QUANTIFYING FIRE SEVERITY AND CARBON AND NITROGEN POOLS AND EMISSIONS IN ALASKA’S BOREAL BLACK SPRUCE FOREST

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To Alaska,
Thanks for all the wonderful memories
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# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>ACKNOWLEDGMENTS</td>
<td>4</td>
</tr>
<tr>
<td>LIST OF TABLES</td>
<td>7</td>
</tr>
<tr>
<td>LIST OF FIGURES</td>
<td>8</td>
</tr>
<tr>
<td>ABSTRACT</td>
<td>9</td>
</tr>
<tr>
<td>1 INTRODUCTION</td>
<td>11</td>
</tr>
<tr>
<td>2 METHODS</td>
<td>16</td>
</tr>
<tr>
<td>Study Area</td>
<td>16</td>
</tr>
<tr>
<td>Experimental Design and Measurements</td>
<td>17</td>
</tr>
<tr>
<td>Patterns of Post-Fire Soil Organic Matter</td>
<td>17</td>
</tr>
<tr>
<td>Sampling Design: Randomly Located and Tree Base Points</td>
<td>18</td>
</tr>
<tr>
<td>Pre-fire Organic Soil Depth</td>
<td>18</td>
</tr>
<tr>
<td>C and N Sampling</td>
<td>18</td>
</tr>
<tr>
<td>Tree Biomass, Stand Structure and Combustion</td>
<td>19</td>
</tr>
<tr>
<td>Unburned Sites</td>
<td>19</td>
</tr>
<tr>
<td>Lab Analysis</td>
<td>20</td>
</tr>
<tr>
<td>Horizon Depths in Relation to Total Organic Soil Depth</td>
<td>21</td>
</tr>
<tr>
<td>Pre- and Post-Fire C and N Pools</td>
<td>21</td>
</tr>
<tr>
<td>CBI and Combustion</td>
<td>23</td>
</tr>
<tr>
<td>Statistical Analysis</td>
<td>24</td>
</tr>
<tr>
<td>3 RESULTS</td>
<td>26</td>
</tr>
<tr>
<td>Burned Black Spruce Stands</td>
<td>26</td>
</tr>
<tr>
<td>Reconstructing Pre-Fire Depth of the Soil Organic Layer</td>
<td>27</td>
</tr>
<tr>
<td>Intra-site Variation in Post-Fire Soil Organic Layer Characteristics</td>
<td>27</td>
</tr>
<tr>
<td>Fire Severity of Organic Soil</td>
<td>29</td>
</tr>
<tr>
<td>Reconstructing Depth of Organic Soil Horizons</td>
<td>30</td>
</tr>
<tr>
<td>Reconstructing Depth of Organic Soil Horizons</td>
<td>32</td>
</tr>
<tr>
<td>Soil Organic Layer C and N Pools and Combustion</td>
<td>33</td>
</tr>
<tr>
<td>Tree Biomass, C and N Pools and Combustion</td>
<td>34</td>
</tr>
<tr>
<td>CBI and Combustion Losses</td>
<td>34</td>
</tr>
<tr>
<td>4 DISCUSSION</td>
<td>47</td>
</tr>
<tr>
<td>Adventitious Root Height</td>
<td>47</td>
</tr>
<tr>
<td>C and N Pools</td>
<td>48</td>
</tr>
<tr>
<td>Canopy Fire Severity and Biomass</td>
<td>49</td>
</tr>
<tr>
<td>CBI</td>
<td>49</td>
</tr>
</tbody>
</table>
### LIST OF TABLES

<table>
<thead>
<tr>
<th>Table</th>
<th>page</th>
</tr>
</thead>
<tbody>
<tr>
<td>3-1</td>
<td></td>
</tr>
<tr>
<td>3-2</td>
<td></td>
</tr>
<tr>
<td>3-3</td>
<td></td>
</tr>
</tbody>
</table>
### LIST OF FIGURES

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>2-1</td>
<td>Map of interior Alaska, including a map of the areas burned by wildfire in 2004 and study sites.</td>
<td>25</td>
</tr>
<tr>
<td>3-1</td>
<td>Frequency, mean and horizon depths of post-fire organic soils at burned sites.</td>
<td>36</td>
</tr>
<tr>
<td>3-2</td>
<td>Mean soil organic nitrogen and carbon pools in post-fire soil organic layers by horizon and depth class.</td>
<td>37</td>
</tr>
<tr>
<td>3-3</td>
<td>Percent frequency of sites and tree density in basal area classes across 38 sites burned in 2004.</td>
<td>38</td>
</tr>
<tr>
<td>3-4</td>
<td>Frequency of 28 unburned sites among 9 adventitious root height depth offset classes.</td>
<td>39</td>
</tr>
<tr>
<td>3-5</td>
<td>Depth of soil organic horizons at randomly located points compared to depths at tree base points across 38 sites burned in 2004.</td>
<td>40</td>
</tr>
<tr>
<td>3-6</td>
<td>Difference between soil organic layer depths at randomly located sampling points and depth at tree base points compared to mean tree density/ha.</td>
<td>41</td>
</tr>
<tr>
<td>3-7</td>
<td>Total soil organic layer depth compared to soil horizon depth and horizon depth as percent of total depth.</td>
<td>42</td>
</tr>
<tr>
<td>3-8</td>
<td>Mean carbon (C) emissions and percent of total C combustion by post-fire soil organic layer depth classes.</td>
<td>43</td>
</tr>
<tr>
<td>3-9</td>
<td>Mean nitrogen (N) emissions and percent of total N combustion for four post-fire soil organic layer depth classes across 38 burned sites.</td>
<td>44</td>
</tr>
</tbody>
</table>
Fire severity can be defined as the amount of biomass combusted by wildfire. Stored carbon (C) and nitrogen (N) are emitted into the atmosphere as wildfires consume vegetation and soil organic layers, thus C and N emissions should be related to fire severity. Since boreal forests store 30% of the world’s terrestrial C and are subject to high-intensity, stand-replacing wildfires, it is critical to be able to estimate C fluxes from wildfires. Furthermore, quantifying fire severity is important for predicting post-fire vegetation recovery and future C sequestration. We reconstructed pre-fire organic soil layers and quantified fire severity levels from the 2004 wildfires in Interior Alaska with the adventitious root height (ARH) method. We tested the ARH method in unburned stands and by comparing our reconstructed values in burned stands with actual pre-fire measurements. We found that ARH correlated to organic soil height in unburned stands (with a small offset of 3 cm). We measured organic soil (using the ARH method) and stand characteristics in boreal black spruce forest and estimated the amount of soil and canopy biomass consumed by fire. We compared these results to the composite burn index (CBI), a standardized visual method, which has not been widely used in the boreal forest. CBI assessments were significantly related to our ground and canopy fire severity estimates. We calculated C and N
pools using C and N concentration and bulk density estimates from soils sampled in burned and unburned stands. We conclude that the ARH method can be used to reconstruct pre-fire organic soil depth, C and N pools and to assess fire severity. Furthermore, CBI shows promise as a way of estimating fire severity quickly and is a reasonably good predictor of biomass and soil C loss.
CHAPTER 1
INTRODUCTION

Wildfire is the major disturbance in Alaska’s boreal forest and consequently is one of the major factors that controls the distribution of soil and plant carbon (Harden et al. 2000). Fires vary considerably in severity, or the amount of surface and canopy fuel consumed (Wang 2002). Fire severity is a measure that integrates active fire characteristics and immediate fire effects, and is estimated as the proportion of biomass combusted (Lentile et al. 2006). Wildfires burn heterogeneously throughout the boreal landscape, leading to varying levels of fire severity in post-fire ecosystems. Aspect, elevation, soil moisture, and weather conditions concomitantly act with variations in vegetation fuel types and forest structure to influence fire severity patterns as well (Johnson 1992). Furthermore, interannual variation in area burned is high and the severity (Harden et al. 2000) and configurations (Kasischke and Johnstone 2005) of wildfire effects are often linked to seasonal changes in fuel conditions. Patterns of fire severity influence post-fire vegetation composition and regrowth (Arseneault 2001, Johnstone and Chapin 2006, Wang 2002), and subsequent carbon uptake or emissions (LeComte et al. 2006). Therefore, in order to measure the magnitude of the fire disturbance and understand effects on soil and plant carbon accumulation, it is necessary to develop quantitative measures to describe fire severity.

Boreal forests of interior Alaska are dominated by even-aged stands of black spruce (Picea mariana) and white spruce (Picea glauca) that are generally rooted in thick (5- >50 cm) layers of organic material overlying mineral soil. These surface organic horizons are largely derived from live and dead mosses and inputs from vascular plant litter, root turnover and lichen (Miyanishi and Johnson 2002). According to the Canadian system of soil classification, these organic soil horizons can be categorized as litter (recently cast and unaltered plant remains), fibric (slightly decomposed, but still identifiable material) and humic (more decomposed and not identifiable),
with mineral soil below (Canada Soil Survey Committee 1978). These thick horizons of organic material on the mineral soil surface make boreal forests vastly different from other temperate forests in carbon sequestration and emissions as well as fire effects. Soil carbon pools in the boreal forest are estimated to be 20-60% of the world’s terrestrial soil carbon pool (Dixon et al. 1994, McGuire et al. 2000). The Alaskan boreal forest, which is estimated to cover about 17 million ha, stores about 4.8 Mg C of this C or 27.6 Mg C/ha (Yarie and Billings 2002). Outputs from the surface organic horizon are controlled by heterotrophic respiration of organic matter, and by fire consumption (Harden et al. 2000). Fire return intervals are estimated to be approximately 80-150 years for the boreal forest (Johnson 1992, Payette et al. 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). Disturbance from wildfire regenerates the forest into early successional states of forest stands that include deciduous tree species such as aspen (*Populus tremuloides*) and Alaskan birch (*Betula neoalaskana*). These young forests have different carbon dynamics than the mature forest and tend to decrease the carbon sink (Amiro et al. 2003). Wildfire severity has a strong influence on the composition of early successional forests and thus carbon dynamics over time (Johnstone 2006, Aresenault 2001, LeComte et al. 2006).

Fire behavior and severity patterns in the boreal forest differ greatly from many other fire regimes due to the high fire intensity and flame length that characterizes boreal fires (Johnson 1992). Additionally, the canopy often burns in a fast-paced, high intensity crown fire which often results in near total canopy death (Johnson 1992) while the thick organic soil horizons may burn in active flames or in smoldering consumption (Miyanishi and Johnson 2002). This combination of high frequency of 100% aboveground plant mortality plus the importance of quantifying the
volume or depth of surface fuel consumption means that methods of quantifying fire severity in other temperate ecosystems cannot necessarily be easily applied to the boreal forest. Although fires in the boreal forest can be high intensity, there is considerable variability in ground fire severity ranging from lightly-scorched to fully-combusted organic soil leaving just ash and mineral soil, which is a strong control on post-fire vegetation (Johnstone and Chapin 2006). Deciduous trees such as aspen (*Populus tremuloides*) may show a positive correlation with high fire severity while black spruce shows a negative response to increasing burn severity (Johnstone and Kasischke 2005). Early post-fire stand density and composition are good predictors of future stand patterns (Johnstone et. al 2004). Therefore, constraining fire severity in the boreal forest may also be helpful in predicting future forest stand patterns.

Fire severity is a good indicator of the carbon flux from fire in the boreal forest (Kasischke et al. 1995), and an accurate method of measuring it would enhance carbon accounting. Fire severity, by definition, is directly linked to the amount of biomass that is consumed during a fire, and therefore it can be a good indicator of how pools of carbon change during a disturbance cycle (Kasischke et al. 2000). As atmospheric carbon dioxide levels continue to rise throughout the world and influence changing fire regimes, it is important to be able to quantify these boreal forest carbon pools and the response to disturbance.

Within studies examining effects of wildfires on ecosystem recovery and carbon storage patterns, many different methods have been used to quantify fire severity. Three main methods that have commonly been used by most studies to estimate fire severity in the boreal forest are: 1) depth of post-fire organic soil and mass remaining, and depth of organic soil consumed (deGroot et al. 2004, Johnstone and Chapin 2006, Kasischke and Johnstone 2005, Miyanishi and Johnson 2002), 2) the amount of canopy biomass consumed (Aresenault 2001, Greene et al. [224x571] Populus tremuloides [323x571]/
2004, Purdon et al. 2004) and 3) remote sensing, such as Landsat or aerial photography, that combines reflectance from remaining canopy and ground layers (Bigler et al. 2004, Epting and Verbyla 2005, Roy et al. 2006). Within most of these studies, organic soil and canopy consumption were visually estimated and some of these studies used more than one method to estimate fire severity. Subsequently, these estimates of fire severity were used as a parameter for predicting future change in canopy and understory composition, or for quantifying carbon fluxes. All of these methods are based on surveying post-fire conditions. The Composite Burn Index (CBI) has been developed as a standardized visual estimate method of measuring fire severity within the United States that combines information on soil and canopy combustion together (Key and Benson 2005). CBI was developed in the continental United States but has not been extensively tested for its applicability to boreal systems. Fire severity levels are often based on visual combustion estimates, but in order to estimate the proportion of biomass consumed by fire, it is necessary to estimate the pre-fire biomass. In other words, in order to consistently calculate how much was lost during the fire, it is necessary to know or estimate what was there before the fire.

In our study, we tested a method for determining pre-fire conditions and subsequent combustion losses by measuring post-fire forest stand conditions. In particular, we wanted to discover if a method of measuring adventitious root height on black spruce boles could be used to: 1) reconstruct pre-fire organic soil height, 2) quantify pre and post-fire carbon and nitrogen pools, and 3) constrain wildfire organic soil combustion estimates. We used comparisons between burned and unburned black spruce forest stands to address the following questions:

1. Is adventitious root height above post-fire organic soil equivalent to unburned and pre-fire organic soil height?

2. Does the adventitious root height method bias our estimates of soil consumption because pre-fire and residual organic soil depth is measured only at the base of trees?
3. Are post-fire depth disparities at sampling points located randomly or at tree bases due to systematic differences in combustion rates or pre-fire organic soil depths under trees?

4. How are the depths of individual soil horizons related to total organic soil depth?

5. Does the adventitious root collar method correlate with the visually-estimated Composite Burn Index?

6. What is the relationship between C and N emissions and burn severity?

This study presents data from a range of black spruce forests distributed across gradients of moisture availability and fire severity that were used to characterize stand-level patterns of fire severity across the landscape.
CHAPTER 2
METHODS

Study Area

We established 90 sites in forest stands that burned in the summer of 2004 in three different fires (Dalton Complex, Taylor Complex and Boundary Fire) and 28 unburned forest sites paired with the three fires. The approximately 250,000 km² study area (figure 2-1) that encompasses these sites is located within central interior Alaska with boundaries extending north to the Brooks range (~67° N), south to the Alaska Range (~63° N), east to the Alaska-Canada border (~142° W) and west to the Dalton Highway (~150° W) (Hollingsworth et al. 2006). The area includes small mountain ranges, slightly sloped uplands along with large flatland areas and broad floodplains adjacent to braided rivers (Hollingsworth et al 2006). Open to closed-canopy black spruce (*Picea mariana*) in mostly even-aged stands was the dominant vegetation type in our study area with occasional white spruce (*Picea glauca*) and deciduous species such as aspen (*Populus tremuloides*) and birch (*Betula papyrifera*). Vegetation across the study area includes three black spruce community types: acidic black spruce/ lichen forest, nonacidic black spruce/rose/horsetail forest and tree-line black spruce woodland (Hollingsworth et al 2006). Temperatures across this region are extreme and range from -70° C to 35° C with mean annual precipitation at about 285 mm including about 35% from snow (Hinzman et al 2005). Soils of interior Alaska are generally undeveloped and primarily (~90%) consist of Inceptisols, Gelisols, Histosols and Entisols (Ahrens et al 2004).

For our study, we selected sites that represented a range of fire severity or for which we had pre-fire data (Hollingsworth et al. 2006). We intensively studied a subset of 38 of these sites (six of which were at tree-line), which were chosen to maximize variation in fire severity and edaphic conditions. These sites were selected from areas burned by the three different wildfires;
the fire severity varied among and within the fires from low to high. Unburned sites were chosen from those described in Hollingsworth et al. (2006) and were selected to correspond to general locations and edaphic conditions of the burned sites.

**Experimental Design and Measurements**

In June 2005, we established plots to estimate pre and post fire soil organic carbon and nitrogen pools in 38 burned sites for intensive study. The experimental unit was a 30 m x 30 m square plot which was sampled with a 1 x 30 m belt transect. Measurements in the plots included post-fire organic soil depth, carbon (C) and nitrogen (N) pools; tree density, basal area (BA) and canopy consumption. As part of a broader study, post-fire vascular plant species cover and composition, and tree seed rain and 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 values necessary to reconstruct pre-fire soil C and N pools. These sites are referred to as ‘burned’ and ‘unburned,’ respectively in this paper.

**Patterns of Post-Fire Soil Organic Matter**

Across all burned sites, combustion ranged from low, wherein a large proportion of the fibric or upper duff layer had not burned, to high, where the fibric layer was completely combusted and the humic or lower duff layer was partially or fully combusted (Rowe et al 1983). Within these sites, depth of remaining soil organic layers (SOL) were measured at 11 randomly selected points on a transect in order to characterize site-wide post-fire SOL. At each point, we measured the depth of each of the following horizons: dead moss (undecomposed or slightly decomposed dead moss), fibric (moderately decomposed organic matter with more roots than moss or Oe horizon) and humic (highly humified or decomposed organic matter or the interface between the humic horizon and the A horizon) down to the mineral soil horizon (Canadian Agricultural Services Coordinating Committee 1988, Soil Survey Staff 1998, Neff et.al. 2005).
Sampling Design: Randomly Located and Tree Base Points

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 a given random sampling point and SOL depth was sampled as close to the bole as possible, although, the distance to bole varied due to large roots that prohibited digging. At tree sampling points, we also measured the height from the top of the remaining SOL to the highest adventitious root on the bole of the tree, henceforth referred to as adventitious root height (ARH). Since pre-fire SOL depth was only reconstructed at tree sampling points, we compared SOL depth at tree base and random sampling points (burned and unburned sites) in a t-test to determine if sampling only at trees would bias our measurements (Question 2).

Pre-fire Organic Soil Depth

We then combined ARH with post-fire SOL depth (at tree bases) to estimate pre-fire SOL depth. Thus, pre-fire SOL depth was equal to post-fire SOL depth plus ARH. SOL combustion was the difference between pre-fire SOL depth and post-fire SOL depth. To test if our reconstructed pre-fire SOL depths were accurate (Question 1), we compared our values to actual pre-fire SOL measurements (Hollingsworth et al 2006).

C and N Sampling

In addition to measuring SOL depth, we also sampled soils at four sampling points that were representative of intra-site variation in fire severity. Organic soil horizons were sampled volumetrically and separated into the horizons noted above; dead moss (DM), fibric (F) and humic (H). Mineral soil was sampled via volumetric coring at 0-5 cm, 5-10 cm depths. Soil samples were stored in coolers with ice packs in the field and in freezers prior to laboratory analyses.
Tree Biomass, Stand Structure and Combustion

Besides our soil measurements, we also characterized forest structure at the burned and unburned sites. We measured the diameter of trees at breast height (DBH; 1.4 m) for all trees greater than or equal to 1.4 m tall and basal diameter for trees less than 1.4 m tall that were rooted within six, 2 x 5 m subplots along the transects. Fallen trees were included in this census if we estimated that they had been rooted in the subplot. We used these values to calculate tree density, basal area and aboveground biomass (excluding the bole). We visually estimated % fire consumption in five classes (0, 25, 50, 75 or 100 percent) of four components of the tree canopy: cones, needles, fine branches and coarse branches. To calculate pre-fire biomass of canopy (excluding tree bole) components, we grouped trees into three diameter and height classes and applied allometric equations that predicted standing dry biomass from DBH of individual trees. Classes consisted of 1) DBH greater than 2.7 cm and height greater than 1.4 m (Mack et al. In Press), 2) DBH less than 2.7 cm and height greater than 1.4 m (M.C. Mack, unpublished data) and 3) height less than 1.4 m (M.C. Mack, unpublished data).

We combined the visual estimates of % consumption times the pre-fire biomass to determine canopy biomass fire consumption (in g of dry mass) for each tree. Moreover, we calculated canopy C and N pools and subsequent emissions for each canopy component. We used 50% C concentrations for estimating C biomass and 0.4% N for cones, fine branches and coarse branches and 1% N for needles (Gower et al 2000).

Unburned Sites

In addition to soil and tree measurements in burned sites, we measured soil characteristics and forest structure in 28 unburned sites using an identical experimental design. Since we measured ARH in burned sites as a proxy for pre-fire organic soil depth, we also measured ARH in relation to the surface of the green moss at the tree bases (Question 1). We measured SOL
depths at 11 randomly located points and at 11 points at tree bases along a 30-m belt transect in each site. Tree density, DBH and species identity were estimated in six-2 m x 5 m subplots. SOL horizons were divided into similar categories as the burn plots but the dead moss horizon was referred to as brown moss (BM) and we added a fourth horizon, green moss (GM). We volumetrically sampled soils and measured horizons as described above at eight points (four tree bases and four randomly located). Finally, we compared horizon depths, bulk density (\(\rho_b\)) and C and N concentration at tree and randomly located points in unburned forest stands to discover if there were biases due to tree proximity (Question 3).

**Lab Analysis**

Approximately 370 cores comprising ~1500 total soil samples were collected from 37 burned and 28 unburned sites. We calculated the volume of each soil layer from surface area and depth measurements and processed soils in the lab to obtain oven dry soil weight, \(\rho_b\) (g/cm\(^3\)), moisture content (g/g), pH and carbon and nitrogen content. Soils were homogenized and any material that could not be mixed such as coarse (>5 mm sticks) or rocks were removed from the sample and the weight and volume of the rocks was subtracted from total wet sample weight and volume. Sub samples were initially weighed wet and then dried at 105 deg C for 24-48 hours to determine moisture content. Additional sub samples (dried at 65 deg C) were rolled into tins and carbon and nitrogen content was determined using a Costech Elemental Analyzer (Costech Analytical, Los Angelas, California, USA). We measured pH of all burned soil samples and a sub-set of the first mineral layer of the unburned soil samples using the WBL method No. 2 (Thomas 1996).
Horizon Depths in Relation to Total Organic Soil Depth

We used the ARH measurements to estimate pre-fire SOL depth at the tree bases within the intensive burned sites. Therefore pre-fire SOL depth is equal to post-fire organic soil depth plus ARH and a correction factor of 3.2 cm to account for displacement in location of uppermost roots relative to the top of the green moss layer, as determined from the unburned stands (see results, section III-B). After estimating pre-fire depth using the adventitious method, we estimated pre-fire depths of each individual horizon (question 4).

Since we measured SOL height in the unburned sites, we compared those sites’ individual horizon depths to the total SOL depth (question 4) and other forest stand structural variables (tree density, BA, etc.). We examined the relationship between total organic soil 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 (See results, section III-E). In other words, green moss was a similar thickness no matter how deep the organic soil, while the other horizons varied as a constant proportion of overall organic matter thickness. Consequently, all of the other horizons (BM, F and H) were estimated as a proportion of the total mean depth and equaled 14, 46 and 29 percent respectively. These proportions and the GM constant were applied to the re-constructed pre-fire organic soil depth. The reconstructed horizon depths were then used to calculate pre-fire C and N pools as well as combustion losses.

Pre- and Post-Fire C and N Pools

To quantify pre and post-fire C and N pools, we used values from our burned and unburned sites and accounted for post-fire differences (question 6). To start with, we calculated mean site values for each horizon’s $\rho_b$ and percent C and N from destructively harvested cores
at all burned (n= 4) and unburned (n=8) sites. These mean burned site values were used with the post-fire, randomly located sampling point horizon depths (n=11) to calculate general post-fire soil organic carbon (SOC) and soil organic nitrogen (SON) pools:

\[
\text{Post-fire SOC or SON pool (kg/m}^2\text{)} = \sum (\rho_{b_{DM}} \times \text{depth}_{DM} \times \% C_{DM} \text{ (or } \% N_{DM})) + (\rho_{b_{F}} \times \text{depth}_{F} \times \% C_{F} \text{ (or } \% N_{F})) + (\rho_{b_{H}} \times \text{depth}_{H} \times \% C_{H} \text{ (or } \% N_{H}))
\]

Our next step, however, was to reconstruct pre-fire soil C and N pools for the burned sites and subsequent combustion emissions. However, if we simply added on the missing depth to our post-fire pools, we might not account for missing mass. Besides, horizons that were present, but partially burned may have had burned material deposited from the horizon or vegetation above them, which could alter, and in most cases enhance, the nutrient content and bulk density relative to the equivalent unburned horizon (Neff et al. 2005). Including this residual material as indicative of the pre-fire pool size of the layer would result in an over-estimate of the pre-fire pool for that horizon.

In order to correct for these deposits, we used values from both burned sites (\(b\)), which were mean site values and unburned (\(u\)) values, which were the means from all the unburned sites. We calculated pool size for each of the 11 tree base points using the following values to account for the deposits. If DM were present (thus, F and H were intact), then we used the following values:

1. DM = depth_{b}, \(\rho_{b_{u}}\), [C or N]_{u},
2. Fibric (F) = depth_{b}, \(\rho_{b_{b}}\), [C or N]_{b},
3. Humic (H) = depth_{b}, \(\rho_{b_{b}}\), [C or N]_{b}.

If the F horizon were present, then we used these values:

1. F = depth_{b}, \(\rho_{b_{u}}\), [C or N]_{u}, \(\rho_{b_{b}}\),
2. H = depth_{b}, \(\rho_{b_{b}}\), [C or N]_{b}.
Finally, if only the H horizon were present then we calculated the nutrient pool using these values: depth, $\rho_{b\_u}$, $[C]$ or $[N]_u$. By using the unburned values for the partially burned horizons, we were able to avoid mixed values from possible ash deposits.

We applied these rules when re-constructing pre-fire pools. Thus, we used the post-fire values for $\rho_b$, $[C]$ and $[N]$ for intact burned layers and the unburned mean values for partially or wholly consumed horizons in combination with the reconstructed pre-fire depths (at each tree point) to calculate SOC and SON pools. Finally, the pre and post-fire values were compared to estimate SOC and SON losses (kg/m²).

**CBI and Combustion**

Our final objective for this study was to discern whether CBI, a quick visual assessment method would be related to our more intensive assessment with adventitious roots and stand structure (Question 5). CBI is a standardized index that was developed by the US Forest service and can be used to ‘score’ fire severity and then link it to remote sensing data. CBI was designed to capture the variability of burns within five vertical strata: 1. substrate (litter and duff), 2. herbaceous and small trees and shrubs (less than 1 meter), 3. tall shrubs and trees (1-5 meters), 4. intermediate trees or sub-canopy trees, and 5. upper canopy or dominant trees (Key and Benson 2005). The five vertical strata were also grouped for further analysis (according to CBI standards) into the understory score (1 and 2) and the overstory score (3, 4 and 5). We chose the overstory score for comparison to our canopy biomass loss estimates since our canopy biomass estimates included all trees that would be equivalent to intermediate and tall trees. We compared total CBI scores as well as overstory, understory and substrate CBI scores (Verbyla, unpublished data 2005), to our organic soil and tree canopy biomass combustion assessments.
Statistical Analysis

In analyzing data, we determined each ‘site’ to be a unit and therefore, used the means of the 11 sampling points within each site to characterize a 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 for our analyses. We performed a series of paired t-tests to compare randomly selected versus tree base sampling points (within sites) (Questions 3 and 4) Additionally, we explored relationships between: randomly located and tree sampling point depth differences in burned sites and adventitious height in the unburned sites to organic soil height, tree density and basal area (Question 2); CBI scores and combustion rates in burned sites as well in a series of regressions (Question 5). We compared our quantified fire severity for each site with the CBI score for each site in a regression analysis.
Figure 2-1. Map of interior Alaska, including a map of the areas burned by wildfire in 2004 and study sites.
CHAPTER 3
RESULTS

Burned Black Spruce Stands

Post-fire SOL depth, tree basal area and density as well as post-fire soil C and N pools varied considerably across the 38 burned sites. Post-fire SOL depth ranged from 0-21 cm with 16 sites having 5 cm or less of organic matter depth, 15 sites having 7-15 cm of organic matter left and 7 sites having 15-21 cm of organic matter remaining (Figure 3-1a). Across all sites, average soil organic horizon depths ranged from a shallow humic layer remaining to the full soil profile (Figure 3-1b). SOC pools followed similar trends and ranged from 0.43 to as much as 14 kg C/m², with an average of 3.46 ± 0.46 kg C/m² (Figure 3-2a). SON pools varied from 0.017 – 0.403 kg N/ m² and averaged 0.126 ± 0.016 kg N/ m² (mean ± 1 SE) across all 38 sites (Figure 3-2b).

Tree densities at burned sites ranged from 2,000 to 8,000 trees per hectare (Figure 3-3a). Additionally, basal area ranged from 0-5 m² per hectare to as much as 30 m² per hectare with 11 sites in the lowest basal area class, 15 sites between 5-10 m² per hectare and 12 sites between 10-30 m² per hectare (Figure 3-3b). Stand age ranged from 30 – 176 years with a mean of 91.3 ± 4.7 years old (mean ± 1 SE; J. F. Johnstone, unpublished manuscript). Age was not related to basal area or stand density (data not shown). Mean tree density across all sites was 6,210 ± 750.8 trees per hectare and mean basal area was 9.4 ± 1.2 m² per hectare (both values mean ± 1 SE). Unburned stands had generally the same characteristics as burned stands, however, tree density and basal area were significantly greater; 17,148 ± 147 trees per hectare and 16.8 ± 2.2 m² per hectare (both values mean ± 1 SE).
Reconstructing Pre-Fire Depth of the Soil Organic Layer

Because adventitious root development is stimulated by moss and humus cover (Krause and Morin 2005, and Johnstone and Kasischke 2005), we explored the applicability of using the adventitious root scars on burned trees to estimate pre-fire organic soil depth (Question 1).

Johnstone and Kasischke (2005) hypothesized that the height of the ARH in burned stands indicated the minimum height of the pre-fire SOL surface, or more specifically, the top of the green moss layer. To test this hypothesis, we measured the height of the ARH in relation to the top of the green moss layer, hereafter the adventives root height offset (ARHo), in our 28 unburned sites. ARHo ranged from -7.9 cm below the green moss layer to +3.2 cm above (Figure 3-4) with a mean value of $-3.2 \pm 0.43$ cm (mean $\pm$ 1 SE).

To better understand factors that might explain ARHo variation, we identified moss type and measured distance to tree from sampling point, DBH of tree, pH, soil moisture, depth of total organic soil and depth of each layer (GM, BM, F and H). Across all sites, most sampling points were occupied by feather moss (254), with substantially fewer points occupied by sphagnum (35), unidentified moss species (12) or lichen (1). Site mean ARH offset was not related to moss type, distance to tree, mineral soil pH, soil moisture, total SOL depth or basal area (data not shown). ARHo was, however, significantly positively related to tree DBH ($ARHo = -5.07 + 0.31 \times DBH, R^2=0.23, F_{1,26}=7.59, P=0.01$). Because this predictor did not explain much of the variation in the ARHo, we used the mean offset of -3.2 cm to correct our calculations of pre-fire SOL depth (sections D and E below).

Intra-site Variation in Post-Fire Soil Organic Layer Characteristics

After ascertaining that the ARH method was effective for determining pre-fire SOL depth, we determined whether measuring post-fire SOL depth only at tree bases might bias our estimates of mean SOL at a site (Question 2). Across the burned sites, total organic soil depth
was 8.2 ± 1.0 cm (mean ± 1 SE) at randomly located sampling points and was comprised of three horizons with the following mean depths: 1.1 ± 0.3 cm (DM), 3.7 ± 0.5 cm (F) and 3.3 ± 0.4 cm (H) (mean ± 1 SE; Table 3-1). Total organic soil depth was slightly (6.4%) but significantly shallower at tree bases (7.5 ± 0.9 cm, mean ± 1 SE), than at randomly located sampling points (paired-t1, 37=2.40, P=0.02). Site means at tree base and randomly located organic soil depths were highly correlated (Figure 3-5). The difference in mean total depth was primarily due to shallower DM horizon depth near trees (0.4 ± 0.2 cm (mean ± 1 SE); paired-t1, 37=3.30, P=0.02). H horizon depth, by contrast, was greater near trees, 3.8 ± 0.5 cm (mean ± 1 SE); paired-t1, 37=-2.20, P=0.03).

Shallower residual SOL depths under trees versus randomly located points may have been due to: (1) greater organic consumption under trees (Miyanishi and Johnson 2002 and our Question 2) or (2) less pre-fire organic matter accumulation under trees or a combination of both factors (Question 3). However, we found that in unburned forest stands, total SOL depth under trees was not significantly different from SOL depth at randomly located points (paired-t1, 27=0.37, P=0.71), suggesting that shallower SOL depths under trees in the burned sites were due to greater combustion under trees. Across the unburned sites, mean total SOL depth at random points was 24.8 ± 1.3 cm (mean ± 1 SE). Bulk density (\( \rho_b \)), soil moisture and C and N concentrations were not different at tree and random points for all organic soil horizons but did differ between horizons (Table 3-2). Although GM and BM horizons accounted for 24% of the total SOL depth at random points, they only accounted for 10.4% of total profile organic matter, 11.9% of the total SOC pool and 8.8% of the total SON pool.

Since we determined that the random/tree depth bias was not due to pre-fire depth disparities, we considered whether other stand characteristics explained the bias. Random versus
tree differences (depth at randomly sampled points minus depth at tree bases) in total depth or individual horizon depths were not significantly related to mean site DBH or basal area (data not shown). Tree density, by contrast, was significantly related to the F and H horizons’ random versus tree difference; these horizons comprise >80% of total depth (figure 3-6). However, tree density was not significantly related to the total SOL or DM depth (data not shown).

In order to account for the random/tree depth bias in our reconstruction of pre-fire and post-fire SOL, we calculated a correction factor for each horizon that accounted for the random versus tree depth bias (random: tree ratio). Bias-corrected depths for the DM and F horizons were not related to stand structure and thus were:

\[
\begin{align*}
    \text{DM}_{\text{corrected}} &= 1.1 \times \text{Dm}_{\text{tree}} + 0.7 \\
    \text{F}_{\text{corrected}} &= 0.9 \times \text{F}_{\text{tree}} + 0.7 \\
    \text{H}_{\text{corrected}} &= 0.7 \times \text{H}_{\text{tree}} + 0.6
\end{align*}
\]

Adding the corrected values yields a total corrected post-fire SOL depth (SOD\text{corr. post-F}), therefore:

\[
\text{SOD}_{\text{corr. post-F}} = \text{DM}_{\text{corrected}} + \text{F}_{\text{corrected}} + \text{H}_{\text{corrected}}.
\]

We used these depth corrections with our pre-fire depth estimates to calculate post-fire organic soil depth and subsequently organic soil consumption at each tree sampling point.

**Fire Severity of Organic Soil**

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 \(\rho_b\), %C and %N to estimate SOL mass, and SOC and SON combustion. We first used the following equation to estimate pre-fire SOL depth (SOD\text{pre-F}) for our burned sites.

\[
\text{SOD}_{\text{pre-F}} = \text{SOD}_{\text{post-F}} + \text{ARH} + \text{ARH}_o.
\]
Next, since we calculated the $\text{SOD}_{\text{pre-F}}$ at tree bases, we used our random/tree bias corrected residual SOL depth to estimate total SOL combustion:

$$\%\text{SOL combustion} = \left(\frac{\text{SOD}_{\text{pre-F}} - \text{SOD}_{\text{corr.post-F}}}{\text{SOD}_{\text{pre-F}}}\right) * 100$$

Percent SOL combustion across all sites was generally high with a mean value of 66.8 % ± 3.7 (mean ± 1 SE), 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, but our measurements show that overall most of the sites were burned severely.

Since the ARH method is based on accurately reconstructing pre-fire depth, compared our estimates with data collected prior to the wildfire (Hollingsworth et al. 2006) for 13 of our burned sites (Question 1). Our reconstructed SOL depth of 26.6 ± 1.66 cm, (mean ± 1 SE) for these sites was not significantly different from measured pre-fire depths of 23.3 ± 1.55 cm (mean ± 1 SE, Hollingsworth unpublished data; paired-t$_1$, 12=1.65, P=0.13).

**Reconstructing Depth of Organic Soil Horizons**

After reconstructing $\text{SOD}_{\text{pre-F}}$ with the ARH method, we also had to divide total depth into horizons to quantify C and N pools (Questions 4 and 6). We examined a number of factors in the unburned forest stands to determine if they could be used as predictors of the depth of the soil horizons, focusing on stand characteristics that could also be easily measured at burned sites. First, we compared the depth of each horizon to the total SOL depth and all were significantly positively related (Figure 3-7a). Next, we found that the F and H horizons as a percent of total depth were not significantly related to total depth. The GM horizon was negatively related to total depth, while the BM horizons were positively related (Figure 3-7b).

For F and H, we used a constant mean proportion (derived from the unburned sites) of 46% and 30%, respectively, to divide the total SOD into horizons. We compared other easily
measured stand-level variables to GM and BM horizons to better understand why these layers varied as a percent of total depth. Green moss depth was not related to tree density or basal area. We measured $\rho_b$, and C and N concentrations in the burned and unburned sites and coupled these values with SOL depths to quantify pre-fire and post-fire C and N pools (Question 6, See methods section F). In the burned sites, soil core sampling points were not stratified by random or tree points (Table 3-1). Conversely, the eight unburned soil sample cores were extracted at tree and randomly located points (four each); there were no significant differences between $\rho_b$, and C and N concentrations between these two sampling schemes (data not shown, Table 3-2). Mean C and N concentrations for the horizons ranged from 32.9 –42.5% and 0.08 – 1.07%, respectively. Only the F horizon, where roots are likely to be most dense (Neff et al. 2005), 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 (mean ± 1 SE)). Moisture content was not significantly different at random versus tree points for the other three horizons (data not shown).

Reconstructed post-fire SOC pools ranged from 0.33 kg/m$^2$ to 10.63 kg/m$^2$ (for a site with very little burning) with a mean of 2.99 ± 0.40 kg/m$^2$ (mean ± 1 SE) 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$^2$ (mean ± 1 SE). Reconstructed post-fire element pools were 17.0 ± 3.9 (SOC) and 19.3 ± 3.8 % (SON) less than direct pool measurements (Section A above; SOC paired-$t_{1, 37} = 3.31$, $P=0.002$ and SON paired-$t_{1, 37} = 3.45$, $P=0.001$). Additionally, the proportion of SOC and SON lost ranged from as low as 0% to as high as 94% for with mean losses of 52.9% ± 4.8 and 49.8% ± 5.04 (mean ± 1 SE) respectively, across the 38 sites (Figures 3-8 and 3-9). SOC emissions were 41.6 ± 5.6 times greater than SON emissions.
Reconstructing Depth of Organic Soil Horizons

After reconstructing SOD$_{pre-F}$ depth with the ARH method, we also had to divide total depth into horizons to quantify C and N pools (Questions 4 and 6). We examined a number of factors in the unburned forest stands to determine if they could be used as predictors of the depth of the soil horizons, focusing on stand characteristics that could also be easily measured at burned sites. First, we compared the depth of each horizon to the total SOL depth and all were significantly positively related (Figure 3-7a). Next, we found that the F and H horizons as a percent of total depth were not significantly related to total depth. The GM horizon was negatively related to total depth, while the BM horizons were positively related (Figure 3-7b).

For F and H, we used a constant mean proportion (derived from the unburned sites) of 46% and 30%, respectively, to divide the total SOD into horizons. We compared other easily measured stand-level variables to GM and BM horizons to better understand why these layers varied as a percent of total depth. Green moss depth was not related to tree density or basal area (data not shown), but it was only $10.4 \pm 0.62\%$ of total soil organic matter depth and it was not highly variable, with a mean of $2.4 \pm 0.14$ cm (mean $\pm$ 1 SE) and a range between 0.82 and 3.9. Therefore, we used the mean value as a constant for all GM layers. Brown moss depth was $13.7\% \pm 1.91$ (mean $\pm$ 1 SE) of total organic soil depth and was significantly related to basal area (BM depth = $-6.07 - 0.14$ * (BA/ha), $R^2=0.18$, $F_{1, 25}=5.50$, $P=0.03$) and total depth (Figure 3-7a). Combining the two variables in a multiple regression did not increase the predictive power above that of total depth alone (data not shown). However, the negative intercept of the equation resulted in improbable values for sites with shallow organic layers. Therefore, we calculated BM depth as a constant proportion of total depth (13.7%).
Soil Organic Layer C and N Pools and Combustion

We measured $\rho_b$, and C and N concentrations in the burned and unburned sites and coupled these values with SOL depths to quantify pre-fire and post-fire C and N pools (Question 6, See methods section F). In the burned sites, soil core sampling points were not stratified by random or tree points (Table 3-1). Conversely, the eight unburned soil sample cores were extracted at tree and randomly located points (four each); there were no significant differences between $\rho_b$, and C and N concentrations between these two sampling schemes (data not shown, Table 3-2). Mean C and N concentrations for the horizons ranged from 32.9 – 42.5% and 0.08 – 1.07%, respectively. Only the F horizon, where roots are likely to be most dense (Neff et al. 2005), had significantly different gravimetric moisture content (paired-t1, 27= -2.24, P=0.03; random mean= 251.1 ± 41.1 and tree mean= 213.4% ± 32.7 moisture (mean ± 1 SE)). Moisture content was not significantly different at random versus tree points for the other three horizons (data not shown).

Reconstructed post-fire SOC pools ranged from 0.33 kg/m² to 10.63 kg/m² (for a site with very little burning) with a mean of 2.99 ± 0.40 kg/m² (mean ± 1 SE) while SON pools ranged from 0.01 kg/m² to 0.30 kg/m² with a mean of 0.11 ± 0.02 kg/m² (mean ± 1 SE). Reconstructed post-fire element pools were 17.0 ± 3.9 (SOC) and 19.3 ± 3.8 % (SON) less than direct pool measurements (Section A above; SOC paired-t1, 37= 3.31, P=0.002 and SON paired-t1, 37= 3.45, P=0.001). Additionally, the proportion of SOC and SON lost ranged from as low as 0% to as high as 94% for with mean losses of 52.9% ± 4.8 and 49.8% ± 5.04 (mean ± 1 SE) respectively, across the 38 sites (Figure 3-8, a-d). SOC emissions were 41.6 ± 5.6 times greater than SON emissions.
Tree Biomass, C and N Pools and Combustion

We used allometric biomass equations to calculate pre-fire canopy biomass and combined these with visual combustion estimates to calculate canopy biomass consumed by fire. Mean pre-fire total canopy biomass throughout all sites was 8,686 ± 1,080 kg/ha (mean ± 1 SE). Conversely, canopy biomass losses were 6,618 ± 960 kg/ha (mean ± 1 SE), with a mean proportional consumption across all sites of 64% ± 4 (mean ± 1 SE). We did not include the bole in our measurements since it was almost always charred or black from ash, regardless of the severity of the fire, and therefore difficult to visually estimate consumption. This likely results in an underestimate of canopy consumption.

Assuming a general canopy C concentration of 50% and N concentrations of 1% for needles and 0.4% for cones, fine and coarse branches, pre-fire C and N biomass mean values were 0.43 ± 0.05 kg/m² and 0.0054 ± 0.001 kg/m² (mean ± SE) and ranged from 0.001 to 1.21 kg/m² for C and 0.0001 to 0.01 kg/m² for N. Conversely, C and N losses from combustion were 0.37 ± 0.05 kg/m² and 0.005 ± 0.0006 kg/m² (mean ± SE), respectively, and ranged from 0.001 to 1.16 kg C/m² and <0.0001 to 0.014 kgN/m² (figure 3-9 a and b). These canopy C and N combustion values are equivalent to mean canopy losses of 80.2% ± 2.5 and 80.6 % ± 2.7 respectively.

CBI and Combustion Losses

We compared our organic soil and canopy combustion estimates with CBI scores from each site (Question 5). We evaluated the following CBI scores in relation to our measurements: total (a total site value), overstory (upper and mid-canopy trees and tall shrubs), understory (substrate and vascular plants) and substrate (soil organic layers and litter). CBI scores range from 1 (low severity) to 3 (high severity) and mean total CBI scores were 2.3 ± 0.07 (mean ± 1
SE), while mean substrate, understory and overstory CBI scores were: 1.9 ± 0.14, 2.2 ± 0.09 and 2.5 ± 0.06 (mean ± 1 SE). Generally, substrate and understory scores were more frequently lower while canopy scores were often higher and total CBI scores were relatively evenly distributed among the score classes between 1.5 and 3.

The overstory CBI score was positively related to % of canopy biomass and C combusted and explained 44% of the variation (Table 3-3), but was negatively related to C emitted (27% of variation). Total CBI score only explained ≤15% of the variation in all canopy measures (Table 3-3). Total, understory, and substrate CBI scores were significantly related to all SOL measurements and between 33-63% of the variation were explained. Although, only one comparison between substrate CBI and SOL C emissions had an R² value as low as 33% and the rest were 42% or greater (Table 3-3). Total CBI scores were negatively related to ecosystem mass and C combustion and C emissions and explained ≤45% of the variation (Table 3-3). In general, CBI scores were good estimates of % mass lost (for all components), however, it was not good at estimating the amount of C emissions. However, CBI was better for estimating SOL or forest floor C emissions than canopy C emissions. Since CBI is a visual estimate, there may be some variation in C concentration or other variables that is not easily visually detected.
Figure 3-1. Frequency, mean and horizon depths of post-fire organic soils at burned sites. A) Frequency of mean (+ 1 SE) depth. B) Horizon depths of post-fire soil organic layers. *indicates the number of sites in each class.
Figure 3-2. Mean soil organic nitrogen and carbon pools in post-fire soil organic layers by horizon and depth class. A) Soil organic nitrogen. B) Soil organic carbon.
Figure 3-3. Percent frequency of sites and tree density in basal area classes across 38 sites burned in 2004. A) Frequency of sites. B) Tree density per hectare.
Figure 3-4. Frequency of 28 unburned sites among 9 adventitious root height depth offset (ARHo) classes (cm). ARHo are differences in depth between adventitious root and the surface of the green moss horizon. ARHo estimates above are derived from mean site values.
Figure 3-5. Depth of soil organic horizons at randomly located points (DepthR) compared to depths at tree base points (DepthT) across 38 sites burned in 2004. Values are means of 11 tree and 11 random points, from each site. Horizons are: dead moss (DM), fibric (F) and humic (H) as well as total depth.
Figure 3-6. Difference between SOL depths at randomly located (Depth\textsubscript{R}) sampling points and depth at tree base points (Depth\textsubscript{T}) compared to mean tree density/ha across 38 sites burned in 2004. The fibric (F) and humic (H) horizons are shown.

- For fibric horizon (F):
  \[
  \text{Depth}_\text{R} - \text{Depth}_\text{T} = -0.46 + 1.4 \times 10^{-4} \times \text{density/ha} \\
  R^2 = 0.14, P = 0.02
  \]

- For humic horizon (H):
  \[
  \text{Depth}_\text{R} - \text{Depth}_\text{T} = 0.49 - 2.0 \times 10^{-4} \times \text{density/ha} \\
  R^2 = 0.28, P < 0.001
  \]
Figure 3-7. Total soil organic layer depth compared to soil horizon depth and horizon depth as percent of total depth across 28 unburned Alaskan boreal forest sites. There are four organic soil horizons: green moss (GM), brown moss (BM), fibric (F) and humic (H). A) Soil horizon depth comparison. B) Horizon depth as percent of total depth.
Figure 3-8. Mean (± 1 SE) carbon (C) emissions and percent of total C combustion by post-fire soil organic layer (SOL) depth classes. A) Carbon emissions. B) Percent of total carbon combustion. Canopy does not include tree bole. Ratios of organic soil to canopy emissions (kg/m²) and combustion (%) are indicated at top of each column.
Figure 3-9. Mean (± 1 SE) N emissions and percent of total N combustion for four post-fire soil organic layer (SOL) depth classes across 38 burned sites. A) Nitrogen emissions. B) Percent of total N combustion. Canopy does not include tree boles. Ratios of organic soil to canopy emissions (kg/m²) and combustion (%) are indicated at top of each column.
Table 3-1. Post-fire soil organic horizons’ mean depth, bulk density (ρ_b), C and N concentration (Mean ± 1 SE). Values are means from 38 Alaskan sites burned in 2004.

<table>
<thead>
<tr>
<th>Horizon</th>
<th>Mean depth (cm)</th>
<th>ρ_b (g/cm³)</th>
<th>C conc. (%)</th>
<th>N Conc. (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dead moss (DM)</td>
<td>1.12 ± 0.3</td>
<td>0.04 ± 0.004</td>
<td>40.2 ± 1.4</td>
<td>0.97 ± 0.1</td>
</tr>
<tr>
<td>Fibric (F)</td>
<td>3.69 ± 0.5</td>
<td>0.10 ± 0.01</td>
<td>41.4 ± 0.8</td>
<td>1.28 ± 0.04</td>
</tr>
<tr>
<td>Humic (H)</td>
<td>8.15 ± 1.0</td>
<td>0.21 ± 0.01</td>
<td>30.0 ± 1.0</td>
<td>1.25 ± 0.04</td>
</tr>
</tbody>
</table>

Table 3-2 Soil characteristics by horizon for 28 unburned sites (mean ± 1 SE). Values Include mean depth, bulk density (ρ_b) and C and N concentration.

<table>
<thead>
<tr>
<th>Horizon</th>
<th>Mean depth (cm)</th>
<th>ρ_b (g/cm³)</th>
<th>C conc. (%)</th>
<th>N Conc. (%)</th>
</tr>
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</tr>
<tr>
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<td>0.21 ± 0.01</td>
<td>30.0 ± 1.0</td>
<td>1.25 ± 0.04</td>
</tr>
</tbody>
</table>
Table 3-3. Soil organic layers (SOL), tree canopy and ecosystem mass and C combustion as well as C emissions compared to CBI scores (Total, understory, substrate and overstory) for 38 sites in Alaskan forests burned in 2004.

<table>
<thead>
<tr>
<th>Measurement</th>
<th>CBI*</th>
<th>Equation</th>
<th>R²</th>
<th>P-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soil organic layers (SOL)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>% depth combustion</td>
<td>Tot</td>
<td>-28.54 + 42.0 * (CBI-Tot)</td>
<td>0.57</td>
<td>&lt;.0001</td>
</tr>
<tr>
<td></td>
<td>Und</td>
<td>-3.05 + 32.11 * (CBI-Und)</td>
<td>0.56</td>
<td>&lt;.0001</td>
</tr>
<tr>
<td></td>
<td>Sub</td>
<td>33.67 + 17.61 * (CBI-Sub)</td>
<td>0.42</td>
<td>&lt;.0001</td>
</tr>
<tr>
<td>% mass combustion</td>
<td>Tot</td>
<td>-39.7 + 45.0 * (CBI-Tot)</td>
<td>0.63</td>
<td>&lt;.0001</td>
</tr>
<tr>
<td></td>
<td>Und</td>
<td>-13.0 + 34.7 * (CBI-Und)</td>
<td>0.63</td>
<td>&lt;.0001</td>
</tr>
<tr>
<td></td>
<td>Sub</td>
<td>27.5 + 18.6 * (CBI-Sub)</td>
<td>0.45</td>
<td>&lt;.0001</td>
</tr>
<tr>
<td>% C combustion</td>
<td>Tot</td>
<td>-66.3 + 52.56 * (CBI-Tot)</td>
<td>0.54</td>
<td>&lt;.0001</td>
</tr>
<tr>
<td></td>
<td>Und</td>
<td>-36.6 + 41.1 * (CBI-Und)</td>
<td>0.56</td>
<td>&lt;.0001</td>
</tr>
<tr>
<td></td>
<td>Sub</td>
<td>9.84 + 22.9 * (CBI-Sub)</td>
<td>0.44</td>
<td>&lt;.0001</td>
</tr>
<tr>
<td>C emissions (kg/m²)</td>
<td>Tot</td>
<td>-3.0 + 2.60 * (CBI-Tot)</td>
<td>0.44</td>
<td>&lt;.0001</td>
</tr>
<tr>
<td></td>
<td>Und</td>
<td>-1.42 + 1.97 * (CBI-Und)</td>
<td>0.43</td>
<td>&lt;.0001</td>
</tr>
<tr>
<td></td>
<td>Sub</td>
<td>0.83 + 1.08 * (CBI-Sub)</td>
<td>0.33</td>
<td>0.0002</td>
</tr>
<tr>
<td>Tree canopy</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>% mass combustion</td>
<td>Tot</td>
<td>34.3 + 16.51 * (CBI-Tot)</td>
<td>0.14</td>
<td>0.02</td>
</tr>
<tr>
<td></td>
<td>Over</td>
<td>9.6 + 2.83 * (CBI-Over)</td>
<td>0.44</td>
<td>&lt;.0001</td>
</tr>
<tr>
<td>% C combustion</td>
<td>Tot</td>
<td>48.6 + 14.15 * (CBI-Tot)</td>
<td>0.15</td>
<td>0.02</td>
</tr>
<tr>
<td></td>
<td>Over</td>
<td>8.39 + 28.7 * (CBI-Over)</td>
<td>0.44</td>
<td>&lt;.0001</td>
</tr>
<tr>
<td>C emissions (kg/m²)</td>
<td>Tot</td>
<td>-0.25 + 0.28 * (CBI-Tot)</td>
<td>0.14</td>
<td>0.03</td>
</tr>
<tr>
<td></td>
<td>Over</td>
<td>-0.74 + 0.45 * (CBI-Over)</td>
<td>0.27</td>
<td>0.002</td>
</tr>
<tr>
<td>Ecosystem</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>% mass combustion</td>
<td>Tot</td>
<td>-37.0 + 43.9 * (CBI –Tot)</td>
<td>0.64</td>
<td>&lt;.0001</td>
</tr>
<tr>
<td>% C combustion</td>
<td>Tot</td>
<td>-61.1 + 50.6 * (CBI- Tot)</td>
<td>0.56</td>
<td>&lt;.0001</td>
</tr>
<tr>
<td>C emissions (kg/m²)</td>
<td>Tot</td>
<td>-3.26 + 2.85 * (CBI- Tot)</td>
<td>0.45</td>
<td>&lt;.0001</td>
</tr>
</tbody>
</table>

*CBI-scores by strata: total (Tot), understory (Und), substrate (Sub) and overstory (Over).
CHAPTER 4
DISCUSSION

Existing methods estimate fire severity in boreal forest by examining post-fire conditions. This is adequate for capturing canopy severity as tree boles can be used relatively accurately to reconstruct pre-fire aboveground biomass conditions. In contrast, depth measurements of post-fire organic soil may not in themselves accurately represent pre-fire depths, or how much organic soil was lost. This study provides evidence that adventitious root heights (ARH) on burned black spruce trees can be used, once adjusted, as a proxy for pre-fire organic soil height. This extends previous observations that were made in a few sites (Kasischke and Johnstone 2005). By reconstructing pre-fire soil depths, this ARH method was used in combination with post-fire soil depth measurements to quantify fire severity, and C and N emissions from fire in boreal black spruce forest. Lastly, this method was also used to validate CBI, a semi-quantitative visual estimate of fire severity, in this forest type.

Adventitious Root Height

Here we described a new method for quantifying fire severity by first estimating pre-fire organic soil depths. The adventitious root method includes measuring, at tree bases, the post-fire SOL depth and height to highest adventitious root on tree bole at a number of points within a site. When we measured this in unburned sites as well, we found that the adventitious root did correspond to organic soil height, but overall the highest root was 3.2 cm (mean across unburned sites) below the top of the green moss layer. Thus, the pre-fire SOL depth is a combination of post-fire SOL depth, adventitious root height plus 3.2 cm (for the offset). In addition, found no significant difference between our re-constructed pre-fire depths and actual pre-fire organic soil measurements (Hollingsworth, unpublished data), which offers further support to the ARH method. However, measuring SOL only at tree bases underestimates post-fire organic soil by
about 6%. Although, there is this post-fire depth discrepancy between tree and randomly located points, there is no pre-fire difference (as measured in the unburned sites), suggesting that organic soil at the base of trees burns more. We developed corrections to account for these post-fire differences for each horizon, since each has unique bulk densities, C and N concentrations and total depth does not capture this variability. While, the ARH method can be useful across a wide range of sites and severities, it may not be as effective at sites in which the trees have fallen over and there is almost no residual organic soil. Trees can root in organic soil and if that all burns away then the tree will fall over. ARH can still be measured on the tree bole to the root collar (area where large roots separate), but measuring this way could omit a significant amount of organic soil.

**C and N Pools**

After reconstructing pre-fire depth, we used these values to reconstruct pre-fire soil C and N pools and calculate emissions as well. We calculated the mean unburned equivalent proportion of total pre-fire depth for each of three horizons, which were: 14% (BM), 46% (F) and 30% (H). GM was calculated to be a constant mean value of 2.5 cm, which was generally consistent across all sites as it is the photosynthesizing horizon. Post-fire C and N pools were calculated using actual post-fire SOL depths and mean values from each burned site for C and N concentration and bulk density for the intact horizons. Pre-fire horizon depths were estimated from reconstructed pre-fire depth and then mean values for C and N concentration and bulk density from all of the unburned sites were used to reconstruct C and N pools for the burned biomass. Finally, emissions were: re-constructed pre-fire pool minus the post-fire pool.

In the course of reconstructing organic soil C and N pools, it was necessary to make a few assumptions and to use averages from all unburned sites. We controlled organic soil depth, since post-fire SOL depth as well as height to adventitious root on the bole of a tree are easily
measured in a burned site. Then, we used mean values from across all unburned sites to obtain bulk density and C and N concentration values for each horizon. Using these mean values for all sites does not capture all of the variability inherent in these organic nutrient pools; however, it is an attempt to more accurately calculate pre-fire and post-fire pools and emissions on the ground than previous studies. Therefore, post-fire SOL depth and re-constructed pre-fire depth become the independent variables in calculating C and N pools.

**Canopy Fire Severity and Biomass**

Canopy fire severity and biomass losses were estimated by Canopy (minus bole) combustion was visually assessed and then allometric equations were used to determine biomass from DBH and biomass combusted. C concentration in the canopy biomass is about 50% and N concentration ranges from 0.4-1%, so canopy C and N pools were calculated too. Finally, fire severity was analyzed as the missing amount of biomass from the ground and the canopy and mean losses across our sites were about 65% of biomass. We compared our time-consuming destructive fire severity measurements to a quicker visual assessment (CBI) to see how well CBI worked.

**CBI**

Our data suggests that CBI shows promise as a quick method of assessing fire severity on the ground. Total CBI scores were significantly but weakly related to percent biomass consumed for canopy (minus the bole) but were highly correlated with organic soil combustion. However, since most wildfires in black spruce forest are considered stand-replacement, it can be argued that there is not as much variability in stand consumption as there is in organic soil combustion (at least that can be visually estimated quickly). In other words, since the majority of trees die in most wildfires in black spruce forests, it can be difficult to differentiate between varying degrees of severity. Therefore, even though the correlation between CBI and our combustion estimates is
weak, on the whole, it may be that there is not that much canopy combustion variability to capture.

Interestingly enough, our canopy and organic soil combustion loss estimates were not significantly related to each other, which is consistent with the different kinds of combustion. While canopy combustion is usually burned during active, high-intensity fire (with visible flames), organic soil mostly burns during slower, smoldering combustion for often-long periods of time (days or months).

**Other Methods of Measuring Fire Severity and Emissions**

**Organic Soil**

Several studies have used the amount of organic soil consumed or remaining after a fire, by weight, depth or visual class, as a method of measuring fire severity, however, these measurements were not linked to pre-fire organic soil amounts. There was no standardized method of quantifying organic soil consumption as a parameter for fire severity, in the literature. Most studies classified fire severity into unburned, low, moderate and severe categories based qualitatively on the amount of organic soil consumed (Turner et al. 1997, Wang et al. 2001, de Groot et al. 2004, Greene et al. 2004, Johnstone and Kasischke 2005, Johnstone and Chapin 2006). Conversely, other studies assessed fire severity by measuring post-fire organic soil depth. Bergner et al. 2004 stated that a mean post-fire SOL depth of 7.5 cm was a low severity class, while 2.1 cm could be considered a severe burn. Areseneault (2001) used a combination of the thickness of the remaining humic layer and canopy consumption measurements to estimate fire severity, however this method cannot assess those sites with little to no post-fire organic soil.

In assessing these other fire severity methods, it is important to note that measuring post-fire organic soil is very different from estimating combustion. Post-fire SOL depth is linked to post-fire successional vegetation trajectories, however, it does not indicate how much matter was
lost. However, fire severity is defined by amount lost and not amount left behind, therefore, it is important to note that the two measurements are not comparable.

**Canopy Consumption and Tree Mortality**

Our canopy component biomass combustion estimates may be a more comprehensive visual way of quantifying tree fire severity in terms of biomass lost and incorporating it into total ecosystem fire severity. Canopy consumption and tree mortality estimates have been used in previous studies as measures of fire severity, however very few studies used only canopy consumption or mortality. The boreal forest often experiences complete canopy mortality while soil fire severity patterns are much more variable (Miyaniishi and Johnson 2002) and therefore canopy measurements alone are inadequate. Proportion of canopy mortality was used as one fire severity quantifier within three studies (Greene et al. 2004, Johnstone et al. 2004 and Purdon 2004), though only the second study used this parameter exclusively. Some of these studies used degree of consumption or percentage of tree mortality as indicators. However, total ecosystem fire severity estimates cannot necessarily be quantified strictly from the canopy.

**C and N Pools**

Carbon and nitrogen pools in boreal forests as well as emissions from forest fires are poorly constrained and limited by uncertainties in quantifying pre-fire spatial surface variation as well as organic soil biomass consumed (Neff et al. 2005, French et al. 2004). Many studies calculate carbon emissions from fire as a product of the fuel combusted during the fire and the area that burned (Amiro et al. 2001) or have quantified carbon also using carbon density and emission factors (French et al. 2004). Models are used to calculate carbon and nitrogen pools and subsequent emissions with a certain degree of error that is propagated throughout the model and much of this uncertainty is due to variability in organic soil C loss (French et al. 2004, Neff et al. 2005). Furthermore, some models have not estimated C emissions from wildfires, which will
become increasingly important as fire frequency may be increased due to climate change (Yarie and Billings 2002). Neff et al. in 2005 used a “Tau” model to calculate burned and unburned C pools and they stated that Tau consistently underestimated the heterogeneity of the soil horizons and thus C pools. Our adventitious root height method accounts for some of this soil surface spatial variation as well as depth and C and N concentration variation.

**Conclusions**

C and N fluxes are intrinsically linked to fire effects and fire severity in the boreal forest; therefore, it is imperative to have a satisfactory way of measuring fire severity throughout the boreal landscape. Since, many studies use fire severity as a gradient or parameter for examining other ecosystem processes, fire severity is often not directly quantified, but estimated. These studies also indicate that the co-factors that influence fire severity, such as seasonality of burn, weather, and topography and soil moisture are good indices for estimating fire severity. Methods such as CBI show strong potential to be a satisfactory way of standardizing fire severity.

Since most boreal forests experience almost total canopy death, it would seem that measuring fire severity in the canopy alone does not accurately capture the variability found within sites. In summary, it seems that fire severity estimates could be best quantified by a combination of SOL combustion measurements (depth or percentage removed), soil moisture content, site drainage and seasonality or timing of burn. The ARH method accounts for organic soil combustion and surface and depth spatial variation thereby overcoming some of the limitations of previous boreal forest C and N estimates and fire losses.


BIOGRAPHICAL SKETCH

Leslie A. Boby attended Morgan Park High School in Chicago, graduating in 1995. She studied at University of Illinois, Urbana-Champaign, IL and obtained a Bachelors of Science degree in biology in 1999. Immediately following university, Leslie moved to Africa and served as a Peace Corps volunteer in rural Ndori, Kenya and taught agroforestry techniques to farmers. After returning to the U.S., Leslie moved out to New Mexico in 2002 and worked for the Bureau of Land Management as a wildland firefighter and biological technician. She continued further west and worked as a field assistant at an Audubon Sanctuary in southern California. Leslie returned to university life in 2005 as a graduate student at the University of Florida in Gainesville, FL. She completed her Masters thesis in interdisciplinary ecology in December 2007. Her next objective is to return to the working world and obtain a position as a land manager burning forests and fighting exotic species.