (DeBano et al., 1998). Therefore, the total impact of fire on soil and SOM will largely depend on fire severity.

Soil organic matter includes both humic and nonhumic organic substances associated with organic and mineral soil. Nonhumic substances are generally any materials that can be identified and classified. Humic substances are refractory, dark-colored, heterogeneous, organic compounds produced as byproducts of microbial metabolism (Stevenson, 1994). Another pool that may represent up to 45% of the SOM is BC (Skjemstad et al., 2002). Black carbon is the heterogeneous, aromatic, and C-rich residue of biomass burning and fossil-fuel combustion that includes charcoal, soot, and graphite (Goldberg, 1985). These classes of BC can be thought of as existing on a continuum that increases in aromaticity, condensation, C/H ratio, and C/O ratio with charcoal < soot < graphite.

Operational definitions have been developed to define classes of SOM based on alkaline extraction and subsequent solubility in an acidic solution. Soil organic matter solubility in an alkaline solution is inversely related to molecular size and solubility and positively related to O content (Stevenson, 1994). Of these SOM classes, humin is insoluble in an alkaline solution, is composed of the largest molecules, and has the greatest degree of aromaticity and the lowest concentration of O. Black carbon is often included in the insoluble humin fraction. Humic acid (HA) is extracted by an alkaline extractant but precipitates when the solution pH is lowered to 1 and is relatively immobile in soils. The FA fraction is extracted by an alkaline solution and is soluble in a subsequent acidic condition. Fulvic

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acid is often purified from saccharides, low-molecular-weight organic acids, and inorganic salts through the use of a nonionic DAX-8 resin (Malcolm, 1990; Swift, 1996). Soluble nonhumic (NH) materials do not adsorb to the DAX-8 resin, while FA adsorbs to the resin at a pH of 1 (Leenheer, 1981).

Soil organic matter plays a leading role in regulating nutrient supply to plants, as a source of cation exchange capacity, and as a reservoir of available nutrients that are ready to be mineralized by microorganisms (Stevenson, 1994). The availability and accessibility of SOM to microorganisms is dependent on its nutrient content, chemical structure, and physical protection within the soil (Baldock and Skjemstad, 2000; Baldock and Smernik, 2002; Kelleher et al., 2006). Hockaday et al. (2006, 2007) have found that charcoal may be more degradable than previously thought; however, highly condensed and aromatic substances such as charcoal, along with lignin and waxes, are thought to be less bioavailable than simpler molecules (e.g., saccharides and amino acids) (Shneour, 1966; Baldock and Skjemstad, 2000; Kelleher et al., 2006).

### Fire Effects on Carbon Mineralization

In large part, the effects of fire on soil properties and processes are the result of direct changes in the quantity and quality of SOM. Fire consumes and alters organic matter at the surface through the processes of combustion. Consumption of organic matter by fire is often incomplete and BC is produced. A portion of the energy produced from the burning of organic matter penetrates the mineral soil and may alter SOM. In general, the chemical changes that occur in SOM after heating and combustion are increases in aromatic structures and disproportionate losses of H and O relative to C (Almendros et al., 1990; Baldock and Smernik, 2002; Almendros et al., 2003; Gonzalez-Vila and Almendros, 2003; Gonzalez-Perez et al., 2004; Knicker et al., 2005). Increased heating of soil has been shown to decrease the O content of the SOM, thereby reducing FA and HA fractions while increasing humin content and aromaticity, indicating greater recalcitrance and lower bioavailability (Almendros et al., 1990; Fernandez et al., 1997, 2001, 2004). Due to the changes in the decomposition rates of fire-affected SOM, fire may be a process by which C can be sequestered into the soil (Kuhlbusch and Crutzen, 1995).

Mineral soil C decomposition after fire has been shown to be more complex. Some researchers have noted that there is a flush of C and N mineralization after burning, but that with time less C is mineralized from burned soils (Bauhus et al., 1993; Fernandez et al., 1999; Choromanska and DeLuca, 2002). The flush of C mineralization has been attributed to the release of soluble organics from the microbial biomass (Choromanska and DeLuca, 2002). Carbon mineralized on a mass basis ( $\text{g CO}_2\text{-C kg}^{-1}$  soil) has been shown to decrease after burning due to a reduction in total soil C (Fernandez et al., 1997, 1999, 2004). When adjusted for C lost through burning, the remaining C appears to be more labile, with burned soil C mineralization increasing after burning (Fernandez et al., 1997, 1999). Soils collected from the field have shown increases in C mineralization due to incorporation of fire-induced litter fall (Almendros et al., 1990; Fernandez et al., 1999). Guerrero et al. (2005) showed that as mineral soils are heated to 500°C, the proportion of C mineralized increases. The increase in C mineralization was attributed to a release of labile organic materials from the microbial biomass while the downturn in mineralization that occurred above 500°C was caused by decreased total C and an increase in recalcitrant materials. Decreases in C min-

eralization appear to occur at relatively high heating or fire severity, which is where most research regarding fire severity and whole soil has occurred. There has been very little research characterizing SOM behavior after low- to moderate-severity fires.

This study examined the effect of increasing fire severity on C mineralization and SOM forms by incubating soils treated to escalating fire severity. The objective was to determine how fire severity affects the mineralization rates of both organic and surface mineral soils. The results are presented in conjunction with preincubation SOM quality data to examine the factors controlling the C mineralization rates of fire-affected organic and mineral soils.

## MATERIALS AND METHODS

### Laboratory Burning

Laboratory burns were designed to represent prescribed fire in the understory of a ponderosa pine (*Pinus ponderosa* P. Lawson and C. Lawson) forest and are described in Hatten (2007). Clay loam soil samples were collected from a Dinkelman soil (a coarse-loamy, isotic, frigid Vitrandic Haploxeroll) beneath a ponderosa pine tree in a Douglas-fir [*Pseudotsuga menziesii* (Mirb.) Franco]–ponderosa pine forest located near Cashmere, WA, on the east side of the Cascade Mountain Range (47°27'00" N, 120°37'54" W, 1070-m elevation).

Organic and A horizons were air dried and assembled into O (6 cm), A1 (0–1 cm), and A2 (1–2 cm) horizons at bulk densities that were similar to the soil at the collection site. Fire severity was controlled by adjusting the fuel moisture and applying heated air to the surface of the O horizon. The O horizon had 18% moisture content for the low-severity treatments, while 9% moisture content was used for moderate- and high-severity treatments. To achieve the highest severity burns, a heat gun was positioned 30 cm above the surface of the O horizon. The temperature of the burns was monitored with three thermocouples positioned at the surface of the O and A1 horizons and 2 cm into the A2 horizon. Thermocouples were connected to a datalogger that recorded temperature once every minute. Preincubation laboratory burn conditions and soil characteristics are summarized in Table 1.

### Incubation

Following laboratory burns, the O and A horizons were incubated at 24°C for 180 d to determine the effect of the burn severity on the decomposition characteristics of the SOM present after burning. One hundred grams of air-dried mineral soil or 10 grams of organic soil was placed into a 2-L canning jar. Inoculating solution was produced by shaking 400 g of soil with 4 L of deionized water for 24 h. The solution was separated from the residual soil using qualitative filter paper with a vacuum applied to a Buchner funnel. The A horizons were moistened with enough inoculating solution to bring the moisture content to 35% gravimetric moisture content (~85% of field capacity), while the O horizons were moistened with solution to achieve 100% gravimetric moisture content. Approximately 35 and 10 mL of inoculant were added to organic and mineral soils, respectively.

Carbon mineralization was analyzed using soda-lime traps as described by Zibilske (1994). A preweighed 50-mL beaker filled with 30 g of oven-dried soda lime was placed onto a stand elevated above the sample. The 2-L canning jar was capped with an air-tight lid. At the end of each measurement period, soda-lime traps were removed, oven dried, and weighed to determine the amount of CO<sub>2</sub> absorbed. For the first 4 wk, soda-lime traps were analyzed and replaced weekly. Gasses in the incubation vessel were renewed by removing the lid for

**Table 1. Laboratory burn characteristics and soil chemical attributes of O and A horizons (mean ± standard deviation) after low, moderate, and high levels of fire severity and an unburned control (n = 4). The P values are from a one- (severity [ $P_s$ ]) or two- (severity × depth [ $P_d$ ,  $P_{sxd}$ ]) factor ANOVA.**

Parameter	Horizon or depth	Control	Low	Moderate	High	$P_s$	$P_d$	$P_{sxd}$
Max. temperature, °C†	O	–	272	294	406			
	0 cm	–	98	120	125			
	2 cm	–	23	53	66			
O horizon mass burned, %			32 ± 13 a‡	67 ± 8 b	80 ± 4b			
pH	O	4.9 ± 0.4 a	7.2 ± 1.3 b	9.7 ± 0.2 c	10.5 ± 0.4 c	0.000*		
	A1	6.3 ± 0.2 e	6.5 ± 0.2 f	6.6 ± 0.1 f δ§	6.9 ± 0.1 g δ	0.001	0.000	0.000*
	A2	6.4 ± 0.1	6.4 ± 0.1	6.2 ± 0.0 δ	6.4 ± 0.2 δ			
C content, g kg <sup>-1</sup> soil	O	407 ± 5 a	414 ± 14 a	376 ± 16 a	226 ± 6 1 b	0.000*		
	A1	52 ± 3	53 ± 7	47 ± 4	50 ± 4	0.454	0.438	0.740
	A2	46 ± 3	48 ± 8	47 ± 5	50 ± 5			
N content, g kg <sup>-1</sup> soil	O	6.9 ± 0.5 a	8.1 ± 0.6 a	11.1 ± 0.7 b	6.5 ± 2.1a	0.001*		
	A1	2.7 ± 0.2	2.6 ± 0.2	2.9 ± 0.2 δ	2.9 ± 0.2 δ	0.887	0.089	0.003*
	A2	2.9 ± 0.0 m	2.7 ± 0.5 mn	2.4 ± 0.2 n δ	2.4 ± 0.1 n δ			
C/N ratio	O	69 ± 6 a	60 ± 3 a	40 ± 2b	42 ± 7 b	0.000*		
	A1	23 ± 0 ef δ	24 ± 2 e	19 ± 1 f δ	20 ± 1 f δ	0.106	0.289	0.000*
	A2	19 ± 1 m δ	21 ± 5 mn	23 ± 1 n δ	24 ± 2 n δ			

\* Significant at the  $\alpha = 0.05$  level.

† Average maximum temperature at the surface of the O horizon (O), the surface of the mineral soil (0 cm), and at 2-cm depth in the A2 horizon.

‡ Letters indicate similar subsets (rows) as determined by Tukey's HSD (a,b,c) or pairwise contrasts (e,f,g for A1 and m,n for A2).

§ d indicates that the A1 and A2 horizons are significantly different at that fire-severity level.

at least 15 min and allowing a fan to circulate air over the chambers. At the time of gas exchange, soil gravimetric moisture content was brought up to 35 and 100% for mineral and organic horizons, respectively, using deionized water. The frequency of trap exchange lengthened to 2 wk and eventually to 4 wk; however, gas exchange always occurred at least every 2 wk. A blank jar and soda-lime trap were used to determine the quantity of CO<sub>2</sub> absorbed from the atmosphere while conducting the experiment. Soda-lime traps were replaced once any trap increased its initial mass by 6% (mean of 2.4% across all traps). The adjusted weight gain of each soda-lime trap was converted to C adsorbed as CO<sub>2</sub> as a proportion of the soil mass using the following formula:

$$\text{CO}_2\text{-C/soil mass} = W_{\text{SL}} (1.69 \text{ mol CO}_2 \text{ mol}^{-1} \text{ CaCO}_3) \times (0.273 \text{ kg C kg}^{-1} \text{ CO}_2) \quad [1]$$

where CO<sub>2</sub>-C/soil mass is the blank-corrected C adsorbed as CO<sub>2</sub> to a soda-lime trap as a proportion of soil mass and  $W_{\text{SL}}$  is the weight gained by the soda-lime trap. The correction value of 1.69 mol CO<sub>2</sub> mol<sup>-1</sup> CaCO<sub>3</sub> was advanced by Grogan (1998) to adjust the weight increase for water created during the absorption of CO<sub>2</sub> by Ca(OH)<sub>2</sub>. To calculate CO<sub>2</sub>-C as a proportion of total soil C, the following formula was used:

$$\text{CO}_2\text{-C/C}_S = \frac{W_{\text{SL}} (1.69 \text{ mol CO}_2 \text{ mol}^{-1} \text{ CaCO}_3) (0.273 \text{ kg C kg}^{-1} \text{ CO}_2)}{C_S} \quad [2]$$

where CO<sub>2</sub>-C/C<sub>S</sub> is the blank-corrected C adsorbed as CO<sub>2</sub> to a soda-lime trap as a proportion of total soil C and C<sub>S</sub> is total soil C. Average cumulative CO<sub>2</sub>-C on a soil-mass basis released with time for each horizon at each severity was fitted to a double-exponential model proposed by Andren and Paustian (1987):

$$\text{CO}_2\text{-C/soil mass} = C_L [1 - \exp(-k_L t)] + (C_S - C_L) [1 - \exp(-k_R t)] \quad [3]$$

where  $C_L$  is the initial amount of total C as labile C in the substrate,  $k_L$  is the rate constant for labile C,  $(1 - C_L)$  is the amount of C in a recalcitrant pool,  $k_R$  is the rate constant for the recalcitrant pool, and  $t$  is time in days.

The following equation was used to model cumulative CO<sub>2</sub>-C released with time as a proportion of the total soil C:

$$d_e = \frac{(a_m - a_n)}{(a_d - a_n)} \quad \text{with } (a_d \neq a_n) \quad [4]$$

where  $(1 - C_L/C_S)$  is the proportion of total soil C in a recalcitrant pool. The double-exponential model allows the comparison of a system with materials that decompose at two different rates, providing a labile and a recalcitrant pool. Since fire and heat may be converting labile material into recalcitrant forms, this model has been found to be more appropriate than the single-compartment first-order model, which would imply that all components of the substrate decompose at one average rate (Fernandez et al., 1997, 2004; Rasmussen et al., 2006). For comparison, the cumulative CO<sub>2</sub>-C mineralized as a proportion of soil C was fitted to a single-parameter model:

$$C_T/C_S = 1 - \exp(-kt) \quad [5]$$

where  $k$  is a single-pool decomposition constant.

Nonlinear parameter estimation by each severity, horizon, and replicate ( $n = 4$  for each combination of severity and horizon) was determined using SPSS 10.1.3 (SPSS Inc., Chicago). The Levenberg-Marquardt procedure of parameter estimation was used. Convergence was obtained by the iterative minimization of the residual sum of squares to within the absolute value of  $1 \times 10^{-8}$ . Initial parameter values for  $k_L$  and  $k_R$  were 0.1 and 0.0001, while  $C_L$  was initialized at the maximum CO<sub>2</sub>-C mineralized for the particular treatment. To avoid errors due to convergence on local minima, parameter estimates were used after they were found to converge on the same values, given initialization values 50% above and below (Updegraff et al., 1995). The  $r^2$  values of the single-parameter model and double-exponential model were used to compare the fit of each to the cumulative CO<sub>2</sub>-C data. The above

procedure was used to estimate the parameters for each replicate to calculate means and standard deviations by treatment and horizon.

The mean residence times of the labile and recalcitrant pools were calculated using

$$\tau = 1/k_L \text{ or } \tau = 1/k_R \quad [6]$$

where  $\tau$  is the mean residence time.

## Soil Analysis

The pH of all soil samples was measured before incubation using the saturated-paste method (Van Miegroet et al., 1994). Water repellency or hydrophobicity of each horizon before incubation was determined by measuring the amount of time that a 0.5-mL drop of water took to completely infiltrate the soil (Krammes and DeBano, 1965). Subsamples of each horizon from pre- and post-incubation were ground and analyzed for C, H, and N concentrations using a PerkinElmer 2400 CHN analyzer (PerkinElmer, Waltham, MA). Carbon, H, and N concentrations were adjusted for moisture content present in the air-dry samples.

Soil organic matter was extracted pre- and post-incubation from each horizon (O, A1, and A2) using a method modified from Schnitzer (1982). Ten grams of mineral soil and 1 g of organic soil were extracted with 100 mL of 0.1 mol L<sup>-1</sup> NaOH under N<sub>2</sub>. The solution was separated from the insoluble residue using a centrifuge at a force of 6635 × *g* for 10 min. The residue contained humin and mineral material from the A horizons and insoluble (IS) organic material, e.g., lignin and cellulose, from the O horizons. The supernatant solution and one rinse containing the FA and HA fractions were collected for further processing. The residue, which included the humin and IS fractions, was dried in a convection oven at 50°C, weighed, and prepared for loss-on-ignition (LOI, 550°C for 6 h) and C, H, and N analysis.

The supernatant containing the FA and HA fractions was acidified to pH 1 using 6 mol L<sup>-1</sup> HCl and allowed to stand overnight to precipitate HA. The FA fraction was separated from the HA by centrifuging at a force of 6635 × *g* for 10 min. Humic acid was freeze-dried in a bench-top lyophilizer, weighed, and stored in a light-protected desiccator.

Schnitzer (1982) defined the FA fraction as those materials that remain soluble after base extraction of soils and subsequent acidification. This fraction can contain a large component of materials that may not be classified as FA and could be affected by fire severity. Fulvic acid was purified of salts and nonhumic substances using a nonionic resin (Malcolm, 1990; Swift, 1996). The solution containing the FA fraction was passed through a column containing 60 mL of DAX-8 resin (Supelco Supelite DAX-8, Sigma-Aldrich Chemical Co., St. Louis, MO; methyl methacrylate ester). Fulvic acid adsorbed to the resin at a pH of 1 while the soluble NH fraction passed through. The column was rinsed with three bed-volumes of deionized H<sub>2</sub>O, which was combined with the NH fraction. Fulvic acid was desorbed by eluting the resin with two bed-volumes of 0.1 mol L<sup>-1</sup> NaOH; this material was identified as FA. Other hydrophobic materials (HO) remain adsorbed to the column after elution with 0.1 mol L<sup>-1</sup> NaOH. The eluate containing FA was collected and passed over a column containing Dowex H<sup>+</sup> exchange resin (Dow Water Solutions, Midland, MI) to remove Na<sup>+</sup>. The salt- and acid-free solution of FA was freeze-dried, weighed, and stored in a light-protected desiccator. Before C, H, and N analysis, FA and HA samples were placed in preweighed tins and dried at 50°C for 48 h. Humic acid and FA subsamples were analyzed for C, H, and N concentrations.

The solution containing NH materials was analyzed on a Shimadzu TOC/TN total organic C and N analyzer (Shimadzu Corp., Kyoto, Japan). The content of other hydrophobic C or N that does not desorb from the DAX-8 resin column (HO) was determined by difference using the following equation:

$$HO = T - R - HA - FA - NH \quad [7]$$

where *T* is the total soil C or N, *R* is C or N in the humin fraction (mineral soil) or insoluble fraction (O horizon), HA is C or N from the humic acid fraction, FA is C or N from the FA that desorbed from the DAX-8 resin column on elution with 0.1 mol L<sup>-1</sup> NaOH, and NH is C or N from the soluble nonhumic fraction. The HO compounds that remain adsorbed to a DAX-8 resin column after elution with 0.1 mol L<sup>-1</sup> NaOH have been shown to have a large content of aliphatic groups and may be somewhat hydrophobic (Dai et al., 2006).

The O and A horizons were analyzed for BC using a method adapted from the CTO375 method outlined by Gustafsson et al. (1997). This method uses the ability of BC to resist thermal oxidation at 375°C. This method may artificially create BC if conditions in the combustion process are anoxic, thereby promoting pyrolysis. By analyzing a range of sample weights, it was determined that <1.0 and 0.1 g of A and O horizons placed in ceramic crucibles (35-mm diameter) prevented charring. These samples were weighed to 0.1 mg and then placed into a preheated muffle furnace (375°C). After 20 h, the samples were removed and weighed. Samples were subsequently returned to a preheated (550°C) muffle furnace for LOI to determine the amount of LOI<sub>375-550</sub> which would contain BC and black nitrogen (BN). The amount of LOI<sub>375-550</sub> as a proportion of the dry soil was determined using

$$LOI_{375-550} S_i^{-1} = (A_{375} - A_{550}) / S_i \quad [8]$$

where *A* is the ash or residue after heating at 375 or 550°C, and *S<sub>i</sub>* is the initial amount of soil.

The C and N from 10 selected O and 10 selected A1 horizon samples were analyzed after 20 h in the muffle furnace at 375°C to develop two ratios that would convert LOI<sub>375-550</sub> to BC and BN. The LOI<sub>375-550</sub> had a significant correlation (*P* < 0.000) with BC and BN from the A horizons with *r*<sup>2</sup> values of 0.971 and 0.872, respectively. Black carbon and BN from the A horizons were found to make up 37.2 ± 6.9% (95% CI) and 3.7 ± 1.6% (95% CI) of LOI<sub>375-550</sub>, respectively. Nelson and Sommers (1982) reported that, depending on soil type, C may account for 40 to 58% of SOM, which agrees well with the ratio used to convert mineral soil LOI<sub>375-550</sub> to BC. For the O horizons, LOI<sub>375-550</sub> had a significant relationship (*P* < 0.000) with BC and BN with *r*<sup>2</sup> values of 0.935 and 0.767, respectively. Black carbon and BN from the O horizon were found to make up 51.4 ± 19.4% (95% CI) and 1.3 ± 0.8% (95% CI) of LOI<sub>375-550</sub>, respectively.

## Statistical Analysis

To determine the effect of incubation on soil and SOM composition, the difference between pre- and post-incubation values was calculated. Treatment effects on O horizon soil characteristics and differences were tested using a one-factor ANOVA. Tukey's test for HSD was used to delineate significantly different homogeneous subsets among different burn severities ( $\alpha = 0.05$ ).

A two-factor ANOVA was used to test the effect of burn severity level and A horizon depth on soil characteristics and differences. If

**Table 2. Total C mineralized after 8 and 180 d of incubation (mean ± standard deviation) after low, moderate, or high fire severity levels and an unburned control (n = 4). The P values are from a one- (severity [ $P_s$ ]) or two- (severity × depth [ $P_d$ ,  $P_{sxd}$ ]) factor ANOVA.**

Treatment	Horizon	Cumulative CO <sub>2</sub> Respired			
		8 d		180 d	
		Soil basis g CO <sub>2</sub> -C kg <sup>-1</sup> soil	C activity basis g CO <sub>2</sub> -C kg <sup>-1</sup> soil C	Soil basis g CO <sub>2</sub> -C kg <sup>-1</sup> soil	C activity basis g CO <sub>2</sub> -C kg <sup>-1</sup> soil C
<u>O horizon</u>					
Control		9.5 ± 1.8 a†	23.4 ± 4.5	96.8 ± 10.2 a	238.4 ± 27.7 a
Low		6.2 ± 1.5 b	15.0 ± 4.0	68.7 ± 10.8 b	166.7 ± 30.7 b
Moderate		6.3 ± 0.7 b	16.6 ± 1.4	30.1 ± 8.0 c	79.6 ± 19.0 c
High		3.5 ± 0.9 b	16.3 ± 6.5	18.8 ± 2.5 c	85.8 ± 14.4 c
$P_s$		0.000*	0.114	0.000*	0.000*
<u>A horizon</u>					
Control	A1	1.1 ± 0.2 e δ‡	21.7 ± 3.5 e	5.4 ± 1.0 δ	103.5 ± 18.4 δ
	A2	0.8 ± 0.3 m δ	18.3 ± 6.9	3.9 ± 0.5 δ	86.8 ± 16.9 δ
Low	A1	1.1 ± 0.2 e	22.2 ± 6.3 e	5.2 ± 1.3 δ	100.4 ± 35.1 δ
	A2	1.0 ± 0.2 mn	20.6 ± 3.8	4.0 ± 0.3 δ	86.1 ± 20.7 δ
Moderate	A1	2.0 ± 0.1 f δ	42.1 ± 2.5f δ	5.4 ± 0.4 δ	115.7 ± 3.4 δ
	A2	1.2 ± 0.1 n δ	26.5 ± 2.3 δ	4.3 ± 0.3 δ	91.8 ± 12.4 δ
High	A1	1.7 ± 0.1 f δ	34.2 ± 3.5f δ	5.1 ± 0.7 δ	103.0 ± 18.0 δ
	A2	1.2 ± 0.4 n δ	23.2 ± 7.1 δ	4.3 ± 0.7 δ	85.5 ± 11.5 δ
$P_s$		0.000	0.000	0.891	0.585
$P_d$		0.000	0.000	0.000*	0.003*
$P_{sxd}$		0.028*	0.029*	0.931	0.926

\* Significant at the  $\alpha = 0.05$  level.

† Letters indicate similar subsets (columns) as determined by Tukey's HSD (a,b,c) or pairwise contrasts (e,f,g for A1 and m,n for A2).

‡  $\delta$  indicates that the A1 and A2 horizons are significantly different at that fire-severity level.

severity was significant at  $P \leq 0.05$ , then Tukey's HSD was used to define homogeneous subsets. If the interaction between horizon depth and severity was significant at  $P \leq 0.05$ , then the interaction was decomposed using pairwise contrasts. Pairwise contrasts were used to determine differences between severity levels at each depth (12 contrasts) and both A horizons at each severity level (four contrasts). The chance of making a Type I error increases beyond the established value when making simultaneous multiple comparisons; Bonferroni's procedure was used to reduce this chance to an  $\alpha$  value of 0.05.

**Table 3. A comparison of models fit to cumulative CO<sub>2</sub>-C data from low, moderate, and high levels of fire severity and an unburned control. Data are from nonlinear regressions using single-parameter (Eq. [5]) and double-exponential models (Eq. [3] and [4]) (Andren and Paustian, 1987).**

Treatment	Horizon	$r^2$ values	
		Single Parameter	Double Exponential
<u>O horizon</u>			
Control		0.91	0.96
Low		0.86	0.89
Moderate		0.60	0.86
High		0.52	0.79
<u>A horizon</u>			
Control	A1	0.64	0.95
	A2	0.64	0.86
Low	A1	0.46	0.68
	A2	0.57	0.81
Moderate	A1	0.13	0.98
	A2	0.42	0.92
High	A1	0.27	0.86
	A2	0.41	0.87

## RESULTS AND DISCUSSION

The C mineralization characteristics of both organic and mineral soil horizons were affected by burn severity (Table 2); however, the magnitude and persistence of these fire effects differed between the two horizon types.

### The O Horizon

Altered SOM composition caused by burning appears to have been controlling the C mineralization rates of the O horizon. The total amount of C mineralized (on a mass basis) at 8 and 180 d decreased significantly after moderate-severity burning of the O horizon (Table 2). Low-severity burning left a large portion of the O horizon unburned, leading to more C being mineralized relative to the highly charred O horizons from the moderate- and high-severity burns. The difference in the amount of C mineralized among the different severities was due to changes in the decomposition rates.

The double-exponential model (Eq. [4]) always provided a better fit to the cumulative CO<sub>2</sub>-C data than the single-parameter model (Eq. [5]), as shown by higher  $r^2$  values (Table 3). These results are similar to those of Updegraff et al. (1995), who found that the double-exponential model fit cumulative C mineralization data from humified organic soils better than a single-parameter model. The  $r^2$  of the single-parameter model was closer to the double-exponential model for unburned or low-fire-severity O horizons. Because of the greatly improved fit, only the double-exponential model was utilized.

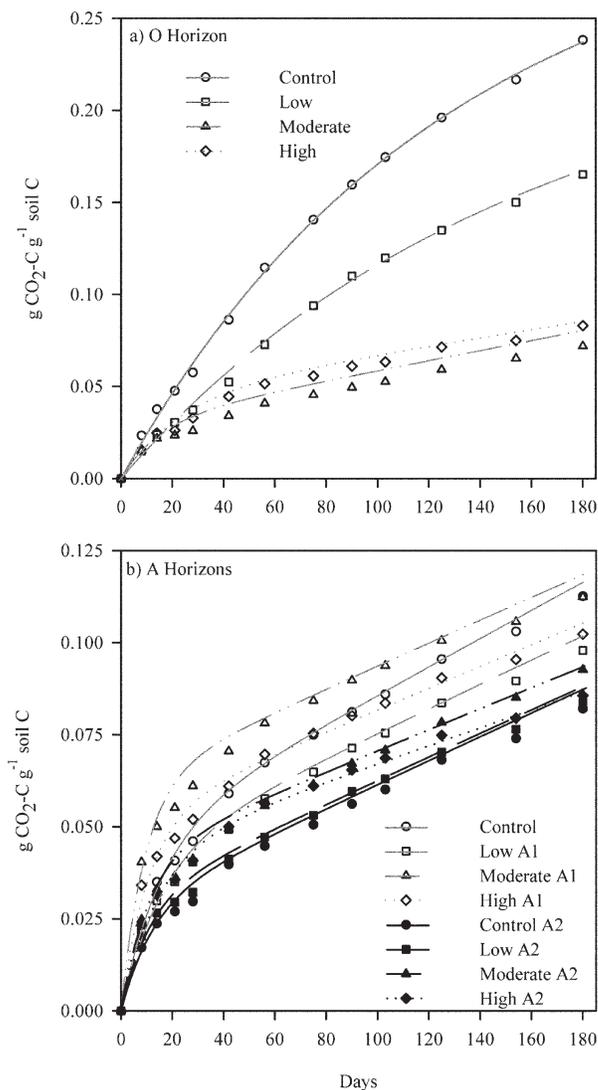
The mineralization curves of the O horizon have distinctive slopes resulting in different decomposition constants (Fig. 1); however, these differences were not statistically significant (Table 4). The decomposition rate of the labile pool ( $k_1$ ) increased with increasing fire severity, while the amount of labile

C ( $C_L$ ) decreased. The labile pool will be depleted more quickly after moderate- and high-severity burns as this O horizon fraction had a mean residence time of 11 and 7 d, respectively, while the control and low-severity-burn O horizons had mean residence times of 32 and 25 d, respectively. Once the labile pool is depleted, however, the long-term mineralization rate of these materials will be controlled by the recalcitrant SOM decomposition rate ( $k_R$ ), which decreased with increasing fire severity. Increasing the mean residence time of the recalcitrant pool of C may be a means by which recalcitrant forms of C can accumulate in the soil, as suggested by Kuhlbusch and Crutzen (1995). Both Knicker (2007) and Czimczik and Masiello (2007) pointed out that physical protection of recalcitrant materials by mixing deeper into the soil profile or burial by sediments may be a strong controller of whether recalcitrant forms of C, e.g., BC, accumulate or are lost from the soil.

The mineralization rates of the O horizon appear to be controlled by altered SOM composition caused by burning. The concentrations of HA and FA fractions were significantly ( $P = 0.000$ ) reduced while BC was increased by burning at higher severities (Table 5). Carbon mineralized after 8 d was positively correlated with NH-, FA-, and HA-C concentrations and negatively correlated with BC in the preincubation samples (Table 6). After 180 d, the quantity of NH-C was no longer significantly correlated with mineralized C, suggesting that it is only important for short-term C mineralization rates. Carbon mineralized after 180 d was negatively correlated with the quantity of BC and the C/H ratio of HA, suggesting that the presence of fire-altered SOM was still causing a depression in C mineralization rates. Short-term mineralization appears to be controlled by the quantity of NH, FA, and HA, while long-term mineralization appears to be controlled by the quantity of FA- and HA-C and the quality of HA.

Labile forms of C seem to be the source of C mineralized throughout the entire 180-d incubation of the O horizons. Incubation reduced the amount of FA-C of the control and low-severity-treated soils by an average of 13% (Fig. 2). There was a significant correlation between C mineralized at 180 d and a decrease in FA-C from pre- to post-incubation ( $r = -0.564$ ;  $p < 0.05$ ). There was also a 32% reduction in NH-C across all treatments. Recalcitrant forms of C, such as IS and BC, do not appear to be major sources of C as they did not decrease due to incubation (Fig. 2). The FA fraction appears to be a major C source for short- and long-term C mineralization and, as mentioned above, NH-C may provide C during the early stages of C mineralization.

Humification was evident during the incubation and was correlated to C mineralization. Humic acid C, HA-N, and IS-N increased significantly after incubating the control and low-severity-burn soils, but not the moderate- or high-severity treatments (Fig. 2). Carbon mineralized after 180 d was significantly correlated with the increase in O horizon HA-C content ( $r = 0.802$ ,  $P > 0.05$ ). Qualls (2004) found that HA extracted from decomposing cottonwood (*Populus fremontii* S. Watson) leaves decomposed more slowly than other SOM fractions, which is supported by the results from this study. The increase in HA-C with C mineralization also suggests that HA-C is not a primary source of C for C mineralization in the O horizon,



**Fig. 1. Cumulative C mineralized during 180 d from (a) O and (b) A1 and A2 horizons after burning at low, moderate, and high fire severity levels and an unburned control. Points displayed are the means of four replicates; lines are double-exponential model fit to cumulative  $\text{CO}_2\text{-C}$  data (Eq. [4]).**

further supporting the assertion that the primary sources of mineralized C are FA- and NH-C fractions.

Baldock and Smernik (2002) found that when *Pinus resinosa* wood was heated to higher temperatures, it had a lower bioavailability as measured by the amount of C mineralized after a 120-d incubation. During the incubation, they found that unaltered wood lost 20% of its initial C, and heating wood to 150°C reduced this C loss to 13%. Carbon loss due to mineralization was <2% when the wood was heated above 200°C. They attributed this reduction in available C to a reduction in cellulose and hemicellulose, which occurred mostly when the wood was heated to 200°C as determined by nuclear magnetic resonance spectroscopy.

The effect of fire on the O horizon C mineralization is not necessarily entirely due to temperature, but may be more dependent on the amount of material that was consumed. In the current study, the O horizons were not heated evenly throughout the profile; they simulated real conditions during combustion of

**Table 4. Initial labile C pool ( $C_L$ ) and decomposition rate constants of C mineralization ( $k_L$  for the labile pool and  $k_R$  for the recalcitrant pool) during a 180-d incubation (mean  $\pm$  standard deviation) fit to the double-exponential model in Eq. [3] and [4] ( $n = 4$ ) after low, moderate, or high levels of fire severity and an unburned control. The  $P$  values are from a one- (severity [ $P_s$ ]) or two- (severity  $\times$  depth [ $P_s$ ,  $P_d$ , and  $P_{s \times d}$ ]) factor ANOVA and  $t$  is the average residence time calculated as the inverse of the mineralization constant ( $k_L$  or  $k_R$ ).**

Treatment	Horizon	$C_L$		$k_L$	$\tau$ ( $k_L$ )	$k_R$	$\tau$ ( $k_R$ )
		Soil basis	C activity basis				
		mg CO <sub>2</sub> -C g <sup>-1</sup> soil	mg CO <sub>2</sub> -C g <sup>-1</sup> soil C	d <sup>-1</sup>	d	d <sup>-1</sup> $\times 10^4$	yrs
<u>O horizon</u>							
Control		77.3 $\pm$ 70.6	179.5 $\pm$ 161.7	0.03 $\pm$ 0.03	32	6.0 $\pm$ 6.2	5
Low		73.5 $\pm$ 45.4	103.1 $\pm$ 106.7	0.04 $\pm$ 0.06	25	2.9 $\pm$ 4.5	10
Moderate		12.6 $\pm$ 4.3	33.2 $\pm$ 10.8	0.09 $\pm$ 0.08	11	2.8 $\pm$ 1.4	10
High		9.7 $\pm$ 4.8	41.5 $\pm$ 20.5	0.15 $\pm$ 0.20	7	2.4 $\pm$ 1.6	11
$P_s$		0.066	0.179	0.473		0.476	
<u>A horizon</u>							
Control	A1	2.3 $\pm$ 0.8 $\delta$ †	47.7 $\pm$ 11.0	0.08 $\pm$ 0.06	12	3.9 $\pm$ 0.5 $\delta$	7
	A2	1.4 $\pm$ 0.4 $\delta$	29.9 $\pm$ 8.3	0.09 $\pm$ 0.05	11	3.3 $\pm$ 0.8 $\delta$	8
Low	A1	2.2 $\pm$ 0.8 $\delta$	42.4 $\pm$ 18.2	0.09 $\pm$ 0.07	11	3.5 $\pm$ 0.9 $\delta$	8
	A2	1.5 $\pm$ 0.3 $\delta$	34.5 $\pm$ 11.7	0.12 $\pm$ 0.11	8	3.2 $\pm$ 0.2 $\delta$	8
Moderate	A1	2.9 $\pm$ 0.3 $\delta$	61.8 $\pm$ 4.4	0.11 $\pm$ 0.02	9	3.4 $\pm$ 0.2 $\delta$	8
	A2	2.0 $\pm$ 0.4 $\delta$	42.2 $\pm$ 10.1	0.11 $\pm$ 0.06	9	3.0 $\pm$ 0.2 $\delta$	9
High	A1	2.6 $\pm$ 0.5 $\delta$	51.9 $\pm$ 11.4	0.10 $\pm$ 0.03	10	3.2 $\pm$ 0.3 $\delta$	9
	A2	2.2 $\pm$ 0.5 $\delta$	42.9 $\pm$ 7.6	0.07 $\pm$ 0.02	15	2.6 $\pm$ 0.4 $\delta$	11
$P_s$		0.056	0.054	0.756		0.067	
$P_d$		0.001	0.002	0.886		0.018	
$P_{s \times d}$		0.711	0.623	0.725		0.878	

†  $\delta$  indicates that the A1 and A2 horizons are significantly different at that fire-severity level.

the O horizon. There was a temperature gradient that was hottest where the material was burning and coolest near the surface of the mineral soil; this gradient would only be partly represented by the maximum temperature of the O horizon. Maximum temperature and O horizon consumed were both similarly correlated with short-term C mineralization (Table 6). After 180 d of incubation, there was only a significant correlation between the amount of O horizon consumed and C mineralized and no significant correlation with maximum temperature. Temperature may control alterations to SOM at a small scale (fuel particle); however, the effect of fire on the whole O horizon is dependent on larger scale phenomena, such as the proportion of O horizon consumed.

Figures 3 and 4 show the difference in the proportion of C and N, respectively, from each SOM fraction relative to the control, pre- and post-incubation. When values are below the

zero line, then the treated soil was depleted in that SOM fraction relative to the control, while values above the zero line mean that the treated soil was enriched in that fraction. The SOM composition remained unchanged relative to the control after incubation of the O horizon. Only HO-C and -N were elevated relative to the control following incubation after burning at moderate and high severity. These compounds did not occur in the pre- or post-incubation control soil and, therefore, may be the degradation products of fire-altered SOM. Hockaday et al. (2006 and 2007) showed that degradation products of charcoal are condensed aromatic ring structures that are present in soil pore waters as dissolved organic matter. These condensed aromatic ring structures may behave similarly to the HO fraction in this study, i.e., they are soluble in alkaline extract, and after subsequent acidification, they adsorb

to a column of DAX-8 resin. The HO fraction may be more mobile in soil, as it was extracted from the soil along with FA, and may leach out of the O horizon and into the mineral soil where it could be mineralized or complexed with mineral surfaces.

The high rate of HA formation in the control caused the proportion of HA-C of burned O horizons to be reduced relative to the control after incubation (Fig. 3 and 4). Slow mineralization rates of the moderate- and high-severity-burn soils kept the distribution of C and N relatively static. Recalcitrant materials produced by burning may accumulate with time relative to unburned

**Table 5. Black carbon (BC as estimated by the CTO375 loss-on-ignition method) and change in BC (difference as post-incubation minus preincubation) due to incubation (mean  $\pm$  standard deviation) after low, moderate, or high levels of fire severity and an unburned control. The  $P$  values are from a one- (severity [ $p_s$ ]) or two- (severity  $\times$  depth [ $p_s$ ,  $p_d$ , and  $p_{s \times d}$ ]) factor ANOVA, significant values are in bold ( $\alpha = 0.05$ ).**

Parameter	Horizon	g BC kg <sup>-1</sup> soil				$P_s$	$P_d$	$P_{s \times d}$
		Control	Low	Moderate	High			
Post-incubation	O	ND† a‡	0.4 $\pm$ 0.8 ab	2.8 $\pm$ 1.5 bc	4.7 $\pm$ 0.8 c	0.001*		
	A1	4.2 $\pm$ 0.8	4.8 $\pm$ 0.6	4.7 $\pm$ 0.3	4.8 $\pm$ 0.7		0.383	0.732
	A2	4.5 $\pm$ 0.6	4.5 $\pm$ 0.8	4.7 $\pm$ 0.4	5.0 $\pm$ 0.6			0.755
Difference	O	-1.9 $\pm$ 1.8	-2.2 $\pm$ 1.6	-2.0 $\pm$ 1.3	-0.4 $\pm$ 1.0	0.152		
	A1	-1.2 $\pm$ 0.9 e $\delta$ §	0.5 $\pm$ 0.3 f	0.1 $\pm$ 0.5 f	0.3 $\pm$ 0.1 f	0.000	0.030	0.009*
	A2	0.1 $\pm$ 0.3 $\delta$	0.4 $\pm$ 0.2	0.0 $\pm$ 0.3	0.6 $\pm$ 0.2			

\* Significant at the  $\alpha = 0.05$  level.

† ND, not detected.

‡ Letters indicate similar subsets (rows) as determined by Tukey's HSD (a,b,c) or pairwise contrasts (e,f for A1).

§  $\delta$  indicates that the A1 and A2 horizons are significantly different at that fire-severity level.

**Table 6.** Pearson correlation coefficients of O and A horizon CO<sub>2</sub>-C evolved at 8 and 180 d (on a soil basis) with soil and preincubation soil organic matter characteristics.†

Horizon	O horizon consumed	Max temp.	Time temp >100°C	IS/Humin			Humic acid			Fulvic acid			NH C (n = 4)	HO C (n = 4)	BC
				C	C/N	C/H	C	C/N	C/H	C	C/N	C/H			
Total C mineralized after 8 d (dry soil basis)															
O	-0.622*	-0.677*	-0.200	0.431	0.616*	-0.319	0.827*	-0.094	-0.663*	0.813*	0.606*	-0.278	0.983*	-0.736	-0.797*
A1	0.775*	0.744*	0.936*	-0.686*	-0.533*	-0.038	-0.401	0.215	0.819*	-0.794*	-0.798*	0.198	-0.999*	0.736	-0.132
A2	0.357	0.469	0.349	-0.081	0.170	-0.294	0.206	0.136	-0.056	-0.123	-0.319	-0.392	-0.507	0.692	0.347
Total C mineralized after 180 d (dry soil basis)															
O	-0.890*	-0.544	-0.617*	0.429	0.806*	-0.201	0.841*	-0.086	-0.628*	0.873*	0.839*	-0.392	0.576	-0.752	-0.841*
A1	-0.231	0.002	0.087	0.024	0.349	-0.020	0.178	0.284	0.013	0.399	0.158	-0.136	-0.171	-0.436	0.010
A2	0.087	0.146	0.191	0.075	-0.078	0.065	-0.074	-0.212	0.294	-0.353	-0.521*	-0.384	-0.797	0.948	-0.022

\* Significant at the  $P \leq 0.05$  level.

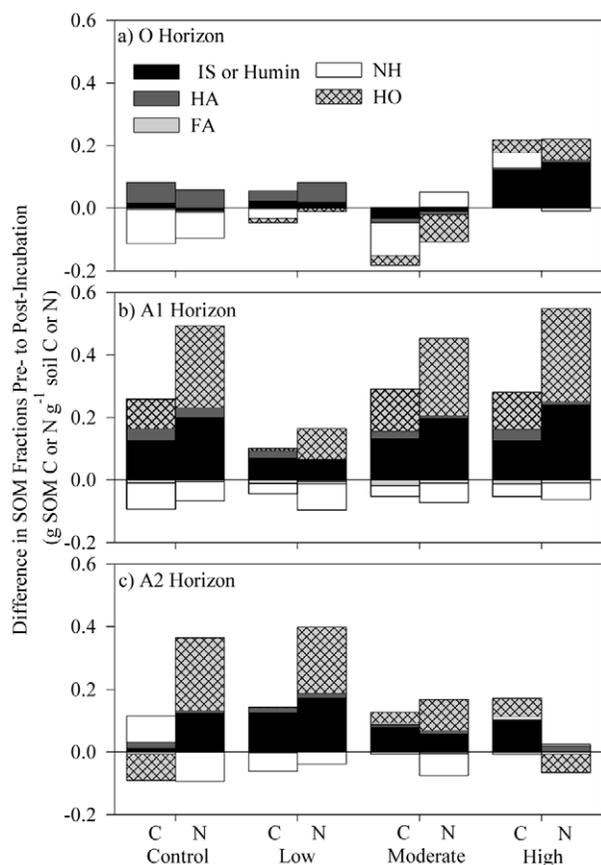
† O horizon consumed = mass of O horizon consumed by fire, max temp. = maximum temperature in the horizon during burning, time temp >100°C = amount of time the temperature was above 100°C at the surface of the mineral soil (0 cm), IS = insoluble (O horizon), HO = other hydrophobic materials, and NH = soluble nonhumic, BC = black carbon.

material since they are slower to decompose. The production of slower decomposing materials through humification in the unburned O horizon, however, may offset slower decomposition by BC and sequester a similar amount of C with time.

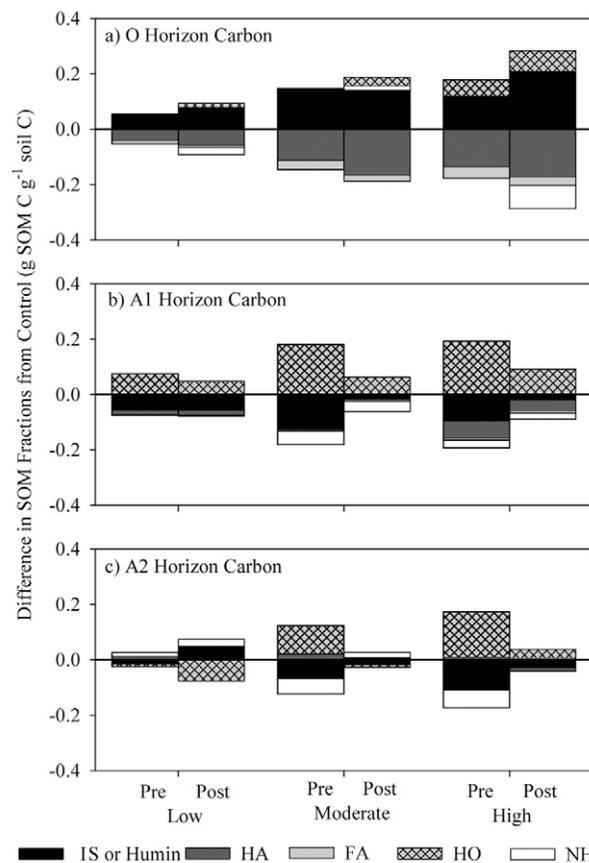
### The A Horizon

The quantity of C mineralized from both A horizons after 8 d was dependent on both fire severity and A horizon depth (Table 2). Carbon mineralized from both A1 and A2 horizons at

8 d in the moderate- and high-severity treatments was increased over the control and low-severity treatment. Carbon mineralized from moderate-severity burned A horizons, however, was not significantly different from the high-severity burned A horizons. Low-severity burning did not have a significant effect



**Fig. 2.** Change in proportion of C and N in soil organic matter (SOM) fractions from preincubation to post-incubation of (a) O horizon and (b and c) two A horizons after low, moderate, and high burn severities and an unburned control. Abbreviations are: IS = insoluble (O horizon), HA = humic acid, FA = fulvic acid, HO = other hydrophobic materials, and NH = soluble nonhumic.



**Fig. 3.** Differences in the proportion of C content of each soil organic matter (SOM) fraction at low, moderate, and high burn severities from an unburned control. When values fell below the zero line, the treated soil was depleted in that SOM fraction while values above the zero line indicated the treated soil was enriched in that fraction. Pre- and post-incubation differences from the control are shown for (a) O, (b) A1, and (c) A2 horizons. Abbreviations are: IS = insoluble (O horizon), HA = humic acid, FA = fulvic acid, HO = other hydrophobic materials, and NH = soluble nonhumic.

on C mineralized from the A1 or A2 horizons compared with the control. Differences caused by burning at various severity levels disappeared during the course of the incubation, so that by the end of the incubation experiment (180 d) only the A1 and A2 horizons were significantly different from one another.

The control A1 horizons may have incorporated a significant (*t*-test,  $P < 0.05$ ) amount of O horizon and could have elevated the C mineralized of the control A1 compared with the A2 horizons. There was about a 9 g O horizon  $\text{kg}^{-1}$  A1 horizon increase as determined by the difference in LOI between the control A1 and A2 horizons. This amount of O horizon would have added approximately 4 g of C  $\text{kg}^{-1}$  A1 horizon in the control. Incorporation of the O horizon may have elevated the amount of C mineralized at 8 and 180 d from the A1 above the A2 horizon of the control. The higher temperatures achieved during burning in the A1 horizon caused a significant increase in C mineralized over the A2 horizon of the low, moderate, and high fire severity treated soils.

Differences in total C mineralized are due to changes in the recalcitrant pool decomposition rate ( $k_R$ ) and the size of the

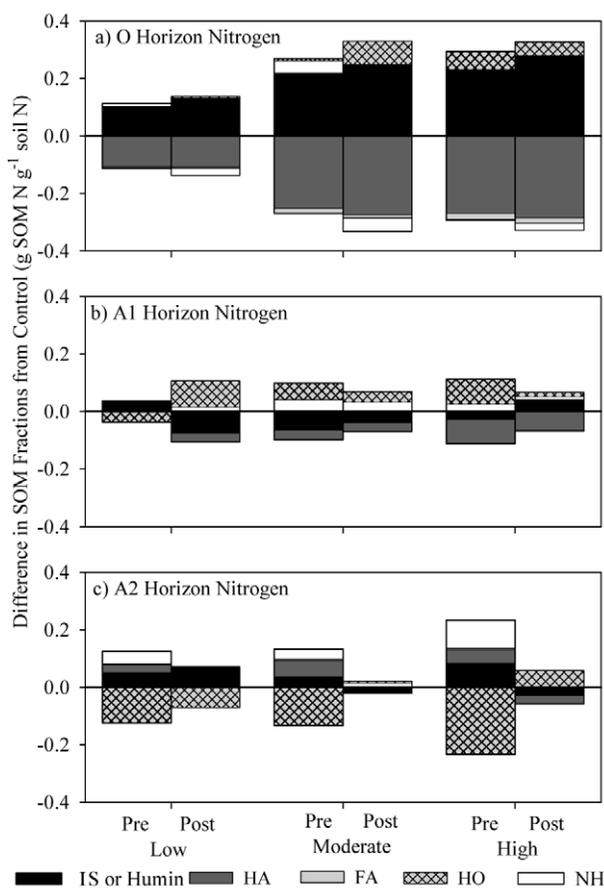
labile pool ( $C_L$ ) (Table 4). The labile pool was larger and recalcitrant materials decomposed at a significantly faster rate in the A1 horizon than the A2 horizon. The elevated  $C_L$  contributed to the short-term increase in C mineralized (8 d), while in the long-term (180 d), the elevated  $k_R$  of the control and low-severity treated soil erased differences caused by burning at higher severity. The O horizons from the control soils had higher  $C_L$  and  $k_R$  than the mineral soils from those treatments, thereby elevating these parameters of the A1 horizon when O horizon material is incorporated into the mineral soil. Fire severity significantly increased the short-term C mineralized and C mineralization rates of the moderate- and high-severity treated soils, while long-term mineralization was not affected.

It appears that short-term C mineralization increased with fire severity due to an improved quality of substrate for microbial growth and a possible increase in labile compounds. Carbon mineralized from A1 horizons after 8 and 180 d was negatively correlated with the C/N ratio of humin and FA. Mineralization at 8 d was negatively correlated with the quantity of FA in the A1 horizon, suggesting that the quality of this fraction is more important than quantity in determining C mineralization. The soluble nonhumic C concentration of the preincubated soils and C mineralized at 8 d were strongly negatively correlated. Fritze et al. (1998) showed that water-soluble materials, such as NH materials, may contain microbial growth inhibitors.

The mineralization of C from moderate- and high-severity burned A1 horizons is similar to the results of Fernandez et al. (1997), who studied mineral soils after high-severity wildfires. They saw an increased rate of C mineralization (on a total C basis) in burned soils compared with an associated unburned control soil. They attributed the increase in C mineralization results to an increase in labile compounds after burning. In another study of fire effects on C mineralization, Fernandez et al. (2004) found that a soil heated to 385°C for 10 min had a slightly lower rate of C mineralization than its unheated counterpart. High temperatures in the A1 horizons of the current study were associated with higher rates of short-term mineralization (Table 6). Table 1 shows that the average maximum temperature of the surface A horizon from the current study was 197 and 243°C for the moderate- and high-severity burns, much lower than the temperatures used by Fernandez et al. (2004) (Fig. 1). There may be a point at which fire severity is high enough to convert all SOM to recalcitrant forms. This threshold would appear to be >243°C (the maximum temperature achieved in the mineral soil of this study).

Of all SOM fractions, FA was most consistently lowered in all treatments and both A horizons after incubation (Fig. 2). The decrease in FA is probably due to mineralization, as suggested by the significant relationship with the FA C/N ratio and short-term mineralization rates (Table 6). There were averages of 61 and 38% reductions in FA-C concentrations of A1 and A2 horizons, respectively, caused by incubation. The FA fraction may be preferentially used as a C source in the mineral soil.

Figures 3 and 4 show the difference in the proportion of SOM as C and N, respectively, of each treatment from the control of the A1 (Fig. 3b and 4b) and A2 (Fig. 3c and 4c) horizons. When values are below the zero line, the treated



**Fig. 4.** Difference in the proportion of N content of each soil organic matter (SOM) fraction at low, moderate, and high burn severities from an unburned control, pre- and post-incubation. When values fell below the zero line then the treated soil was depleted in that SOM fraction relative the control while values above the zero line indicated the treated soil was enriched in that fraction. Pre- and post-incubation differences from the control shown for O (a), A1 (b), and A2 (c) horizons. Abbreviations are: IS = insoluble (O horizon), HA = humic acid, FA = fulvic acid, HO = other hydrophobic materials, and NH = soluble nonhumic.

soil was depleted in that SOM fraction relative to the control, while values above the zero line indicate that the treated soil was enriched in that fraction. Generally, the result of burning and incubation on the proportion of total soil C and N as SOM fractions was a return to control proportions except at the low-severity burn, as shown by a small deviation from 0 (no difference from the control). Moderate- and high-severity-burn treated soils were more different than controls before incubation; however, the faster mineralization rates of these soils reduced these differences. The proportions of total C and N as humin, HA, and NH were reduced to nearly control levels after incubation of both A horizons. The production of HO-C and -N were the main differences caused by incubation between the control and soils burned at moderate and high severities; this may be caused by higher microbial biomass of decomposition products of fire-affected SOM of the A horizon. The low-severity-burn treated A horizons were not significantly different from the control. Furthermore, the resulting SOM C and N contents of the low-severity-burn treated A horizons of any fraction were never significantly different from the control after incubation ( $P > 0.05$ ). In general, there does not appear to be a major long-term effect of prescribed burning on the composition of SOM.

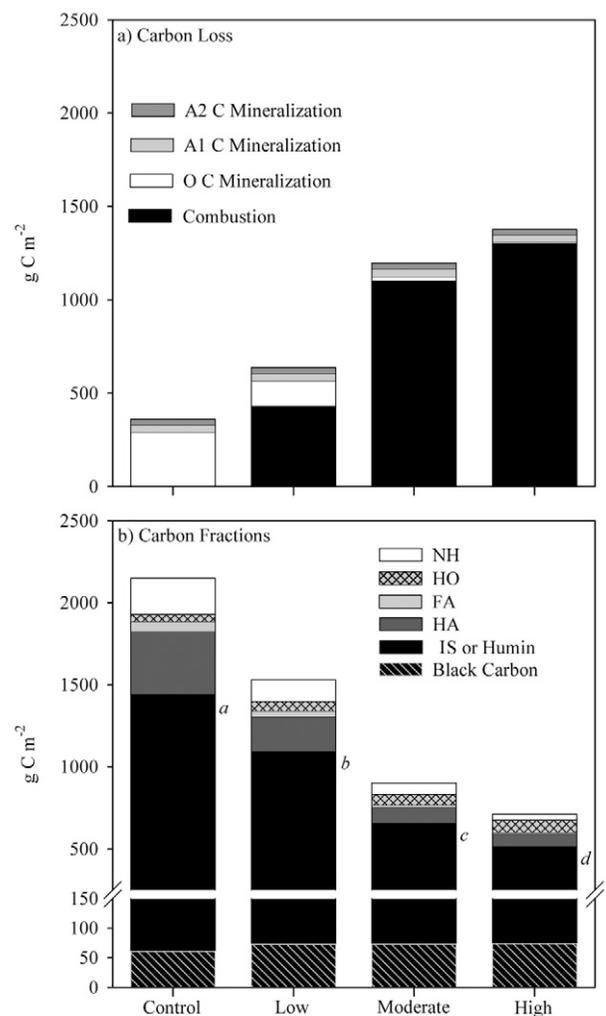
Black carbon of the burned A horizons appears to be more robust against biological oxidation during incubation of the burned soils. Black carbon decreased significantly in the control soil but was unaffected or increased in mineral soils treated with fire (Table 6).

Guerrero et al. (2005) found that unheated soils and soils heated at temperatures  $<300^{\circ}\text{C}$  had similar extractable C before and after incubation. The current study supports these findings in that none of the mineral soils achieved a temperature  $>300^{\circ}\text{C}$  and the most labile forms of C and N (the sum of FA, NH, and HO) were not significantly different among the burn severities after incubation ( $P_s = 0.906$  and  $P_s = 0.960$  for C and N, respectively, where subscript  $s$  refers to the burn severity factor).

Fernandez et al. (2004) found an increase in the proportion of HA and humin after an 84-d incubation of a soil heated to  $385^{\circ}\text{C}$ . That level of soil heating was more severe than the burn treatments in the current study and probably combusted or transformed the majority of labile C and N. Additionally, they did not use a control soil to determine how SOM from an unheated soil would respond to incubation. A higher severity fire on the soils of the current study might have produced similar results to those of Fernandez et al. (2004).

## Total Carbon and Nitrogen

Figures 5 and 6 show the total C and N lost from the entire soil profile (O horizon [6 cm] and 2 cm of A horizon) from combustion at each of the severity levels and from incubation. Combustion of the O horizon dominates the C losses across burn treatments. Nitrogen was lost during incubation of A horizons from the control and low-severity-burn treated soils and combustion of the O horizon in the moderate- and high-severity-burn treatments. Volatilization of  $\text{NH}_4^+$  as  $\text{NH}_3$  may have occurred throughout the A horizon since it can occur at pH values (6.2–6.9) similar to these soils (He et al., 1999). The

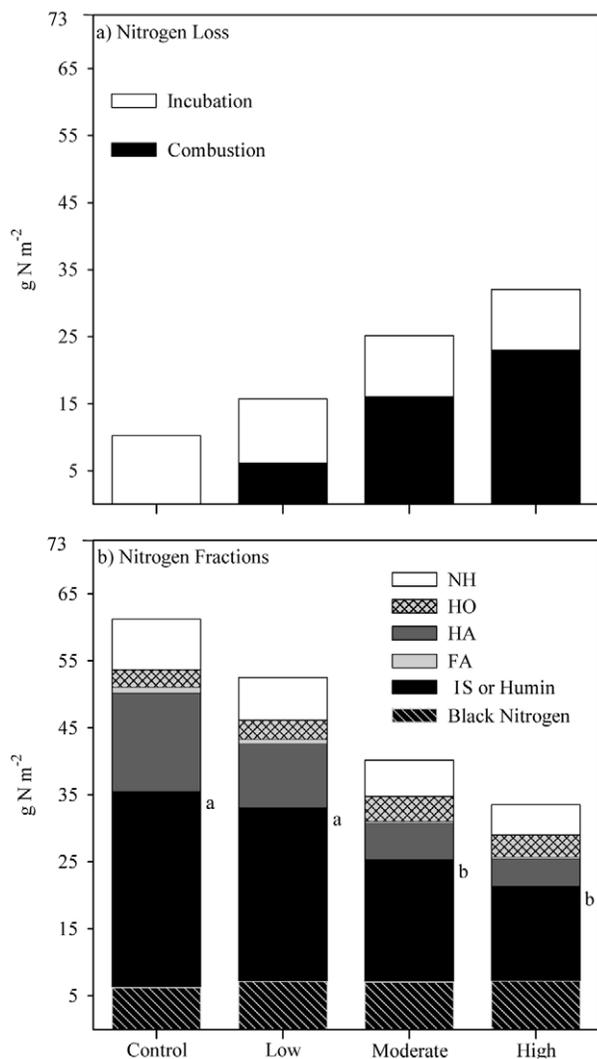


**Fig. 5. (a) Total C lost due to combustion and C mineralization and (b) quantity of C fractions remaining after burning at low, moderate, and high fire severity levels and incubating O and A horizons. Initial C content of the entire profile was  $2500 \text{ g C m}^{-2}$  before treatment. Total insoluble C decreased with increasing fire severity ( $P = 0.000$ ). Letters indicate statistically different humin + insoluble (IS) material content as tested by Tukey's HSD. Abbreviations are: IS = insoluble (O horizon), HA = humic acid, FA = fulvic acid, HO = other hydrophobic materials, and NH = soluble nonhumic.**

control O and A horizons mineralized nearly as much C as was lost through combustion in the low-severity burn.

Total recalcitrant, insoluble material (humin and IS) C and N decreased with increasing fire severity ( $P_s = 0.000$  for both C and N) (Fig. 3 and 4). The proportion of total C and N that was in a recalcitrant form accounted for 72 to 75 and 58 to 63%, respectively, which were not significantly different between fire severities ( $P_s > 0.05$ ). Fire does not appear to have affected the proportion of recalcitrant, insoluble materials.

The total content of BC was not significantly affected by burn severity ( $P_s = 0.119$ ) but as the total C and N decreased, the proportion of these very recalcitrant materials increased ( $P_s = 0.000$ ). The total soil C as BC increased from  $28 \text{ g BC kg}^{-1}$  soil C to 48, 81, and  $103 \text{ g BC kg}^{-1}$  soil C after burning at low, moderate, and high severity, respectively. Carbon sequestration through the production of BC comes with a high production rate of recalcitrant forms of N, which would have also increased



**Fig. 6. (a) Total N lost through combustion and volatilization and (b) quantity of N fractions remaining after burning at low, moderate, and high fire severity levels and incubating O and A horizons. Initial N content of the entire profile was 73 g m<sup>-2</sup> before treatment. The total insoluble N decreased with burning ( $P = 0.000$ ). Letters indicate statistically different humin + insoluble (IS) material content as tested by Tukey's HSD. Abbreviations are: IS = insoluble (O horizon), HA = humic acid, FA = fulvic acid, HO = other hydrophobic materials, and NH = soluble nonhumic.**

in proportion. Recalcitrant forms of N have been shown to affect N mineralization rates and available N and may limit forest productivity with time (Guinto et al., 1999).

As mentioned above, BC and charcoal may need to be protected from a succeeding fire through mixing lower in the soil profile in order for it to accumulate (Czimczik and Masiello, 2007). Researchers have found accumulations of BC incorporated in the top 10 cm of grassland soils (Glaser and Amelung, 2003) and as a proportion of total C with depth in a savanna soil (Dai et al., 2005). If left at the surface, these materials are susceptible to erosion or may be combusted if the site is reburned. Dai et al. (2005) found that repeated burning did not significantly increase BC in soils collected from a savanna treated with prescribed burning. Czimczik et al. (2005) suggested that BC was not different among Scots pine (*Pinus sylvestris* L.) stands burned at differing frequencies and severities due to consumption of BC by high-severity

wildfire. Depending on field conditions and fire-return intervals, prescribed burning may allow recalcitrant forms of C to accumulate in the soil if it is able to be protected from reburning through mixing into the mineral soil.

## CONCLUSIONS

Increasing fire severity significantly reduced the C mineralization rate of O horizons. The decrease in C mineralized from the O horizon with increasing fire severity appeared to be caused by fire-induced reductions of FA- and NH-C. Short-term C mineralization of A horizons increased with fire severity while long-term C mineralization was not significantly affected by burning. It appears that short-term C mineralization of mineral soils increased with fire severity due to an improved quality of substrate for microbial growth and a possible increase in labile compounds. After burning, the SOM composition of burned A horizons returned to control levels while the SOM composition of O horizons remained different from the control. Exacerbating differences in O horizon HA content among the treatments was the positive correlation between the production of HA and C mineralization rates. In general, burning had little effect on the SOM quality of the A horizon after incubation, suggesting that there will be little long-term impact to SOM composition caused by burning. The total content of recalcitrant (humin and IS) C and N decreased with increasing fire severity, while BC and BN were unaffected by fire severity. Production of recalcitrant materials through fire has been suggested as a way in which C may be sequestered in soils. It may take a long time for recalcitrant materials to build up in a burned soil relative to an unburned soil due to C combustion; however, the role of coarse woody debris in these ecosystems was not examined. When coarse woody debris is excluded, prescribed fires at moderate and moderately high severity may have the greatest ability to sequester C through production of recalcitrant materials that decompose more slowly than unburned materials.

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