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Quantifying fire severity, carbon, and nitrogen emissions in Alaska's boreal forest

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Abstract. The boreal region stores a large proportion of the world's terrestrial carbon (C) and is subject to high-intensity, stand-replacing wildfires that release C and nitrogen (N) stored in biomass and soils through combustion. While severity and extent of fires drives overall emissions, methods for accurately estimating fire severity are poorly tested in this unique region where organic soil combustion is responsible for a large proportion of total emissions. We tested a method using adventitious roots on black spruce trees (*Picea mariana*) in combination with canopy allometry to reconstruct prefire organic soil layers and canopy biomass in boreal black spruce forests of Alaska (USA), thus providing a basis for more accurately quantifying fire severity levels. We calibrated this adventitious-root-height method in unburned spruce stands and then tested it by comparing our biomass and soils estimates reconstructed in burned stands with actual prefire stand measurements. We applied this approach to 38 black spruce stands burned in 2004 in Alaska, where we measured organic soil and stand characteristics and estimated the amount of soil and canopy biomass, as well as C and N pools, consumed by fire. These high-intensity quantitative estimates of severity were significantly correlated to a semiquantitative visual rapid assessment tool, the composite burn index (CBI). This index has proved useful for assessing fire severity in forests in the western United States but has not yet been widely tested in the boreal forest. From our study, we conclude that using postfire measurements of adventitious roots on black spruce trees in combination with soils and tree data can be used to reconstruct prefire organic soil depths and biomass pools, providing accurate estimates of fire severity and emissions. Furthermore, using our quantitative reconstruction we show that CBI is a reasonably good predictor of biomass and soil C loss at these sites, and it shows promise for rapidly estimating fire severity across a wide range of boreal black spruce forest types, especially where the use of high-intensity measurements may be limited by cost and time.

Key words: adventitious roots; Alaska, USA; allometric equations; black spruce; carbon emissions; forest fire; nitrogen; organic layer depth; Picea mariana; *soil carbon; surface fuel consumption.*

Introduction

Boreal forests typically accumulate large pools of carbon (C) in surface organic soil layers as a result of poorly decomposable plant litter, cold temperatures, and waterlogged soil that together contribute to slow decomposition rates (Hobbie et al. 2000). As a result, soil C pools in the boreal region are estimated to represent a large fraction of the total global terrestrial soil C pool (Gorham 1991, Dixon et al. 1994, Jobbagy and Jackson 2000). While heterotrophic respiration of soil organic matter is a continuous process that largely controls annual to decadal rates of soil C accumulation, periodic wildfire, the dominant disturbance in the boreal forest, can combust soil organic layers and thus is a major episodic factor controlling the decadal to century scale distribution of C in the boreal biome (Harden et al. 2000). Fire return intervals are estimated to be ~80–150 years for the boreal forest of western North America (Johnson 1992, Payette 1992). However, climate change is expected to increase the frequency and the intensity of wildfires as well as the duration of the fire season (Flannigan et al. 2000), thus increasing ecosystem C loss and potentially acting as a positive feedback to climate change (Kasischke et al. 1995, Chapin et al. 2008).

Thick horizons of organic material overlaying the mineral soil surface make boreal forests quite different from temperate forests in terms of C sequestration, fire emissions, and the ecological impacts of fire. Fire affects ecosystem C balance immediately via direct C emissions as surface organic layers are consumed during wildfire, and also over time by affecting the composition and growth rate of postfire successional forests (Kasischke et al. 2000, Lecomte et al. 2006). Boreal tree seedling recruitment generally increases with exposure of the

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mineral soil below the organic soil layers, with small-seeded, deciduous species being most sensitive to this effect (Charron and Greene 2002, Johnstone and Chapin 2006, Greene et al. 2007). Early postfire recruitment is a good predictor of future stand patterns (Johnstone et al. 2004, Peters et al. 2005) and thus has direct impacts on the density, composition, and C sequestration potential of future forests (Johnstone and Chapin 2006, Lecomte et al. 2006, Greene et al. 2007).

Boreal wildfires vary considerably in intensity (the amount of energy) and severity (the proportional change in forest structure) as they burn across the landscape, creating heterogeneity in both direct C emissions and the ecological controls over future forest recruitment. Fire behavior and severity patterns in the boreal forest differ greatly from many other forests due to the high fire intensity and flame length that characterizes boreal fires (Johnson 1992). In a severe fire, the canopy often burns in a fast-paced, high-intensity crown fire, which results in near total canopy death (Johnson 1992), while the thick organic soil horizons may burn in active flames or in smoldering consumption later in time (Miyanishi and Johnson 2002). Boreal forest fires interact with physical conditions such as site aspect, elevation, soil moisture, and weather conditions as well as with biological properties such as vegetation fuel type and forest structure to influence overall fire severity patterns on the landscape (Johnson 1992, Hely et al. 2001, Duffy et al. 2007). In turn, patterns of fire severity influence the amount of direct C emissions (Kasischke et al. 1995, Amiro et al. 2001), the postfire vegetation recovery (Greene et al. 2004, Johnstone and Chapin 2006), and subsequent ecosystem C balance (Lecomte et al. 2006).

Fire severity is a general term that refers to the proportion of consumption of organic material or vegetation mortality that occurs as the direct consequence of a fire (Rowe 1983, Lentile et al. 2006). As such, measurements of fire severity are key to estimating C emissions and remaining nitrogen (N) pools that will be available for future forest growth. In boreal forests, a substantial portion of the fuel consumption occurs in the surface soil organic layers, so characterization of fire severity requires consideration of both canopy and soil components. Currently, there is no standardized method of quantifying fire consumption of organic soil layers in boreal forests. As a result, semiquantitative assessments of severity used by land managers have been largely untested against measurements of C and N emissions and remaining pools in boreal forests. The composite burn index (CBI), which was developed in the western United States, includes visual assessment of both canopy and organic soil consumption (Key and Benson 2005), yet few studies have compared this rapid index against quantitative measurements of C and N consumption or residual pools. An accurate, quantitative method of measuring fire severity would provide the basis for these comparisons, enhancing C accounting, and significantly contributing to assessments of how changes in fire regime may affect atmospheric CO_2 and future climate (de Groot et al. 2007).

Many studies of fire in boreal forests have categorized levels of fire severity based on measurements of the amount of organic soil remaining after fire (Turner et al. 1997, Arseneault 2001, Wang 2002, Bergner et al. 2004, de Groot and Wein 2004, Greene et al. 2004, Johnstone and Kasischke 2005, Johnstone and Chapin 2006). However, this approach assumes that the amount of postfire residual organic soil was proportional to the amount of organic soil consumption. While postfire soil organic depth is likely to be affected by consumption, it is also strongly influenced by the thickness of the organic soil layers that were present before the fire. Thus, estimates of fire severity based solely on measurements of residual organic matter are likely to be confounded by prefire differences in biomass and soil (Miyanishi and Johnson 2002). Techniques used to avoid this bias include the use of prefire data, which are rarely available for remote boreal wildfires, paired-sample studies where residual biomass in burned sites is compared to unburned sites assuming no significant between-site heterogeneity (Kasischke and Johnstone 2005), and last, detailed analyses of surface ash concentrations to estimate organic soil consumption that must be carried out immediately after fire (Turetsky and Wieder 2001).

Recently, a new approach to estimating fire severity in boreal forests has been developed that uses adventitious roots of black spruce (*Picea mariana*) to reconstruct prefire organic layer depths after a stand has burned (Kasischke and Johnstone 2005). Adventitious roots grow above the initial root collar of black spruce trees into the organic soil/moss layer that surrounds the tree (Lebarron 1945), and the distribution of these roots is clearly visible on burned trees for many years after fire. In our study, we tested whether height measurements of small (<2 mm) adventitious roots on black spruce boles above the remaining soil organic material can be used to: (1) reconstruct prefire organic soil depth, both near and away from tree bases, (2) quantify pre- and postfire C and N pools, and (3) constrain wildfire organic soil combustion estimates. We also applied an approach for estimating canopy severity that combined allometry-based estimates of fine fuel biomass with visual consumption estimates to measure total biomass loss from the canopy. We used these field-based approaches to develop quantitative estimates of organic matter consumption and N and C emissions for 38 black spruce stands distributed across a range of site moisture conditions in interior Alaska that burned in 2004, the largest fire season on record (Todd and Jewkes 2006). Finally, these quantitative measurements were compared to semiquantitative, but rapid, consumption assessments obtained from the same sites using the CBI to determine if this quicker and cheaper metric developed in other forests might be applicable to boreal systems.

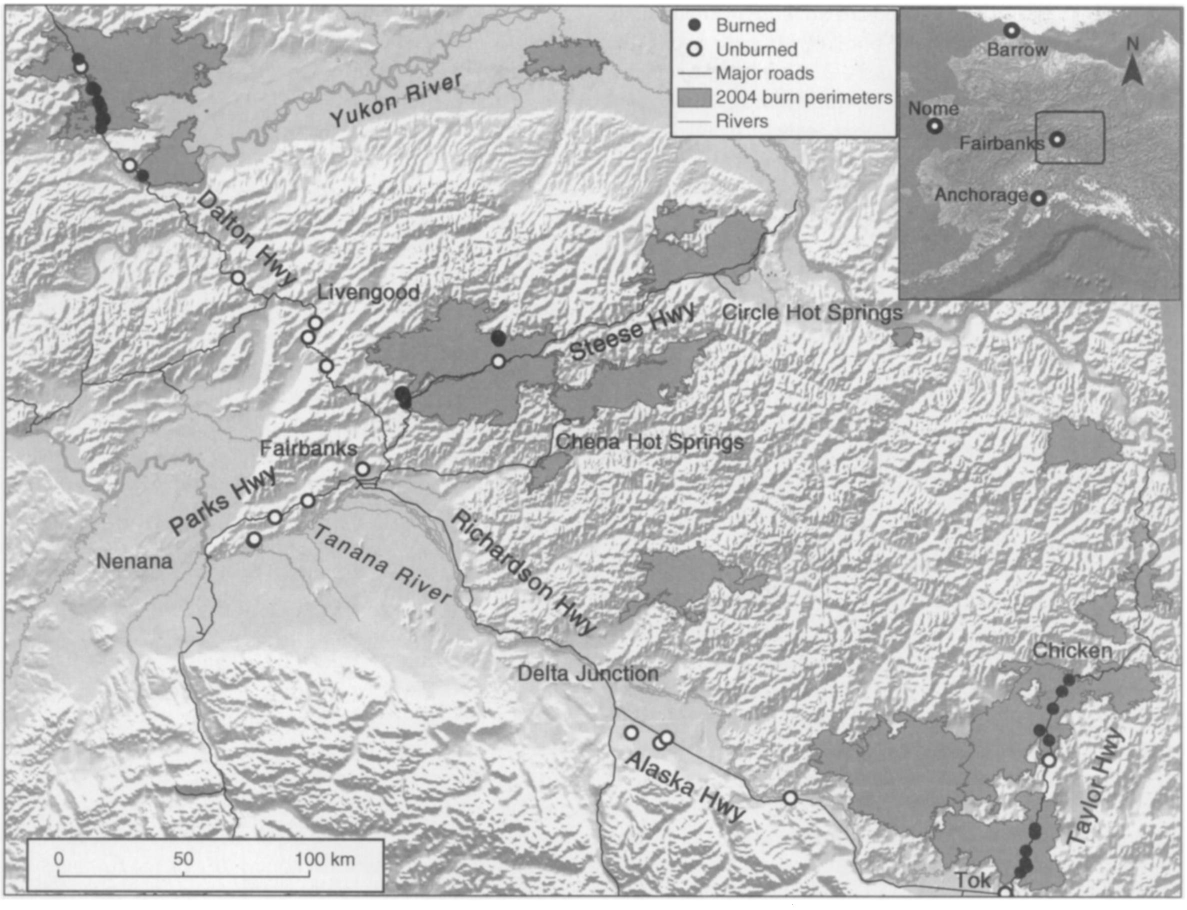

FIG. 1. Map of interior Alaska, USA, delineating the areas burned by wildfire in 2004 and the location of the 38 burned and 28 unburned study sites. Note that the burn perimeter outline is the maximum extent of burn and includes some unburned area within, and that some site symbols overlap.

METHODS

Study area

The Alaskan boreal forest covers ~17 million ha and stores about 4.7×10^8 Mg C, or 27.6 Mg C/ha (Yarie and Billings 2002). Our study sites in interior Alaska were located in three large fire complexes that burned in 2004 along the Dalton, Steese, and Taylor Highways (Fig. 1). The ~250 000-km^2 study area encompassing these sites is bounded by the Brooks Range to the North (~67° N), the Alaska Range to the South (~63° N), the Alaska–Canada border to the East (~142° W), and the Dalton Highway to the West (~150° W). The area includes small mountain ranges, flat to sloping uplands, and broad lowland floodplains adjacent to braided rivers (Hollingsworth et al. 2006). Temperatures across this region are highly continental and range from −70°C to 35°C with mean annual precipitation at ~285 mm, including ~35% of that from snow (Hinzman et al. 2005). The dominant vegetation type in the study area is open- to closed-canopy black spruce (*Picea mariana*), occurring in mostly even-aged stands (Hollingsworth et al. 2006). Black spruce forest includes three distinct community types: acidic black spruce/lichen forest, nonacidic black spruce/rose/horsetail forest, and tree-line black spruce woodland (Hollingsworth et al. 2006). In addition, white spruce (*Picea glauca*) and deciduous species such as aspen (*Populus tremuloides*) and birch (*Betula neoalaskan*) are also locally abundant. Soils of interior Alaska are undeveloped and primarily (~90%) consist of Inceptisols, Gelisols, Histosols, and Entisols (Ahrens et al. 2004), and our sites are underlain by permafrost or seasonal ice. Black spruce trees are generally rooted in thick (5 to >50 cm) layers of organic material overlying the mineral soil (Johnson 1992). These surface organic horizons are largely derived from live and dead mosses or lichens and inputs from vascular plant litter and root turnover (Miyanishi and Johnson 2002). Using the Canadian system of soil classification, these organic soil horizons can be categorized as litter (recently deposited and largely unaltered plant remains, including moss), fibric (slightly decomposed, but still identifiable plant material), and humic (more decomposed and not identifiable), with mineral soil below (Canada Soil Survey Committee 1978).

For this study, we selected 38 sites in burned black spruce forest from a larger pool of 90 road-accessible burned sites distributed across the study region (Johnstone et al. 2009). The 38 sites were not a random selection of all burned areas, but instead were roughly equally distributed across the full range of fire severity (low to high) and drainage class (poor to good) as determined by the larger pool of 90 sites. For 13 of these sites, we also had prefire soil and vegetation data (Hollingsworth et al. 2006). Six sites were located in burned tree-line black spruce woodland communities, and the remaining in burned acidic and nonacidic black spruce forests. We also selected 28 additional sites from nearby, unburned areas that had previously been sampled by Hollingsworth et al. (2006). The unburned stands were selected to cover a similar range of black spruce stand types with respect to tree density and drainage class.

Experimental design

The study sites were established in June 2005, one year after fire. Each site was represented by a 30 × 30 m square plot, within which soil and stand measurements were made along a 2 × 30 m belt transect located near the center of each plot. Soil measurements in the plots included postfire organic soil depth, and C and N pools in the organic layer and near-surface mineral soil. Boreal fires leave behind unburned or lightly charred tree stems that can usually be easily identified to species (Johnson 1992). We used these stems to estimate prefire tree density, basal area (BA), and tree canopy consumption. As part of a broader study, postfire vascular plant species cover and composition, and tree seedling recruitment were also measured in these plots. Identical belt transects were established in adjacent unburned forest stands in the summer of 2006 in order to obtain the empirical relationships between ecosystem structure and element pools necessary in order to reconstruct prefire soil C and N pools. These sites are referred to as "burned" and "unburned," respectively.

Soil measurements

Across all burned sites, combustion ranged from low, wherein a large proportion of the fibric or upper litter layer had not burned, to high, where the fibric layer was completely combusted and the humic layer was partially or fully combusted (Rowe 1983). To quantitatively reconstruct C emissions, we used a series of linked measurements that included: (1) an estimate of the organic matter remaining after the fire, (2) an estimate of the organic matter present before the fire, and (3) a test of whether organic matter measurements made near or away from tree bases were different, because our organic matter reconstruction using adventitious roots could only be made at tree bases. These measurements were made at both burned and unburned stands to test the methods, and are described in more detail in the subsequent paragraphs (Supplement).

Within each burned site, the depth of remaining soil organic layers (SOL) was measured at 11 randomly selected points on the transect in order to characterize site average postfire SOL. At each sampling point, we used a serrated knife to view the horizons, and measured the depth of each of the following horizons: brown moss (BM, undecomposed or slightly decomposed brown moss of any taxa, equivalent to the litter layer), fibric (F, moderately decomposed organic matter with more roots than moss), and humic (H, highly humified or decomposed organic matter including the interface between the humic horizon and the A horizon) down to the mineral soil horizon.

In addition to our randomly located sampling points, we also measured SOL depth near the base of trees. Tree sampling points were chosen at the tree nearest to each random sampling point and SOL depth was sampled as close to the bole as possible while avoiding large roots. At tree sampling points, we measured the height from the top of the remaining SOL to the middle of the highest adventitious root on the bole of the tree, henceforth referred to as the adventitious root height (ARH). Because prefire SOL depth could only be reconstructed at tree sampling points with the ARH method, we compared SOL depths at tree bases and at random sampling points in both burned and unburned sites to determine if sampling only at trees would bias our measurements of soil combustion. To test if our reconstructed prefire SOL depths were accurate, we compared our values to actual prefire SOL measurements at 13 sites where we had both prefire and postfire data (Hollingsworth et al. 2008).

To convert plot-scale SOL depth measurements to mass, we sampled soils at four points that were representative of the range of within-site variation in fire severity. Organic soil horizons were sampled volumetrically with a serrated knife and separated into horizons. Mineral soil was sampled via volumetric coring at 0–5 cm and 5–10 cm depths. Soil samples were stored in coolers with ice packs in the field and frozen prior to laboratory analyses.

To test the ARH method of estimating the prefire soil pools, we also measured these same soil characteristics in the 28 unburned sites using an identical plot and transect design. The SOL was divided into similar horizons as the burn plots but we added a fourth horizon, green moss (GM). We volumetrically sampled soils with a serrated knife and a soil corer and measured horizons at eight points (four tree bases and four randomly located points), and measured the height of adventitious roots in relation to the green moss surface.

Stand measurements

In burned sites, we measured the diameter of trees at breast height (dbh; 1.4 m) for all trees ≥1.4 m tall and the basal diameter of trees <1.4 m tall that were originally rooted within six 2 × 5 m subplots along the 30-m transects. Fallen trees killed by the fire were included in this census if they had been rooted in the subplot before they fell. We used stem diameter and allometric equations to calculate tree density (number per hectare), basal area (square meter per hectare), and aboveground biomass (grams dry mass per hectare) of branches, leaves, and cones. For each stem, we visually estimated percentage fire consumption using five classes (0, 25%, 50%, 75%, or 100%) for four separate components of the remaining tree canopy: cones, needles, fine branches, and coarse branches, basing this on previous direct observation of similar sized unburned trees. To calculate prefire biomass of canopy components (excluding the tree bole), we grouped trees into three diameter and height classes and applied different allometric equations that predicted standing dry biomass from dbh of individual trees. Classes consisted of (1) dbh > 2.7 cm and height > 1.4 m, (2) dbh < 2.7 cm and height > 1.4 m, and (3) height < 1.4 m, using basal diameter (Mack et al. 2008; Appendix).

We multiplied visual estimates of percent canopy consumption by the calculated prefire tree biomass to estimate canopy biomass fire consumption (grams dry mass) for each tree. Then, we calculated canopy C and N pools and subsequent emissions for each canopy component using 50% C concentration for estimating C mass and 0.4% N for cones, fine branches, and coarse branches and 1% N for needles (Gower et al. 2000). The same stand inventory measurements were made in the unburned stands without the estimate of combustion.

To compare these quantitative combustion estimates to a standard fire severity metric, we measured the composite burn index (CBI) one year postfire (summer 2005) as a rapid assessment tool for fire severity estimates (Key and Benson 2005). The CBI was designed to capture the variability of fire effects within five vertical strata defined as: (1) substrate (litter and surface soil organic layers), (2) herbaceous plants and small trees and shrubs (<1 m), (3) tall shrubs and small trees (1–5 m), (4) intermediate size trees or subcanopy trees, and (5) upper canopy or dominant trees. Each of these strata is divided into four or five subcategories, which are each visually assessed for percent consumption and then averaged to determine the overall strata score. Each subcategory is given a score between 0 and 3; a CBI score of ~0–1 is considered low severity, ~1–2 is moderate severity, and ~2–3 is high severity. These five vertical strata are then grouped into the integrated understory score (average of strata 1, 2, and 3), and the integrated overstory score (average of strata 4 and 5), as well as the total CBI score that averages the scores of all five strata. If a site did not contain particular strata, such as sites without upper canopy trees, then those strata would not be included in the understory, overstory, or total score. By combining these individual assessments of smaller components, CBI provides an index to estimate the magnitude of fire effects and thus amount of consumption within a stand.

Laboratory analysis

Approximately 370 cores comprising ~1500 individual soil samples were collected in total from the 38 burned and 28 unburned sites. We calculated the volume of each soil layer from surface area and depth measurements and processed soils in the laboratory to obtain oven dry soil mass, bulk density (ρ_b), and C and N content. Soils were homogenized, coarse organic materials (e.g., >5 cm sticks and coarse roots) or rocks were removed from the sample, and the mass and volume of this coarse material was subtracted from total wet sample mass and volume. Subsamples were initially weighed wet and then dried at 105°C for 24–48 hours to determine dry matter content. Soil subsamples were also dried at 65°C and ground using a Wiley mill with a 40-mm sieve; C and N content was then determined using a Costech Elemental Analyzer (Costech Analytical, Los Angeles, California, USA).

Soil calculations

To quantify pre- and postfire C and N pools, we used values from our burned and unburned sites to account for changes in horizon element composition that may have occurred during the fire. First, we calculated mean site values for each soil horizon using ρ_b and percentage C and N from soil cores sampled within each burned (n = 4) and unburned (n = 8) site. The burned site soil values were then used with the postfire horizon depths measured separately at the randomly located sampling points (n = 11) to calculate postfire soil organic carbon (SOC) and soil organic nitrogen (SON) pools for each site.

For reconstructing prefire soil C and N pools in the burned sites, we needed to account for soil layers that were either partially or fully consumed by fire. First we reconstructed the total depth of the prefire soils using the ARH measurements and then estimated the depths of individual soil horizons using data from the unburned soils (described in *Results*). To estimate prefire element pools in the burned stands, we also used values from unburned soil horizons for all horizons that were completely or partially consumed by fire, because element values for partially consumed horizons in the burned stands may have included some material from horizons above. Finally, we subtracted the direct postfire soil measurements from the reconstructed prefire soil measurements to estimate total (kilograms per square meter) and proportional (percentage) SOC and SON loss.

Statistical analysis

For data analysis, we used the mean of the 11 subsampled points to create a mean value ± SE for each site. Thus for the burned sites, we had n = 38 sites and for the unburned sites, we had n = 28 sites. Data were normally distributed and homoskedastic and we used standard parametric methods for our analyses, or they were transformed when necessary. We performed paired

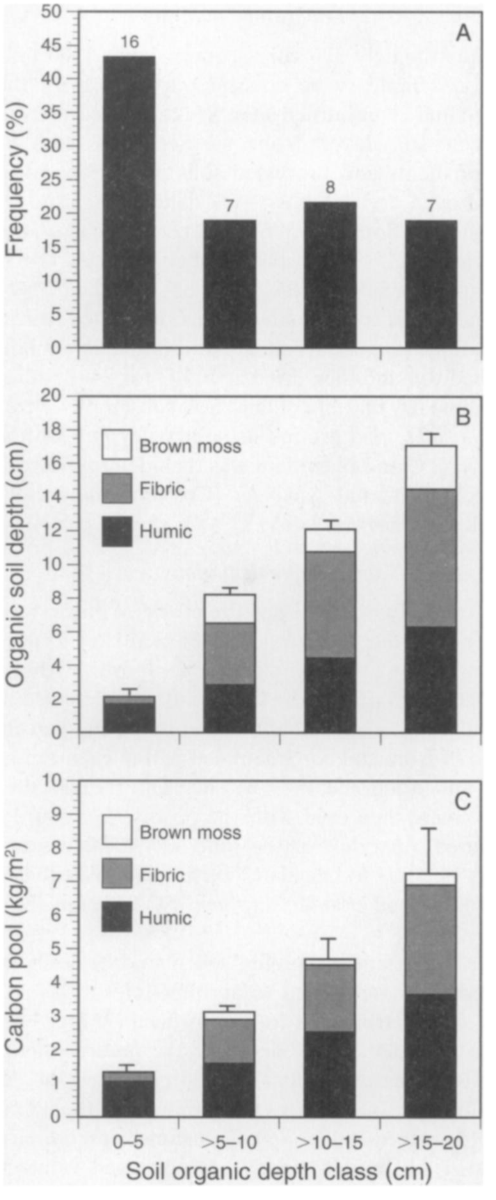

FIG. 2. Soil characteristics of 38 burned black spruce (*Picea mariana*) sites grouped by the depth of the soil organic layer that remained following fire: (A) the actual number of study sites in each soil depth class, (B) the thickness (depth) of the horizons in the remaining soil organic layer, and (C) the C pools contained in the remaining soil organic layer, by horizon type. Error bars show +SE for the total pool.

t tests to compare randomly selected points vs. tree base sampling points across sites. Additionally, we used correlation analysis and linear regression to explore relationships between different ecosystem attributes.

RESULTS

Black spruce stand characteristics

Postfire SOL depth, tree basal area and density, as well as postfire soil C and N pools, varied considerably across the 38 burned sites. Postfire SOL depth ranged from 0 to 21 cm with 16 sites having 5 cm or less of soil organic matter remaining, 15 sites having 7–15 cm, and 7 sites having 15–20 cm organic matter remaining (Fig. 2A). Across all sites, soil organic layers that remained after fire ranged from a shallow ash–humic layer to nearly the full soil profile with all three layers (Fig. 2B). Postfire soil C pools followed similar trends and ranged from 0.43 kg C/m^2 to as much as 14 kg C/m^2, with an average of 3.46 $\pm$ 0.46 kg C/m^2 (mean $\pm$ SE) across all sites (Fig. 2C). Postfire SON pools averaged 0.126 $\pm$ 0.016 kg N/m^2 with the pattern mirroring SOC pools because of the tight coupling between soil C and N.

Mean tree densities in our burned sites ranged from 2000 trees/ha to >8000 trees/ha, with a mean density of 6210 $\pm$ 751 trees/ha (Fig. 3A). Basal area ranged from 0.05 to 28.00 m^2/ha, with mean basal area of 9.4 $\pm$ 1.2 m^2/ha. The majority of our study sites had relatively low basal area reflecting small trees and/or sparse stands, both which are typical for black spruce forests (Fig. 3B). Stand age determined by ring counts of five trees per stand ranged from 30 to 176 years across all sites with a mean age of 91.3 $\pm$ 4.7 years (Johnstone et al. 2010). Age was not related to basal area or stand density (data not shown).

Reconstructing prefire soil organic layers

Because adventitious root development is stimulated by moss and humus cover (Lebarron 1945, Krause and Morin 2005), we explored the applicability of using the adventitious root remains (hereafter called "scars") on burned trees to estimate prefire organic soil depth. Kasischke and Johnstone (2005) hypothesized that ARH in burned stands indicated the minimum height of the prefire soil surface, or more specifically, the top of the green moss layer. To test this hypothesis, we measured ARH in our 28 unburned sites to determine if there was any systematic offset between the ARH and the top of the green moss; this difference is hereafter referred to as the adventitious-root-height offset (ARH_o). The ARH_o was normally distributed around a mean value of 3.2 $\pm$ 0.43 cm below the surface. Site mean ARH_o was not related to moss type, soil pH, soil moisture, total SOL depth, or basal area (data not shown). ARH_o was, however, positively related to tree dbh ($ARH_o = -5.07 + 0.31 \times \text{dbh}$, $R^2 = 0.23$, $F_{1,26} = 7.59$, $P = 0.01$). Because this predictor explained only a small proportion of the total variation in the ARH_o, we added a mean offset of 3.2 cm to correct our calculations of prefire SOL depth in order to keep this method as simple as possible.

Next, we determined whether measuring postfire SOL depth only at tree bases might bias our estimates of remaining soil organic material for the site, which could occur if either soil organic matter accumulation or combustion was different under trees. Across all burned sites, average organic soil depth was 8.2 $\pm$ 1.0 cm at randomly located sampling points and was comprised of

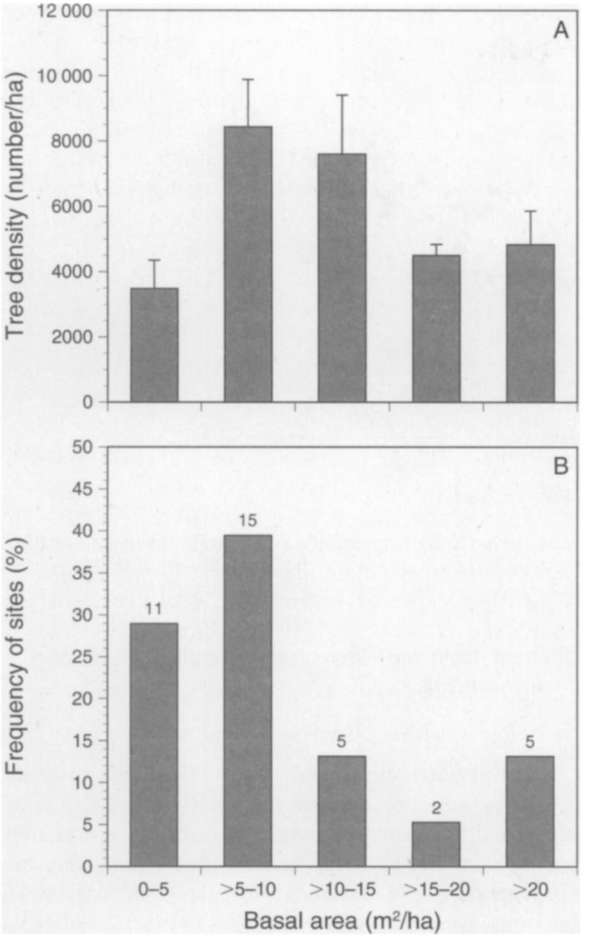

FIG. 3. Stand characteristics of 38 burned black spruce sites grouped by basal area class: (A) tree density (mean + SE) and (B) the frequency of study sites in each basal area class. The actual number of sites is shown above each bar in panel (B).

three horizons with the following mean depths: 1.1 ± 0.3 cm (BM), 3.7 ± 0.5 cm (F), and 3.3 ± 0.4 cm (H) (Table 1). Across all sites, mean SOL depths at tree bases and randomly located organic soil depths were highly correlated ($R^2 = 0.91$, $P < 0.001$). But, total postfire SOL depth in the burned plots was significantly shallower at tree bases by 6.4% compared to the random points (paired $t_{1,37} = 2.40$, $P = 0.02$). The difference in postfire SOL depth was primarily due to a thinner BM horizon near trees (paired $t_{1,37} = 3.30$, $P = 0.02$), which offset a somewhat thicker H horizon (paired $t_{1,37} = -2.20$, $P = 0.03$).

This pattern of shallower residual SOL depths under trees vs. randomly located points in burned plots (hereafter called tree bias) may have been due to: (1) greater organic consumption under trees (Miyanishi and Johnson 2002, Greene et al. 2007), and (2) less prefire organic matter accumulation under trees, or a combination of both factors. As a test of (2), we found that in unburned forest, total SOL depth under trees was not significantly different from SOL depth at randomly located points (paired $t_{1,27} = 0.37$, $P = 0.71$). This then suggests that (1), greater combustion under trees, is the cause of shallower residual SOL depths under trees in the burned sites. Across the unburned sites, mean total SOL depth at random points was 25.3 ± 1.3 cm (Table 1). Layer depth, bulk density, soil moisture, and C and N concentrations were not different at tree bases as compared to random points for all organic soil horizons but did differ among horizons. While GM and BM horizons accounted for 24% of the total SOL depth in the unburned forest, they only accounted for 10.4% of total mass of soil organic matter, 11.9% of the total SOC pool, and 8.8% of the total SON pool because of the lower bulk density in those upper horizons.

In order to account for increased combustion at tree bases in our reconstruction of prefire and postfire SOL, we calculated a correction factor for each horizon in order to extrapolate measurements at tree bases to the whole stand. Corrections were empirically determined from measurements in the unburned stands near and away from trees ($BM_{corr} = 1.10 \times BM_{tree} + 0.67$, $R^2 = 0.91$, $P < 0.001$; $F_{corr} = 0.91 \times F_{tree} + 0.73$, $R^2 = 0.91$, $P < 0.001$; $H_{corr} = 0.71 \times H_{tree} + 0.62$, $R^2 = 0.91$, $P < 0.001$). The sum of these corrected horizon values yielded the total unbiased postfire SOL depth (referred to as $SOL_{c,post\text{-}F}$). We used these depth corrections along with our prefire depth estimates to calculate organic soil consumption for each site.

TABLE 1. Organic soil characteristics by horizon for 38 black spruce (*Picea mariana*) forest sites that burned in 2004 and for 28 unburned black spruce sites, in interior Alaska, USA.

Horizon	Horizon thickness (cm)	Bulk density (g/cm^3)	Carbon concentration (%)	Nitrogen concentration (%)
Burned				
Brown moss (BM)	1.12 ± 0.3	0.04 ± 0.004	40.2 ± 1.4	0.97 ± 0.1
Fibric (F)	3.69 ± 0.5	0.10 ± 0.01	41.4 ± 0.8	1.28 ± 0.04
Humic (H)	3.30 ± 0.4	0.21 ± 0.01	30.0 ± 1.0	1.25 ± 0.04
Unburned				
Green moss (GM)	2.49 ± 0.14	0.03 ± 0.01	42.5 ± 0.54	1.07 ± 0.04
Brown moss (BM)	3.79 ± 0.69	0.03 ± 0.003	41.4 ± 0.61	1.03 ± 0.04
Fibric (F)	11.41 ± 0.79	0.05 ± 0.004	41.4 ± 0.74	1.16 ± 0.06
Humic (H)	7.56 ± 0.39	0.14 ± 0.01	32.9 ± 1.44	1.30 ± 0.07

Note: Values are mean ± SE.

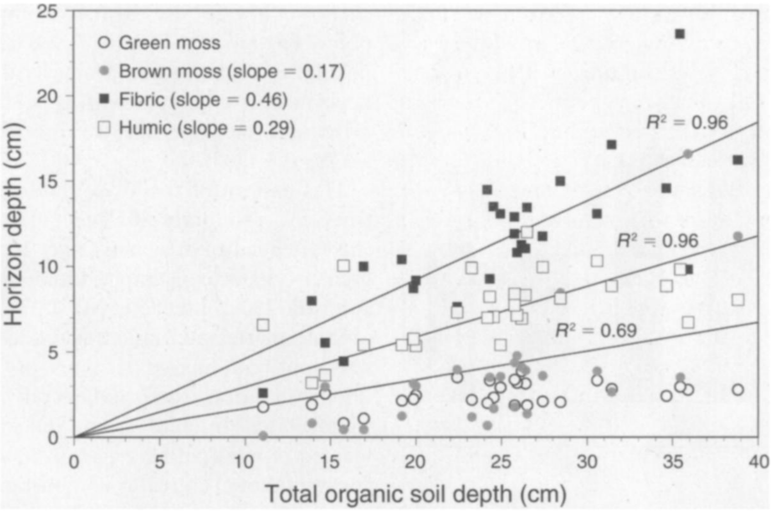

FIG. 4. Total depth of the soil organic layer compared to individual soil horizon thickness (green moss, GM; brown moss, BM; fibric, F; and humic, H) for 28 unburned black spruce sites. Linear relationships are shown for all horizons except for GM, where thickness of this horizon was not significantly related to overall soil organic layer depth. For all slopes, $P < 0.001$.

Organic soil fire severity

We combined our measurements from burned and unburned stands to calculate organic soil combustion as a percentage of total original SOL depth and then used those same depths with bulk density, %C, and %N to estimate SOL mass, and SOC and SON combustion. We first used the following equation to estimate prefire soil depth ($SOL_{pre\text{-}F}$) for our burned sites:

$$SOL_{pre\text{-}F} = SOL_{post\text{-}F} + ARH + ARH_o.$$

Next, because we calculated the $SOL_{pre\text{-}F}$ at tree bases and because combustion was higher under trees, we used our random/tree bias corrected residual SOL depth to estimate total SOL combustion:

$$\text{SOL combustion} = SOL_{pre\text{-}F} - SOL_{c,post\text{-}F}.$$

Note that the $SOL_{pre\text{-}F}$ does not need to be corrected for increased burning at tree bases because we use $SOL_{post\text{-}F}$ measurements from the tree base as well as ARH from the same point, and measurements in unburned stands show no bias in SOL depth under trees. Percentage SOL combustion across all sites was generally high with a mean value of 66.8% ± 3.7%, with loss ranging from 34% to 96% of the organic soil depth. In the original experimental design, our aim was to select burn sites along a continuum from low to high fire severity. While we achieved that aim as shown by the range of estimated combustion across sites, the mean value overall demonstrates that more sites had high combustion losses. Because the ARH method is based on accurately reconstructing prefire depth, we compared our prefire estimates with independent data collected prior to the wildfire (Hollingsworth et al. 2006) for 13 of our burned sites where we had data. Our reconstructed SOL depth of 26.6 ± 1.66 cm for these sites was not significantly different from measured prefire depths (paired $t_{1,12} = 1.65$, $P = 0.13$).

Reconstructing depth of organic soil horizons

After reconstructing total prefire SOL depth with the ARH method, we divided the total SOL depth into individual horizons to quantify C and N pools because each layer differed in bulk density and element concentration. To estimate the depth of individual horizons, we examined correlations between total SOL depth and each individual horizon from the 28 unburned sites and found that green moss (GM) was a constant depth for all points, while brown moss (BM), fibric (F), and humic (H) horizons were generally constant proportions (Fig. 4). This model is not necessarily the best fit line, but instead has a biological mechanism with the depth of green moss a function of light attenuation in the soil, with the remaining horizons varying as a constant proportion of overall organic matter thickness. Green moss depth averaged 2.4 ± 0.14 cm and ranged between 0.82 and 3.9 cm. The BM, F, and H horizons were estimated as 18%, 50%, and 32%, respectively, of the remaining soil (total mean SOL depth minus the green moss average: 2.4 cm). Using other measured stand variables in multiple regression models did not improve the prediction of individual horizon thickness as compared to using the total SOL depth alone. Thus, these proportions and the GM constant value were then applied to the reconstructed prefire organic soil depth to estimate the depth of individual soil horizons that had been partially or wholly consumed in the burned stands.

Soil organic layer C and N pools and combustion

In the burned sites, soil core sampling points were taken randomly across the plots. In contrast, the eight unburned soil sample cores were stratified at tree bases and randomly located points away from trees (four each). Because there were no significant differences between ρ_b, and C and N concentrations between these two groups, these soil data were pooled within each unburned site (Table 1). In terms of other measured soil parameters, the F horizon alone had significantly different gravimetric moisture content (paired $t_{1,27} = -2.24$, $P = 0.03$; random mean = 251.1% ± 41.1% and tree mean = 213.4% ± 32.7% moisture) close to and away from trees, which could relate to the increased burn depth observed at tree bases.

Our estimates of postfire SOC pools ranged from 0.33 kg/m^2 to 10.63 kg/m^2 with a mean of 2.99 ± 0.40 kg/m^2, while SON pools ranged from 0.01 kg/m^2 to 0.30 kg/m^2 with a mean of 0.11 ± 0.02 kg/m^2. Reconstructed postfire element pools using unburned stand element values were 17.0% ± 3.9% (SOC) and 19.3% ± 3.8% (SON) less than direct pool measurements in burned stands (SOC paired $t_{1,37} = 3.31$, $P = 0.002$ and SON paired $t_{1,37} = 3.45$, $P = 0.001$), suggesting that there was some accumulation of C and N in the remaining SOL that came from combusted soil horizons and biomass above. Comparing prefire SOL pools to what remained after fire, we calculated that the proportion of SOC and SON lost ranged from as low as 0% to as high as 94%, with mean losses of 52.9% ± 4.8% and 49.8% ± 5.04%, respectively, across the 38 sites (Fig. 5A). Overall, SOC emissions were 41.6 ± 5.6 times greater than SON emissions (Fig. 5B).

Tree biomass, C and N pools, and combustion

We used allometric biomass equations to calculate prefire canopy biomass (not including boles) and combined these with visual combustion estimates to calculate canopy biomass consumed by fire. Mean prefire total canopy biomass throughout all burned sites was 8686 ± 1080 kg/ha. Of this amount, canopy biomass losses were 6618 ± 960 kg/ha, with a mean proportional consumption across all sites of 64% ± 4%. We did not include the tree bole in our measurements because it was almost always charred or black from ash or soot, regardless of the severity of the fire, and therefore difficult to visually estimate consumption. This likely results in an underestimate of canopy consumption, but tree boles remain largely unburned even in severe fires so this underestimate should be relatively small (Gutsell and Johnson 1996).

Prefire C and N biomass of the tree canopy (excluding bole) averaged 0.43 ± 0.05 kg/m^2 and 0.0054 ± 0.001 kg/m^2, about an order of magnitude less than that contained in the organic soil. These estimates assume a general canopy C concentration of 50% and N concentrations of 1% for needles and 0.4% for cones, fine, and coarse branches (see *Methods*). In our burned stands, C and N losses from combustion were 0.37 ± 0.05 kg/m^2 and 0.005 ± 0.0006 kg/m^2, respectively, and are equivalent to mean losses of 80.2% ± 2.5% of canopy C and 80.6% ± 2.7% of canopy N (Fig. 5A, B).

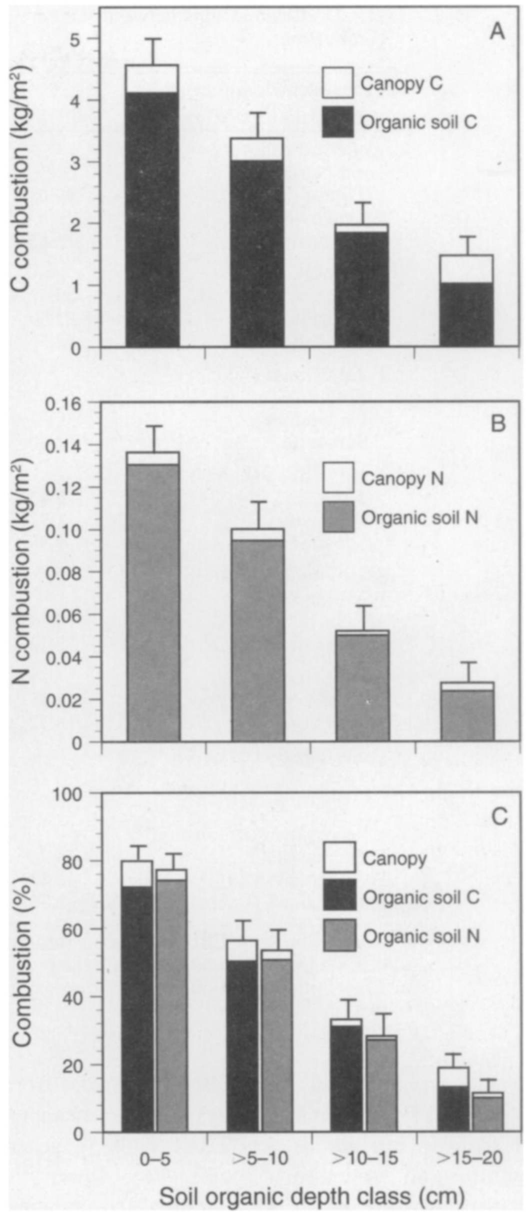

Fig. 5. (A) Carbon emission, (B) nitrogen emission, and (C) percentage of the total C and N pools lost during fire from 38 burned black spruce sites, grouped by the depth of the soil organic layer that remained following fire. The canopy estimate does not include tree boles, which typically burn very little. Error bars show +SE for the total combustion estimate.

CBI and combustion losses

We compared our organic soil and canopy combustion estimates with CBI scores from each site in order to relate our intensive quantitative estimate to a severity metric that can be assessed more rapidly. We evaluated the following CBI scores in relation to our measurements: total (a total site value), overstory (upper plus mid-canopy trees and tall shrubs), understory (substrate, herbaceous plants, and small shrubs), and substrate (soil

TABLE 2. Relationships between the composite burn index (CBI) and quantitative measures of combustion.

Y, ecosystem components, and X (CBI score)	Slope	Intercept	R^2	P	n
Organic soil combustion					
Total depth (%)					
Total	39.01	−21.05	0.50	<0.0001	36
Understory	29.63	3.03	0.50	<0.0001	36
Substrate	15.85	37.79	0.38	<0.0001	36
Total mass (%)					
Total	43.93	−36.97	0.58	<0.0001	36
Understory	33.50	−10.15	0.59	<0.0001	36
Substrate	17.30	30.37	0.42	<0.0001	36
Total C mass (%)					
Total	51.42	−63.49	0.50	<0.0001	36
Understory	39.97	−33.77	0.52	<0.0001	36
Substrate	17.30	30.37	0.42	<0.0001	36
Total C mass (kg/m^2)					
Total	2.47	−2.72	0.39	<0.0001	36
Understory	1.87	−1.19	0.39	<0.0001	36
Substrate	0.98	1.06	0.28	<0.0001	36
Tree canopy combustion					
Total mass (%)					
Total	14.15	48.63	0.15	0.02	36
Overstory	28.72	8.38	0.44	<0.0001	33
Total C mass (%)					
Total	14.15	48.63	0.15	0.02	36
Overstory	28.72	8.38	0.44	<0.0001	33
Total C mass (kg/m^2)					
Total	0.28	−0.25	0.14	0.02	36
Overstory	0.45	−0.74	0.27	0.002	33
Total ecosystem combustion					
Total mass (%)	43.20	−35.23	0.61	<0.0001	35
Total C mass (%)	49.83	−59.10	0.52	<0.0001	35
Total C mass (kg/m^2)	2.80	−3.14	0.41	<0.0001	35

Notes: The total CBI score comprises individual understory, soil substrate, and overstory CBI scores. Regression equations relate the predictive value of these unitless CBI scores to quantitative measures of combustion of different ecosystem components for Alaskan black spruce forests that burned in 2004.

organic layers and litter). The CBI range varies from 0 (low severity) to 3 (high severity) and the mean total CBI score in our stands was 2.3 ± 0.07. In general, substrate and understory scores were lower than overstory scores; mean CBI scores for substrate, understory, and overstory were 1.9 ± 0.14, 2.2 ± 0.09, and 2.5 ± 0.06, respectively.

Total CBI scores were positively related to proportional and absolute metrics of ecosystem mass loss and C emissions, and explained 41–61% of the variation in combustion overall (Table 2, Fig. 6). Overall, CBI scores were better for predicting the relative mass loss (percentage) across all ecosystem components as compared to predicting absolute C emissions (kilograms per square meter) due to variation in biomass and SOL among stands (Table 2). However, CBI was better for estimating SOL or forest floor C emissions than canopy C emissions. Total, understory, and substrate CBI scores were significantly related to all SOL combustion measurements and between 28% and 59% of the variation were explained. Surprisingly the total CBI score was the best predictor for soil combustion overall, even better than the understory or substrate CBI scores alone. The overstory CBI score was positively related to percent of canopy biomass and C combusted and explained 44% of the variation of this proportional metric, but only 27% of the variation in the absolute amount of C emitted. Total CBI score only explained ~15% of the variation in tree canopy combustion (Table 2). Because CBI is a visual estimate of consumption that does not really account for initial stand biomass and forest floor, it is reasonable that overall CBI was a better predictor of proportional combustion than actual mass combusted.

DISCUSSION

The most commonly used methods for estimating fire severity in forests rely on quantification of postfire conditions (Robichaud 2000, Keeley et al. 2005). Postfire assessment may adequately index the amount of aboveground biomass consumed because of the predictive relationship between remaining boles and prefire biomass in many forest types. In boreal forests,

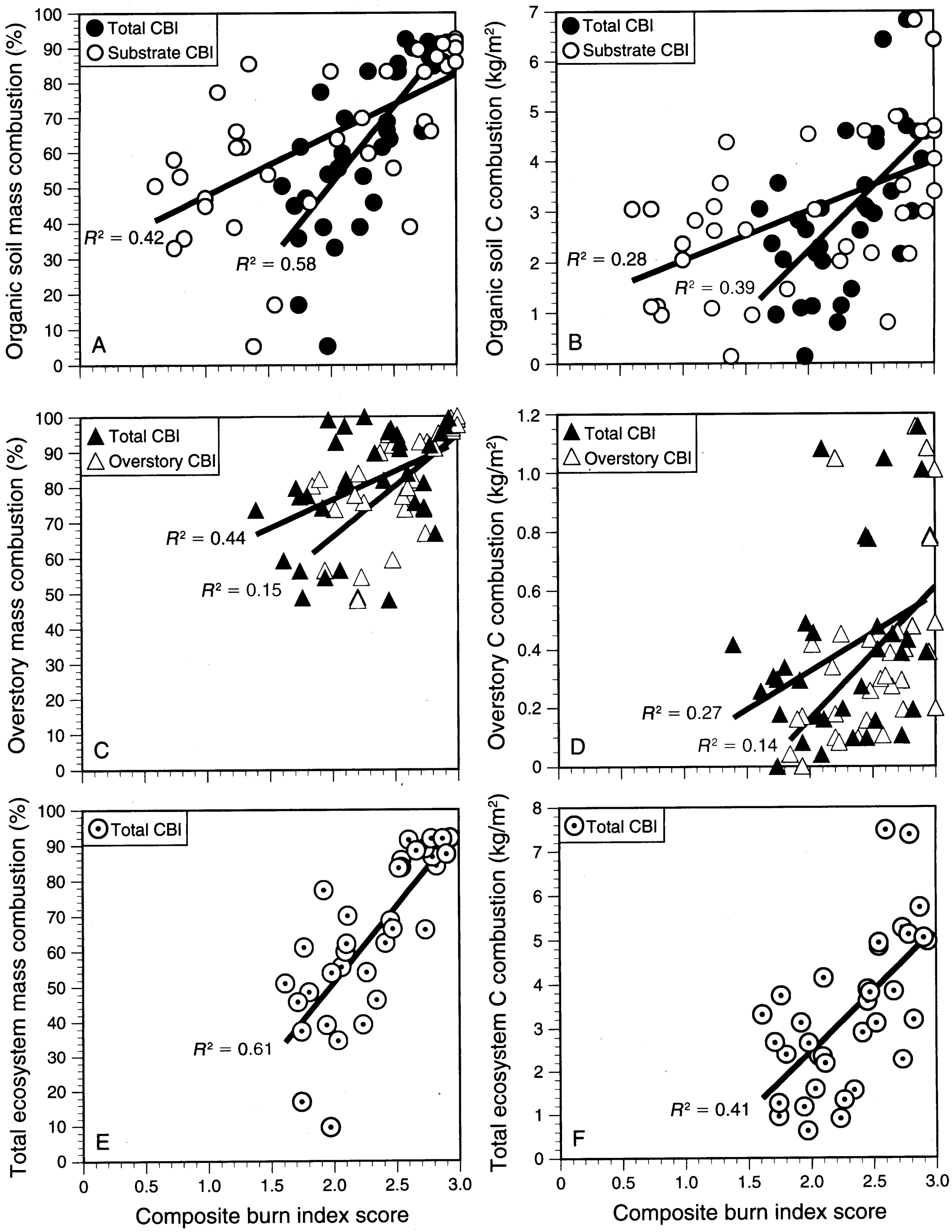

FIG. 6. Relationships between the composite burn index (CBI) and different quantitative measures of combustion for (A, B) soil, (C, D) overstory canopy, and (E, F) total ecosystem. All regressions are significant at $P < 0.01$ (see Table 2 for parameters).

however, >50% of ecosystem organic matter stocks are stored belowground (Dixon et al. 1994). Postfire assessment of residual organic soil depth alone is unlikely to be adequate for estimating combustion of organic soil due to the large amount of variation in prefire organic soil accumulation across the boreal landscape.

Our study provides evidence that the height of adventitious roots scars on burned black spruce trees can be used as a proxy for prefire organic soil height in boreal forests, allowing both the determination of prefire soil organic layer depth and the depth consumed by fire. In Table 3, we summarize how pre- and postfire depths can be used with measurements of bulk density and element concentration to reconstruct prefire pools and fire-driven consumption of organic matter. This method can be used to generate a metric of burn severity in terms of the mass of organic matter, C, or N consumed per

TABLE 3. Steps for application of the adventitious root method to estimate wildfire consumption of organic matter and emissions of C and N in interior Alaska or in other regions.

		Task	
Step	Measurement	Application to interior Alaska	Application to other regions
1	Adventitious root height (cm)	Measure from highest AR to burned soil surface. Add 3.2 cm to correct for moss surface offset.	Calibrate regional surface offset.
2	Postfire total SOL depth (cm)	Measure from burned surface to mineral soil surface. Note soil layer exposed (green moss, brown moss, fibric, or humic). Correct for tree bias by multiplying by 1.06.	Measure depth of individual soil horizons and correct tree bias by horizon with regional calibration.
3	Prefire total SOL depth (cm)	Sum depths in steps 1 and 2.	
4	Prefire SOL depth by horizon (cm)	Starting with the total prefire soil depth, subtract 2.4 cm for green moss. Then multiply the remainder by the following constant proportions: brown moss = 0.18, fibric = 0.50, and humic = 0.32 to get thickness of individual horizons.	
5	Prefire OM, C, and N pools (g/m^2)	Multiply horizon depths from step 4 by bulk density, [C], and [N] in Table 1 and sum horizons.	Calibrate regional bulk density, [C], and [N] values.
6	Postfire SOL depth by horizon (cm)	If the depth in step 2 is greater than the depth increment of the deepest horizon in 4, then that horizon is intact and its postfire depth is equal to its depth in step 4. Move up soil profile, comparing each horizon, until an incomplete horizon is reached; this is the depth of burning. Check the horizon identity against field notes to confirm.	
7	Postfire OM, C, and N pools (kg/m^2)	Multiply horizon depths from step 6 by bulk density, [C], and [N] in Table 1 and sum horizons.	Measure bulk density, [C], and [N] values at profiles in step 2, or calibrate regional values.
8	Combustion loss of OM, C, and N (kg/m^2)	Subtract pool sizes in step 7 from step 5 for each pool.	

Note: Key to abbreviations: ARH, adventitious root height; SOL, soil organic layer; OM, organic matter.

unit area. It also enables assessment of within- and among-stand heterogeneity in fire severity, a key driver of ecological processes in the boreal forest. The metric provides a quantitative baseline for assessing the efficiency of widely used semiquantitative methods, such as the CBI that we explored in our study. Finally, the units of this metric are globally comparable and should facilitate direct comparison of burn severity and emissions between boreal forests and the structurally diverse ecosystems around the world that are impacted by fire.

While the ARH method has previously been used to estimate the depth of burning (Kasischke and Johnstone 2005, Kasischke et al. 2008), key assumptions of the method were based on relatively few data (Kasischke et al. 2008). We verified these assumptions by making extensive measurements in burned and unburned black spruce stands in interior Alaska. Across 28 independent unburned stands, we found that the average height of the highest adventitious roots on the stem corresponded to the surface of the moss layer; roots were, on average, 3.2 ± 0.43 cm below the surface of the green moss. This pattern was consistent across a range of understory moss communities, including feather mosses, *Sphagnum* spp., and other moss species (Hollingsworth et al. 2008). The diverse array of woody plant species where adventitious root formation has been observed (Paolillo and Zobel 2002) makes it likely that the relationship between adventitious roots and soil organic matter could be used to determine prefire organic layer depth in other systems, following the general process outlined in Table 3.

In our burned stands, measurements at tree bases alone underestimated the site mean depth of postfire organic soil by 6.4%. In unburned stands, by contrast, we found that soil organic layer thickness was not different between the bases of trees and randomly sampled points, and did not vary systematically with distance to tree bases. Taken together, these observations suggest that organic soils burned more severely at the bases of trees than on average across the stand. Although this bias was relatively small across our stands, the pattern has been observed in many other coniferous forest types (Miyanishi and Johnson 2002, Greene et al. 2007, Rein et al. 2008) and should be considered prior to the application of this method in other systems. Deeper burning under tree canopies has been ascribed to drier fuel beneath tree canopies due to interception of precipitation (Miyanishi and Johnson 2002) or to a reduced latent heat sink during propagation of the combustion front associated with tree roots and stems (Greene et al. 2007).

While we found no significant difference between soil organic matter pools calculated with this reconstruction method and prefire measurements reported by Hollingsworth et al. (2008) for the same sites, this method may be ineffective for estimating pools in intense fires that leave trees uprooted, or in sites where trees were rooted within a layer of organic soil that was completely combusted, leaving no evidence of the rooting position of the prefire trees. In such situations, the ARH method can only provide a minimum estimate of prefire SOL depth. Despite the high intensity of the 2004 fire season, we encountered only two sites in our survey that fell into these categories, suggesting that the adventitious root method should be generally useful to provide unbiased estimates of SOL consumption in boreal Alaska and perhaps in boreal forests elsewhere.

C and N pools and emissions

Our estimates of carbon emission rates from the 2004 fires averaged 3.3 kg C/m^2 and ranged from 1.5 to 4.6 kg C/m^2. Mean emissions calculated with our method were similar to values reported for comparable boreal ecotypes in North America, including interior Alaska (2.5–3.0 kg C/m^2; Kasischke et al. 1995), Boreal and Taiga Cordillera ecozones (3.23 and 3.06 kg C/m^2, respectively; Amiro et al. 2001), and diverse boreal peatlands in Canada (3.2 kg C/m^2; Turetsky et al. 2002). Our mean emission value is substantially larger than other values reported from Canada, including a direct measurement of emissions from a bog (2.1 kg C/m^2; Benscoter and Wieder 2003), an estimate of average C emissions over multiple fire cycles (<1.0 kg C/m^2; Harden et al. 2000), and estimates of emissions from the taiga and boreal shield ecozones (1.9 to 2.5 kg C/m^2; Amiro et al. 2001).

Nitrogen emission rates for the 2004 fires averaged 0.09 kg N/m^2 and ranged from 0.03 to 0.14 kg N/m^2. There are few published values to compare to our estimate, but the magnitude alone indicates that fire is an important pathway of N loss from these ecosystems. Nitrogen deposition rates in boreal Alaska are low (0.00003 kg $N \cdot m^{-2} \cdot yr^{-1}$; Jones et al. 2005) and inputs from biological fixation are estimated to be slightly higher (Billington and Alexander 1983, DeLuca et al. 2002). If we assume linear inputs of an average of 0.0002 kg $N \cdot m^{-2} \cdot yr^{-1}$, then the 2004 fires emitted, on average, 450 years of N accumulation. Although this is clearly an oversimplification of nitrogen mass balance, the sheer magnitude of the loss makes it likely that fire plays a role in maintaining nitrogen limitation in these forests.

Assessing CBI for black spruce forests

Comparisons of visual estimates of fire severity with quantitative estimates of canopy and surface fuel consumption indicate that CBI is a viable method for assessing overall patterns of fire severity in black spruce forests in Alaska. The total CBI score, a composite score including visual estimation of above- and belowground consumption, showed the strongest correlations with SOL consumption expressed as percentage soil organic mass combusted (Table 3, Fig. 6). Interestingly, correlations of CBI with SOL combustion were stronger when using the total or understory (ground-layer mosses, dwarf shrubs, and herbs) CBI scores, and were comparatively weak when using substrate (i.e., organic soil layer) CBI scores. This suggests that observers may have a poor ability to visually estimate the categories of percentage substrate consumption used in CBI, perhaps because only the surface of the soil can be seen. Nevertheless, our quantitative estimates of surface fuel consumption were strongly correlated with total and understory CBI, suggesting that consideration of all strata in the CBI provides an improved ability to estimate consumption in poorly observed layers.

Canopy CBI scores significantly predicted percentage biomass consumption of canopy fine fuels, although these relationships were weaker than for organic soil consumption. Differences in predictive power are unlikely to be related to differences in the observed ranges of canopy vs. soil consumption, as the range of canopy fuel combustion (29–98%) was similar to that of organic soil consumption (34–96%). However, the percentage tree mortality of most of our sampled stands was very high (only two stands had <90% stem mortality). Canopy CBI scores are derived from estimates of percentage stem mortality, char height, and proportions of green, scorched, and charred canopy (Key and Benson 2005). Consequently, this visual index is likely to be relatively insensitive to variations in canopy fuel consumption once much of the tree canopy has been charred.

Rapid, repeatable, and quantitative methods of estimating severity and emissions are crucial for understanding the impacts of fire on the structure and function of the boreal landscape. Because of the large scale of our sampling effort, our calibration of the ARH method should be directly applicable to estimating burn severity and emissions in interior Alaska and possibly to other ecosystems where trees initiate adventitious roots into organic soils. Managers in Alaska could use their own field measurements of adventitious roots with our depth calibrations and estimates of bulk density and element concentration to calculate burn severity and emissions (Table 3). Alternatively, these data can also be used to calibrate CBI measurements to actual combustion, depending on the needs of the assessment.

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APPENDIX

Allometric equations for predicting canopy biomass from the diameter of interior Alaska *Picea mariana* trees in three size classes (*Ecological Archives* A020-060-A1).

SUPPLEMENT

Ecosystem characteristics of 38 *Picea mariana* stands in interior Alaska that burned in 2004 (*Ecological Archives* A020-060-S1).