

More frequent burning increases vulnerability of Alaskan boreal black spruce forests

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More frequent burning increases vulnerability of Alaskan boreal black spruce forests

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Abstract

Much recent research has investigated the effects of burning on mature black spruce (*Picea mariana*) forests in interior Alaska, however little research has focused on how frequent reburning affects soil organic layer (SOL) vulnerability in these ecosystems. We compared organic soil layer characteristics in black spruce stands that burned after two fire-free intervals (FFI), including an intermediate-interval (37–52 years) and a more typical long-interval (70–120 years). We found that depth of burn varied significantly between intermediate-interval and long-interval sites, and as there was less material available to burn in intermediate-interval stands, percent depth reduction was greater in these stands ($78.9\% \pm 2.6\%$) than in long-interval stands ($62.9\% \pm 1.5\%$). As a result, less residual organic soil carbon remained post-fire in intermediate-interval than long-interval stands. Post-fire organic soil carbon stocks averaged $0.51 \pm 0.08 \text{ kg C m}^{-2}$ in the intermediate-interval sites, which is less than estimates of soil carbon stock for long-interval fire events (ranging from 2.07 to 5.74 kg C m^{-2}). In addition to altering soil carbon storage, a depletion of the SOL during more frequent fire events will likely delay the recovery of permafrost and could trigger a change in the possible successional trajectory of a site, from black spruce dominated to deciduous or even shrub dominated ecosystems in the future.

Introduction

The largest carbon sink present in North America is in forests (King *et al* 2007) and the boreal forest biome is one of the largest terrestrial carbon stores across North America, mainly due to the large carbon pool stored in the soils of peatlands and forests of this region (Kasischke *et al* 1995). These northern permafrost regions are believed to hold $1035 \pm 150 \text{ Pg}$ of soil organic carbon (SOC) (in the top 0–3 m of soil), where almost 21% of this carbon is in the soil organic layer (SOL) pool found in the top 30 cm of the organic soil ground layer (Hugelius *et al* 2014). The forest structure of upland forests located in the discontinuous permafrost zone of this region have remained relatively stable for thousands of years (Kelly *et al* 2013), with two main stability domains present based on SOL properties. Johnstone *et al* (2010a) proposed that stability domains in upland Alaskan boreal forests where conditions allow for permafrost to form are based on

organic layer thickness, with different ecosystem structure and processes related to the thickness of the organic soil layer. Based upon patterns of burning in surface organic layers, the production and decomposition of plant litter between fire events, and other environmental site conditions (such as soil drainage), Johnstone *et al* (2010a) suggested two domains exist, one with thick organic soil layers, and another with thin organic soil layers. Within these stability states feedbacks and interactions within the ecosystem are related to forest soils, disturbance, and plant traits. In the thick organic layer domain, soils are generally underlain by permafrost, and dominated by conifers, while in the shallow organic layer domain, warm and well-drained soils contain deciduous-dominated climax communities. Shifts from the thick organic layer domain to the shallow domain are believed to be driven by the patterns of deep burning in organic soils and the susceptibility of sites to the invasion and establishment of deciduous tree species.

The organic soil layers of the conifer stability domain, and in particular, mature black spruce (*Picea mariana*) forests in Alaska, can range from <10 to >40 cm in depth (Hollingsworth *et al* 2006, Kasischke *et al* 2008, Boby *et al* 2010, Turetsky *et al* 2011). This range can be controlled by differences in the rates of production and decomposition of plant litter and moss (Harden *et al* 2000), and is also dependent on the frequency and severity of fires (Turetsky *et al* 2011). These thick organic soils insulate the subsoil from warm summer air temperatures and allow for the development of permafrost below the surface (Viereck 1983, Jorgensen *et al* 2010), which in turn can affect site drainage. In mature black spruce forests, active layer thickness and soil moisture in sites with permafrost are proportional to the depth of the surface organic layer, such that sites with deeper organic layers have colder soils, shallower active layers, and wetter soils (Zhuang *et al* 2002, Kasischke and Johnstone 2005). In contrast, the shallow organic layer domain (where surface organic layers are generally <10 cm thick) is dominated by warm, well-drained soils (Van Cleve *et al* 1983) which provides for the rapid decomposition of dead plant material (Johnstone *et al* 2010a). These deciduous forests, consisting of trembling aspen (*Populus tremuloides*) or Alaskan paper birch (*Betula neoalaskana*) are often found in upland areas of the landscape. In the black spruce forests of interior Alaska, the thick organic soils have sequestered 5.5 ± 0.8 Tg C annually (Turetsky *et al* 2011). However, deciduous forests, with their thinner soil layers, do not store the same amount of carbon in the soil layer. In these thick soils, fire disturbance can eliminate the permafrost that had formed in favorable ecosystem and climate conditions (called ecosystem-driven permafrost), and can also disrupt the reformation of permafrost formed in favorable ecosystem conditions (such as ecosystem-protected permafrost in poorly drained, low-lying or north-facing slopes) (Shur and Jorgenson 2007).

The stability domains proposed by Johnstone *et al* (2010a) predict that a thick organic layer site can be converted to a thin organic layer site after an unusual fire event. However, much of the recent research into boreal forest burning has focused on factors controlling depth of burn within the mature black spruce forests found in the thick organic layer stable state domain. For example, in mature black spruce forests, topography can be correlated with depth of burn because warmer and drier sites (such as south facing slopes and flat uplands) are more susceptible to deep burning than other topographic positions (Kane *et al* 2007, Turetsky *et al* 2011). In contrast, cooler and wetter sites have been found to be generally resistant to deep burning, although changing climate could affect site vulnerability (Kasischke *et al* 2010, Turetsky *et al* 2011). Seasonality of the fire event has been shown to be important, with differences in depth of burn between early and late season burning (Kasischke and

Johnstone 2005, Turetsky *et al* 2011). Generally, early season fires occurring at a time when seasonal thawing of the active layer has yet to occur, do not burn as deeply into the SOL as fires occurring later in the growing season when a deeper active layer results in more well-drained soils. Fire size has also been linked with depth of burn into the SOL (Turetsky *et al* 2011), where the depth of burning increased with fire size during early-season burning (however this relationship was absent during late-season burning). Regardless of burn conditions, research has shown that mature black spruce forests located on flat lowland sites are resistant to the deep burning fires that can result in shifts to shallow organic layer conditions (Kane *et al* 2007, Turetsky *et al* 2011).

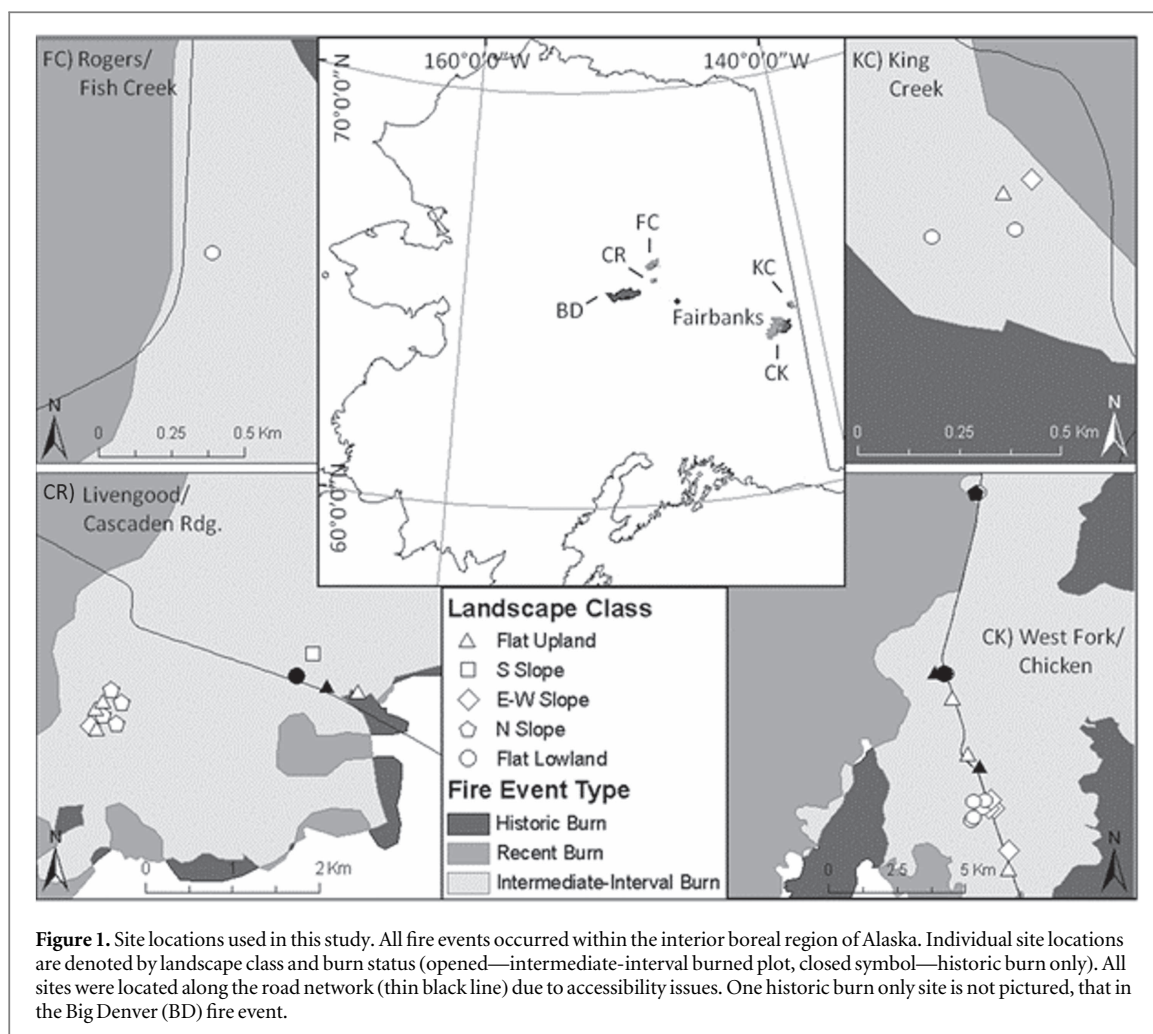
Where these previous studies have addressed factors controlling fire severity in mature stands which burn (long-interval burns), here we are examining factors affecting the vulnerability of the SOL when there is a burn after only a short interval of time (37–52 year). We explore how an unusual fire event can result in the shallow organic layer state proposed by Johnstone *et al* (2010a). In this two-step process, a mature black spruce forest is fire disturbed, and then the recovering black spruce forest is disturbed by fire again, after only a short time interval. As the depth of the organic layer is one of the controls on ecosystem driven and ecosystem-protected permafrost in the forested discontinuous permafrost zone (Shur and Jorgenson 2007), recovering forests with shallower organic layer depths can be underlain by less permafrost, making them more vulnerable to burning than mature forests with deeper organic layer depths and thicker permafrost. As a result, reburning of black spruce forests during short- to intermediate-interval fires represents an additional pathway for triggering a domain change to the thin organic soil state discussed by Johnstone *et al* (2010a).

Materials and methods

While the shorter-fire-interval pathway between the two forest steady states was previously identified in research by Johnstone (2006) and Brown and Johnstone (2011), unlike during these previous studies, here we collected data across a number of topographic positions in stands that had burned at both intermediate and long fire-free intervals (FFI) to provide the ability to assess the vulnerability of SOL to frequent burning. Data were also collected in early and late season fires.

Study area and plot locations

This study was conducted in interior Alaska, which stretches from the Brooks Range in the north to the Alaska Range in the south and encompasses multiple topographic and permafrost gradients. Black spruce forests represent 45% of the land cover in the interior



of Alaska and are the prevailing forest type in Alaskan (66% of all forests) (Turetsky *et al* 2011) and Canadian boreal forests (Amiro *et al* 2001). These forests occur primarily in areas with discontinuous permafrost (Ferrians 1998), which can greatly influence site drainage conditions and the organic soil layer thickness. However, some have suggested that climate-fire-vegetation interactions may lead to decreased black spruce forest cover and increased deciduous forest cover throughout this landscape (Kelly *et al* 2013), although the rate of change in response to recent changes in Alaska's fire regime is under debate (Barrett *et al* 2011, Mann *et al* 2012).

At the landscape scale, changes in fire frequency are analyzed as the FFI between fire events (Johnstone 2006, Johnstone and Chapin 2006). Field observations within black spruce stands which burned twice in the last 37–52 years (considered here to be intermediate-interval fire events) were investigated and compared with data previously collected in long-interval (with a FFI at least >70 years) fire events (Kane *et al* 2007, Kasischke *et al* 2008, Turetsky *et al* 2011). Measurements were collected in black spruce forest stands located in four intermediate-interval fire events throughout the interior of Alaska (figure 1) (the data for this study are available in Hoy *et al* 2016). In each of

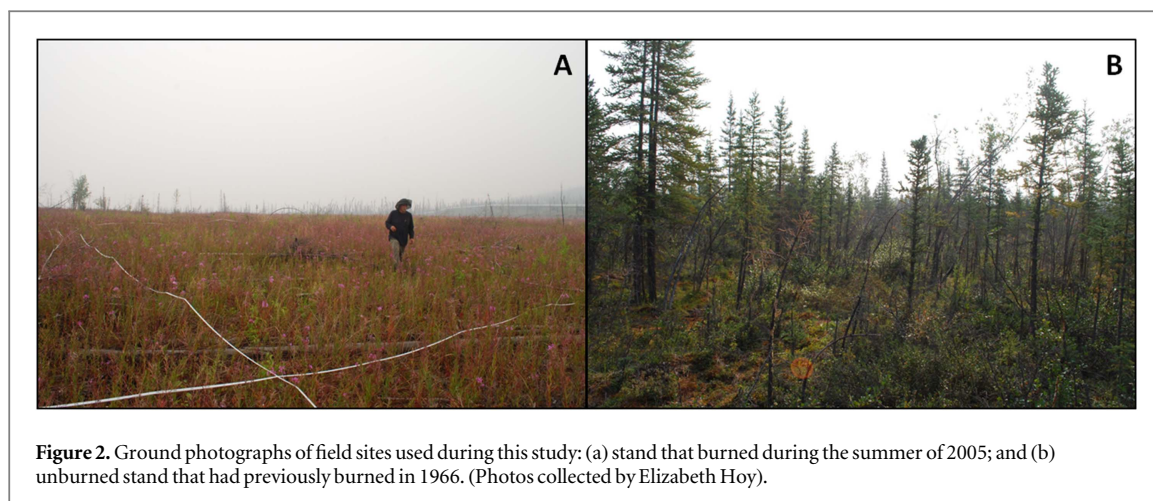
the intermediate-interval fire events, a fire first occurred in the 1950s or 1960s, with the sites burning again in the 2000s (table 1).

For all intermediate-interval sites, data were collected in plots that were located in both burned stands and adjacent unburned stands of a similar age (figure 2). Unburned stands were located across multiple topographic positions and were dominated by live, intermediate-aged (~37–52 years) black spruce trees (figure 2(b)). There were no live trees present in the intermediate-interval burned stands (figure 2(a)). One indicator used in plot selection was the presence of severely weathered and charred trunks of black spruce trees which had burned in the 1950s and 1960s and remained as either standing dead or fallen dead until the time of the second fire event. Plots were selected where the intermediate-interval burned stands had been dominated by black spruce trees both prior to the historic burn (in the 1950s and 1960s) and the more recent burn (in the 2000s).

Individual plots were located within the four intermediate-interval fire events studied, consisting of an area at least 30 by 40 m on the same topographic position with similar fire severity. As site accessibility is an issue in Alaska, data collections were restricted to areas near highways and other roads accessible to field

Table 1. Summary of fire events. A summary of the intermediate-interval fire events used in this study.

Code	Historic burn		Recent burn		Intermediate-aged sites		
	Fire event	Discovery date	Fire event	Discovery date	Burned (<i>n</i>)	Unburned (<i>n</i>)	FFI (yrs)
FC	Rogers	6/16/1967	Fish Creek	6/16/2005	10	2	38
KC	King Creek	6/22/1969	King Creek	6/22/2004	4	—	37
CR	Livengood	6/4/1958	Cascaden Rdg.	6/3/2010	1	—	52
CK	West Fork	7/23/1966	Chicken	6/15/2004	14	4	38
BD	Big Denver	6/16/1969	—	—	—	1	—



vehicles and hiking short distances (<2 km). All plots were located at least 100 m from paved roads to avoid local effects of the road on the natural environment and fire behavior. Following the design of previous studies (Kane *et al* 2007, Turetsky *et al* 2011), sample sites were located across different topographic positions (also referred to as landscape classes) representing a gradient of well-drained to poorly-drained areas including flat uplands (FU); south (S) facing backslopes; east and west facing backslopes (EW); north (N) facing backslopes; and flat lowlands (FL) (see table 2 for a list of sites by landscape class).

Measurement of organic layer characteristics in burned and unburned stands

The organic layer sampling methods followed Kane *et al* (2007) and Kasischke *et al* (2008). Date of burn from the most recent fire event was established for each plot using MODIS hotspot data (Giglio *et al* 2006). In the intermediate-interval burned plots, the 21 soil depth measurements collected in each plot consisted of a measurement from the top of the remaining SOL following fire to the mineral soil layer, and a breakdown of soil type was noted (including the char, fibric, mesic and humic soil layers (Canadian Agricultural Services Coordinating Committee 1998)). The 21 adventitious root (AR) measurements were collected by measuring the distance from the top AR to the mineral soil using black spruce trees ≥ 2 m tall and believed to have burned during the most recent fire event (during the 2000s).

Unburned intermediate-aged black spruce stands adjacent to intermediate-interval burned sites, or located in black spruce stands of a similar age to the intermediate-interval fire events studied, were sampled in order to estimate pre-fire depth using ARs. Similar to the design used to make depth measurements in burned stands, SOL measurements were made in unburned stands from the top of the SOL to the mineral soil including a breakdown of soil type (moss, fibric, mesic and humic soil). As in the collection of AR data in burned stands, AR measurements were collected in the 7 unburned black spruce stands used in this study. These included the measurement of the top of the organic layer to the top AR, and from the top of the AR to the mineral soil. Using the relationship between the AR depth above the mineral soil and total organic layer depth in unburned stands, we were able to estimate pre-fire organic layer depths in burned stands following the approaches of Boby *et al* (2010) and Kasischke *et al* (2008).

Changes in soil carbon

SOC storage and losses were estimated using empirical relationships between organic horizon depth (cm) and SOC (kg m^{-2}) developed by Turetsky *et al* (2011) from published soil data for Alaskan black spruce forests stratified by landscape (topographic) class. In burned stands, the estimated depth of burn derived from AR measurements less the char layer was used in the carbon loss analysis to account for ecosystem carbon

Table 2. Soil organic layer depth measurement results (in cm unless noted) within intermediate-interval study sites. A comparison to the long-interval sites of Turetsky *et al* (2011) is provided.

Season	Landscape class (<i>n</i>)	Pre-fire	Post-fire	Depth of burn	Depth reduction (%)
Early	Flat upland (4)	14.6 ± 1.4	4.3 ± 1.5	10.3 ± 0.7	73.0 ± 9.12
	S slopes (1)	11.7	1.0	10.7	91.6
	EW slopes (2)	14.0 ± 0.2	3.3 ± 1.7	10.7 ± 1.5	76.4 ± 12.0
	N slopes (0)	—	—	—	—
Late	Flat lowland (7)	18.6 ± 1.9	6.2 ± 1.2	12.4 ± 1.4	67.5 ± 5.30
	Flat upland (4)	12.5 ± 1.1	1.5 ± 0.2	11.0 ± 1.0	87.8 ± 1.7
	S slopes (0)	—	—	—	—
	EW slope (4)	13.9 ± 0.8	2.4 ± 1.1	11.5 ± 0.5	83.9 ± 6.4
	N slopes (4)	11.5 ± 0.3	1.1 ± 0.0	10.4 ± 0.3	90.2 ± 0.3
	Flat lowland (3)	17.2 ± 1.6	3.8 ± 0.7	13.4 ± 2.2	76.8 ± 6.5
	Intermediate-interval Site Mean (29)	14.9 ± 0.7	3.4 ± 0.5	11.4 ± 0.5	78.9 ± 2.6
Long-interval Site Mean ^a (178)	25.2 ± 0.5	9.6 ± 0.5	15.6 ± 0.5	62.9 ± 1.5	

^a Long-interval site data from Turetsky *et al* (2011).

retained in the soil as char or charcoal (Turetsky *et al* 2011).

Data analysis

Organic layer depths in intermediate-interval burned sites were analyzed using three measures of fire severity (Kasischke *et al* 2008): (1) depth of burn (or absolute depth reduction), the amount of organic matter which burned during the fire, (2) percent depth reduction (or relative depth reduction), the relative amount of organic matter removed during the fire when compared to pre-fire organic layer levels, and (3) the post-fire depth at the site following the intermediate-interval burn. The characteristics of the organic layer depths found in intermediate-interval burned sites were compared with those from the long-interval sites previously sampled by Turetsky *et al* (2011) using linear mixed effects models, which can account for any non-normality in the dataset as well as random variables (Pinheiro and Bates 2010). Fixed effects included in the models were FFI (Interval), landscape class (the five topographic positions described above), Julian date, and the interaction between interval and landscape class, while the random effect of fire identity was used to account for differences among fire events used in the analysis. Other fixed effects terms (such as annual-area burned) which have been shown to be significant in past studies of long-interval fires in black spruce forests (Turetsky *et al* 2011) were not included in these models as there was a clear focus here to investigate potential factors with specific relevance to intermediate-interval burns. The influence of individual fire events on the models was investigated using the Cook's D and Covariance Ratios for both fixed effects and covariance parameters of the combined long- and intermediate-interval datasets. It was determined that the main results were robust enough to account for any variation due to individual fire events. The significance of the random effects was assessed through a Wald test.

Simple linear regression was used to analyze differences between pre- and post-fire organic layer depths, depth of burn and the date of burn in intermediate-interval burned stands and the relationship between AR depth to mineral soil and the total organic layer depth in unburned stands. All data are presented as means ± one standard error. The data from plots of the same landscape class located ~2 km or less from one another were combined to form a single site for statistical analysis to account for potential spatial correlation between the plots.

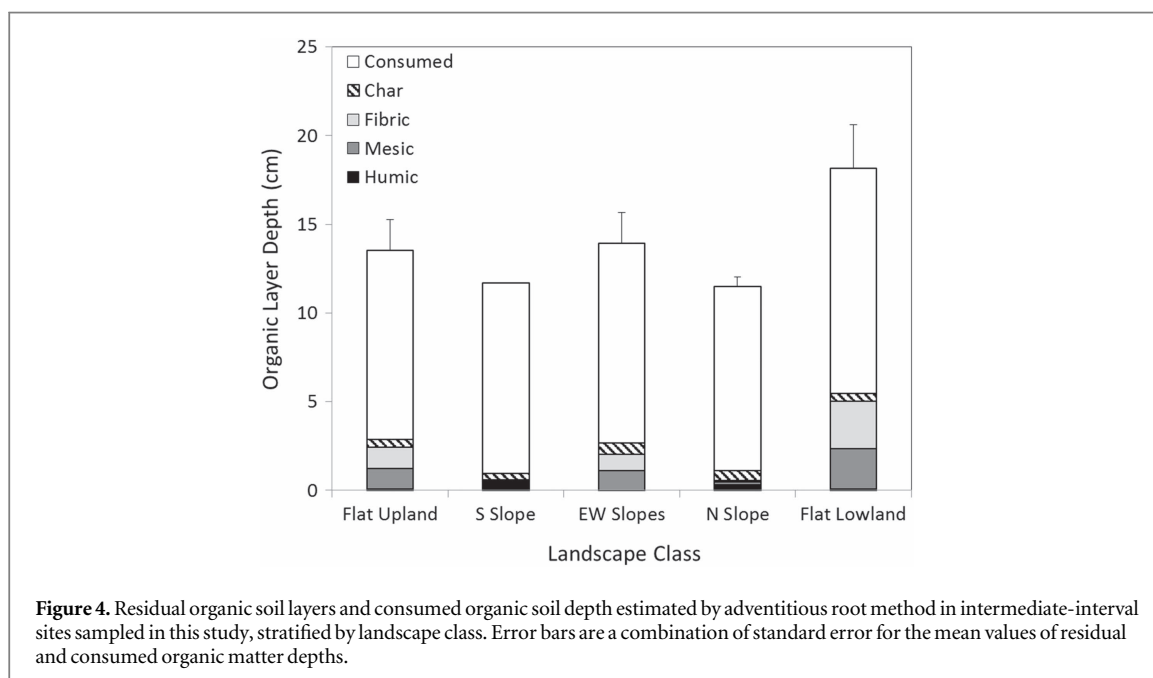
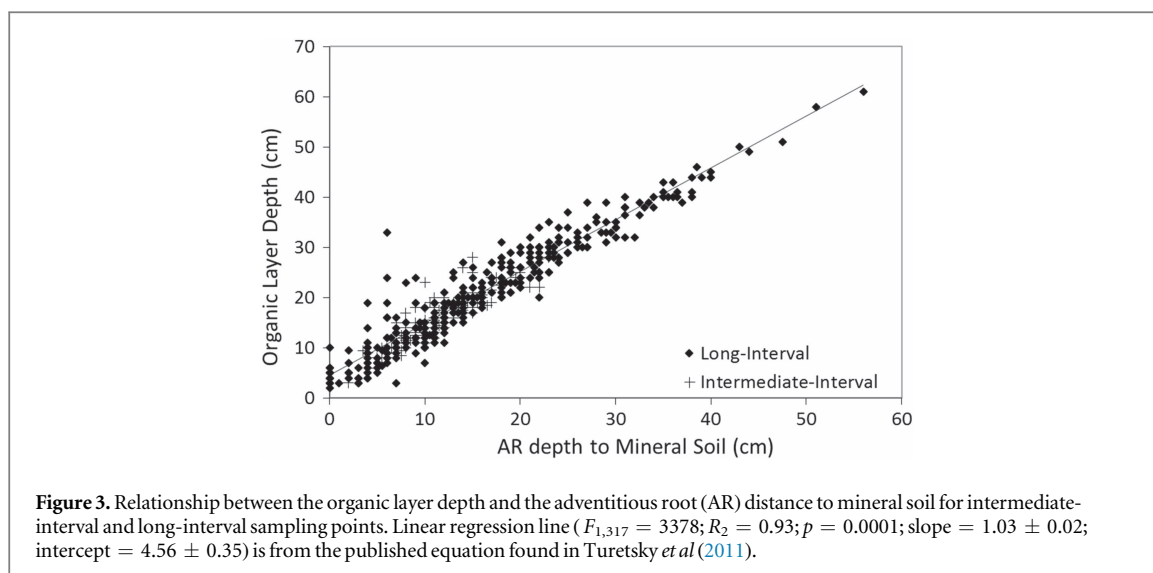
Results

Estimating pre-fire organic layer depth

An initial relationship was developed between the organic layer depth and the AR depth to mineral soil using only the sample points from the seven intermediate-aged unburned black spruce sites. Based on overlapping confidence intervals for the slope and intercept of each equation, this relationship did not vary significantly from the relationship published in Turetsky *et al* (2011) to relate AR data with total organic matter depth in mature black spruce stands (linear regression model from Turetsky *et al* (2011): $F_{1,317} = 3378$, $R^2 = 0.93$, $p = 0.0001$, β_0 (y -intercept) = 4.56 ± 0.35 , β_1 (slope) = 1.03 ± 0.02) (figure 3). As a result, this previously published relationship was used to estimate pre-fire depth in the intermediate-interval burned stands.

Intermediate-interval SOL depths

Post-fire organic layer depths in intermediate-interval burned sites ranged from 0.4 ± 0.1 cm in a flat upland site to 10.1 ± 1.2 cm in a flat lowland site, with an average post-fire depth of 3.4 ± 0.5 cm. Fire had burned down to the mineral soil, leaving only a thin char layer behind, in 40.5% of all individual sample measurements across all plots. An average of



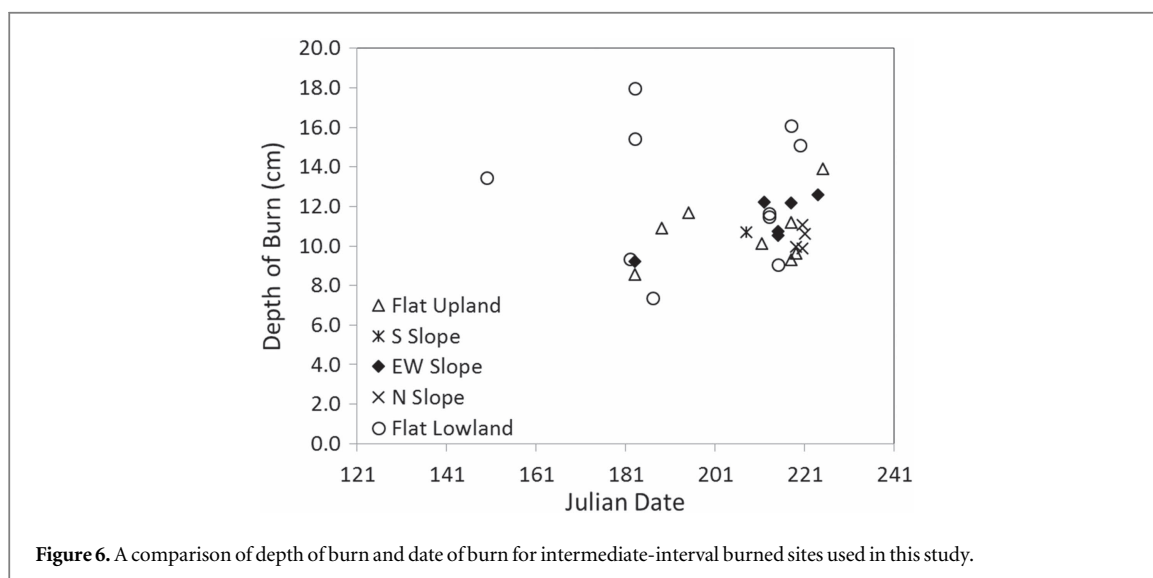
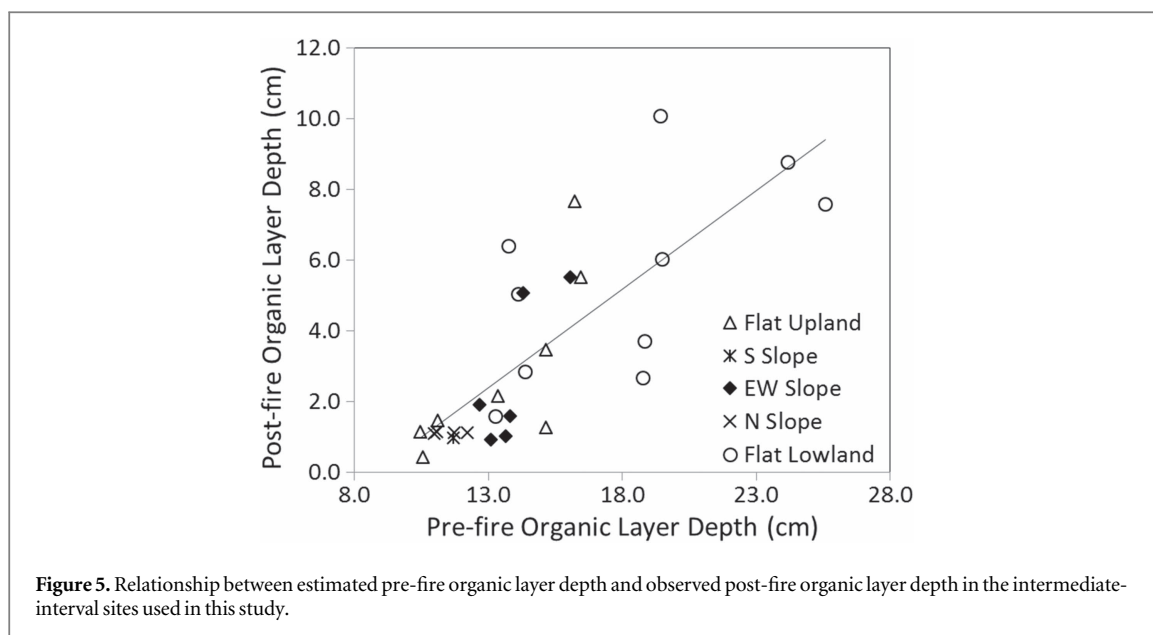
11.4 ± 0.5 cm of organic matter was consumed within the intermediate-interval burn sites (with a range of 7.4 ± 1.0 – 18.0 ± 1.2 cm), resulting in depth reduction of $78.9\% \pm 2.6\%$ (table 2, figure 4). Pre-fire depth was found to explain 59.9% of the variation in post-fire depth across sites ($F_{1,27} = 40.39$, $R^2 = 0.5993$, $p < 0.0001$, $\beta_0 = -4.87 \pm 1.3$, $\beta_1 = 0.54 \pm 0.09$; figure 5).

Based on the spatial interpolation of date of burn observed from processing the MODIS hotspot data, 14 of the sites sampled for this study burned early in the fire season (between May and July), while 15 sites burned later in the fire season (after July 31st). Depth of burn, stratified by landscape class, did not vary greatly across early and late season intermediate-interval sites (table 2). The day in year that an intermediate-interval plot burned was not correlated with the variation in depth of burn ($F_{1,27} = 0.08$, $R^2 = 0.003$,

$p = 0.78$, $\beta_0 = 12.94 \pm 5.24$, $\beta_1 = -0.0073 \pm 0.03$; figure 6). However, an analysis of the relationship between depth of burn and Julian date for individual landscape classes (excluding *N* facing slopes as only one was sampled) showed that only depth of burn for EW slopes was significantly correlated (at $p < 0.1$) with Julian date ($F_{1,4} = 7.95$, $R^2 = 0.67$, $p = 0.048$, $\beta_0 = -4.55 \pm 5.61$, $\beta_1 = 0.074 \pm 0.027$).

Comparison of intermediate-interval and long-interval sites

Results of the linear mixed-effects model showed that depth of burn varied with interval and Julian date ($p = 0.0608$ and $p = 0.0003$, respectively), but did not vary with landscape class ($p = 0.2773$) (table 3). The models for the percent depth reduction and post-fire depth varied with interval length ($p = 0.0042$ and $p = 0.0002$, respectively), landscape



class ($p = 0.0019$, $p = <0.0001$, respectively), and Julian Date ($p = <0.0001$ and $p = 0.0018$, respectively) (table 3). The organic layers of long-interval sites were $\sim 70\%$ thicker at the time of burning than those found in the intermediate-interval sites. Post-burn, the organic layers were almost 65% thinner in intermediate-interval sites than in long-interval sites (table 2). Percent depth reduction was 16 percentage points more ($\sim 25\%$ greater) in intermediate-interval sites than in the long-interval sites used in this comparison ($\sim 79\%$ and $\sim 63\%$ respectively, table 2). The interaction between interval and landscape class was significant in the depth of burn and post-fire depth model ($p = 0.0348$ and $p = 0.0064$, respectively), but was not significant for the percent depth reduction model (and $p = 0.1289$). Fire identity was a significant random effect in the depth of burn model ($p = 0.0407$), but not in the percent depth reduction

and post-fire depth models ($p = 0.1341$ and $p = 0.1619$, respectively) (table 3).

Similar to trends in SOL depths, the post-fire SOL carbon stock was lower in intermediate-interval sites than in long-interval sites (table 4). In all landscape classes where we were able to sample both intermediate-interval and long-interval sites during the early and late fire seasons, post-fire SOL carbon stock was greater in the long-interval landscape class. There was also less variability in carbon stocks found across the intermediate-interval landscape classes than the long-interval landscape classes (table 4).

We used these data to estimate carbon losses associated with burning. Carbon losses in intermediate-interval stands ranged from $1.61 \pm 0.33 \text{ kg C m}^{-2}$ in early-season EW slopes, to 3.03 kg C m^{-2} in the early-season S slope and $2.99 \pm 0.66 \text{ kg C m}^{-2}$ in the flat lowland late-season intermediate-interval sites

Table 3. Fire severity mixed-effects models. Depth of burn, percent depth reduction, and post-fire mixed-effects model parameters and results for the black spruce sites within the study region. The significance of the random effects was assessed through a Wald test.

Model	Fixed effects term	Fixed effects F value	DF (Num, Den)	<i>p</i>	Random effects term	Estimate	Std. error	Wald Z score	<i>p</i>
Depth of burn	Interval	3.56	1164	0.0608	Fire identity	5.2372	3.0050	1.74	0.0407
	Landscape class	1.29	4164	0.2773	Residual	25.2419	2.6889	9.39	<0.0001
	Julian date	13.87	1164	0.0003					
	Landscape class x interval	2.66	4164	0.0348					
Percent depth reduction	Interval	8.43	1164	0.0042	Fire identity	24.0304	21.7039	1.11	0.1341
	Landscape class	4.46	4164	0.0019	Residual	248.74	26.5545	9.37	<0.0001
	Julian date	26.46	1164	<0.0001					
	Landscape class x interval	1.81	4164	0.1289					
Post-fire depth	Interval	14.38	1164	0.0002	Fire identity	1.6980	1.7208	0.99	0.1619
	Landscape class	7.68	4164	<0.0001	Residual	22.2965	2.3717	9.40	<0.0001
	Julian date	10.06	1164	0.0018					
	Landscape class x interval	3.71	4164	0.0064					

Table 4. Carbon storage and losses. Ecosystem carbon storage and losses for intermediate-interval and long-interval fire events. A comparison to the long-interval sites of Turetsky *et al* (2011) is provided.

Season	Landscape class	Post-fire C storage (kg C m ⁻²)		C losses (kg C m ⁻²)	
		Intermediate-interval	Long-interval ^a	Intermediate-interval	Long-interval ^a
Early	Flat upland	0.76 ± 0.29	1.79 ± 0.11	1.94 ± 0.14	2.60 ± 0.21
	S slopes	0.11	1.4 ± 0.35	3.03	3.90 ± 0.29
	EW slopes	0.31 ± 0.22	1.05 ± 0.33	1.61 ± 0.33	2.15 ± 0.22
	N slopes	—	2.62 ± 0.24	—	3.33 ± 0.27
	Flat lowland	1.04 ± 0.25	4.01 ± 0.44	2.68 ± 0.41	3.26 ± 0.34
Late	Flat upland	0.24 ± 0.04	0.97 ± 0.16	2.08 ± 0.22	3.50 ± 0.30
	S slopes	—	0.62 ± 0.42	—	7.11 ± 1.12
	EW slopes	0.20 ± 0.13	0.58 ± 0.40	1.78 ± 0.12	8.29 ± 0.84
	N slopes	0.16 ± 0.00	2.30 ± 0.56	2.16 ± 0.07	5.56 ± 0.97
	Flat lowland	0.50 ± 0.13	5.36 ± 1.19	2.99 ± 0.66	3.58 ± 0.65

^a Long-interval site data from Turetsky *et al* (2011).

sampled (table 4). Intermediate-interval early-season losses are slightly lower than those reported in Turetsky *et al* (2011) for the different landscape classes, however the intermediate-interval late-season values are considerably less than those previously reported (table 4).

Discussion

Effects of FFI

An important question asked in this study is whether or not more frequent burning has increased the vulnerability of SOL in Alaskan black spruce forests. Increased SOL vulnerability would provide the conditions needed for a shift from the thick organic soil stable state found in black spruce forests to the thin organic soil stable state generally found in the deciduous stands of Alaskan boreal forests. We show that fire interval is an important control on the vulnerability of black spruce stands recovering from fire (all three mixed-effects models included interval as a significant fixed-effect term, table 3). Absolute depth reduction (depth of burn) is essential for understanding combustion rates and factors related to the fire itself (Turetsky *et al* 2011, Kasischke and Hoy 2012). Additionally, it is the relative depth reduction (percent depth reduction), and the post-fire depth, that are useful to discuss important post-fire impacts to the landscape, such as how fire will likely affect forest succession (Barrett *et al* 2011, Genet *et al* 2013) and the permafrost regime (Yoshikawa *et al* 2002, Yi *et al* 2009). The relative depth reduction is much greater in the intermediate-interval stands sampled, and both the post-fire depth and depth of burn are less, as compared to the long-interval sites previously examined (table 2). As mentioned above, 40.5% of all individual sample measurements across all intermediate-interval burned plots had burned down to the mineral soil. This lack of an insulating soil layer at the site is likely to result in the thick to thin organic layer domain shift discussed in Johnstone *et al* (2010a). In

another study which assessed short-interval fires (14–15 year FFI), Brown and Johnstone (2011) found pre-fire depths in short-interval stands to range from 12.1 to 24.8 cm and post-fire depths similar to those found in the intermediate-interval stands studied here. The depth reduction reported by Brown and Johnstone in the short-interval plots they studied, at 75%, was similar to that reported here (78.9% ± 2.6%) across all intermediate-interval sites (table 2). Overall, these results indicate that an intermediate-interval fire could be an important mechanism for triggering a deciduous post-fire trajectory through creating a thin organic soil layer (Johnstone *et al* 2010a, Barrett *et al* 2011, Johnstone *et al* 2011).

Factors controlling SOL depth of burn

While landscape position has been shown to be a significant factor in controlling depth of burn in long-interval burn stands (Kane *et al* 2007, Turetsky *et al* 2011), landscape class did not represent a significant control on depth of burn in the intermediate-interval sites assessed in this study (figure 4). All landscape classes burned relatively consistently across the intermediate-interval sites (table 2, figure 4). It is possible that many of the intermediate-interval sites sampled for this current study, while on different topographic positions, could have had similar drainage conditions due to properties intrinsic to stand development. While data on active layer thicknesses from regrowing, intermediate-interval black spruce stands are not available, Kasischke *et al* (2012) showed that in mature black spruce stands located across landscape position, active layer thickness increased as organic layer thickness decreased, while Kane *et al* (2007) demonstrated that organic soil moisture decreased as organic layer thickness decreased. These results indicate that the thinner organic layers found in the 37–52 year old, intermediate interval sites may not yet have had adequate time to redevelop the organic soil and permafrost layers common to mature black spruce forests. In sites with the same soil texture,

thinner organic soil layers can lead to thicker active layers, which in turn result in drier conditions, even on traditionally poorly-drained, flat lowland sites. These drier conditions could result in similar levels of burning across topographic positions in intermediate-interval events, as evidenced by the frequent occurrence of fire burning down to the mineral soil in all the intermediate-interval sites studied. Additionally, while depth of burn has been found to vary seasonally in long-interval black spruce stands (Turetsky *et al* 2011), in the intermediate-interval sites studied here it was only in the EW slopes that were significantly correlated with Julian date (figure 6). This represents another possible indication that the intermediate-interval sites had similar drainage conditions throughout the fire season, leading to similar burn conditions whether or not a site was burned in early-season or late-season.

An almost equal number of sites burned during the early and late time periods of the fire season (14 early-season and 15 late-season sites). However we did not have replication in some combinations of topographic position by seasonality (i.e. there were no early-season fires on north facing slope sites and no late-season fires on south facing slope sites) and this could have affected our analysis. Turetsky *et al* (2011) found that depth of burn increased with time throughout the fire season in flat upland and all sloped sites, but not in flat lowland sites, which burned to the same degree throughout the growing season. In the intermediate-interval sites studied here, there was very little change in depth of burn throughout the growing season across the different landscape positions. These differences could be due to the difficulty in locating and accessing a wider range of sites in multiple landscape classes.

Ecosystem carbon storage and losses

Post-fire organic soil carbon stocks averaged $0.51 \pm 0.08 \text{ kg C m}^{-2}$ in the intermediate-interval sites studied here. These carbon stocks were much lower than have been previously reported. For example, C stocks of various FFI within boreal regions of Alaska and Canada have been shown to range from 2.07 to 5.74 kg C m^{-2} (Kane *et al* 2007, Brown and Johnstone 2011, Turetsky *et al* 2011, Harden *et al* 2012). Carbon losses estimated in this study (table 4) are somewhat lower than those reported by Turetsky *et al* (2011), indicating that as less material was stored in intermediate-interval sites prior to a fire, less C was also consumed in the SOL during burning relative to long-interval sites. However, the results from this study clearly show that the more frequent burning of black spruce stands will result in further depletion of the large carbon reservoir that currently exists in black spruce forests.

Conclusions

As the landscape burns more frequently, there is the potential for a decrease in carbon storage in both aboveground and belowground biomass. Here we showed that three depth reduction metrics (depth of burn, percent depth reduction, and post-fire depth) differed between intermediate- and long-interval stands due to the inadequate time available to re-accumulate organic soil following an initial fire event. Shorter FFI in black spruce-dominated forested will result in more vulnerable SOLs and the reduced chance of recovery in these soils. This could lead to diminishing duff and peat thickness over several fire cycles. These thin post-fire organic soil depths can cause profound changes in the successional trajectories of black spruce forests, including a shift from the black spruce dominated thick organic soil state to an increase in the dominance of deciduous or shrub species (Johnstone *et al* 2010a, Barrett *et al* 2011, Johnstone *et al* 2011) and changes to permafrost conditions (Jorgenson *et al* 2010). Future research is needed to better document post-fire recovery in these intermediate-aged stands that burn, as this type of burning is likely to become more common with changing climate in this boreal region.

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