Topographic influences on wildfire consumption of soil organic carbon in interior Alaska: Implications for black carbon accumulation

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[1] We measured characteristics of soil organic carbon (SOC) and black carbon (BC) along opposed north- and south-facing toposequences in recent (2004) and old (~1860–1950) burn sites throughout interior Alaska. Surface fuel consumption did not vary between different topographic positions, with 3.3 ($\pm$0.5) kg C m^{-2} being consumed on toe slope sites, 4.0 ($\pm$0.2) kg C m^{-2} on north-slope sites, and 3.6 ($\pm$0.3) kg C m^{-2} on south-slope sites. On a relative scale, 43% of the organic matter depth was removed through biomass burning on toe slopes, 62% on north-slopes, and 77% on south-slope sites. Mineral soil BC stocks (measured using a chemical/thermal oxidation method isolating more graphitic BC) ranged from 112 $\pm$ 24 g C m^{-2} to 173 $\pm$ 43 g C m^{-2} on north- and south-facing aspects, respectively. These data supported the expectation that deeper and wetter ground fuels occurring in north-facing and toe-slope forests burned less completely, which decreased the amount of BC incorporated into mineral soil where it could be protected from subsequent fires. Thus, warmer and drier forests harbored less total SOC, but following wildfire aggraded larger BC stocks. BC was therefore an important component of stable soil C in warmer and drier forests which had higher C turnover rates in other soil pools (determined by density fractionation, δ^{13}C, and Δ^{14}C). These data provide a basis for understanding how variable patterns of organic layer depths and soil moisture mediate the consumption of SOC in wildfire, as well as the long-term accumulation of BC.

1. Introduction

[2] Over the past four decades, arctic and boreal regions of the Northern Hemisphere have undergone a higher degree of warming than any other region on earth [*Serreze et al.*, 2000; *Chapin et al.*, 2005], and as one result, the frequency of fire in the North American boreal forest region has more than doubled over the past four decades [*Gillett et al.*, 2004; *Kasischke and Turetsky*, 2006]. Moreover, the increasing temperatures forecasted by general circulation models are likely to result in further increases in fire frequency [*Flannigan et al.*, 2005]. While much research has focused on understanding how climate change is affecting the structure and function of boreal forests [e.g., *Chapin et al.*, 2006], much uncertainty still exists as to exactly how fire affects surface organic layer characteristics, which in turn, mediate energy exchange between the atmosphere and land surface [*Dyrness et al.*, 1986; *Chambers and Chapin*, 2002; *Liu et al.*, 2005].

[3] Many boreal forests contain deep organic layers that are partially or entirely consumed during fires. These deep organic layers are a significant reservoir of terrestrial carbon and their burning in wildfires not only release large amounts of trace gasses to the atmosphere [*Kasischke et al.*, 2005], but also regulate long-term carbon storage [*Harden et al.*, 2000]. In addition, variation in depth of burning of surface organic layers in boreal forests regulates soil temperature and moisture and therefore has consequences for postfire soil C cycling [*O'Neill et al.*, 2002; *Bergner et al.*, 2004], tree recruitment [*Landhaeusser and Wein*, 1993; *Johnstone and Kasischke*, 2005; *Johnstone and Chapin*, 2006], and permafrost maintenance [*Yoshikawa et al.*, 2002; *Harden et al.*, 2006].

[4] Black spruce (*Picea mariana* [Mill.] BSP) forests are part of the most extensive wildfire fuel types in the North American boreal region [e.g., *Amiro et al.*, 2001]. While black spruce forests exhibit several traits that make wildfire nearly inevitable in this forest type regardless of landscape position [*Dyrness et al.*, 1986; *Harden et al.*, 2003], physiography at the local scale integrates soil temperature and moisture effects on forest structure and organic layer depth [e.g., *Van Cleve and Yarie*, 1986], which largely

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determine the fuel types available for combustion [*Dyrness and Norum*, 1983; *Ryan*, 2002; *Miyanishi and Johnson*, 2002; *Kasischke and Johnstone*, 2005]. North-facing and toe-slope forests receive less insolation than do those on southerly slopes and therefore are cooler, wetter, have deeper organic layers, and are more likely to contain permafrost [*Rieger*, 1983; *Hinzman et al.*, 2006]. Cooler and wetter forests provide a niche for bryophyte proliferation [e.g., *Oechel and Van Cleve*, 1986], which insulates the soil and allows for the formation and maintenance of permafrost [*Yoshikawa et al.*, 2002]. In turn, permafrost impedes soil drainage and therefore the depth of soil thaw throughout the fire season largely dictates the amount of dry fuel available for combustion. Therefore, more organic matter could be vulnerable to combustion in warmer and drier sites without permafrost [*Kasischke et al.*, 2000]. However, colder and wetter forests have deep organic soil layers that could become dry enough to burn during drought or late in the season when water tables and active layers reach a maximum depth [*Kasischke and Johnstone*, 2005; *Turetsky et al.*, 2002, 2006].

[5] Although the fraction of soil organic carbon (SOC) released to the atmosphere in boreal forest fires can be considerable (between 16%–100% of SOC stocks [*Kasischke et al.*, 1995; *Harden et al.*, 2000, 2006]), little is known about the amount or fate of fire-transformed C in soils. Pyrogenic C in soils exists along a continuum from partially-charred plant material to more graphitic black carbon (BC) particles, owing to microclimatic variation in burn temperature, burn duration, fuel type, and oxygen availability during a fire [*Sekiguchi et al.*, 1983; *Shindo*, 1991; *Gleixner et al.*, 2001]. While these factors make BC in soils difficult to consistently identify [e.g., *Goldberg*, 1985; *Schmidt and Noack*, 2000], its composition of highly aromatized components affords operational definitions based on its resistance to thermally and chemically oxidizing conditions [*Kuhlbusch*, 1995; *Schmidt et al.*, 2001; *Preston and Schmidt*, 2006]. Moreover, the highly-condensed molecular structure of BC suggests a high resistance to microbial degradation. Decay resistant BC therefore represents a sink for rapidly cycling C between the atmosphere and biosphere [*Kuhlbusch and Crutzen*, 1995] and is thought to comprise a significant amount of net biome production in fire-prone ecosystems [*Schulze et al.*, 1999]. The contribution of BC to very slowly cycling SOC pools should increase with successive fire cycles [*Harden et al.*, 2000; *Schulze et al.*, 2000]. However, BC stocks that have accumulated over time could be subject to combustion during severe fire activity, making it difficult to ascertain the C legacy of past wildfires [*Schmidt*, 2004].

[6] Here, we report on processes that regulate the depth of burning, as well as SOC and BC accumulation, in the soils of black spruce forests in interior Alaska. In this study we capitalize on the extensive wildfires that occurred in Alaska during the summer of 2004, which burned a record 2.7×10^6 ha. Sites included opposed north- and south-facing toposequences and adjacent foot- and toe-slopes in forests affected by these recent as well as older ($\sim$1860–1950) fire events. Since duff moisture exerts major control over the severity and extent of burning within a given wildfire, we hypothesized that the relative amount of surface fuels consumed would be higher on southerly slopes compared to north-facing and toe/foot-slope forests. We focused on BC accumulation at the organic/mineral soil interface (A horizons) to investigate long-term pyrogenic C accumulation across sites because organic horizon C stocks are vulnerable to burning. We expected to find greater BC accumulation in south facing forests because more complete consumption of shallower, dryer organic soils should increase the likelihood of BC integration with surface mineral soil, where it is more likely to be protected from consumption in subsequent fires.

2. Methods

2.1. Unburned Study Sites

[7] Site establishment, temperature records, and soil profile and stand descriptions and analyses for 12 unburned stands ($\sim$60–160 y old) in this study were previously described in detail by *Kane et al.* [2005]. Briefly, four replicate gradients in black spruce productivity and soil temperature were established across interior Alaska, ranging in latitude from $63°$–$65°$N ($\sim$365 km) and in longitude from $142°$–$148°$W ($\sim$550 km) (Figure 1). Study areas were named for the roads used to access them and were established (from west to east) along the Parks Highway (P), Murphy Dome Rd. (M), the Elliott Highway (E), and the Taylor Highway (T). In addition to these 12 sites, we sampled 9 unburned stands located within or near the burn units studied on the Steese and Taylor Highways, and 4 unburned stands located in the Fairbanks region in order to better understand soil moisture changes with organic layer depth. General soil physical and climate data are presented for each unburned landscape position in Table 1.

[8] We classified our sites into primary landscape attributes including aspect (north and south facing slopes) and local relief (upland and flat toe-slopes, <5% slope). We used end-of-growing-season mineral soil temperature and moisture along with measures of the depths of the organic layer profiles to confirm that flat, toe-slope and north-facing forests had cooler, wetter soils than south-facing stands, following *Kasischke and Johnstone* [2005]. Continuous soil temperature measurements within each genetic horizon at 12 stands were as previously reported by *Kane et al.* [2005]. Organic and mineral soil (5 cm) gravimetric moisture contents were also determined (bi weekly) with soil cores obtained through the growing seasons of 2004–2005 at these 12 sites. Intermittent permafrost occurred at the north-facing and toe-slope sites (Typic Historthels and Aquic Haplorthels), and Inceptisols occurred at the other sites (Cryaquepts and Cryochrepts).

2.2. Burned Study Sites

[9] In June and July of 2005, we sampled black spruce stands that burned during the summer of 2004. Our sites were located within two different fire events that occurred in close proximity to the unburned stands described above – the 217,000 ha Boundary fire (BY) and the 115,000 ha Porcupine fire (PE) (Figure 1). Burned sites also were located along opposed north- and south-facing toposequences, from uplands to lower foot and toe-slopes. We sampled 12 sites on south slopes, 11 on north slopes, and 8 on foot and toe slopes. Analysis of satellite hotspot signatures from the MODIS satellite showed that sites in the Boundary fire
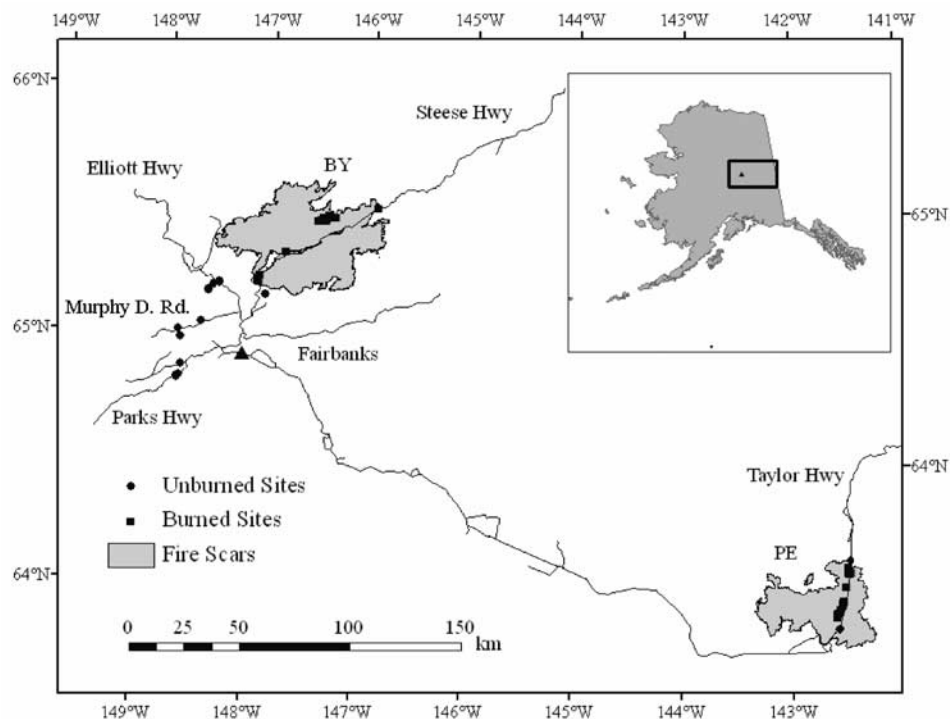
Figure 1. Distribution of the unburned (∼1860–1950) study sites and sites within fire scars from wildfires occurring in 2004 in the Yukon-Tanana Valley uplands of interior Alaska (some overlapping points not discernable at this scale). Burned sites studied were located in the Porcupine unit (PE; $n = 15$) and Boundary unit (BY; $n = 16$) fire events. Inset figure shows the relative position of the study region in the state of Alaska, USA.

burned between 25 and 27 June 2004 while sites in the Porcupine fire burned between 15 and 27 July 2004.

[10] Mean stand age (as determined in the laboratory by counting incremental growth rings on basal sections obtained from dominant trees in a given stand) of the BY fire sites was approximately 131 y (north = 134 y, south = 123 y, toe = 129), and of the PE fire sites was 94 y (north = 87 y, south = 95 y, toe = 105), prior to burning in 2004. The ranges in mean annual basal area increment (BY: 0.08–0.11 m^2 ha^{-1} y^{-1}; PE: 0.13–0.24 m^2 ha^{-1} y^{-1}) overlapped the range of mean annual basal area increment in the unburned stands (0.11–0.27 m^2 ha^{-1} y^{-1}), confirming that stand characteristics in the burned sites were similar to those in the unburned sites.

2.3. Soil Characteristics in Unburned Stands
2.3.1. Soil Profile Descriptions and Analyses
[11] Twelve soil pits (approximately 0.6 m^2, to a depth of 5 cm into the B horizon) were dug at each unburned site.

Genetic horizons were delineated in the field into the fibric (O_i), mesic and humic ($O_e + O_a$), and the mineral soil A and B horizons, following *Schoenberger et al.* [2002] (see *Harden et al.* [2004] for comparison between U.S. and Canadian classification). Macroscopic soil charcoal pieces were also harvested from A horizons in the field.

[12] Mineral soils from the A horizon were subsampled from 6 pits at each unburned site, chosen at random, to be separated by density into fractions <1.6 g cm^{-3} (light) and >1.6 g cm^{-3} (dense) using sodium polytungstate solution (Sometu Co., Sherman Oaks, California) [*Golchin et al.*, 1994; *Baisden et al.*, 2002]. Elemental analysis (C, H, N) and loss on ignition (400°C for 7 h) were determined on light fractions; percent oxygen was calculated by difference, following *Haumaier and Zech* [1995], using a LECO CHN 1000 analyzer (LECO Co., St. Joseph, Michigan).

[13] Stable isotope measurements were performed with a GEO 20-20 duel-inlet isotope ratio mass spectrometer coupled with a PDZ Europa solid preparation module.

Table 1. General Soil Physical and Chemical Properties of Unburned Stands in This Study[a]

	Mean Stand Age, years	Organic Matter (SE)[b]					September Means (SE)[c]		
Aspect		Depth, cm	Bulk Density, g cm^{-3}	Total C, kg C m^{-2}	GDD[d] (>0°C)	n	OM Depth, cm	Temperature (30 cm; °C)	Moisture (30 cm; g g^{-1})
South	95	13.33 (0.47)	0.09 (0.01)	4.43 (0.44)	839	9	15.00 (1.20)	3.60 (0.67)	0.32 (0.05)
North	108	20.39 (1.67)	0.07 (0.01)	5.74 (0.73)	530	11	22.24 (1.44)	1.76 (0.66)	0.48 (0.06)
Flat/Toe-slope	95	15.67 (3.00)	0.07 (0.01)	4.10 (0.46)	379	5	20.54 (1.34)	1.12 (0.25)	0.73 (0.04)

[a]Means are presented by landscape position.
[b]Mean organic matter characteristics for all organic horizons (not including green moss); data from *Kane et al.* [2005].
[c]Mean values integrated from the top 30 cm of mineral soil from pits dug in September 2005.
[d]Growing Degree Day heat sum (0°C) from continuous measurements in the middle of the mesic horizon.

Results are expressed in standard $\delta^{13}C$ notation, as the deviation (‰) relative to the isotopic ratio of Pee Dee belemnite standard. The samples used for $\delta^{13}C$ analysis were the same as those used for total C analysis and in the density fractionations. Charcoal samples were washed in HCl for several hours and rinsed with deionized water prior to analysis [*Bennett et al.*, 1990]. Samples were analyzed at least in duplicate such that replicates differed by <0.2‰ from the mean.

[14] We analyzed the $\Delta^{14}C$ (‰) content of dense fraction (>1.6 g cm^{-3}) soils to determine C mean residence times (turnover rate^{-1}) within this specific SOC pool [see *Baisden et al.*, 2002]. Mean residence times were estimated through use of a homogenous one-pool model of $\Delta^{14}C$ incorporation (following *Trumbore* [2000]).

2.3.2. Black Carbon Determination

[15] We measured the aromatic BC content of surface mineral soils (A horizons) obtained from 6 soil pits at each unburned site. We quantified C percentages in these samples after two pretreatments: a solvent extraction followed by a thermal treatment [*Kuhlbusch*, 1995]. The solvent extraction entailed placing ~1.3 g of pulverized soil into a 50 mL centrifuge tube and treating it with different solvents (10–20 mL) in the order: 2 × NaOH (1 M), 1 × 70 mass percent HNO$_3$, 5 × 1 M NaOH, 1 × 1 mass percent HCl, and 2× de-ionized water. The sample was placed in an ultrasonic bath (10–20 minutes), centrifuged (3,000 RPM), and the supernatant was decanted, in between solvent treatments (11 solvent treatments per sample). The sample was then dried, pulverized again, and ~0.75 g was placed in a chamber (in a pure oxygen flow at 1,000 mL min^{-1}) inside a muffle furnace maintained at 340 ± 4°C for 2 h. Darco 4 × 12 granular charcoal (Norit Americas Inc.; Atlanta, Georgia) was pulverized and used as a blank sample in the thermal treatments (mean loss of 0.03 g g^{-1} by mass). The volume of the thermal treatment chamber was 2.6 L, enabling 12 samples in ceramic boats to be heated at a time. The C that was resistant to the solvent extractions and the thermal treatment, defined by *Kuhlbusch* [1995] as BC, was determined by the difference in C contents in each fraction using a LECO CNS analyzer (LECO Co., St. Joseph, Michigan).

[16] In a comparative analysis of BC determination in soils, *Schmidt et al.* [2001] found that BC concentrations could vary by over two orders of magnitude for an individual sample, depending on the method-dependent operational definition of BC. The method used in this study [*Kuhlbusch*, 1995] yielded the third lowest amount of BC among the 6 methods reviewed by *Schmidt et al.* [2001]. *Skjemstad et al.* [1999] estimated the BC content of reference materials, a German Mollisol and an Australian Vertisol, to be 4.7 and 10.4 g C kg^{-1} respectively, using photo-oxidation and nuclear magnetic resonance (http://www.geo.unizh.ch/phys/bc/). Consistent with *Schmidt et al.* [2001], our analysis of these BC reference soils provided ~60% lower BC yields (1.63 ± 0.15 and 4.63 ± 0.12 g C kg^{-1} for the Mollisol and the Vertisol, respectively). Therefore, estimates of soil BC yields reported herein are conservative in comparison with determinations by other methods. It is important to note that this method likely does not isolate slightly charred biomass in the soil and reflects more graphitic BC, charcoal, and soot particles [*Masiello*, 2004].

2.4. Residual Soil C and Consumption Rates in Burned Stands

[17] At each site, we located a 40 m baseline transect in a homogeneous patch of burned forest. The baseline was oriented in a random direction, and bisected three 30 m transects, one located at the center, and two located at random distances in each direction from the center. Sample points were located every 5 m along each 30 m transect (7 per transect) and an additional 4 points were located along the baseline (at 5, 15, 25, and 35 m), for a total of 25 points per site, along which the depth of different organic layers (moss, lichen, residual char, fibric soil, mesic soil, and humic soil) was measured.

[18] *Kasischke and Johnstone* [2005] showed that adventitious roots (AR) on black spruce trees (roots formed above the base of the original root collar [see *LeBarron*, 1945]) in interior Alaska were located approximately 6 cm below the surface of the organic layer and therefore provided a baseline for prefire organic layer depths. We measured the distance from AR above the burned organic layer (two measures were obtained, the minimum and maximum distance) to the top of the mineral soil (n = 21) along our transects at the BY and PE sites (E. S. Kasischke et al., Evaluation of the composite burn index for assessing fire severity in Alaskan Black Spruce Forests, submitted to *International Journal of Wildland Fire*, 2007). We also obtained the same measurements in 15 unburned stands within or near the BY and PE sites. Total organic layer depths in unburned stands increased linearly with the depth measured from AR to mineral soil (r^2 = 0.78, p < 0.001, n = 15, β_0 = 8.01 ± 2.43, β_1 = 0.89 ± 0.13). We used the empirical relationship between the distances of the adventitious roots above the mineral soil and total organic layer depths to estimate total organic layer depths prior to burning. Appendices containing residual soil depth data, surface fuel consumption (SFC), and AR depths for all burned sites can be found at http://www.lter.uaf.edu/research_vignettes.cfm.

[19] Soil organic C in burned stands was estimated using measured horizon depths of residual soil, bulk density, and C concentration data values measured within each burn unit as previously described. Measured depths from adventitious roots to residual soil were used to estimate SOC consumed in wildfire through use of an empirical relationship between organic horizon depth (cm) and SOC (kg m^{-2}) developed from published soil profile data in Alaskan black spruce forests (*O'Neill* [2000], *King et al.* [2002], *Harden et al.* [2004], *Kane et al.* [2005], *Vogel et al.* [2005], *Ping et al.* [2005]; r^2 = 0.64, p < 0.001, n = 23, β_0 = 2.39 ± 0.50, β_1 = 0.16 ± 0.03).

2.5. Data Analysis

[20] Two soil samples were chosen at random from each plot for $\delta^{13}C$ isotope analyses (n = 6). Unburned cross-site comparisons involving annual soil temperature and gravimetric soil moisture have an n = 10 because two monitoring sites were burned in the PE unit fire of 2004.

[21] Differences among sites in mean annual temperature and soil profile depths were tested with one-way analysis of variance pairwise contrasts at α = 0.05 (Scheffe error protection), or with analysis of covariance with landscape position as a class variable [*Cody and Smith*, 1997]. Pearson
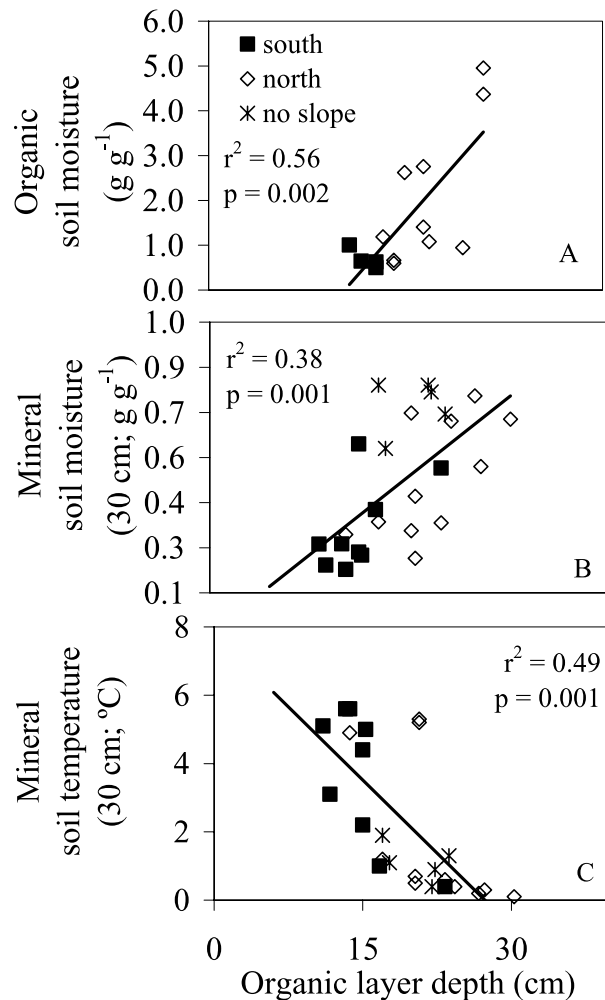
Figure 2. Organic layer depth increased with organic soil moisture (a) and mineral soil moisture (b), and declined with increasing mineral soil temperature (c) in unburned black spruce forests. Mineral soil measurements were averaged from the upper mineral soil profile (30 cm) and incorporated locations with the most and least organic matter accumulation at each plot. Organic soil moisture was measured at a subset of sites throughout 2004 and 2005 (no flat toe-slopes were sampled).

correlation coefficients demonstrated relationships between variables ($\alpha = 0.05$). Multiple regression analysis (forward selection procedure) developed empirical relationships between SOC, SFC, and physiographic properties. Descriptive statistics were performed with Analyze-it statistical module (Analyze-it Software, Ltd. Leeds, UK) and regressions and ANCOVA were developed through PC SAS (version 8.2, SAS institute, Cary, North Carolina).

3. Results

3.1. Landscape Controls on Temperature and Moisture in Unburned Stands

[22] North-facing aspects and foot/toe-slopes (<5% slope) exhibited cooler soil temperatures than southerly slopes both annually and seasonally (Table 1 and Figure 2). Soil temperature measurements taken at the end of the growing season were highly correlated with mean annual soil temperatures ($r = 0.95$, $p = 0.004$, $n = 7$), supporting our assumption that end-of-growing-season soil temperature and moisture data can be used to analyze factors influencing these characteristics. Soil temperature decreased while soil moisture increased with increasing organic matter depth across all unburned sites (60–160 y old) in this study (Figure 2). Organic layer moisture was highly correlated to mineral soil moisture at 5 cm depth ($r = 0.74$, $p = 0.003$, $n = 14$). Mean mineral soil moistures differed significantly with organic layer depths when values were adjusted for aspect (ANCOVA, $F = 9.01$, $p < 0.01$), with least squares mean soil moisture values of 0.7, 0.4, and 0.4 g g^{-1} occurring on toe-slopes, north-facing and southerly slopes, respectively.

3.2. Patterns of Organic Matter Consumption in Wildfire

[23] Across all sites and both fire events, total prefire organic horizon depths estimated from measurements of adventitious root distance to mineral soil (±standard error) were thicker on foot/toe-slopes and north facing aspects (29.8 ± 1.9 and 28.7 ± 1.4 cm, respectively) than on southerly slopes (24.1 ± 1.5 cm; 1-way ANOVA pairwise, $F = 4.06$, $p = 0.03$). Following fire, mean organic horizon depths were lower in south-facing sites (6.1 ± 1.3 cm) than in north-facing (11.5 ± 1.6 cm) and foot/toe-slope sites (16.7 ± 1.0 cm; 1-way ANOVA pairwise, $F = 13.26$, $p < 0.001$; Figure 3). Prefire organic layer depths and depths of consumed organic matter were normally distributed across all sites (Shapiro-Wilk coefficients = 0.97 and 0.96; $p =$
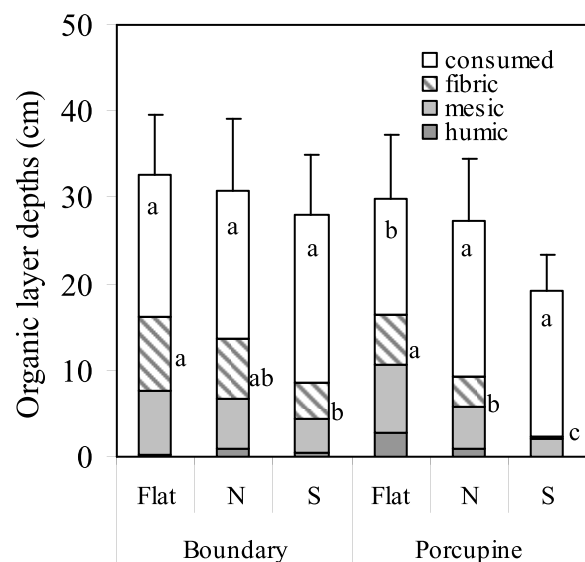

Figure 3. Residual organic horizon depths measured along opposed north and south facing toposequences in the Boundary and Porcupine Unit fires of 2004. Toposequences were measured along north (N), south (S), and flat (toe-slope, <5%) areas. Error bars represent combined standard errors of the mean values for residual and consumed organic matter depths. Letters denote significant differences in postfire organic matter and consumption within a burn unit (ANOVA pairwise comparisons; $\alpha = 0.05$).
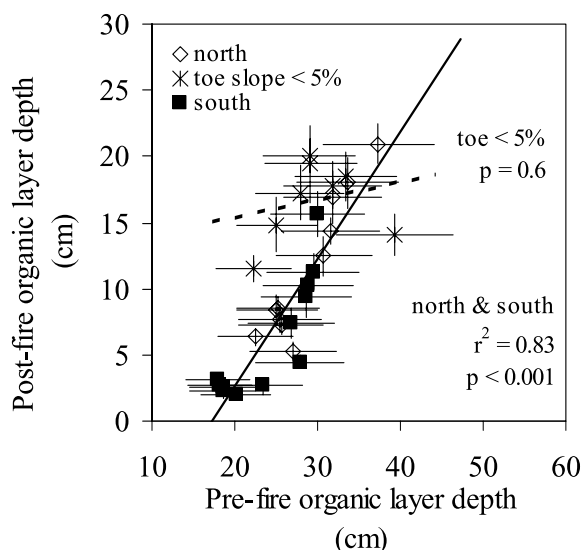
Figure 4. The depth of organic horizons remaining after a fire increases with increasing depth of organic horizons prior to burning, as estimated from residual tree root collars. The slope of the relationship between prefire and postfire organic layer depths was heterogeneous across aspects and therefore toe slopes <5% (dotted line) were removed from the regression. North and south facing aspects fit the line: $\beta_0 = -16.46 \pm 2.52$, $\beta_1 = 0.96 \pm 0.09$. Error bars are standard errors of the mean.

0.59 and p = 0.39, respectively). Organic layer depths prior to burning explained 83% of the variance in postfire organic layer depths on upland sites with slopes >5% (Figure 4). This relationship differed among landscape positions, as there was a prefire depth x landscape position interaction
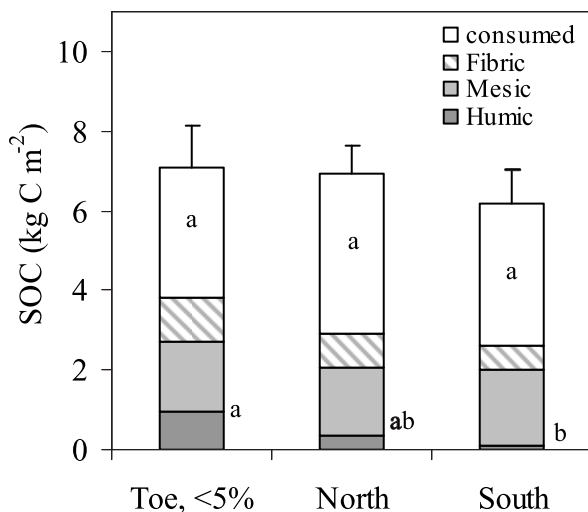
Figure 5. Residual soil organic carbon stocks from the Boundary and Porcupine unit fires are averaged for a given landscape position. Letters denote significant differences in residual C stocks and C consumption across landscape positions (1-way ANOVA pairwise comparisons; $\alpha = 0.05$). Error bars represent combined standard errors of the mean values for residual and consumed SOC.
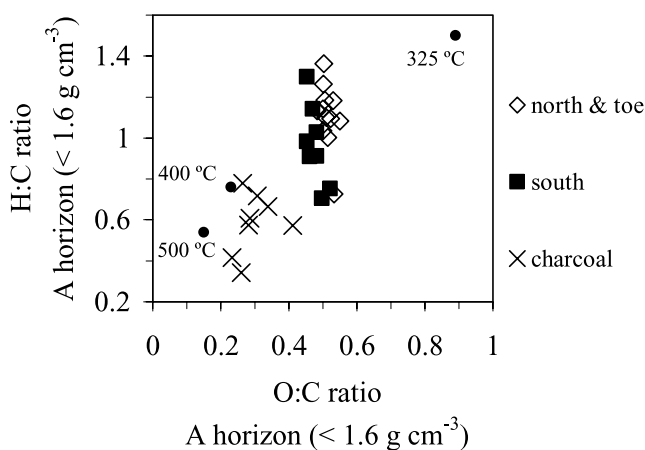
Figure 6. Atomic H:C vs. atomic O:C diagram of light fraction (<1.6 g cm^{-3}) A horizon mineral soils sampled on north and south facing aspects (burned 60–160 years ago). Values for macroscopic soil charcoal (X's) obtained from the organic/mineral soil interface at each site are also plotted. Solid circles are values for cellulose and cellulose chars obtained by heating at several temperatures (data from *Sekiguchi et al.* [1983], plotted for comparison).

(F = 8.12, p = 0.002). The relationship between prefire and postfire organic layer depths was not significant in foot/toe-slope forests (p = 0.6; Figure 4).

[24] The depth of soil organic matter reduction during the two fire events only differed in foot/toe-slope forests within the PE burn (Figure 3). However, when expressed as a percentage of total organic layer depths, consumption rates did vary across the different landscape positions. On average, 43%, 62%, and 77% (±4%) of total soil organic layer depths were consumed in the foot/toe-slope, north-facing, and south-facing sites, respectively (1-way ANOVA pairwise; F = 17.80, p < 0.001). Consistent with reductions in organic layer depths, average C emissions due to consumption did not vary across the different topographic positions (1-way ANOVA pairwise; F = 1.15, p = 0.33). The average amount of organic matter combustion across all sites was 3.66 ± 0.19 kg SOC m^{-2} (Figure 5).

3.3. Patterns of BC Accumulation; δ^{13}C, Δ^{14}C, O:C

[25] Charcoal pieces found at the organic-mineral soil interface from mature forests in this study were more enriched in δ^{13}C (mean ± SE: −25.4‰ ± 0.2; n = 10) than both light (<1.6 g cm^{-3}; −25.9‰ ± 0.1; n = 12) and dense fraction (>1.6 g cm^{-3}; −26.4‰ ± 0.1; n = 12) A horizon organic matter. Dense fraction C concentration in the A horizon increased with increasing Δ^{14}C enrichment across all sites (r^2 = 0.55, p = 0.03), with warmer and drier south-facing sites exhibiting the most Δ^{14}C (‰) enrichment. Moreover, the light fraction atomic O:C ratio was lower in soils from south-facing aspects (0.48 ± 0.01) than from north-facing aspects (0.50 ± 0.01; ANOVA; p < 0.05), which could be due in part to the incorporation of soil charcoal owing to its lower O:C ratio (soil charcoal O:C of 0.30 ± 0.02; Figure 6). The H:C ratio of soil organic matter did not vary significantly between aspects (Figure 6).

[26] The proportion of BC to SOC changed significantly between aspects, with south facing forest soils having a

Table 2. Long-Term Accumulation of BC (Likely Composed of More Graphitic BC Soot and Charcoal) in Surface Mineral Soil (A Horizons)[a]

	Initial BD, kg m^{-3}	Total OC, g C kg^{-1} soil	Acid Insoluble,[b] g C kg^{-1} soil	Black Carbon,[c] g C kg^{-1} soil	BC:Total OC, g kg^{-1}	BC Stocks, g m^{-2}
South aspect[d]						
M1	441 (19)	165.2 (18.7)	97.6 (5.6)	9.2 (1.2)	53.3 (5.0)	68.9 (5.3)
M2	412 (12)	140.4 (5.8)	74.6 (5.1)	12.7 (3.6)	90.3 (22.4)	141.2 (14.8)
P1	394 (7)	178.9 (11.4)	89.3 (8.1)	24.7 (4.7)	143.7 (29.4)	223.8 (4.0)
T1	473 (8)	128.8 (4.9)	62.7 (7.3)	17.7 (4.4)	143.3 (24.9)	259.4 (4.4)
Average[e]	430 (17)	153.3* (11.42)	81.0* (7.7)	16.1 (3.4)	107.7* (22.0)	173.3 (42.7)
North and no aspect						
E1	478 (27)	196.5 (16.4)	105.0 (16.5)	7.9 (1.3)	38.9 (3.7)	45.3 (6.2)
E2	384 (12)	201.8 (19.8)	81.2 (11.9)	8.0 (1.1)	54.7 (14.8)	40.0 (4.2)
E3	285 (39)	211.0 (16.2)	169.0 (22.4)	18.0 (2.9)	57.4 (4.9)	71.8 (8.3)
M3	442 (6)	198.6 (16.2)	122.5 (21.3)	8.2 (1.0)	39.7 (3.0)	86.9 (4.4)
P2	466 (3)	188.1 (14.8)	84.3 (13.7)	16.3 (1.7)	94.3 (6.8)	152.0 (7.9)
P3	467 (31)	244.8 (9.9)	144.0 (19.8)	20.6 (3.1)	84.6 (10.3)	221.2 (14.5)
T2	297 (21)	210.6 (5.3)	125.7 (13.8)	10.6 (1.0)	49.5 (4.5)	81.9 (3.0)
T3	305 (17)	226.3 (14.1)	109.0 (5.5)	17.8 (1.6)	77.2 (9.8)	195.6 (4.9)
Average	391 (30)	209.7* (6.5)	117.6* (10.4)	13.4 (1.9)	62.0* (7.4)	111.8 (24.4)

[a]Sample $n = 12$ for Bulk Density determination and $n = 6$ for subsequent analyses. Standard Errors of the mean are in parentheses.
[b]Fraction of OC remaining after sequential acid (NO$_3$) and base (NaOH) extraction, following *Kuhlbusch* [1995].
[c]Additional nonhydrolyzable OC remaining after combustion at 340 °C in pure O$_2$ for 2 h.
[d]Site labels describe their location on the Elliott Hwy. (E), Taylor Hwy. (T), Parks Hwy. (P), and Murphy Dome (M). Number is site replicate (three sites per study area).
[e]Arithmetic mean; asterisks denote significant differences in mean values between aspects ($p < 0.05$; 1-way ANOVA).

BC:SOC ratio approximately 1.7 times higher than the north-facing forests (Table 2). Black carbon comprised roughly 11% and 6% of total A horizon SOC on south- and north-facing aspects, respectively. Surface mineral soil BC stocks and BC:SOC both decreased with increasing soil moisture content measured at the end of the growing season across all sites (with one poorly-drained permafrost site removed as an outlier; Figure 7). Additionally, mean C residence times in the A horizon soils were longer in the cooler, wetter forests, and BC stocks and concentrations decreased as the mean residence time of dense fraction C increased across sites (Figure 7).

4. Discussion

### 4.1. Patterns of Organic Matter Consumption

[27] Contrary to our hypothesis, the total depth of consumption only varied at one toe-slope forest, and total amounts of SOC lost to wildfire did not change with landscape position (Figures 3 and 5) across the Boundary and Porcupine unit fires in interior Alaska. Given the greater soil organic layer fuel loads on toe-slopes and north-facing aspects, it is likely that soil moisture (Figure 2) largely determined the vulnerability of organic material to burning in these two wildfire events. Organic matter typically accumulates in cooler, wetter environments underlain by permafrost, but during dry periods organic matter at the soil surface is susceptible to drying out, regardless of landscape position. Since the water holding capacity of organic layers can be much higher than mineral soil, sites with deep organic layers likely harbor more soil water deeper in the soil profile during drier periods. Water harbored deep in the soil profile likely constrains the depth of burning and therefore sites with deeper organic layers lose a smaller proportion of their total organic material than sites with shallower organic layer depths.

[28] While these results indicate that the interaction between increased organic layer depth and organic layer moisture is an important control over residual organic layer depths following wildfire in black spruce forests, we hypothesize that increased drought or the recession of permafrost (as happens later in the summer season) could allow for deeper SFC from wetter landscape positions (i.e., north-facing and flat/toe-slopes). It is likely that SFC in early season fires is more constrained by antecedent soil moisture conditions whereas SFC in late-season fires is more limited by total fuel amounts. Further research tracking temporal variation in SFC throughout the fire season would clarify how the interaction between organic layer depth and soil moisture mitigates the proportional amount of organic material remaining following wildfire.

4.2. Patterns of Char Accumulation Within the Soil

[29] Increasing decomposition extent of soil organic matter (SOM) has been linked to δ^{13}C enrichment [*Nadelhoffer and Fry*, 1988; *Boutton*, 1996; *Amundson and Baisden*, 2000] and increasing density of SOM fractions (e.g., >1.6 g m^{-2} [*Baisden et al.*, 2002; *McLauchlan and Hobbie*, 2004]), and deviation from these trends has been attributed to the incorporation of charred remains [*Baisden et al.*, 2002]. Char material is believed to have a density <1.6 g m^{-2} [*Roscoe et al.*, 2001; *Baisden et al.*, 2002]. While soil char can also be occluded in denser soil fractions owing to mineral binding [e.g., *Glaser et al.*, 2000; *Zech et al.*, 2005], the capacity for this in interior Alaskan Inceptisols is probably low because of low rates of clay mineral formation [e.g., *Allan*, 1969; *Ping et al.*, 2005]. In addition, our observation of soil charcoal ^{13}C enrichment relative to other organic matter is consistent with other field studies investigating changes in isotopic composition along continua of soil formation (*King et al.* [2002]; *Preston et al.* [2006]; ~2.0‰); soil charcoal enrichment relative to other organic
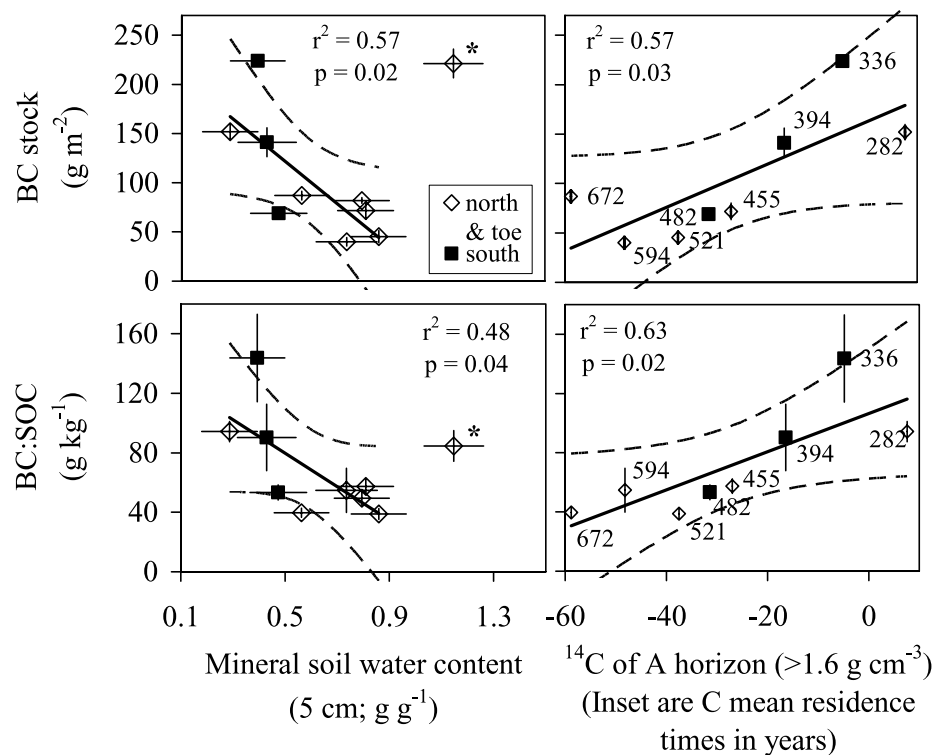
Figure 7. Surface mineral soil BC stocks (likely composed of more graphitic BC soot and charcoal; top) and the ratio of BC to SOC (bottom) both decreased with increasing mineral soil moisture measured in September (left), and increased with the enrichment of $\Delta^{14}C$ (‰) measured in dense fraction (>1.6 g cm^{-3}) A horizon soils (right). Inset C mean residence times (years) were estimated based on the degree of $\Delta^{14}C$ incorporation. Dashed lines are a 95% confidence interval about the values, and error bars represent standard errors of the mean. Asterisk denotes an outlier not included in the linear regression (soil water of 1.2 g g^{-1}; Cook's D statistic = 2.9).

matter is probably due to changes in the isotopic composition of the fuel source. For example, deeper organic layers (mesic and humic material), bark, and coarse woody material are isotopically enriched relative to surface moss and are more likely to burn in severe wildfires [*Schuur et al.*, 2003]. Soil charcoal created in mild wildfires, which would mostly be the product of burning within shallow surface organic material [e.g., *Neff et al.*, 2005], would be more vulnerable to burning in subsequent wildfires owing to its proximity to the surface. The $\delta^{13}C$ of light fraction (<1.6 g cm^{-3}) SOM was likely influenced by soil charcoal incorporation from deeper burning in more severe wildfires because it was isotopically enriched relative to dense fractions, despite being composed of SOM that has undergone less decomposition than dense fraction SOM. These data support the expectation that patterns of accumulated char materials in soil are reflected in light fraction SOM.

[30] Analysis of the atomic H:C and O:C ratios of soil fractions can provide insight into the genesis of pyrogenic materials [*Kuhlbusch and Crutzen*, 1995; *Kim et al.*, 2003; *Preston and Schmidt*, 2006] because heated SOM, as in a wildfire, has a higher degree of aromaticity and undergoes decarboxylation [*Almendros et al.*, 1992]. The O:C ratio of char material declines with increasing temperature during its formation [*Sekiguchi et al.*, 1983] and increasing duration of heating [*Shindo*, 1991]. Therefore, the lower O:C in light-fraction mineral soils from drier, south-facing forests

(Figure 6) probably reflects burn residues from hotter and/or longer duration wildfires, or a higher concentration of pyrogenic C, than occurred in the cooler and wetter stands.

4.3. Patterns of Black Carbon Accumulation

[31] Many studies have found concentrated soil char at the organic/mineral soil interface in boreal forests (Alaska: *Ping et al.* [2005]; Canada: *Harden et al.* [2000], *Preston et al.* [2002]; Siberia: *Schulze et al.* [1999]; and across the loess-belt of Germany: *Schmidt et al.* [1999]). However, reports of BC concentrations within the soil profile vary widely, even within a stand type. Concentrations of more graphitic BC in a Siberian pine stand were very low in the litter and surface organic horizons, and were highest in the surface mineral soil (as determined through a thermal/chemical oxidation method [*Schulze et al.*, 1999]). In contrast, *Czimczik et al.* [2005] used a benzenepolycarboxylic acid technique to quantify a wider spectrum of BC types (ranging from slightly charred biomass to soot) in other Siberian pine forests and found that not only was most (up to 99%) of the BC within organic horizons, but yields were an order of magnitude lower than previous estimates. *Preston and Schmidt* [2006] concluded that BC estimates in boreal forests are very limited and difficult to compare due to variations in sampling and analysis, and offered that the published range in BC (on the order of 100–200 g m^{-2} in the forest floor) may well underestimate total site charcoal

in deeper mineral soil and coarse woody debris pools. While the range of BC stocks reported herein for surface mineral soils in interior Alaska (Table 2) mirrors the range offered by *Preston and Schmidt* [2006], our values underestimate total site BC by the potential amount harbored in organic horizons.

[32] Given the high frequency of stand-replacing fires in spruce forests of interior Alaska (~100 years [*Yarie*, 1981]), the high potential for charcoal production from biomass burning (72.9–93.2 g m^{-2} [*Clark et al.*, 1998; *Lynch et al.*, 2004]), and the persistence of char in soil (~200–1000 y [*Harden et al.*, 2000]), one would expect far more char at the mineral soil surface than we report. Similarly, *Czimczik et al.* [2003] concluded that some form of in situ char degradation must be occurring in fire-prone Siberian forests, with char consumption in subsequent fires offering the most parsimonious explanation for relatively small BC stocks [*Ohlson and Tryterud*, 2000; *Czimczik et al.*, 2005]. One would expect lower consumption of BC in subsequent fires to occur in wetter forests with deeper organic layer depths, owing to protection from fire by increased soil moisture. However, our results show that more black carbon is incorporated into the mineral soils within drier south-facing forests with shallower organic horizons (Figure 7). We hypothesize that BC incorporated with surface mineral soil, which is more likely to occur in drier south-facing forests with shallower organic horizons [*Ping et al.*, 2005], is more protected from burning in subsequent wildfires than BC in organic soil layers.

[33] Organic matter depths and soil moisture, which constrain the combustion process itself by influencing the temperature of combustion, O_2 concentration, and mode of combustion (e.g., flaming or smoldering), changed with landscape position in this study. Black carbon production occurs in smoldering fires in the absence of O_2, after fuels have undergone sufficient drying via distillation [*Gleixner et al.*, 2001]. Declining BC stocks and concentrations with increasing soil moisture across our study sites (Figure 7) suggests that deep, wet ground fuels occurring in north-facing and toe-slope forests burn less deeply than the drier fuels contained in south facing slopes. These combustion patterns decrease the likelihood of residual char becoming integrated with mineral soil in the wetter sites. However, it is also possible that BC is protected from subsequent burning events in very saturated organic soil layers. This could explain why the wettest site in this study (P3; soil moisture was about twice the mean of all other sites) had the second largest BC stock in the surface mineral soil (Figure 7). Further research tracking the fate of BC in saturated ecosystems, including organic and mineral dominated wetlands, would further elucidate the role that soil moisture plays in organic matter consumption, BC production, and the protection of BC from oxidation in subsequent fires.

[34] The physical characteristics constraining soil BC formation and accumulation are different than the driving factors of nonpyrogenic soil organic matter accumulation. While warmer, drier conditions are more amenable to combustion of surface organics, soil organic matter turnover processes also increased in the surface soils of warmer, south-facing stands [*Kane et al.*, 2005]. BC stocks and concentrations were higher in surface mineral soils of warmer, drier forests in spite of increased C turnover rates there (Figure 7). This hints at the recalcitrant nature of BC and suggests that there is preferential decomposition of other organic matter fractions in warmer, drier forests.

[35] While warmer, drier forests harbored less total SOC, wildfire was a mechanism by which more stable C pools (BC) could aggrade despite the rapid turnover rates of C associated with other soil pools. Even though the method used for BC quantification in this study underestimates total soil charcoal in reflecting only the most graphitic soot and charcoal particles [*Masiello*, 2004], BC stocks were small relative to total SOC (4% and 2% of organic horizon SOC on south- and north-facing aspects, respectively). Moreover, stocks of fire-generated BC in soil were small relative to SOC lost during combustion in wildfires (~3%; Figures 5 and 7).

5. Conclusions

[36] Warmer and drier south-facing forests lost a greater proportion of their organic layer depth than did north-facing and toe-slope forests. These data suggest that in these two early-season wildfires the organic layer fuel available for consumption was largely limited by soil moisture, which increased with prefire organic soil depth. However, total amounts of SOC consumed did not vary with landscape position, even though there were significant differences in antecedent soil C stocks. These data suggest that higher C emissions are likely to occur from wildfires occurring in sites with deeper organic layers if conditions in the boreal forest become drier, or with an extension of the summer season.

[37] Black carbon stocks measured in surface mineral soils from unburned forests (60–160 y old) suggested that the trends in organic matter combustion we observed in the 2004 fires might also have occurred during past fire events. Ecosystems with wetter and deeper soils experienced less proportional consumption relative to the drier forest settings, which likely deterred the direct incorporation of BC with surface mineral soil. However, complete saturation of surface soils (as in permafrost dominated sites with perched water tables) could preserve BC stocks from oxidation in subsequent fires, though these BC stocks could become increasingly vulnerable to reburning under future climate regimes. While warmer, drier forests harbored less total SOC, wildfire was a mechanism by which more stable C pools (BC) could aggrade, even though the turnover rates of C in other soil pools also increased. Even though the chemical and thermal oxidation method used to quantify soil BC in this study likely only reflects more graphitic BC particles, BC stocks were small compared to SOC remaining or lost in wildfire. Future work should track the fate of burn residues in boreal wetland soils, and also BC deeper in the soil profile and in organic horizons. These data are necessary in order to better understand the interaction between organic matter depth, soil moisture, and SFC in mediating the lasting effects of fire on SOC stocks in the context of changing fire patterns likely to occur in a warmer climate.

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