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Effects of trees on the burning of organic layers on permafrost terrain

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ABSTRACT

We collected data to estimate depth of the remaining (residual) organic layer as well as data to estimate total pre-fire organic layer depth in 99 plots located in mature black spruce (*Picea mariana* (Mill.) BSP) forests in interior Alaska that burned during the large fire seasons of 2004 and 2005. These data were collected immediately adjacent to trees as well as from throughout the plot along with tree stand characteristics (density and basal diameter), and used to assess if trees influenced depth of burning. While other studies have found residual organic layer depths to be shallower under trees than at randomly located points within a given area, our results showed that mean and median residual organic layer depth, as well as the frequency of depths <3 cm, did not differ at a plot scale versus adjacent to trees. Regardless of proximity to trees, residual organic layer depths were affected by drainage and timing of the fire, with deeper organic layers occurring in poorly drained plots and in plots that burned early in the growing season. The amount of foliar biomass was a significant but weak predictor of residual organic layer depth. There was no interaction between drainage class and mean tree basal diameter, basal area, or foliar biomass in explaining variation in organic layer depths following fires. Since the depth of the organic layer in this region regulates ground temperature, degree of permafrost formation, and site drainage, we hypothesize that the seasonal thaw layer impedes drainage in Alaskan black spruce forests, resulting in a horizontal redistribution of moisture just above frozen soil in plots with permafrost. This reduces the impacts of tree canopies (such as canopy interception of precipitation) on variability in depth of burning of the surface organic layer.

1. Introduction

Black spruce forests represent about 50% of the forest cover in the boreal region of North America (Amiro et al., 2001; Yarie and Billings, 2002) and 66% in the boreal region of interior Alaska (Turetsky et al., 2011). The extent of other forests types, however, is likely to increase if the recent warming trend observed in this region continues (Bonan and Korzuhin, 1989; Rupp et al., 2002; Barrett et al., 2011). The depth of burning of the surface organic layer is a widely used measure of fire and burn severity in black spruce forests (Miyanishi and Johnson, 2002; Greene et al., 2007; Kasischke et al., 2008; Boby et al., 2010), and is one of the factors that will be important in determining the rate of transition from black spruce to other forest types (Landhaeusser and Wein, 1993; Johnstone and Kasischke, 2005; Johnstone and Chapin, 2006; Johnstone et al., 2010; Shenoy et al., 2011). In black spruce forests, the depth of the remaining organic soil also influences vegetative reproduction, where deep burning fires can remove stems and roots that some species depend upon for vegetative reproduction (Johnstone and Kasischke, 2005; Bernhardt et al., 2011). In sites with permafrost, the degree of warming and drying a site experiences after a fire is proportional to the depth of the organic layer remaining after a fire (Viereck and Dyrness, 1979; Dyrness, 1982; Yoshikawa et al., 2002; Kasischke and Johnstone, 2005). Finally, the characteristics of the soil layer remaining after a fire (e.g., fibric, mesic, humic, mineral) control patterns of tree recruitment and growth through controlling the availability of nutrients as well as soil moisture conditions. In particular, some species cannot obtain the necessary moisture from fibric soils to germinate and survive because their low bulk density leads to poor water retention (Johnstone and Chapin, 2006; Greene et al., 2007; Johnstone et al., 2010).

Factors that control the depth of burning into the surface organic layers in black spruce forests include seasonal precipitation and temperature patterns that control duff moisture (Dyrness and Norum, 1983; Miyanishi and Johnson, 2002; Stocks et al., 2004; de Groot et al., 2009), the amount of available fuel (Miyanishi and Johnson, 2002; Kasischke and Johnstone, 2005), bulk density of the deeper organic layers (Miyanishi and Johnson, 2002; Benscoter et al., 2011), and other factors that control surface moisture content such as the fraction of *Sphagnum* moss cover (Shetler et al., 2008),

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differences in site drainage (Swanson, 1996a; Kasischke and Johnstone, 2005; Harden et al., 2006; Kane et al., 2007; Turetsky et al., 2011), and seasonal thawing of the ground layer (Kasischke and Johnstone, 2005; Turetsky et al., 2011). Miyanishi and Johnson (2002) concluded that canopy interception of precipitation also influenced post-fire organic layer depths in jack pine and black spruce forests by reducing duff moisture and allowing more complete duff combustion. Greene et al. (2007) found shallower organic layer depths under trees compared to areas >25 cm away from tree boles, but they concluded that during the extended periods of low rainfall that result in large fires across Canada, interception of precipitation by tree canopies would not have a great effect on duff moisture. They suggested the presence of large roots near the bases of trees results in more complete combustion because less heat was dissipated in evaporating water in these areas. Boby et al. (2010) found that in burned black spruce stands in Alaska, the residual organic layer depths under trees were only slightly shallower (6%) than those away from the trees. Regardless of the cause of variations in depth of burning, both Miyanishi and Johnson (2002) and Greene et al. (2007) concluded that the deeper burning of surface organic matter in areas adjacent to trees was an important process in creating microsites with the bare mineral soils required for the recruitment of many tree species (see also Liski, 1995).

Permafrost is a common characteristic in Alaskan black spruce forests because across interior Alaska, the average annual temperature is below 0 °C. Because of the low solar zenith angles, the slope and aspect of a site plays an important role in site microclimate, with south facing-slopes being warmer than north facing slopes (Slaughter, 1983). As a result, forests located on north-facing slopes tend to be more prone to formation of permafrost. In addition, there is a strong biotic control on the formation and maintenance of permafrost (Ping et al., 2006). By providing an insulating layer on top of the ground surface, the organic layers facilitate the formation of permafrost, with the depth of the active layer (the depth of thawed soil) at the end of the growing season being inversely proportional to the thickness of the surface organic layer (Fig. 1). It has been shown that soil moisture in black spruce forests in interior Alaska is highly correlated to depth of the organic soil layer, and that organic layer moisture decreases as the growing season progresses (Yarie and Van Cleve, 1986; Kasischke and Johnstone, 2005; Kane et al., 2007). On backslope sites, there is a strong correlation between aspect and the extent of frozen ground and organic layer moisture, which are largely driven by variations in insolation (Dingman and Koutz, 1974; Van Cleve and Viereck, 1981; Swanson, 1996b). In previous studies, we found that topographic controls on microclimate and site drainage influenced the organic layer thickness in both burned and unburned stands, and that seasonal thawing of the ground layer in sites with permafrost influenced depth of burning (Kasischke and Johnstone, 2005; Kane et al., 2007; Turetsky et al., 2011).

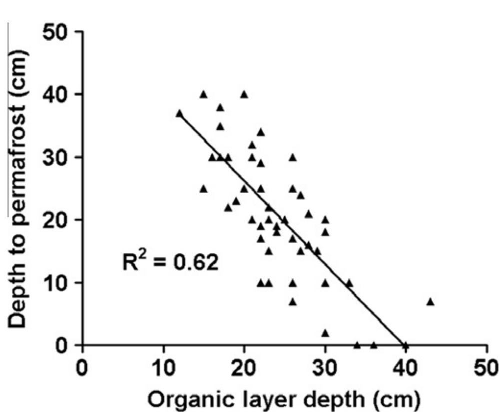

Fig. 1. Relationship between total organic layer depth and depth to permafrost as measured as the distance below the mineral/organic soil interface at the end of the growing season ($F_{1,50} = 83.1$, adjusted $R^2 = 0.62$, $p < 0.0001$). Previous studies by Kasischke and Johnstone (2005) and Kane et al. (2007) examined the relationship between organic layer depth and soil temperature and moisture in unburned black spruce stand. At the same time these measurements were collected, depth to permafrost was also measured, which are presented in this graph. The stands where these data were collected were located in upland areas within the Porcupine, Boundary and Tors fires that were used in this study, as well as other upland stands near Fairbanks and Delta Junction, Alaska in terrains similar to where the sites used in this study were located.

In this study, we examined the effects of trees on organic matter consumption during fires in mature, black spruce stands in interior Alaska. Our objectives were to (1) compare the residual (post-fire) organic layer depth adjacent to tree boles versus the entire stand, (2) examine whether or not variations in tree basal area and foliar biomass had an effect on the residual organic layer depth remaining after a fire, and (3) explore whether relationships between residual organic layer depths and tree basal area or foliar biomass varied among drainage classes. Whereas previous studies in Canada focused on plots without permafrost (Miyanishi and Johnson, 2002) or with sporadic permafrost (Greene et al., 2007), our plots were within the zone of discontinuous permafrost and included 66 plots on moderately-well drained forest sites (south facing and flat upland) and 33 plots on poorly-drained sites (north facing and toe-slope forests). Additionally, we identified sites that burned early (70 plots) versus late (29 plots) in the fire season, allowing us to examine the effects of trees on depth of burning as a function of site drainage controlled by two factors: topography and seasonal thawing of the ground layer. While this study focused on the same fire events used in the research of Boby et al. (2010), this previous study focused on quantifying carbon emissions from fires and did not include a detailed analysis of sources of variations in residual organic layer depth in black spruce forests.

2. Methods

2.1. Study areas and plots

Data were collected in 99 plots within 8 different fire events that occurred during the extreme fire years of 2004 and 2005 in Interior Alaska, when 4.6 million ha were affected by fires. Plots were located on different topographic positions that burned between late June and late August (Table 1, Fig. 2). The period of burning was determined by comparing the location of the plots to the locations of active fire pixels detected by the MODIS sensor (Turetsky et al., 2011).

While only 46% of the 1325 fires in 2004 and 2005 were lightning ignited, these events accounted for 99% of the burned area (Kasischke et al., 2010). Overall, interior Alaska experienced drier and warmer conditions during the summers of 2004 and 2005, especially during late July and early August. Over the longer term, monthly precipitation in interior Alaska is higher in July and August compared to May and June. During 2004 and 2005, the levels of later-growing-season precipitation were much lower than the long-term average, resulting in the continuation of the fire season into August and September. Using fire weather indices generated by the Alaska Fire Service based on the Canadian Forest Fire Danger Rating System (Stocks et al., 1989), the average Duff Moisture Code (DMC) was variable, but all were greater than the median DMC reported by Miyanishi and Johnson (2002) for the two events they studied (median DMC = 24 and 52) (Table 1). The average Drought Code (DC) again was variable (Table 1), but for all fire events studied, the DC all increased throughout the growing season, and thus were higher for the late season burning than for the early season burning.

Table 1
Summary of fire events and plots by topographic position. All the sites in the Dall City and Tors fire events and one site in the Porcupine fire event burned during late-season fires. The remaining sites burned during early season fires.

Fire event	Burn period	Fire size (ha)	Duff Moisture Code average (S.E.)	Drought Code average (S.E.)	Moderately drained sites	Poorly drained sites	Total sites
Boundary	24 June to 7 July 2004	217,000	157.9 (4.3)	265.4 (5.5)	10	7	17
Dall City	9 to 24 August 2004	169,000	13.9 (1.6)	293.6 (15.9)	17	2	19
Tors	20 to 21 August 2004	13,000	77.0 (4.6)	486.8 (19.6)	7	1	8
King Creek	12 to 13 July 2004	16,800	105.2 (7.1)	335.0 (6.3)	2		2
Porcupine	24 June to 28 July 2004	115,000	97.2 (3.5)	348.4 (5.8)	28	21	49
Wall Street	26 to 27 June 2004	19,900	81.3 (1.5)	222.9 (4.0)		1	1
North Bonanza	26 to 27 June 2005	77,300	122.2 (12.3)	337.3 (27.7)	2		2
Chapman Creek	22 to 23 June 2005	69,800	51.7 (14.2)	192.2 (20.3)		1	1
All sites					66	33	99

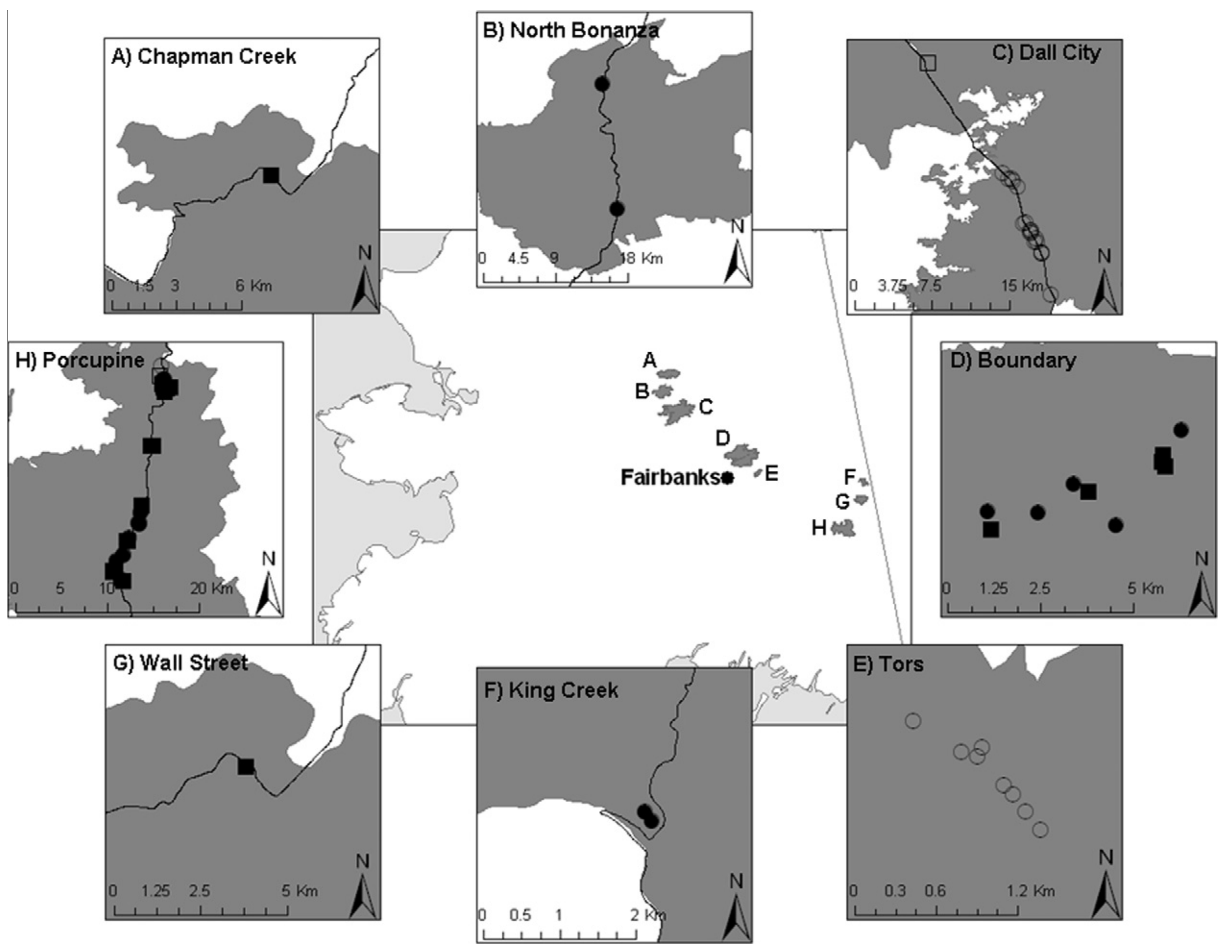

Fig. 2. Locations of plots within the 8 fire events used for this study. Squares represent plots located on poorly drained sites and the circles plots on well drained sites. The filled symbols are sites that burned early in the growing season (prior to 20 July) and the open symbols sites that burned late in the growing season (after 20 July). All sites were located along an existing road (solid lines in the figures) or a trail (not marked).

2.2. Data collection

Data were collected during the summers of 2005 and 2006 as part of a larger study designed to understand the sources of variation in surface fuel consumption in Alaskan black spruce forests (Kane et al., 2007; Shetler et al., 2008; Turetsky et al., 2011) and to evaluate methods for quantifying fire severity in black spruce forests (Kasischke et al., 2008; Hoy et al., 2008). We first conducted a reconnaissance of each area, and located a 100 by 100 m site that had homogenous stand density and burn severity. Only a few of the sites that were selected for sampling had small (<5 m^2) patches of unburned trees, and none of these fell along the randomly located transects that were sampled. A stake was placed in the middle of each site and used as the center of the sampling plot. Its position was determined using a Garman Scientific global positioning system. The topographic position of each plot was noted [flat (<2% slope) upland, flat lowland, and north, east, south, and west backslopes]. We positioned a 40 m baseline in a random direction in the center of the plot. This baseline bisected three 30 m sample transects, one located at the center of the baseline and the other two located at a random distance between 5 and 20 m from the center in each direction. Seven sampling points were located every 5 m along each transect and 4 points were located along the baseline (at 5, 15, 25, and 35 m). At each sample point along the baseline and three transects, we extracted a 20 by 20 cm core of the surface organic layer and measured the total depth to mineral soil, and the depth of each layer (char, live/dead moss, fibric, mesic, humic soil) following Harden et al. (2004). At each sample point along the sample transects, we identified the nearest dead black spruce tree >2 m in height and measured the distance of the highest adventitious root above the mineral soil. The depth of the adventitious root above mineral soil was used to estimate the total organic layer depth prior to the fire based on the approach suggested by Kasischke and Johnstone (2005) (see also Boby et al., 2010) using data collected in unburned stands (Kasischke et al., 2008). Since there was significant variation in the depth of the residual organic layer adjacent to trees in the plots being sampled, we collected two measures of this depth from the shallowest and deepest layers adjacent to the tree within 10 cm of the tree bole. This differs from previous studies that collected a single measure of residual organic layer depths adjacent to trees (Miyanishi and Johnson, 2002; Greene et al., 2007). The basal diameters of these trees were also measured. During the data collections made during the 2005 field season, all trees within ±1 m along each 30 m transect were counted and their basal diameter measured. These data were used to estimate average tree diameter and stand density for the 64 plots sampled.

2.3. Analyses

Across all plots, we used a linear regression model to examine the relationship between the depths of the organic layers under the trees to those throughout the plot. We classified each of the 99 plots into two general landscape classes including moderately-drained (flat uplands, east, west, and south-aspect backslopes) and poorly-drained (flat lowlands and north-aspect backslopes) sites (Turetsky et al., 2011). We also categorized each plot into those that burned early in the growing season (prior to 20 July) versus late in the growing season (after 20 July) based upon previous findings that seasonal deepening of the active layer resulted in more well-drained soils that experienced deeper burning (Kasischke and Johnstone, 2005; Turetsky et al., 2011).

An analysis showed the distribution of the organic layer depths was positively skewed. For statistical analysis, all depth data were logarithmically transformed to meet assumptions of normality. Because of the positive skewness, using the minimum and maximum organic layer depths adjacent to trees would produce a positive bias in estimating average depth. As a result, we also compared median depth values.

An independent samples *t*-test was used to test for differences in pre-fire organic layer depth as a function of site drainage (moderately vs. poorly drained), and also to test for mean differences in residual organic layer depths measured at a plot scale versus under trees ($\alpha = 0.05$). A non-parametric test examined differences in median values ($\alpha = 0.05$). To estimate the aerial extent of canopy coverage at each plot, we applied the allometric relationship between tree basal diameter (BD) and total foliar biomass (TFB) for a given black spruce tree (Yarie et al., 2007: $\text{TFB} = 57.997 \pm 22.13 \times \text{BD} + 7.167 \pm 2.0 \times \text{BD}^2$, $R^2 = 0.77$, $n = 98$ trees) using the mean basal diameter measured at each plot, and multiplied this value by stand density.

A General Linear Model (GLM) was used to examine the effects of categorical variables, including landscape class (well vs. poorly drained), timing of burn (early vs. late season burning), and microtopographical position (beneath or between trees) on residual organic layer depth at the plot level. A separate GLM was used to examine the effects of continuous, stand level factors/variables (basal area, stand density, foliar biomass, and day of year of burning) on residual organic layer depths at the plot level.

As previous studies have shown that residual organic layers less than 3 cm in depth are optimum for germination of and growth tree seedlings (Kasischke and Johnstone, 2005; Greene et al., 2007; Johnstone et al., 2010; Shenoy et al., 2011), we also compared the frequency of shallow organic layers (number of measurement of residual organic layer in a site <3 cm deep) between trees and under trees. These data were arc sine transformed to meet assumptions of normality.

Statistics were conducted with SAS 9.2 (SAS Institute Inc., Cary, NC, USA; Cody and Smith, 1997). All data reported are means ± one standard error.

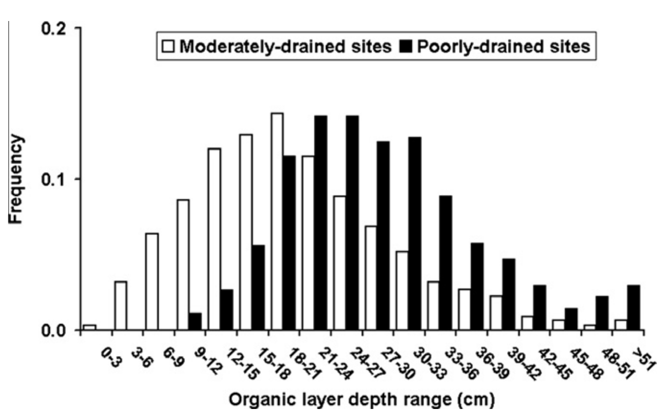

Fig. 3. Histogram of estimated pre-fire organic layer depths from the stands used in this study.

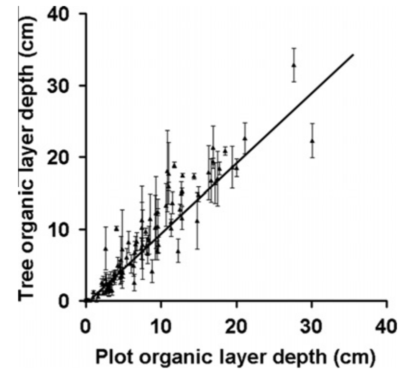

Fig. 4. Relationship between depth of the residual organic layer at the plot scale compared to organic layer depth next to trees. Presented on the *y*-axis are the mid-points between the minimum and maximum depths, with the error bars showing these two values. The correlation (*r*) between plot, tree mid-point, tree minimum and tree maximum depths were all greater than 0.92, $p < 0.0001$). The solid line represents the 1:1 line.

3. Results

3.1. Pre-fire stand conditions

Across the plots, pre-fire organic layer depths ranged from 10.1 to 51.8 cm, and averaged of 25.4 ± 0.8 cm) (Table 2). Plots on poorly-drained sites had thicker organic layers pre-fire (29.0 ± 0.9 cm) than plots on moderately-drained sites (23.9 ± 0.8 cm) ($t = 2.85$ $p < 0.0001$; Fig. 3).

Mean stand densities did not differ between the moderately drained (7145 ± 1009 trees ha^{-1}) and poorly drained (6259 ± 543 trees ha^{-1}) plots ($t = 0.62$, $p = 0.54$). Mean stand basal diameters also did not differ between the moderately drained (6.0 ± 0.3 cm) and poorly drained plots (5.7 ± 0.4 cm) ($t = 0.63$, $p = 0.53$). As expected, mean tree basal diameters declined as stand density increased ($R^2 = 0.51$, $F_{1,62} = 64.51$, $p < 0.001$, density logarithmically transformed).

Table 2
Summary of average and median organic layer depths for the study plots and comparisons of means (parametric *t*-test) and median values (non-parametric comparisons).

	Organic layer depths (mean ± standard error; median ± 95% CI) cm						Plot vs. tree (log transformed)		
	n	Plot			Trees		Means		Medians
		Pre-burn	Mean	Median	Mean	Median	*t*	*p*	*p*
All sites	99	25.4 ± 0.8	7.6 ± 0.6	6.5 ± 1.7	9.0 ± 0.7	7.7 ± 2.3	0.55	0.585	0.570
Sites with early season burns	70	24.7 ± 0.9	8.4 ± 0.7	7.6 ± 2.3	10.0 ± 0.9	8.7 ± 2.5	0.26	0.795	0.398
Sites with late season burns	29	27.0 ± 1.8	5.7 ± 0.9	4.9 ± 2.6	6.6 ± 1.2	4.9 ± 4.7	1.02	0.314	1.000
Moderately-drained sites	67	23.9 ± 0.8	5.3 ± 0.5	4.2 ± 1.3	6.6 ± 0.7	4.9 ± 1.7	0.68	0.495	0.730
Poorly-drained sites	32	29.0 ± 0.9	12.4 ± 1.0	11.8 ± 3.5	14.0 ± 1.3	12.6 ± 5.4	0.36	0.724	0.803

Table 3
Summary of frequency of samples with organic layer depth <3 cm.

	n	Frequency <3 cm (mean ± standard error)		Plot vs. tree (arcsine transformed)	
		Plot	Trees	*t*	*p*
All sites	99	37.6 ± 3.3	38.7 ± 3.5	0.28	0.782
Sites with early season burns	70	30.5 ± 3.6	33.1 ± 3.8	0.49	0.628
Sites with late season burns	29	54.9 ± 6.5	52.1 ± 7.0	0.11	0.912
Moderately-drained sites	68	49.1 ± 4.0	47.8 ± 4.3	0.08	0.936
Poorly-drained sites	31	12.5 ± 2.5	18.8 ± 4.3	1.34	0.185

Table 4
Results of a general linear model testing whether the controls of class variables (timing of fire and site drainage) on depth of burn varies from locations either beneath or between trees. Mean organic layer depths beneath trees (mid point between maximum and minimum depths measured) were used.

Source	DF	Type III SS	MSE	*F*	*p*
Burning season	1	4.73	4.73	0.15	0.6997
Drainage	1	626.65	626.65	19.76	**<.0001**
Location (between or beneath trees)	1	46.41	46.41	1.46	0.2279
Season × location	1	5.20	5.20	0.16	0.686
Drainage × location	1	0.45	0.45	0.01	0.9054
Drainage × season	1	0.50	0.50	0.02	0.9003
Model	6, 197	2166.00	361.10	11.39	<.0001

3.2. Residual organic layer depths

Residual (post-fire) organic layers averaged 7.6 ± 0.8 cm at the plot scale and 9.0 ± 0.7 cm under trees. The median depth was 6.5 ± 1.7 cm at the plot scale and 7.7 ± 2.3 cm under trees. The depth of the average (mid-point) residual organic layer at the plot-scale was strongly correlated with the residual organic layer depth at the tree (Fig. 4). There were no significant differences found between the average and median depths next to trees and those from across the plot, even though for most cases the values under trees were greater than those from across the plot (Table 2). No significant differences between depths at the plot scale and under trees were found when the samples were grouped by drainage category and by timing of the burn during the growing season (Table 2). There were no differences in the frequency of plots with residual organic layers <3 cm between trees versus beneath trees for all the plots or when grouped by drainage class and time of burn during the growing season (Table 3). Differences in average and median depth and frequency of depth <3 cm existed as a function of drainage category and timing of the burn during the growing season (Tables 2 and 3).

When considered separately, mean organic layer depths at the plot level were significantly different between early (8.4 ± 0.7 cm) and late (5.7 ± 0.9) season burns ($F = 6.75$, $p = 0.01$; Table 2). However, when drainage class was also considered the timing of burning became insignificant (Table 4). Such stand attributes as stand density, basal area and total foliar biomass had no explanatory power over residual organic layer depths (Table 5). Taken together, these results suggest that canopy interception of precipitation is not a dominant factor influencing duff moisture at the time of burning in these forests.

4. Discussion

Because the distribution of the depths of the residual organic layers in our study was positively skewed, using measures of the minimum and maximum residual organic layer depths next to trees may result in an estimate that is somewhat higher than the actual average values. This bias in the data is the likely reason why our results showed there was no difference in the depths of the residual organic layers under trees compared to those at the plot scale, while Boby et al. (2010) showed that the depths under trees were marginally shallower (by only 6%). Regardless of these differences, the results from both studies that used sites located in the 2004/2005 Alaska fire events were substantially different from previous findings from research in Canada, where the residual organic layers under trees were substantially shallower than the organic layers from across the plot (Miyanishi and Johnson, 2002; Greene et al., 2007). Added to previous research, our results show that factors controlling plot-scale spatial variations in the depth of the remaining organic soil in black spruce forests after fire are complex, and vary between different regions of the North American boreal forest. In Alaska, permafrost and topography appear to be much more important in creating conditions conducive to generating sites with exposed mineral soil than within-stand variations associated with the impacts of trees.

The presence of permafrost in many Alaska black spruce forests is an important regulator of duff moisture, which in turn contributes to the vulnerability to deep burning. As a result, permafrost characteristics, including the depth of the active layer as well as seasonal patterns of ground thawing, have been used to explain between plot variations in depth of burning in the black spruce forests of this region (Kasischke and Johnstone, 2005; Harden et al.,

Table 5
Results of a general linear model using continuous stand variables to predict the post-fire organic layer depth.

Source	DF	Type III SS	MSE	*F*	*p*
Basal area (BA)	1	7.33	7.33	0.25	0.6173
Trees per hectare	1	5.40	5.40	0.19	0.6679
Foliar biomass per m^2	1	18.72	18.72	0.64	0.4251
Date of Year (DOY) of burning	1	3.98	3.98	0.14	0.7126
Drainage	1	524.97	524.97	18.04	**<.0001**
BA × DOY	1	2.91	2.91	0.10	0.7528
BA × drainage	1	76.07	76.07	2.61	0.1101
Foliar biomass per m^2 × DOY	1	0.09	0.09	0.00	0.9546
Model	8, 83	1862.09	232.76	8.00	<.0001

2006; Kane et al., 2007; Turetsky et al., 2011). The presence of permafrost may also provide a plausible explanation as to why we did not observe significant within-plot variations in organic depth between locations under trees and away from trees. Permafrost restricts the downward seepage of water and results in extremely moist duff layers immediately above frozen soil. During periods when the duff layers are saturated, the presence of frozen soil results in a horizontal redistribution of soil water such that duff moisture is not strongly influenced by tree shadowing of precipitation (Fig. 5). In addition, as previously suggested by Greene et al. (2007), because our plots were located in areas that burned during large fire events that took place in the middle of extended periods of low precipitation, the influence of tree shadowing of precipitation was again minimized. This was also evident in the homogeneity of residual organic layer depths measured near trees and away from trees following late season fires (Table 2), as well as the lack of any relationship between canopy foliage density and residual organic layer depths across all plots measured. However, our results suggest that the size of tree boles (which influences the amount of foliage) may an influence on plot level consumption of organic layer materials during fires, supporting the findings of Greene et al. (2007).

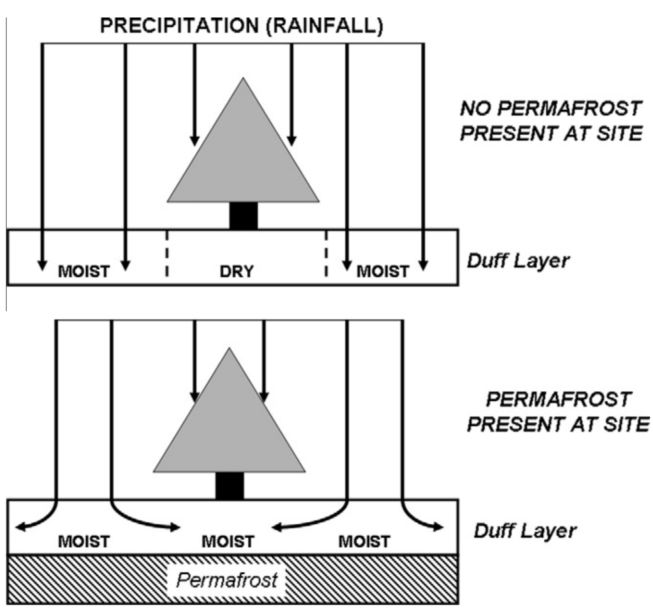

Fig. 5. Schematic diagram of the influence of permafrost on site drainage. The presence of permafrost can result in a horizontal redistribution of moisture in the lower duff layers of mature black spruce forests, which in turn, results in a more uniform deep duff moisture in sites where it is present.

When combined with the recent findings of others, our analyses support the need for continuing research on factors controlling duff moisture and depth of burning in North American boreal black spruce forests. This is especially true for the different ecozones in Canada, where mineral soils and topography (which control site drainage) of sites where black spruce forests are found are often different than found in interior Alaska. Additional research in these other regions is required to understand the full range of factors that influence depth of burning, in particular, the influence of permafrost where it is present. In particular, measurements of duff moisture throughout the growing season as a function of distance from the boles of trees are needed from sites located on different topographic positions with different permafrost characteristics.

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