Variation in postfire organic layer thickness in a black spruce forest complex in interior Alaska and its effects on soil temperature and moisture[1]

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Abstract: This study investigated the relationship between climate and landscape characteristics and surface fuel consumption as well as the effects of variations in postfire organic layer depth on soil temperature and moisture in a black spruce (*Picea mariana* (Mill.) BSP) forest complex in interior Alaska. Mineral soil moisture and temperature at the end of the growing season and organic layer depth were measured in three burns occurring in different years (1987, 1994, 1999) and in adjacent unburned stands. In unburned stands, average organic layer and humic layer depth increased with stand age. Mineral soil temperature and moisture varied as a function of the surface organic layer depth in unburned stands, indicating that as a stand matures, the moisture content of the deep duff layer is likely to increase as well. Fires reduced the depth of the surface organic layers by 5 to 24 cm. Within each burn we found that significant variations in levels of surface fuel consumption were related to several factors, including mineral soil texture, presence or absence of permafrost, and timing of the fires with respect to seasonal permafrost thaw. While seasonal weather patterns contribute to variations in fuel moisture and consumption during fires, interactions among the soil thermal regime, surface organic layer depth, and previous fire history are also important in controlling patterns of surface fuel consumption.

Résumé : Cette étude porte sur la relation entre les caractéristiques du climat et du paysage et la consommation de combustibles de surface ainsi que sur les effets de la variation dans la profondeur de la couche organique sur la température et la teneur en eau du sol après un feu dans un ensemble de forêts d'épinette noire (*Picea mariana* (Mill.) BSP), situées dans la région intérieure de l'Alaska,. Des mesures de température et teneur en eau du sol minéral à la fin de la saison de croissance et des mesures de profondeur de la couche organique et ont été prises dans trois brûlis survenus en 1987, 1994 et 1999 ainsi que dans des peuplements adjacents non brûlés. Dans les peuplements non brûlés, la profondeur moyenne de la couche organique et de la couche d'humus augmentait avec l'âge du peuplement. La teneur en eau et la température du sol minéral variaient en fonction de l'épaisseur de la couche organique en surface dans les peuplements non brûlés, ce qui indique que la teneur en eau de la couche profonde d'humus a sans doute aussi tendance à augmenter à mesure qu'un peuplement vieillit et devient plus mature. Les feux réduisent la profondeur des couches organiques de surface de 5 à 24 cm. Dans chaque brûlis, nous avons observé que des variations importantes dans la consommation de combustibles étaient reliées à plusieurs facteurs, incluant la texture du sol minéral, la présence ou l'absence de permagel et le moment où les feux sont survenus en relation avec le dégel saisonnier du permagel. Tandis que les patrons saisonniers du climat contribuent aux variations dans la teneur en eau des combustibles et leur consommation lorsqu'il y a un feu, les interactions entre le régime thermique du sol, la profondeur de la couche organique et l'historique des feux précédents sont également importants pour déterminer les patrons de consommation des combustibles de surface.

[Traduit par la Rédaction]

Introduction

Black spruce (*Picea mariana* (Mill.) BSP) is a widely distributed tree species throughout northern North America and represents 30% to >90% of the forest cover in the ecoregions of Canada and Alaska (Amiro et al. 2001; Yarie and Billings 2002). Mature stands have well-developed surface organic layers on top of the mineral soil that consist of horizons of litter, lichen, and live and dead mosses on top of partially decomposed organic soils (referred to as duff by the fire science community; Harden et al. 1997, 2004; Kasischke et al. 2000; Miyanishi and Johnson 2002). In drier sites, a layer of lichen forms the top surface of this organic layer, whereas in more poorly drained sites, a layer of moss may be present. In moist black spruce forests, net primary productivity of mosses ranges between 24 and 77 $g\ C{\cdot}m^{-2}{\cdot}year^{-1}$

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(Oechel and Van Cleve 1986; Bisbee et al. 2001), and moss biomass is an important source of the dead material that accumulates in the surface organic layer. The depth of the surface organic layer is between 5 and >50 cm in black spruce forests, depending upon (*i*) inputs from litterfall, moss and (or) lichen production, and root turnover; (*ii*) output from heterotrophic respiration; and (*iii*) the level of burning of this layer during fires (Harden et al. 2000).

Two fire regime characteristics are important in regulating the depth of the surface organic layer: the frequency of fire activity and the amount of organic matter consumed during each fire event (Kasischke et al. 1995; Harden et al. 2000). Kasischke et al. (2000) showed that the levels of consumption of the surface organic layer in black spruce forests in Alaska (where preburned depths ranged between 14 and 40 cm) were variable, reducing organic layer depth by 6 to 24 cm across different fire events and by 8 to 24 cm within a single event. In black spruce forests with shallower organic layer depths (10 to 14 cm), organic layer depth reductions ranged between 5 and 9 cm (Miyanishi and Johnson 2002; Harden et al. 2004). Miyanishi and Johnson (2002) found that changes in the distribution of organic layer depths from normal in unburned stands to positively skewed in burned stands appear to reflect interactions between the propagation of smoldering combustion and biophysical limits on fuel amounts or flammability.

Surface fuel consumption (SFC) or reduction in the depth of the surface organic layer during burning is regulated by the moisture content of the organic layers at the time of the fire and by the duration of the combustion period (Dyrness and Norum 1983; Frandsen 1991; Miyanishi and Johnson 2002). Factors controlling moisture content include seasonal and interannual weather patterns (Amiro et al. 2001), topography and slope (Swanson 1996; Miyanishi and Johnson 2002), soil drainage as influenced by soil texture (Swanson 1996; Harden et al. 1997, 2000), and timing of the fire during the growing season, which influences the depth of seasonal permafrost thaw (Black and Bliss 1978; Viereck 1983; Landhaeusser and Wien 1993; Kasischke et al. 2000).

Fire indirectly influences the depth of the surface organic layer through its effects on energy and water budgets (Chambers and Chapin 2003; Yoshikawa et al. 2003; Zhuang et al. 2001, 2003; Liu et al. 2005). As the depth of the surface organic layer increases in black spruce forests during succession, its insulating properties cool the ground surface and then lead to permafrost formation (Viereck 1983). Direct solar illumination of the forest floor dramatically increases after a fire because of the reduction in foliage interception of direct and diffuse radiation. Fire either increases or decreases surface albedo depending on fire type and severity (French 2002), thereby altering the amount of absorbed solar radiation. Direct energy transfer from the atmosphere to the ground increases because fire consumes a portion of the insulating organic layer, and there is less latent heat loss from the ground surface through transpiration because there is less vegetation. As a result, there is a net transfer of energy to the ground over the entire year, a warming of the soil, and increased thaw of the permafrost layer if it is present. Soil warming can increase heterotrophic respiration (O'Neill et al. 2003; Kim and Tanaka 2003; Bergner et al. 2004) and lower the rate of accumulation of undecomposed organic matter.

The focus of this study was to investigate factors controlling variations in the amount of organic matter remaining after three different fires in the upper Tanana Valley of Alaska. Field measurements of organic layer depths in burned and unburned stands were used to assess SFC and carbon loss from fire in the three burns. We used these data to assess the hypothesis that depth of the organic layer present in a black spruce forest directly influences depth to permafrost, which, in turn, affects the mineral soil drainage and moisture. Permafrost effects on the moisture content within the active layer are expected to occur through control of gravity-driven drainage of water. The moisture content of the active layer plays an important role in surface fuel consumption because moisture in the deeper organic layer results from the upward wicking of water from mineral soil (Samran et al. 1995). We assessed the importance of these interactions in regulating soil conditions by testing relations between organic layer depth and soil temperature and moisture in the upper mineral soil horizons at the end of the growing season in both burned and unburned stands. Based on these data, we present a conceptual model of how antecedent fire history at a site may regulate the moisture level of deep duff layers, thus influencing organic layer consumption during subsequent fires. Research on how variations in surface fuel consumption influence patterns of postfire plant regeneration is presented in a companion paper (Johnstone and Kasischke 2005).

Materials and methods

Study site descriptions

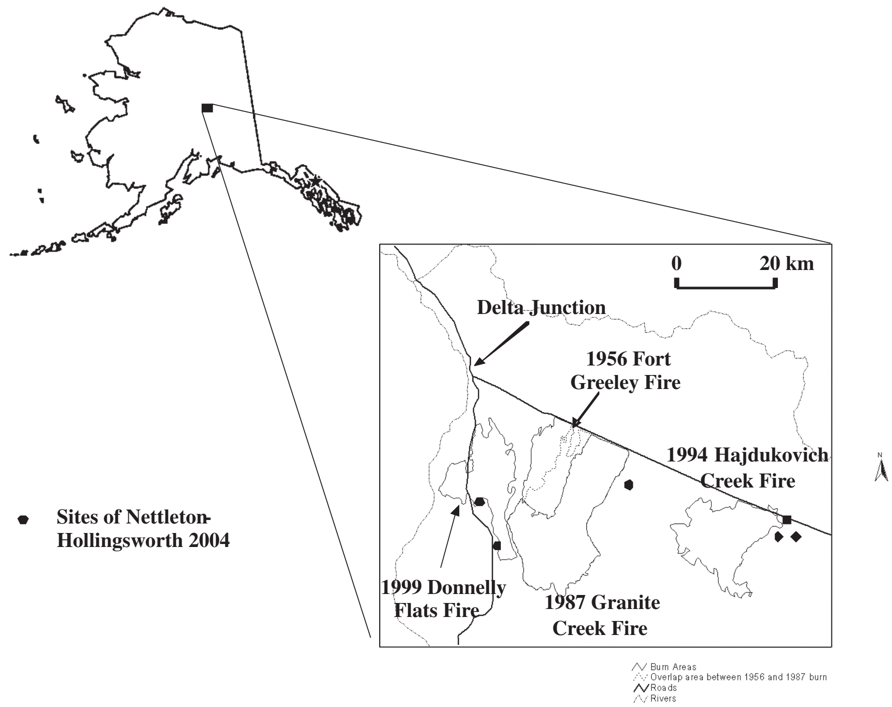
Forest stands sampled for this study were located to the south and east of Delta Junction, Alaska, in the Tanana River valley (this region is centered at 63°50′N, 145°40′W). All stands were located on a flat plain bounded on the north, south, east, and west by the Tanana River, Alaska Range, Gerstle River, and Big Delta River, respectively, and were associated with fires that occurred in 1956, 1987, 1994, and 1999 (Fig. 1). Stands were sampled within the perimeter of these fire events, as well as in adjacent unburned areas or in unburned islands within the burn perimeters.

The nearest climate station with long-term data (1937–2004) was located in Big Delta, Alaska, approximately 30 km to the west of the study region. Average annual temperature at this station was –2.1 °C, with the coldest month being January (–19.7 °C) and the warmest, July (15.6 °C). Average precipitation was 29.0 cm, with three-quarters of this amount occurring during the growing season (May to September). Permafrost is common in the area, particularly in the more poorly drained areas frequently dominated by black spruce.

The majority of the forest stands sampled were associated with the 8900-ha Hajdukovich Creek (HC94) fire that began on 14 June and ended in early September 1994 (Michalek et al. 2000). The active fire perimeter for this event was intermittently mapped, and records indicate the fire started in the far western corner of the event and had spread throughout the southwest two-third of the perimeter by mid-July. At this time the fire became inactive and remained stationary for several weeks. In mid-August, fire activity increased, and the fire spread into the northeast portion of the event.

Average temperature during the summer of 1994 was 1.5 °C above the long-term average (14.2 °C), and precipitation was

Fig. 1. Location of the Delta Junction, Alaska, study region and boundaries of recent fire events.



50% of the average of 12.4 cm for June and July, and 30% of the average of 5.1 cm for August.

The Alaska Fire Service used weather data collected in Delta Junction, Alaska, (Fig. 1) to estimate fire weather indices during the HC94 burn based on the Canadian Forest Service's Canadian Forest Fire Weather Index (FWI) System (Stocks et al. 1989). The FWI System computes three different moisture indices based upon daily noon-time measurements of temperature, precipitation, relative humidity, and wind: the Fine Fuel Moisture Code for foliage, the Duff Moisture Code for the upper surface organic layers, and the Drought Code for the lower surface organic layers. For the Delta Junction region, the Buildup Index (BUI) (a linear combination of the Duff Moisture Code and the Drought Code) increased continuously from 36 in mid-June to 120 in mid-August.

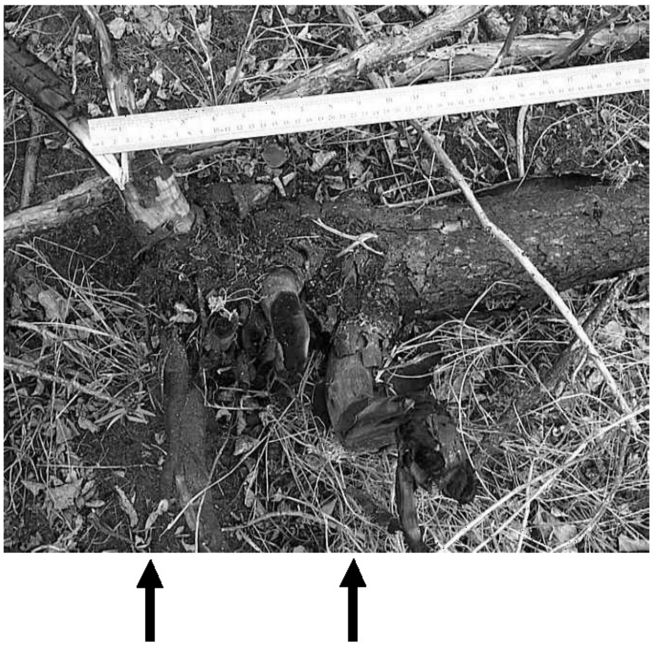
Additional stands were sampled at two other burns — the 1987 Granite Creek fire (GC87) and the 1999 Donnelly Flats (DF99) fire (Fig. 1). The GC87 event was a rapidly spreading, 20 000 ha fire that occurred during the last week of May and first week of June of 1987. The 6700-ha DF99 fire occurred over a 2-week period beginning on 10 June 1999. Using weather data collected at Fort Greely on the northern edge of this fire, the Alaska Fire Service calculated the BUI to be 115 during the first 4 days of this fire when most of the burning occurred. No fire weather indices were estimated for the FG87 burn, but Big Delta weather records showed the highest temperature ever recorded for 1 June was in 1987 (30.6 °C), and the amount of precipitation during March to May was 50% of the long-term average of 3.5 cm. Finally, we measured organic layer depths in one stand located in the 6300-ha 1956 Fort Greeley (FG56) fire.

The overall topography of the study region is flat (slope <1%), with elevations of 560 m near the base of the Alaska Range that gently slope over a distance of 20 km to elevations of 370 m at the northern-most sites near the Alcan Highway. Data from soil pits showed that the mineral soils consisted predominantly of a 20 to 60 cm deep layer of silt loam overlying deposits of sand and gravel. In some areas, active stream deposition resulted in a layer of cobble (stones 5 to >20 cm in diameter) being deposited directly on top of the silt layer. Sites in a till plain located in the northern part of the DF99 burn had shallower silt-loam layers (5 to 20 cm) overlying deposits of gravelly loam. For more detail on the soils of this region, see O'Neill et al. (2003).

An existing classification for black spruce forests in Alaska (Nettleton-Hollingsworth 2004) (which included vegetation samples from within the region; Fig. 1) was used to classify the unburned black spruce stands in this study (Appendix A, Table A1). Mature stands adjacent to the FG87 fire were classified as acidic, dry black spruce forests, and those associated with the HC94 fire were either nonacidic, dry black spruce forests or nonacidic, wet black spruce forests. One wet stand from the HC94 fire was classified as nonacidic, wet black spruce with tussocks, because of the high abundance of cottongrass (*Eriophorum vaginatum* L.) tussocks, which indicated extremely poorly drained conditions. The stands in the northern part of the DF99 fire were acidic elevational woodlands, while those adjacent to the burn in the southern portion were nonacidic, dry black spruce forests.

Mineral soils underlying the black spruce forests in the region were overlain by well-developed organic profiles of variable depth (<10 to >30 cm). The floors of the mature acidic and nonacidic black spruce forests in the study region consisted of a layer of moss (dominated by feathermoss, *Hylocomium splendens* (Hedw.) B.S.G. and *Pleurozium schreberi* (Brid.) Mitt., with scattered patches of sphagnum

Fig. 2. Example of adventitious roots on burned black spruce tree boles.



moss, *Sphagnum* spp.; O'Neill 2000). In the acidic elevational woodlands, the forest floors were mostly covered by lichen (*Cladina* spp., *Cladonia* spp., and *Stereocaulon* spp.) interspersed with patches of feathermoss.

Field measurements

Field measurements were collected during the summers of 2001 to 2003, and data from previous studies were also used (Appendix A, Table A1). Field surveys included measurements of (*i*) organic layer depth; (*ii*) depth to the gravel layer within the mineral soil; (*iii*) depth of adventitious roots; (*iv*) tree diameter and stand density; (*v*) mineral soil temperature and moisture; and (*vi*) year of the previous fire.

Organic layer depth measurements were collected in 19 unburned and 42 burned black spruce stands (Appendix A, Table A1). In most of the 24 HC94 burn stands, organic depth measurements were collected at 5-m intervals along the five 50-m transects used for sampling vegetation ($n = 55$, Johnstone and Kasischke 2005). Three stands in the HC94 fire were sampled during other studies (Appendix A, Table A1). Twelve of the HC94 burned stands burned in July, and 12 burned in August (Appendix A, Table A1). All other burned and unburned stands were sampled by establishing two parallel 100-m transects (separated by 100 m) and measuring depths at 5-m intervals.

At each sample point, we extracted a 20 cm × 20 cm surface organic layer core using a flat-bladed shovel, and we measured the depth of the different layers (lichen, live moss, dead moss, fibric soil, mesic soil, and humic soil) following the approach of O'Neill (2000). In the HC94 burn sites, a soil pit located near the center point of the base transect was excavated to determine the depth of the silt or silt–sand layers present on top of gravel as a measure of relative soil drainage.

Black spruce trees at our study sites commonly exhibited evidence of adventitious root formation. These roots were used to provide an estimate of prefire organic layer depths in sites where we judged severe burns had occurred. Black spruce trees often produce adventitious roots within the organic layer during the course of stand development in response to higher temperatures or aeration in surface layers compared with cold or waterlogged conditions in deeper soil layers that develop as organic matter accumulates (LeBarron 1945). The production of adventitious roots results in a rising of the apparent root collar above the original root collar, which frequently is buried in deeper soil layers or lost to decomposition (DesRochers and Gagnon 1997; Parent et al. 2000). We measured the distance between the base of the rooting zone to the uppermost adventitious roots (Fig. 2) on 20 to 30 trees in nine stands in the HC94 burn and two stands in the GC87 burn. To assess the depth below the organic layer surface at which adventitious roots are formed, we measured the distance from the uppermost adventitious roots to the surface of the organic layer for 39 live trees in two unburned stands adjacent to the HC94 burn.

In the unburned stands, we used the point-quarter sampling technique to estimate stand density and basal diameter of the canopy trees (Mueller-Dombois 1974). In the HC94 burned stands, all dead spruce trees within ±1 m of each 50-m transect were counted, and their basal diameter was measured. Time since last burn (in unburned stands) or since the fire previous to the most recent burn (in burned stands) was determined through ring counts from disks or cores sampled from the base of the tree. The time since last burn was determined from the ages of the oldest trees by O'Neill (2000) and Nettleton-Hollingsworth (2004) for several of our unburned stands and by Johnstone and Kasischke (2005) for the stands in the HC94 burn (Appendix A, Table A1). In the remaining unburned black spruce stands (except for one stand adjacent to the 1987 fire), we collected five stem disks and determined time since last burn following the procedures of Johnstone and Kasischke (2005).

We collected soil temperature and moisture data between 17 and 20 August 2003 to assess relations among organic layer depth, soil temperature, and soil moisture. Measurements in late August can be used to target soil temperature and moisture associated with maximum active layer depths in black spruce forests in interior Alaska. Our approach used data collected across a suite of sites with different organic layer conditions, rather than intensive soil monitoring at a few sites. Because gravel and stone layers were common in our soils, we were unable to use surface probing with a metal rod to assess variations in active layer depth. Data were collected in 17 unburned stands (Appendix A, Table A1). We also collected data in 13 burned stands within the HC94 fire selected to represent the range of depths that occurred within this event (Appendix A, Table A1). Three soil pits, selected to represent the range of organic layer depths at the site, were excavated at each site to the depth of permafrost or to 40 cm below the mineral soil surface when the underlying gravel layer was encountered. We measured the depth of the organic layers on top of the mineral soil, depth of permafrost below the mineral soil – organic soil interface (where possible), and depth of the different organic layers. Beginning at the interface between the organic layer and mineral soil, we measured soil temperature at 5-cm intervals to a depth of 30 cm to within ±0.1 °C using a digital thermometer, and we measured soil moisture on two opposite sides of the soil pit at 10-cm intervals to within ±1% using a Campbell Scientific Hydro-sensor.

Analytical methods

We tested for normality in the distribution of the organic layer depths in the unburned forest types and different groups of burned stands using a Shapiro–Wilk W statistic, and we also tested for significant skewness and kurtosis (Zar 1996). In this analysis, we divided the HC94 sites into two categories based on whether the sites burned in July or August. We also divided the DF99 sites into two categories based on community type: the nonacidic, dry black spruce forests in the southern part of the burn and the acidic elevational woodland sites in the northern part. The northern DF99 sites and the FG87 stands were further divided into categories based on organic layer depths: shallow organic layer sites where >25% of the samples had organic layers depths <1 cm, and deep sites where organic layer depths exceeded this threshold.

We compared the stand age, tree density, basal diameter, and organic layer depth data as a function of black spruce forest type and between burned and unburned stands using a one-way analysis of variance (ANOVA). Significant test results were followed by a Tukey's multiple comparison test to assess differences among forest types. In cases where data distributions were non-normal, we used nonparametric approaches, either the Kruskal–Wallis test (three or more comparisons) or the Mann–Whitney test (two comparisons).

Previous studies used seasonal weather variations as a basis for explaining differences in the levels of consumption of surface organic layer biomass in black spruce forests during fires (Dyrness and Norum 1983; Amiro et al. 2001; Miyanishi and Johnson 2002). Based on data collected during controlled burns, Amiro et al. (2001) developed an empirical model to estimate SFC in black spruce forests as a function of the Buildup Index (BUI) of the FWI System. We used the BUIs computed by the Alaska Fire Service for the HC94 and DF99 events to calculate SFC using the Amiro et al. (2001) model. We compared the model predictions with SFC estimates derived from our field estimates for burned stands within the HC94 and DF99 fires. At three stands in the HC94 fire and five stands in the DF99 fire, burned stands were located immediately adjacent to unburned stands, and we estimated SFC by comparing the organic layer depths. In nine additional stands in the HC94 burn, we used the depths of the adventitious roots as a basis to support an assumption that these stands had a deep organic layer prior to the fire. In this case, we compared the depths of the burned stands with the average depth for all unburned stands in the area. We converted the measurements of organic layer depth to surface-layer carbon by using bulk density and percent carbon measurements from black spruce stands in the Delta Junction and Tok, Alaska, regions (O'Neill 2000 as summarized in Kasischke et al. 2000). We estimated that shallow duff (lichen, moss, and fibric soil) contained 1.5 $t\ C{\cdot}ha^{-1}{\cdot}(cm\ depth)^{-1}$, and deep duff (mesic and humic soil) contained 5.2 $t\ C{\cdot}ha^{-1}{\cdot}(cm\ depth)^{-1}$. To estimate SFC, we subtracted the carbon remaining in the burned area from the carbon present in the unburned stands.

Results

Unburned black spruce stands

The mature black spruce stands in the Delta Junction region exist within a complex landscape mosaic in terms of stand age, plant community structure, organic layer depth, mineral soil texture, and soil temperature and moisture (including the presence or absence of near-surface permafrost). The characteristics of these stands are summarized in Table 1, as are the results of the statistical tests used to compare the stand characteristics. In 2002 the ages of these stands ranged from 75 to 305 years, and they differed as a function of forest type (ANOVA, $F = 8.725$, $p = 0.0015$), with the nonacidic, wet black spruce stands being significantly older than the acidic, dry black spruce and the acidic elevational woodland stands (Tukey, $p < 0.05$; Table 1).

The total depths of the organic layer in all unburned forest types had normal distributions with no significant skewness or kurtosis (Shapiro–Wilk, $p > 0.05$; Table 1), while the humic layer depths were non-normally distributed, with a positive skewness (Shapiro–Wilk, $p < 0.05$). The total depths of the organic layer were significantly different among all forest types (ANOVA, $F = 144.2$, $p < 0.001$; Table 1). The humic layer depths also varied significantly across forest types (Kruskal–Wallis statistic = 222l1, $p < 0.01$), and only the nonacidic, wet black spruce and the nonacidic, wet black spruce with tussocks forest types had similar humic layer depths (Table 1). Mean tree densities did not differ across forest types (ANOVA, $F = 1.64$, $p < 0.17$), although there were significant differences in mean basal diameters (ANOVA, $F = 2.98$, $p = 0.026$; Table 1). These differences were attributable to very low basal diameters of spruce in the nonacidic, wet black spruce with tussocks stand and high diameters in the acidic black spruce stands (Table 1).

Using data from all unburned stands, we observed that the total depth of the surface organic layer and depth of the humic layer both increased as a function of time since last burn and appeared to reach a maximum after 200 years (Fig. 3). There was a positive linear correlation between total depth of the surface organic layer and humic layer depth ($r = 0.72$, $p < 0.001$).

Average temperature in the top 20 cm of the mineral soil was significantly correlated with depth to permafrost in all mature black spruce stands where both variables were measured ($r = 0.79$, $p < 0.0001$). There was also a strong correlation between organic layer depth and late summer soil temperature and moisture in the top 20 cm of mineral soil, with soil temperature being inversely proportional to depth and soil moisture being proportional to depth (Figs. 4*a*, 4*b*). The different forest types can be organized along a temperature–moisture gradient, with the coolest and wettest sites being the nonacidic, wet black spruce forest stands and the warmest and driest being the acidic elevational woodlands (Fig. 4*c*). Both temperature (ANOVA, $F = 29.2$, $p < 0.001$) and moisture (ANOVA, $F = 33.4$, $p < 0.001$) differed significantly among the forest types. Soils in the acidic elevational woodland stands were warmer than soils in other forest types (Tukey, $p < 0.01$), while the nonacidic, dry black spruce and

Table 1. Summary of burn year, stand characteristics, surface organic layer depths, and distribution statistics for the different burned and unburned forest stands in the study region.

		Stand characteristic			Surface organic layer depth (cm)		Distribution statistics		
Forest type	No. of stands	Burn year	Density (stem·ha^{-1})*	Basal diameter (cm)	Total	Humic layer	Shapiro–Wilk W	Skewness	Kurtosis
Unburned stands									
Nonacidic, wet black spruce with tussocks	1	1815ab	5 888 ± 1 074a	4.4±0.2a	33.2±2.2	7.6±1.1a	0.949	0.61	–0.44
Nonacidic, wet black spruce	4	1754±38a	4 892 ± 684a	6.5±0.2ab	25.1±0.2	5.6±0.2ab	0.982	0.33	0.29
Nonacidic, dry black spruce	7	1866±9ab	7 188 ± 1 483a	6.9±0.3ab	21.6±0.3	3.8±0.2ab	0.993	–0.08	–0.12
Acidic, dry black spruce	3	1910±1b	4 973 ± 897a	8.2±0.4b	18.4±0.5	1.8±0.2b	0.979	–0.36	0.38
Acidic elevational woodland black spruce	3	1915±5b	4 512 ± 950a	8.2±0.3b	10.8±0.4	0.6±0.2b	**0.983**	0.32	0.08
Burned stands									
Nonacidic, wet black spruce with tussocks	1	1915	19 440 ± 1 042	3.2±0.001	26.6±1.2	9.2±0.9	**0.914**	**0.78**	–0.29
Acidic, dry black spruce; GC87 area, deep	4				6.8±0.3		**0.980**	**0.42**	**0.09**
Acidic, dry black spruce; GC87 area, shallow	2				2.5±0.4		**0.863**	**1.3**	**1.31**
Nonacidic black spruce; HC94 area, July	12	1860±15	6 931 ± 426	6.2±0.05	9.9±0.3	4.3±0.1	**0.908**	**1.23**	**1.66**
Nonacidic black spruce; HC94 area, August	12	1863±11	9 031 ± 673	5.2±0.04	2.1±0.1		**0.587**	**5.65**	**51.88**
Nonacidic, dry black spruce; DF99 area	3				10.4±0.3		**0.966**	**0.57**	**1.57**
Acidic elevational woodland black spruce; DF99 area, shallow	6				1.5±0.1		**0.970**	**0.44**	**–0.16**
Acidic elevational woodland black spruce; DF99 area, deep	3				4.6±0.2		**0.905**	**1.07**	**1.11**

Note: Data for the stand characteristics and surface organic layer depths are presented as means ± standard error. For the stand characteristics and the total surface organic layer depths of the unburned stands, groups within a column that do not share a letter are significantly different (Tukey multiple comparison test, $p < 0.05$). For the humic layer depths, groups that do not share a letter are significantly different (Mann Whitney test, $p < 0.05$). Values shown in bold in the columns of distribution statistics indicate stands that did not meet the assumption of normality or exhibited a significant degree of skewness or kurtosis (Shapiro–Wilk, $p < 0.05$).

*The standard error for the stand density in the unburned stands was derived by dividing each transect into groups of five sample points

Fig. 3. Relationship between stand age (time since last burn) and surface organic layer and deep-duff depth in unburned black spruce stands in the Delta Junction region. The different symbols represent different black spruce types (open diamond, nonacidic, dry black spruce; filled diamond, nonacidic, wet black spruce; open square, nonacidic wet black spruce forest with tussocks; filled square, acidic, dry black spruce forests; and filled triangle, acidic elevational woodland black spruce). Time since last burn was estimated as the age of the oldest sampled tree. For the total organic soil layer, least squares regression resulted in an equation of the form: depth = 31.8 – 1359/age ($r^2 = 0.62$, $p < 0.001$). For the humic layer, the equation was depth = 6.9 – 391/age ($r^2 = 0.34$, $p < 0.002$).

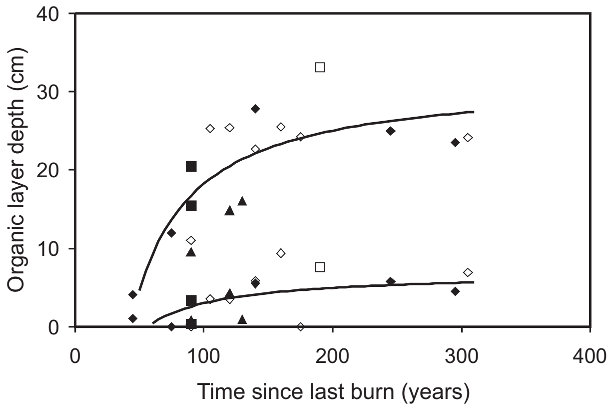
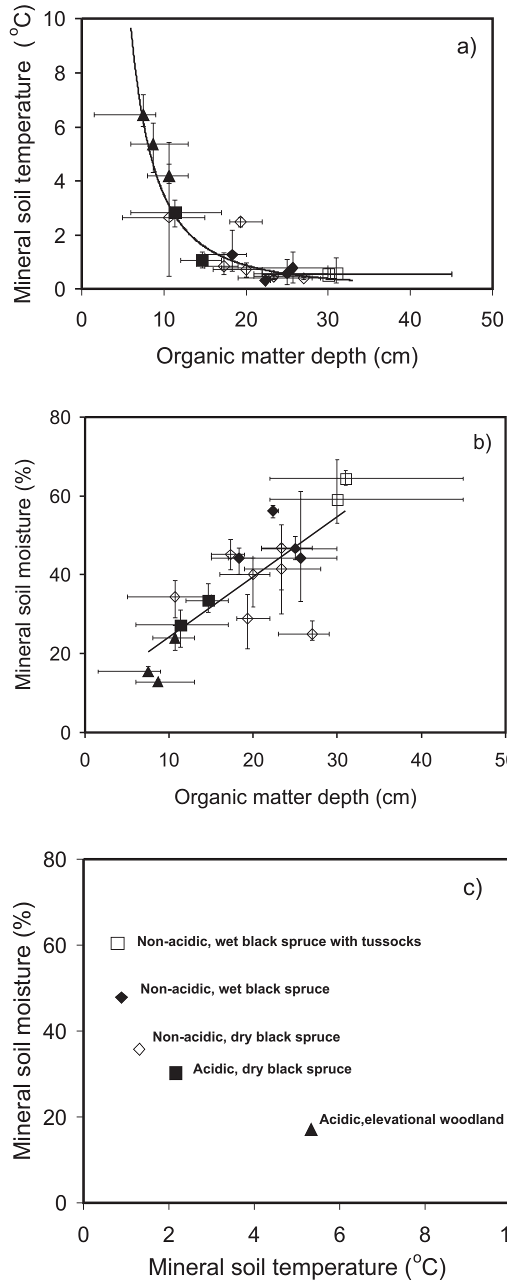


Fig. 4. Average (*a*) soil temperature and (*b*) moisture in the top 20 cm of mineral soil as a function of organic layer depth in unburned black spruce forest stands in the Delta Junction, Alaska region. These data were collected between 17 and 20 August 2003. The error bars represent the range between high and low values collected from three soil pits in each site. The symbols are the same as those used in Fig. 3. For the soil temperature, least squares regression resulted in an equation of the form: temperature = 341(depth$^{-1.99}$) ($r^2 = 0.82$, $p < 0.0001$). For soil moisture, the equation was moisture = 1.54(depth) + 8.86 ($r^2 = 0.61$, $p < 0.001$). (*c*) Relationship between soil temperature and moisture in the different black spruce forest types.



the acidic, dry black spruce stands were the only two forest types that did not differ in soil moisture (Tukey, $p < 0.05$).

In summary, although there were few differences in the forest stand characteristics among forest types, the total depth of the organic layer and the depth of the humic layer varied among forest types. Organic layer depths were correlated with soil temperature and moisture, and soil temperature and depth to permafrost were correlated across all sites.

Burned black spruce stands

Organic layer depths in the burned sites were not normally distributed (Shapiro–Wilk, $p < 0.05$) and exhibited varying degrees of positive skewness or increased kurtosis (Table 1, Fig. 5). Within each burn, the sites with the shallower organic layers were more strongly skewed and kurtotic than sites with deeper organic layers (Fig. 5). In each burn, organic layer depths in the adjacent unburned stands were significantly greater than depths in the one or two categories (deep and shallow organic layers) of burned stands, and the differences between depths in the burned categories were significant (based on pairwise, nonparametric tests; Mann–Whitney, $p < 0.01$). In August 2003 the top 20 cm of the mineral soil profile in the HC94 burn was warmer and drier than that in adjacent unburned stands, with both soil temperature and moisture being linearly proportional to the depth of the organic layer remaining after the fire (Fig. 6).

Several lines of evidence lead us to conclude that variations in postfire organic layer depths in the burned stands were associated with variations in fire severity. The distance between the adventitious and basal roots in the HC94 burned stands ranged between 16.5 cm (SE, ±0.6 cm) and 24.9 cm (±1.2 cm), while the distance from the adventitious root to the organic layer surface in the unburned stands averaged 6.6 cm (±0.6 cm). These measurements suggest that the prefire depth of the organic layers around tree bases in the burned stands ranged from 26.7 cm (±0.3 cm) to 35.9 cm (±0.2 cm) and are consistent with the deeper portions of the

Fig. 5. Distribution of organic layer depths in burned black spruce stands. Each panel presents data from a separate burn, with individual sites separated into classes of deep or shallow depths of remaining surface organic matter.

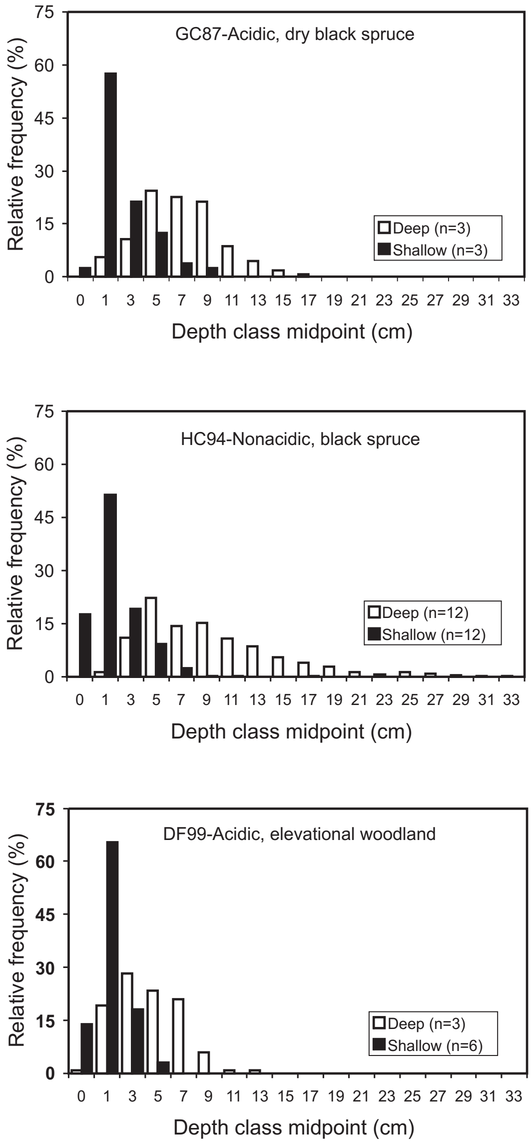
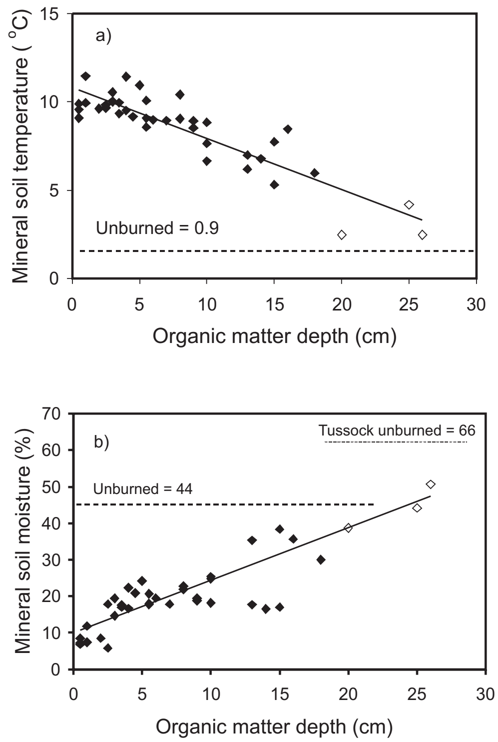


Fig. 6. Average (*a*) temperature and (*b*) moisture in the top 20 cm of mineral soil as a function of organic layer depth in the burned black spruce stands in the HC94 fire based on data collected in August 2003. The broken lines represent the average soil temperature and moisture in the unburned stands adjacent to the fires. The open diamonds are from sites with tussocks. Least squares regression (using all points) resulted in the following equations: temperature = 11.3 – 0.30(depth) (r^2 = 0.80, p < 0.0001); moisture = 10.3 +1.33(depth) (r^2 = 0.74, p < 0.0001).



organic layers observed in the adjacent unburned stands. The distances between the adventitious roots in the two GC87 stands were 15.9 cm (±0.6 cm) and 16.5 cm (±0.6 cm) and are again consistent with the deeper portions of the organic layers found in the adjacent unburned stands. In addition, direct comparisons of depths in structurally similar, adjacent burned and unburned stands from all three fire events suggest that fire severity was the primary factor driving variations in postfire organic layer depths within a burn.

The above measurements suggest that differences in postfire organic layer depths between sites that burned in July and sites that burned August in the HC94 burn are associated with changes in the levels of fuel consumption between the two time periods. There are four possible explanations for the differences in burn depth: (*i*) seasonal variations in fire weather; (*ii*) seasonal thawing of permafrost; (*iii*) age-related variations in depth, which, in turn, control deep duff moisture (Fig. 4*b*); and (*iv*) variations in site drainage controlled by mineral soil texture (depth to gravel). When applied to 1994 conditions, the BUI-based model of Amiro et al. (2001) predicted that SFC consumption would increase from 8.9 t C·ha^{-1} in July to 18.2 t C·ha^{-1} in August. These estimates are low compared with the SFC estimates derived from our field observations of 15.9 t C·ha^{-1} (±7.5 t C·ha^{-1}) (July) and 49.6 t C·ha^{-1} (±0.6 t C·ha^{-1}) (August). While the increase in the depth of burning from July to August can partly be attributed to warmer conditions that occurred at a regional scale in August, it is very unlikely that deep burning of the organic layers in the HC94 burn in August would have occurred without seasonal thawing of permafrost. There was no correlation between stand age or depth to the gravel layer (a measure of site drainage) and depth of burn in the July or August plots (r < 0.2, p > 0.5). Thus, it appears that the most likely explanation for the increased depth of burn between July and August in the HC94 fire was a combination of warmer, drier weather, which dried the upper duff layers, and the progression of seasonal permafrost thaw that allowed moisture to drain from the deep duff layers.

In contrast with the results from the HC94 burn, our field estimates of SFC in the DF99 burn were substantially lower than the 19.7 t C·ha^{-1} predicted by the BUI model. In the nonacidic, dry black spruce sites, comparison of organic layer depths in adjacent burned and unburned stands produced a

SFC of 7.5 t C·ha^{-1} (±0.5 t C·ha^{-1}), while for the acidic elevational woodland sites, the estimate was 9.5 t C·ha^{-1} (±0.1 t C·ha^{-1}). We believe that the SFC in these sites was lower than predicted for two reasons. At the time of the fire in early June 1999, seasonal thawing of permafrost had not yet occurred in the nonacidic, dry black spruce sites, and impeded soil drainage resulted in higher moisture in the lower and upper duff layers. At the acidic elevational woodland sites, permafrost was absent and did not have an effect on duff moisture. However, initial organic layer depths in these stands were low, which provides a direct limitation of the potential SFC and may also restrict the propagation of smoldering combustion (Miyanishi and Johnson 2002).

Discussion

Patterns of surface fuel consumption

Our results are similar to those of Dyrness and Norum (1983) and Miyanishi and Johnson (2002) in that the consumption of the surface-layer organic matter in black spruce forests during fires was highly variable and generated a complex mosaic of surface organic layer depths. Our studies were carried out in a region containing a variety of black spruce forest types whose organic layer depths varied as a function of site drainage, soil chemistry, time since the last burn, and previous fire severity. Because topography varied little across our study area, slope and aspect were not important drivers of soil conditions. Instead, we found that variations in soil temperature and moisture were linked to site-level variations in the depth of the surface organic layer.

The nonacidic black spruce forests in the HC94 burn were similar to the sites where Dyrness and Norum (1983) conducted a series of seven experimental burns. In this study carried out near Fairbanks, Alaska, prefire depths of the surface organic layer averaged 25.3 cm (range of 20.0 to 30.3) and were reduced by an average of 12.2 cm during the controlled burns (Dyrness and Norum 1983). While this value is similar to our estimate of a 14.5 cm average reduction in the July sites of the HC94 fire, it is significantly lower than the average 23.1 cm reduction that occurred in the August sites. This comparison supports the observations of Dyrness and Norum (1983) that their controlled burns did not represent the full range of climate conditions that are typical of natural wildfires and thus are likely to underrepresent the potential range of SFC.

The sites studied by Miyanishi and Johnson (2002) had much shallower surface organic layers (average of 10.3 cm, not including a litter layer) than found in any of our sites, with the exception of the acidic elevational woodland sites in the DF99 burn. The reduction in depth observed by Miyanishi and Johnson (2002) averaged 5.3 cm compared with the 8.3 cm reduction in the DF99 acidic elevational woodland sites. The BUIs estimated for the fires studied by Miyanishi and Johnson (2002) ranged between 38 and 80, compared with 115 for the DF99 burn. The higher BUI in the DF99 burn suggests that differences in SFC between the two studies were due to climatic conditions at the time of fire.

In the three burns we studied, we found that the distribution of surface organic depths in areas experiencing deep burning were more positively skewed and had a higher kurtosis than depths in shallowly burned or unburned stands, a result consistent with the Miyanishi and Johnson (2002) study. This pattern appears to result from an increased proportion of samples where deep burning was limited by physical constraints, such as contact with moisture-saturated mineral soil or frozen organic layers. Consequently, patterns of skewness and kurtosis may provide an indicator of fire severity that can be evaluated separately from overall differences in organic layer depth.

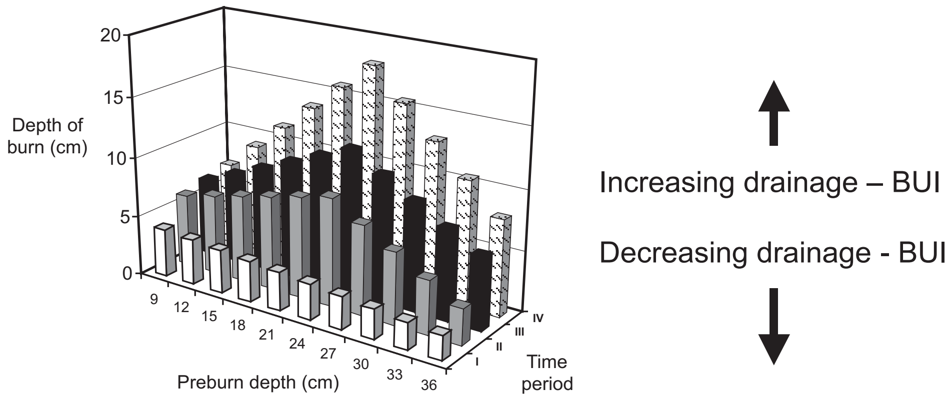
SFC in the black spruce forests of the Delta Junction region ranged between 5.6 and 56.7 t C·ha^{-1}, with the upper level far exceeding the maximum SFC of 21.5 t C·ha^{-1} estimated from the BUI model of Amiro et al. (2001). However, the Amiro et al. (2001) model was based on data collected during experimental burns that did not include black spruce forests with deep organic layers, nor were data collected under extreme drought conditions (B. Stocks, personal communication). These limitations almost certainly contributed to the underestimation of SFC by the Amiro et al. (2001) model for the HC94 fire event, which occurred in forests with thick organic layers and included periods of very dry and severe fire weather.

Factors controlling surface fuel consumption

Previous field-based studies of fire and SFC in black spruce forests have demonstrated the importance of seasonal and interannual variations in fuel moisture, as driven by weather and climate, to patterns of SFC (Dyrness and Norum 1983; Miyanishi and Johnson 2002). In addition, while not directly studying SFC, Swanson (1996) theorized that variations in site drainage driven by topography and soil texture also controlled the depth of burn, with sites located on concave landforms and poorly drained soils supporting more shallow burns than sites located on convex landforms with more well-drained soils. However, the scope of these previous studies has been limited by not including areas with permafrost (Miyanishi and Johnson 2002; Harden et al. 2004) or a full range of fire weather to represent conditions common during natural wildfires (Dyrness and Norum 1983).

This study fills some of the gaps in our understanding of factors controlling SFC in wildfires by explicitly linking patterns of organic layer depth, permafrost distribution, and soil moisture and relating temporal changes in these factors to variations in SFC. Our data suggest that surface organic layer depth in a black spruce stands is an important factor in regulating near-surface soil temperature and permafrost development, which, in turn, affect the moisture content of the upper mineral soils and deep duff layers (Fig. 4*a*). Furthermore, the depth of the surface organic layer is dependent not only on the time since the last fire, but also on the amount of SFC that occurred during previous fires. Extrapolation over time of the relations between organic layer depth and soil temperature and moisture in both unburned and burned stands (Figs. 4 and 6) suggests that that previous fire history at a site also plays a role in SFC during subsequent fires. Shallow burning in a previous fire cycle may create a “legacy” of deep organic layers and cool and moist soil conditions that restrict the potential for deep burning to occur in a subsequent fire event. For example, the deep surface organic layers in the tussock site of the HC94 burn are likely to be the result of low SFC over multiple fire events in the past. At the same time, these thick organic layers may have contrib-

Fig. 7. Conceptual model of variations in reduction in organic layer depth for the forest stands in the Delta Junction, Alaska, region as a function of preburn organic layer depth and time of the fire during the growing season (I, late May; II, early to late June; III, early to late July; IV, after early August). Arrows indicate the direction of effects on depth of burn with changes in mineral soil drainage or climate conditions expressed by the Buildup Index (BUI).



uted to the maintenance of near-surface permafrost and poor soil drainage conditions at the site that restrict the potential for deep burning in a given fire event.

It is important to recognize that interacting controls on organic layer depth, soil temperature, and soil moisture exist within the constraints imposed by the permeability or drainage characteristics of the underlying mineral soils. One would expect that black spruce forests that grow on coarse-textured mineral soils (such as gravel and sands) to be more well-drained than those growing on finer-textured soils (such as silts and clays). For example, the acidic elevational woodlands in the DF99 fire grew on a till plain containing poorly sorted sands and gravels and their well-drained soils resulted in the driest and warmest soils of any of our sites. These sites experienced higher SFC than the nonacidic, dry black spruce stands in the same burn where permafrost was present.

In Fig. 7, we present a conceptual model of the depth of organic layer burning for the black spruce forests found in our study region, across four periods of the fire season (approximately May–August). The actual timing of each period is expected to vary by 1 to 2 weeks depending upon annual weather patterns. Period I is the time immediately after spring snowmelt when the active layer is at its shallowest point and high soil moisture results from melting snow. At this time, depth of burning is low across all sites, with variations depending on depth of the organic layer (which regulates presence or absence of permafrost, hence soil drainage). Following snowmelt, there is typically little precipitation during period II, and as daytime temperatures increases, upper duff moisture decreases because of a combination of evaporation and plant transpiration. At the same time, permafrost begins to thaw and active layers begin to deepen. As a result, depth of burn will increase across all black spruce forest types, with the highest increases occurring in sites with moderately deep organic layers. Because of poorer soil drainage, the fuel moisture content of sites with deep organic soils results in lower depth of burns than at other sites. As permafrost thawing continues through periods III (late June through mid-July) and IV (late July to the end of the fire season), the moisture of the deep duff layers decreases, resulting in deeper burning. At any given time period, increases in soil drainage associated with site differences in soil texture or drier climate conditions (e.g., BUI) at the time of the fire are expected to increase the depth of burn. Across different years, variations in the seasonal thaw depth will also be important in determining the vulnerability of sites to deep burning late in the growing season.

Extension of our results to other areas of the boreal forests will require explicit consideration of other factors likely to be important in contributing to variations in surface fuel consumption in black spruce forests. In particular, the effects of topography on site microclimate and drainage may also play an important role in regulating duff moisture and SFC (Swanson 1996). In addition, the controls on drainage and surface-layer moisture in the organic layers of peatlands common to the boreal region are extremely complex and, in many instances, are not related to seasonal permafrost dynamics. Turetsky and Wieder (2001) and Turetsky et al. (2002) demonstrated that SFC in springtime fires in peatland forests of western Canada was between 20 and 40 t C·ha^{-1}. Finally, the rate of burning of dry deep duff is an important consideration, as once smoldering combustion is initiated in these layers, combustion will continue until a significant precipitation event occurs. Additional studies are certainly needed to develop a more comprehensive understanding of the important process of burning of surface-layer organic matter in black spruce forests and other ecosystems with deep surface organic layers.

Conclusions

The results from this study point towards SFC in black spruce forests as being a complex process dependent on a number of factors, including landscape characteristics, climate, and previous fire history at a site. The wide range in black spruce forest types found throughout interior Alaska (Nettleton-Hollingsworth 2004) and the dependence of organic-layer moisture on seasonal permafrost dynamics present significant challenges to estimating average levels of SFC. An important consideration is the timing of a fire event during the growing season, with late season fires having the potential for deeper burning than those occurring earlier in the growing season. Records for interior Alaska (National Interagency

Coordinating Center, http://www.cidi.org/wildfire/index.html) indicate that although natural fire ignition activity is highest in June, an average of 27% of the annual area burned is burned in late in the season (after August 1), with higher levels of late-season burning occurring during large fire years.

Fire activity (annual area burned) has been increasing in Alaska and throughout the North American boreal forest region over the past four decades of the historical record, with an increase in frequency of large fire years (Kasischke et al. 2005). At the same time, observations of permafrost in interior Alaska suggest that the average temperature of permafrost has been increasing (Osterkamp and Romanovsky 1999). Both changes are likely to influence patterns of SFC owing to increases in the amount of late-season burning and deepening of the active layer that increase the potential for deep burning of the organic layer (Fig. 7). Increased consideration of the role of interactions among initial organic layer depth, soil temperature and moisture conditions, and seasonal timing of a burn is necessary to improve our ability to predict future patterns of SFC under changing fire and ground temperature regimes.

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Appendix A

Appendix appears on the following page.

Table A1. Summary of the different sites and stands used in this study and the sources of information where multiple data sets were compiled.

Location	Year of fire	Site name	Stand name*	Soil depth data source[†]	No. of depth cores	Adventitious root depth data*	Adjacent unburned stands	Previous bun year (data source[†])	Black spruce forest type[‡]	2003 soil moisture and depth data	Forest stand data source[†]
Fort Greely	1956		UB1	2	40						
	1987	FG87	UB1	4	40			1910 (4)	ACD	X	4
			UB2	1	40			1910 (3)	ACD	X	1
			UB3	2	40						2
			B1	4	40						
			B2	1	40						
			B3	1	40						
			B4	1	40						
			B5	1	40						
			B6	1	40						
Hajdukovich Creek	1994	HC94	UB1[§]	4	40	UB		1860 (4)	NAW	X	4
			UB2[‖]	1	40			1705 (3)	NAW	X	1
			UB3	1	40			1755 (3)	NAW	X	1
			UB4[‖]	1	40			1695 (1)	NAW	X	1
			UB5[‖]	1	40			1880 (1)	NAD	X	1
			UB6	1	40			1895 (1)	NAD	X	1
			UB7[§]	4	40	UB		1830 (1)	NAD	X	1
			UB8[§]	4	40			1840 (1)	NAD	X	1
			UB9	1	40			1815 (1)	NAW	X	1
			B1-A	1	55	B		1890 (1)		X	1
			B2-J	1	54			1820 (1)		X	1
			B3-J	1	55			1895 (1)			1
			B4-J	1	55			1915 (1)			1
			B5-A	1	55	B		1885 (1)		X	1
			B6-A	1	55	B		1885 (1)		X	1
			B7-J	1	55			1920 (1)			1
			B8-J	1	55	B		1785 (1)		X	1
			B9-A	1	55	B		1825 (1)		X	1
			B10-J	1	55			1795 (1)		X	1
			B11-J	1	55			1790 (1)		X	1
			B12-J	1	55			1915 (1)			1
			B13-A	1	55	B		1890 (1)			1
			B14-J	1	55			1880 (1)			1
			B15-A	1	55			1885 (1)			1
			B16-A	1	55	B		1860 (1)		X	1
			B17-A	1	40		HC94-UB1			X	1
			B18-J	1	35			1915 (1)			1
			B19-A	1	55	B		1820 (1)			1
			B20-A	1	55	B		1820 (1)		X (2)	1

Table A1. (*concluded*).

Location	Year of fire	Site name	Stand name*	Soil depth data source†	No. of depth cores	Adventitious root depth data*	Adjacent unburned stands	Previous bun year (data source†)	Black spruce forest type‡	2003 soil moisture and depth data	Forest stand data source†
			B21-J	1	55			1865 (1)			1
			B22-A	1	33			1900 (1)			1
			B23-A	1	41		HC94-UB7				
			B24-J	1	22		HC94-UB8	1830 (1)			
Donnelly Flats	1999	DF99	UB1	1	40			1910 (1)	EAW	X	
			UB2	1	40			1925 (1)	EAW	X	
			UB3§	1	40			1910 (3)	EAW	X	1
			UB4	1	40			1880 (1)	NAD	X	1
			UB5§	1	40			1860 (3)	NAD	X	1
			UB6	1	40			1875 (1)	NAD	X	
			B1	1	40		DF99-UB1				
			B2	1	40		DF99-UB2				
			B3	1	40						
			B4	1	40						
			B5	1	40						
			B6	1	40		DF99-UB4, UB6				
			B7	1	40						
			B8	1	40						
			B9	1	40						
			B10	1	40						
			B11	1	40		DF99-UB4, UB6				
			B12	1	40		DF99-UB4, UB6				

*B, burned stand; UB, unburned stand. Stands in the HC94 site that burned in July are denoted with a J, those that burned in August, with an A.
†Data source: 1, this study; 2, data collected by first author during previous study; 3, Nettleton-Hollingsworth (2004); 4, O'Neill (2000).
‡Forest type (after Nettleton-Hollingsworth 2004): ACD, acidic, dry black spruce forest type; NAD, nonacidic dry black spruce forest type; NAW, nonacidic wet black spruce forest type; EAW, acidic elevational woodland forest type.
§Stands sampled by O'Neill (2000).
‖Stands sampled by Nettleton-Hollingsworth (2004).