CSIRO PUBLISHING

International Journal of Wildland Fire **2018**, *27*, 125–134
https://doi.org/10.1071/WF17095

Soil organic layer combustion in boreal black spruce and jack pine stands of the Northwest Territories, Canada

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Abstract. Increased fire frequency, extent and severity are expected to strongly affect the structure and function of boreal forest ecosystems. In this study, we examined 213 plots in boreal forests dominated by black spruce (*Picea mariana*) or jack pine (*Pinus banksiana*) of the Northwest Territories, Canada, after an unprecedentedly large area burned in 2014. Large fire size is associated with high fire intensity and severity, which would manifest as areas with deep burning of the soil organic layer (SOL). Our primary objectives were to estimate burn depth in these fires and then to characterise landscapes vulnerable to deep burning throughout this region. Here we quantify burn depth in black spruce stands using the position of adventitious roots within the soil column, and in jack pine stands using measurements of burned and unburned SOL depths. Using these estimates, we then evaluate how burn depth and the proportion of SOL combusted varies among forest type, ecozone, plot-level moisture and stand density. Our results suggest that most of the SOL was combusted in jack pine stands regardless of plot moisture class, but that black spruce forests experience complete combustion of the SOL only in dry and moderately well-drained landscape positions. The models and calibrations we present in this study should allow future research to more accurately estimate burn depth in Canadian boreal forests.

Additional keywords: adventitious roots, boreal forest, burn depth, fire severity, *Picea mariana*, *Pinus banksiana*, soil organic layer depth, Taiga plains, Taiga shield.

Received 8 June 2017, accepted 17 November 2017, published online 14 February 2018

Introduction

Fire is the primary large-scale disturbance agent in the boreal forest of north-western Canada and Alaska (Bond-Lamberty *et al.* 2007; Kelly *et al.* 2013). Warming and drying in these regions over the last few decades is causing increases in fire frequency, extent, severity and fire season length (Flannigan *et al.* 2005; Kasischke and Turetsky 2006; Balshi *et al.* 2009). Changes to fire regimes will affect the structure and function of boreal forest ecosystems. Globally, one of the most important functions of the boreal forest is its ability to sequester and store carbon (C) in the soil organic layer (SOL). Fire severity can be defined as the loss of above- and belowground organic material that occurs as a direct consequence of fire (Keeley 2009). Net C stocks reflect the mean sequestration rates of C between fires and the combustion of C by fires. Thus, increased fire severity could alter C stocks, from net accumulation over multiple fires to net loss if organic matter is not re-sequestered between consecutive fires (Harden *et al.* 2000). The consumption of the SOL is often measured by the depth of burn, which is a close proxy for the mass of C combusted (Boby *et al.* 2010; Rogers *et al.* 2014). Increases in depth of burning can enhance permafrost degradation, indirectly causing further release of previously inaccessible soil C (Schuur *et al.* 2008). Loss of SOL can also lead to changes in successional trajectories (Johnstone and Chapin

2006; Johnstone *et al.* 2010*b*), rates of decomposition and soil organic matter quality, ultimately changing ecosystem C storage potential (Alexander and Mack 2016). As the boreal forest covers ~17% of terrestrial earth and contains at least 30% of global terrestrial C (Kasischke 2000), such changes are of global concern. Accurately estimating boreal fire severity is therefore essential for forecasting changes in C stocks, permafrost dynamics, ecological communities and their feedbacks to the global C cycle.

In many boreal forest fires, particularly in conifer forests of north-western Canada and Alaska, most of combustion takes place in the SOL (Kasischke *et al.* 1995; Amiro *et al.* 2001; Boby *et al.* 2010). Therefore, estimates of SOL burn depth can be used as a measure of fire severity. The depth of the residual SOL after fire has been used as a metric of fire severity (Greene *et al.* 2004, 2007; Johnstone and Kasischke 2005; Johnstone and Chapin 2006), but this does not take into account the initial thickness of the SOL. One approach to account for this is by comparing residual SOL depths in burned sites to the SOL in paired unburned sites (Kasischke and Johnstone 2005; de Groot *et al.* 2009). A more accurate estimate of burn depth at the site level is to measure the height of black spruce (*Picea mariana* (Mill.) B.S.P) adventitious roots above the residual SOL. These roots form on the stem of black spruce trees as the SOL thickens and are clearly visible after fire (Kasischke and Johnstone 2005; Boby *et al.* 2010). Boby *et al.* (2010) calibrated adventitious root height (ARH) for black spruce stands in interior Alaska, taking into account both the fact that adventitious roots are located below the soil surface in unburned stands, and that there is variability between SOL depths adjacent to trees (where ARH measurements are taken) and SOL depths measured at random points in a site. This method has proven useful in estimating burn depth in black spruce-dominated stands throughout the Alaska Boreal Interior (Hollingsworth *et al.* 2013; Rogers *et al.* 2014; Hoy *et al.* 2016) and Yukon Taiga Cordillera (Brown and Johnstone 2012) ecozones. However, it has rarely been used elsewhere in boreal forests and Veverica *et al.* (2012) suggest that different calibrations might be necessary for boreal ecosystems underlain with different parent material. Moreover, existing calibrations apply only to black spruce-dominated stands.

The boreal forests of the Northwest Territories (NWT), Canada are remote and poorly studied. This is particularly true on the granite bedrock of the Taiga Shield ecozone, even though this is the dominant substrate of boreal forest in North America (Ecological Stratification Working Group 1996). In the summer of 2014, nearly 3.4×10^6 ha burned in the NWT, combusting forest stands dominated by black spruce and jack pine (*Pinus banksiana* (Lamb.)) in both the Taiga Plains and Taiga Shield ecozones (Canadian Interagency Forest Fire Center 2014). These numerous, large fires had the potential for deep burning of organic soils, yet the severity of these fires in this respect remains unknown. In order to quantify burn depth throughout this region, we develop ARH calibrations in paired burned and unburned plots where black spruce trees are present, and in jack pine stands using measurements of burned and unburned SOL depths.

In the present study, we aim to improve methods to accurately estimate depth of burn by assessing sources of variation in depth of burn for different forest types in the NWT by sampling across a gradient of black spruce to jack pine dominance. We address the following questions:

(1) In unburned black spruce-dominated stands, does the depth of adventitious roots below the moss surface differ in association with ecozone, plot-level moisture class, total SOL depth, and pre-fire stand density or basal area? This will address the methodological question of whether there is a generalisable offset to apply to ARH measurements post-fire.

(2) In both burned and unburned black spruce-dominated stands, were there differences in SOL depths at trees, where adventitious root measurements are taken, compared with SOL depths at randomly located points that are not directly under trees? This will ensure that the correct offsets are applied to ARH measurements when assessing plot-level combustion, thereby improving the accuracy of our combustion estimates.

(3) In unburned jack pine-dominated stands, does SOL depth vary with ecozone, plot-level moisture, and pre-fire stand density or basal area? This will allow us to estimate burn depth in jack pine-dominated stands throughout our study region.

We apply these refined methods to our data from the NWT to evaluate how depth of burn and the proportion of the SOL that was combusted varies among forest type, ecozone, plot-level moisture and stand density. In answering these questions, we present a method for estimating depth of burn throughout this region and identify areas that are vulnerable to deep burning.

Methods

Study area and plot selection

This study took place near Yellowknife, NWT, Canada (Fig. 1). Mean annual temperature in this region is −4.3°C and mean annual precipitation is 290 mm (Environment Canada 2015). The study area spanned two ecozones underlain with discontinuous permafrost that differ in their geological history, soils development and parent materials (Ecological Stratification Working Group 1996). The Taiga Plains lie on sedimentary geology and the Taiga Shield is dominated by exposed granite bedrock (Ecological Stratification Working Group 1996). Black spruce forests dominate the fine-textured, glacio-lacustrine soils found in both ecozones, whereas jack pine is dominant on the coarse, alluvial and glacio-fluvial soils. Low density black spruce and jack pine typically dominate the exposed bedrock characteristic of the Taiga Shield.

Between June and August of 2015, we conducted fieldwork in seven spatially independent burn scars, four in the Taiga Plains ecozone and three in the Taiga Shield ecozone, which had burned between June and August 2014 (Fig. 1). Within each burn, we identified pre-fire strata of medium density, low density and sparse conifer by the Land Cover Map of Canada 2005 (LCC05), produced from 250-m Moderate Resolution Imaging Spectroradiometer (MODIS) imagery (Latifovic *et al.* 2008). Where Forest Resource Inventory data was available (Cumming *et al.* 2015), the leading tree species (black spruce or jack pine) was also identified. Random points were then assigned among each of the density strata or leading species

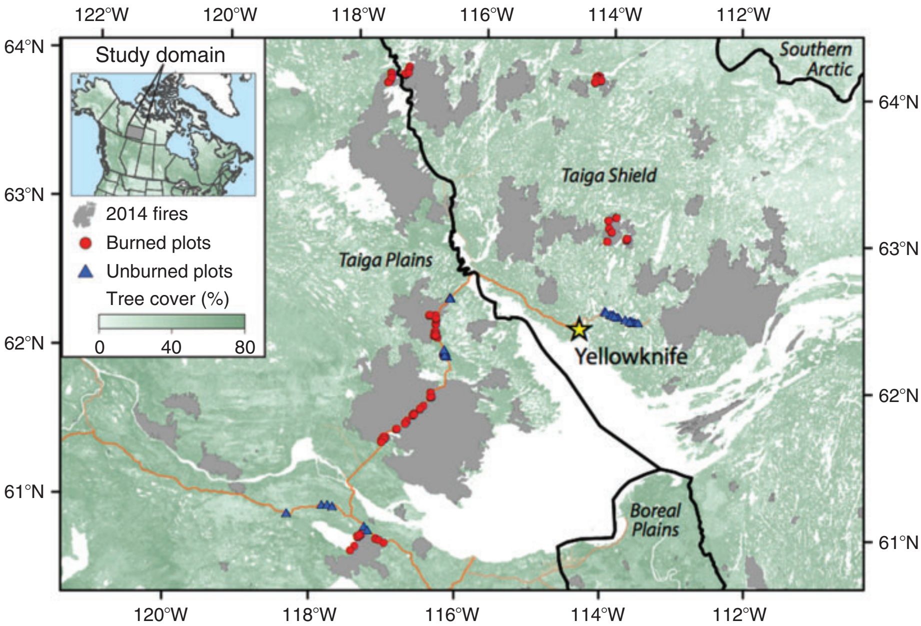

Fig. 1. Map showing burned (red circles) and unburned (blue triangles) sampling plots in seven burn scars (grey areas) and three unburned areas located in the Taiga Plains and Taiga Shield ecozones of the Northwest Territories, Canada.

class within fires. For ease of access these points were constrained to be within 1 km of highways or lake shorelines. In the field, we located 3 to 12 random points within each density stratum or leading species class for each burn. See Tables S1–S4, available as Supplementary material to this paper, for details on sample plot selection, total area burned and accessible area burned within each fire scar. Upon locating an assigned random point in the field we allocated it a moisture class on a six-point scale, ranging from xeric to subhygric, based on topography-controlled drainage adjusted for soil texture and presence of permafrost (Johnstone *et al.* 2008; and Fig. S1, available as Supplementary material to this paper). We established a plot at the random point and then found at least one additional plot, but usually two, that were of a different moisture category and within 100–500 m from the random plot. We define a site as the combination of the random plot and these additional plots. We sampled a total of 213 burned plots nested within 78 sites.

In June of 2016, we conducted fieldwork in three spatially independent areas of forest (two in the Taiga Plains ecozone and one in the Taiga Shield ecozone) that had no historical record of fire (>50 years) (Fig. 1). Our selection procedure for these unburned control plots, which were located outside of the burn perimeters, was designed to ensure they best matched conditions at burned plots and that the full range or variation was represented. Thus, to select an unburned plot, we randomly selected a burned plot and then subset all possible 30-m sampling locations (Fig. 1) to have tree cover (Hansen *et al.* 2013) within ±2%, the same aspect quadrant (N, E, S, W, or flat) and slope as close as possible to the burned plot, based on the Canadian Digital Elevation Model (CDEM, http://ftp.geogratis.gc.ca/pub/nrcan_rncan/elevation/cdem_mnec/, accessed 2 May 2016). We sampled a total of 36 unburned plots. All sampling plots consisted of two 30-m parallel transects that were 2 m apart and ran south to north.

Field measurements

At each plot we recorded latitude, longitude and elevation with a GPS receiver (Garmin GPSMAP 64ST Handheld GPS), and slope and aspect with a clinometer (Suunto PM5/360PC) and compass. Within each burned and unburned plot SOL depth was measured every 6 m along each transect (10 points per plot). When black spruce trees were present, we also measured SOL depth at 10 trees per plot, as close to the boles as possible. In association with these points, we measured the depth from the top of the green moss or lichen to the top of the closest adventitious root on 1–3 adventitious roots per tree in unburned stands and the height from the top of the highest ARH to the top of the residual SOL on 1–3 adventitious roots per tree in burned stands.

In each plot, we measured the diameter at breast height (DBH) at the standard height of 1.3 m from the base, for all trees ≥1.3 m in height and the basal diameter of trees <1.3 m tall that were originally rooted within a 2 × 30-m belt transect. Trees were considered killed by fire if there was visible char and bark or fine branches were present. Fallen trees that were killed by fire were included in this census in order to estimate species-specific stand density and basal area. To estimate stand age, we collected five trees of each dominant species within a stand, either black spruce, jack pine, or both species. We sampled basal tree discs in burned stands and basal tree cores in unburned stands. Discs and cores were taken as close to the ground as possible, but above the root collar, and prepared using standard dendrochronology techniques (Cook and Kairiukstis 1990) to count rings for an estimate of minimum tree age. In most cases, tree ages estimated from ring counts were clearly structured by recruitment cohorts and clustered within 20 years of each other. For these plots, we estimated years since fire as the age of the oldest tree within the dominant age cohort. Less frequently (17.5% of plots), tree ages were uneven, and spanned an age range often much greater than 20 years. This uneven age structure may have arisen from at least one of three different processes: (a) delayed recruitment after fire, (b) partial mortality from fires that left old trees surviving, and (c) ageing errors associated with abnormal growth or poor wood quality. We estimated time since last fire as the age of the oldest tree except in cases where we found two or more trees with similar ages and we had evidence of a similar-aged fire in nearby stands, suggesting a fire that left surviving trees; for these stands we estimated years since last fire as the maximum tree age of the most recent cohort.

Statistical analyses

All data analyses were performed using the R statistical software, ver. 3.4.2 (R Core Team 2017). Each plot was classified as black spruce- or jack pine-dominated based on whether the majority (>50%) of pre-fire trees were black spruce or jack pine. To estimate depth of burn in black spruce-dominated stands we used the adventitious root method (as per Boby *et al.* 2010), where the ARH above the residual SOL is an estimate of the depth of SOL combusted. However, simply using the ARH is likely to result in an underestimation of the SOL combusted, because in unburned (or pre-fire) plots, adventitious roots are located below the top of green moss, not at the surface. In order to calibrate ARH measurements in burned stands, and account for this possible offset, we tested to see if there was a systematic offset between mean adventitious root depth (ARD), defined as the distance from the highest adventitious root to the top of the green moss in unburned stands, based on 1–3 measurements per tree. We examined the following predictor variables: ecozone, moisture class, elevation, SOL depth, dominant tree species, black spruce basal area, black spruce density, jack pine basal area, jack pine density, total stand basal area and total stand density. We removed explanatory variables that were highly correlated with one another (Spearman's $P < 0.05$). The full model tested if ARD varied between ecozones, black spruce density and SOL depth, and any first-order interactions between these variables using a hierarchical linear mixed effect model in the R package 'nlme' (Pinheiro *et al.* 2017) with random effects of plot nested within unburned sample area, to account for spatial non-independence. Model reduction was completed through likelihood ratio tests of the full model against the reduced models, and visual inspection of residual plots for the final model did not reveal any deviations from homoscedasticity or normality.

As we were only able to estimate depth of SOL burn near trees where ARH measurements were taken, we determined if sampling at trees would bias our estimates of burn depth (Boby *et al.* 2010). We did this for both burned (1855 measurements) and unburned plots (246 measurements) to determine if differences in SOL measured under trees compared with randomly located points in burned plots could be explained by either differences in organic matter accumulation or combustion under trees compared with the random points. To model SOL depth at trees, we used a hierarchical, linear mixed-effect model with a random-effect structure as above for unburned plots and with random effects of plot nested within site, nested within burn for burned sites. The full model included fixed effects of organic-layer depth at random points, ecozone and black spruce density, and first-order interactions. Variable selection and visual inspection of the final model proceeded as above.

To assess depth of burn in jack pine-dominated plots, where there are few black spruce trees and therefore ARH measurements were not possible, we measured SOL depth in unburned jack pine-dominated plots as an estimate of pre-fire SOL layers. We fit a hierarchical, linear mixed-effect model with random effects of plot nested with unburned area. We log-transformed SOL to meet assumptions of normality and tested how SOL might be affected by ecozone and moisture category. The full model included ecozone and moisture class as fixed effects, with interaction. Variable selection and model inspection proceeded as above. We tested for differences in SOL between moisture categories using Tukey–Kramer *post-hoc* analysis for multiple comparisons in the R package 'lsmeans' (Lenth 2016).

Based on the above analyses, we calculated burn depth in black spruce-dominated stands by calibrating ARH measurements with the modelled relationship of ARD as a function of SOL depth. We did not need to include an offset for SOL depth measured at trees, as the relationship between SOL measured at trees and random points was of the same magnitude and direction in both burned and unburned stands. To estimate depth of burn in jack pine plots, we subtracted the residual SOL from the unburned average SOL depth associated with each moisture category. In one plot, the residual SOL depth was greater than the average SOL and burn depth was therefore set to zero.

Using the plot-level estimates of burn depth we calculated pre-fire SOL depth (burn depth + residual SOL) and the proportion of SOL that combusted (burn depth ÷ pre-fire SOL depth). We modelled the variation in burn depth and the proportion of SOL combusted in both back spruce- and jack pine-dominated stands. In black spruce plots, we tested if burn depth and proportion combusted varied between ecozone, moisture category, and black spruce basal area and first-order interactions using a hierarchical, linear mixed-effect model with random effects of plot nested within site nested within burn. For jack pine plots we used the same model, except basal area was of the dominant species instead of black spruce. In both cases, visual inspection of the residuals was completed as above. We tested for differences in both burn depth and proportion of SOL combusted between moisture categories using Tukey–Kramer *post-hoc* analysis for multiple comparisons. To determine if and how pre-fire SOL depth affects residual SOL depth we fit hierarchical linear mixed effect models for both black spruce- and jack pine-dominated stands. Random effects and model inspection proceeded as above.

Results

We examined 36 unburned- and 213 burned-forest plots, capturing a broad gradient in environmental characteristics and pre-fire stand composition (Fig. 1, Table 1). Most plots were black spruce-dominated (198 out of 249), but many of these plots also

Table 1. Summary of plot characteristics for unburned and burned black spruce- and jack pine-dominated stands

All values represent mean ± standard deviation and range in parenthesis, other than moisture category which is a median value. ASL, above sea level

	Black spruce		Jack pine	
Variable	Burned ($n = 173$)	Unburned ($n = 25$)	Burned ($n = 40$)	Unburned ($n = 11$)
Moisture category (1–6)	4 (1– 6)	4 (1- 6)	1 (1–3)	1 (1–3)
Elevation (m ASL)	264 ± 63 (189 – 408)	224 ± 18 (185 – 256)	267 ± 30 (197 – 316)	226 ± 16 (190 – 245)
Soilorganic layer (SOL) depth (residual for burned)	15.2 ± 13.9 (0.5 – 65.5)	17.8 ± 9.2 (1.1 – 36.7)	2.1 ± 1.6 (0.1 – 6.8)	6.7 ± 2.5 (3.3 – 11.5)
Black spruce basal area ($cm^2\ m^{-2}$)	8.7 ± 7.3 (0.1 – 37.1)	11.7 ± 8.5 (0.6 – 31.7)	0.6 ± 1.2 (0 – 5.6)	0.4 ± 0.3 (0 – 0.9)
Jack pine basal area ($cm^2\ m^{-2}$)	1.9 ± 4.1 (0 – 19.3)	13.2 ± 8.8 (0 – 28.5)	14.0 ± 7.4 (0.7 – 28.9)	17.6 ± 11.5 (4.8 – 41.5)
Mean stand age (years)	109 ± 45 (19 – 232)	104 ± 60 (49 – 275)	76 ± 34 (33 – 171)	92 ± 24 (69 – 143)

Table 2. Mean ± standard error of unburned soil organic layer (SOL) depth and residual SOL depth in black spruce- and jack pine-dominated stands of different plot moisture classifications

Number in parenthesis represents the number of plots (10–20 measurements were made within each plot). NA, not applicable

	Unburned SOL		Residual SOL	
	Black spruce	Jack pine	Black spruce	Jack pine
Xeric	6.3 ± 0.4 (1)	6.3 ± 0.4 (6)	2.2 ± 0.3 (26)	1.7 ± 0.3 (28)
Subxeric	7.7 ± 1.0 (1)	7.2 ± 0.4 (3)	3.4 ± 0.3 (23)	2.3 ± 0.4 (5)
Mesic–subxeric	14.4 ± 1.0 (6)	10.1 ± 1.3 (2)	8.3 ± 1.1 (28)	3.9 ± 0.3 (5)
Mesic	15.8 ± 0.9 (6)	NA	13.5 ± 1.4 (34)	NA
Mesic–subhygric	18.6 ± 1.3 (3)	NA	24.4 ± 1.5 (34)	NA
Subhygric	26.9 ± 0.9 (8)	NA	34.8 ± 2.5 (28)	NA

had jack pine trees present (Table 1). Similarly, jack pine plots were often not pure stands, but also had black spruce trees present. We occasionally encountered other species, such as white spruce (*Picea glauca*), balsam poplar (*Populus balsamifera*), paper birch (*Betula papyrifera*), trembling aspen (*Populus tremuloides*) and larch (*Larix laricina*), but these were always a small component of stand composition (<20% of stems). Despite the fairly flat terrain of the Taiga Plains and Taiga Shield ecozones, forest types sorted along moisture gradients such that jack pine stands were generally located in well-drained upland positions, whereas black spruce-dominated stands were in more poorly drained lowland areas (Tables 1, 2). Consequently, the two forest types represent differences in moisture categories, SOL depth and stand age (Table 1). The unburned stands captured the full gradient in species composition and environmental characteristics found in burned plots (Table 1) and were therefore relevant for calibrating measurements of burn depth.

ARD in unburned stands followed a normal distribution around a mean value of 3.7 ± 0.7 cm (s.e.) below the surface of the green moss. ARD was not affected by ecozone or black spruce basal area. However, it was related to SOL depth (t-statistic $= -2.94$, marginal $R^2 = 0.06$, $P < 0.01$), lowering it by 0.03 ± 0.01 cm of SOL depth (Fig. 2). The final model of ARD was used to predict ARH offset based on residual SOL depth plus the ARH in burned black spruce-dominated plots.

The relationship between SOL depth measured at trees and random points is of similar direction and magnitude for burned and unburned black spruce-dominated plots. Across the burned plots, average SOL depth at trees and random points were 14.7 ± 0.4 cm and 13.8 ± 0.4 cm respectively. In unburned plots, mean SOL depth was 19.2 ± 0.6 cm near trees and 18.1 ± 0.7 cm at random points. SOL depth measured near trees could be predicted by SOL depth at the randomly located points in both burned (t-statistic $= 27.75$, marginal $R^2 = 0.45$, mean difference $= 0.56$, $P < 0.001$) and unburned (t-statistic $= 8.91$, marginal $R^2 = 0.31$, mean difference $= 0.49$, $P < 0.001$) black spruce stands (Fig. 3). This relationship was not affected by moisture category, ecozone, or pre-fire black spruce basal area.

To estimate depth of burn in jack pine-dominated plots, we measured SOL in unburned plots as an estimate of pre-fire SOL layers (Table 2) and found that SOL was marginally affected by plot moisture (F-statistic $= 2.406$, $P = 0.075$). A Tukey–Kramer *post-hoc* test of multiple comparison revealed no significant pairwise differences in mean unburned SOL between moisture categories ($P > 0.05$).

We estimated mean burn depth in black spruce-dominated stands to be 9.4 ± 0.2 cm, with a range of 4.3 to 18.3 cm of organic layer combusted by fire. These estimates varied between moisture categories and marginally increased with pre-fire basal area of black spruce, but were not affected by ecozone (Table 3, Fig. 4). Mean burn depth in jack pine stands was estimated as 4.9 ± 0.2 cm, ranging from 0 to 7.9 cm, and did not vary significantly with plot moisture class, jack pine basal area, or ecozone (Table 3, Fig. 4). The proportion of SOL combusted in black spruce stands was 49.1 ± 1.8%, with a

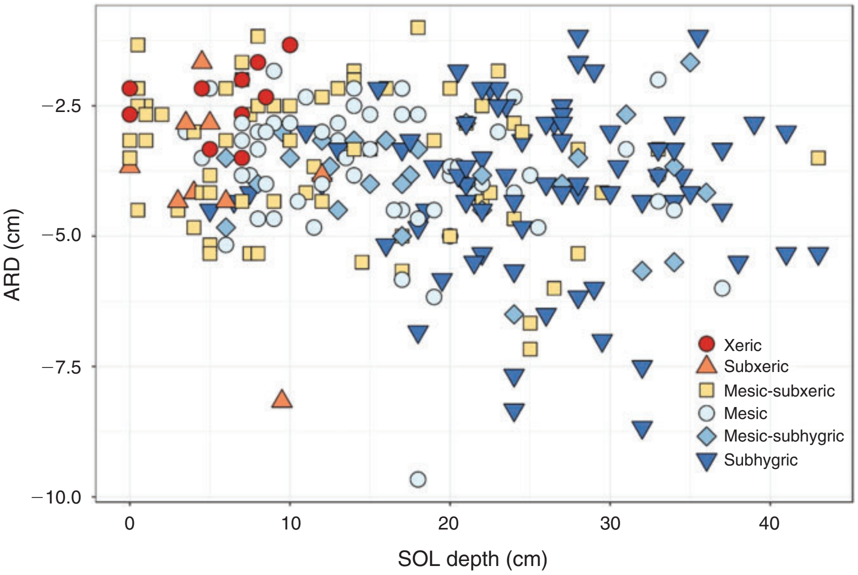

Fig. 2. Average adventitious root depth (ARD) per tree as a function of soil organic layer (SOL) depth in unburned stands.

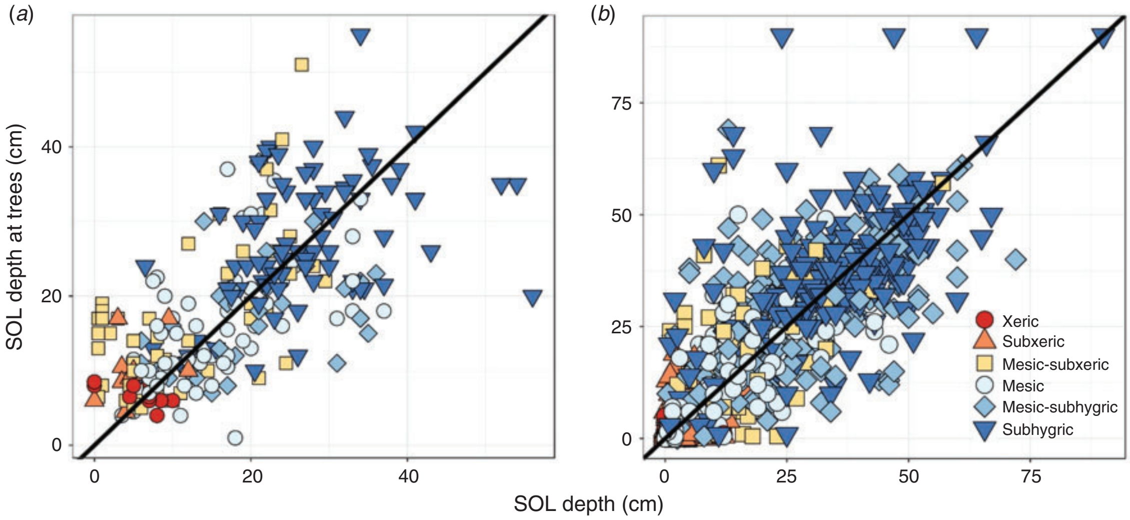

Fig. 3. Soil organic layer (SOL) depth measured at trees plotted against SOL depth measured at randomly located points in (*a*) unburned and (*b*) burned plots. Black line represents 1 : 1 relationship.

range of 9.4 to 90.7% (Table 3, Fig. 4). Proportional losses of SOL depth were greatest in black spruce stands at dry plots, and least in wet plots, despite SOL thickness being greater at wetter plots. In jack pine-dominated stands, the proportion of SOL combusted ranged from 0.0 to 98.4% with an estimated mean of 71.1 ± 3.3% that did not differ between moisture categories (Table 3, Fig. 4). For both forest types, proportion of SOL combusted was not affected by ecozone or basal area of the dominant pre-fire tree species (Table 3). Residual SOL depth was related to pre-fire SOL in both jack pine (t-statistic = 3.69, marginal $R^2 = 0.23$, $P < 0.001$, Fig. 5*a*) and black spruce (t-statistic = 69.75, marginal $R^2 = 0.97$, $P < 0.001$, Fig. 5*b*) plots.

Discussion

The models presented in this study provide a way of estimating depth of burn and pre-fire SOL depth in both black spruce- and jack pine-dominated stands in the Taiga Plains and Taiga Shield ecozones of the NWT, Canada. Fire is the dominant large-scale disturbance throughout these ecozones and estimating burn depth in different forest types is necessary for assessing fire severity and its longer-term impacts. We provide evidence that the height of adventitious roots on burned black spruce trees can be used as a proxy for SOL burn depth, when adjusted for total SOL depth, and without a need to account for differences in SOL depths measured at trees *v.* random points in a stand. In jack

Table 3. Results of hierarchical, linear mixed-effects model of burn depth and proportion of SOL combusted in black spruce- and jack pine-dominated stands as a function of moisture, basal area and ecozone

In the black spruce model, basal area is for black spruce trees, and in the jack pine model it is for jack pine trees. Random effects of plot nested within site nested within burn were included. An asterisk indicates a significant effect in the model ($P < 0.05$) and letters following the ±values (s.e.) indicate significant differences between moisture categories based on Tukey–Kramer *post-hoc* test of multiple comparisons

	Burn depth		Proportion of SOL combusted	
	Black spruce ($R^2 = 0.150$)	Jack pine ($R^2 = 0.094$)	Black spruce ($R^2 = 0.719$)	Jack pine ($R^2 = 0.071$)
(Intercept) Xeric	7.84 ± 0.77 a	5.68 ± 0.89 a	0.78 ± 0.04 a	0.66 ± 0.15 a
Subxeric	1.93 ± 0.76 ab	−0.38 ± 0.88 a	−0.03 ± 0.03 a	−0.11 ± 0.09 a
Mesic–subxeric	2.21 ± 0.73 ab	1.44 ± 0.83 a	−0.17 ± 0.03 b	−0.14 ± 0.09 a
Mesic	2.26 ± 0.73 ab	NA	−0.28 ± 0.03 c	NA
Mesic–subhygric	2.60 ± 0.69 b	NA	−0.46 ± 0.03 d	NA
Subhygric	1.81 ± 0.71 ab	NA	−0.55 ± 0.03 e	NA
Basal area	0.09 ± 0.03*	−0.05 ± 0.05	−0.0004 ± 0.002	0.006 ± 0.006
Ecozone	1.23 ± 0.80	−0.43 ± 0.83	0.05 ± 0.04	0.09 ± 0.24

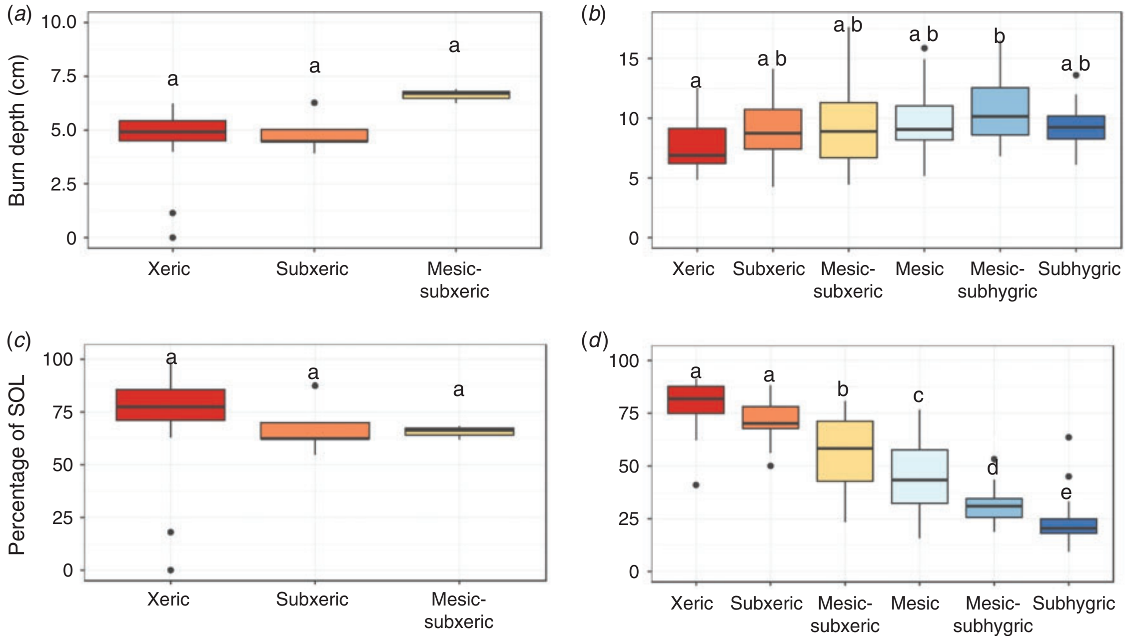

Fig. 4. Mean burn depth in (*a*) jack pine- and (*b*) black spruce-dominated stands and percentage of soil organic layer (SOL) combusted in (*c*) jack pine- and (*d*) black spruce-dominated stands as a function of plot-level moisture. Letters represent significant differences ($P < 0.05$) between moisture classes based on Tukey–Kramer *post-hoc* test of multiple comparisons. See Table 2 for results of hierarchical linear mixed effect models.

pine-dominated stands, we provide estimates of burn depth based on mean unburned SOL depths in different plot-level moisture categories. Our calibrations will allow future studies to estimate burn depth and organic matter combustion from in-burn measurements in these stand types and ecozones. Our methodology may also be applicable to reconstructing depth of burn in other regions of the boreal forest.

This is the first study that we are aware of that uses and calibrates ARDs for estimating burn depth in black spruce-dominated stands in this study region, and more broadly in the boreal forests of western Canada. Our findings of ARD in unburned stands being ~3.7 cm below the surface of the green moss are within the range of measurements found in black spruce stands in interior Alaska of 6.6 cm (Kasischke and Johnstone 2005), 5.1 cm (Kasischke *et al.* 2008), 3.2 cm (Boby *et al.* 2010) and 5.9 cm (Rogers *et al.* 2014), and in northern Michigan, USA, of 2.4 cm (Veverica *et al.* 2012). Boby *et al.* (2010) approximated burn depth by simply adding 3.2 cm to the ARH measurements across all black spruce sites, independent of drainage class or SOL depth. In contrast, we found that SOL depth could model the ARH offset, with every 1-cm increase in SOL depth resulting in a 0.03 ± 0.01 cm increase in ARH offset. These results are similar to Veverica *et al.* (2012), who found that depth from the soil surface to ARH increased as depth from

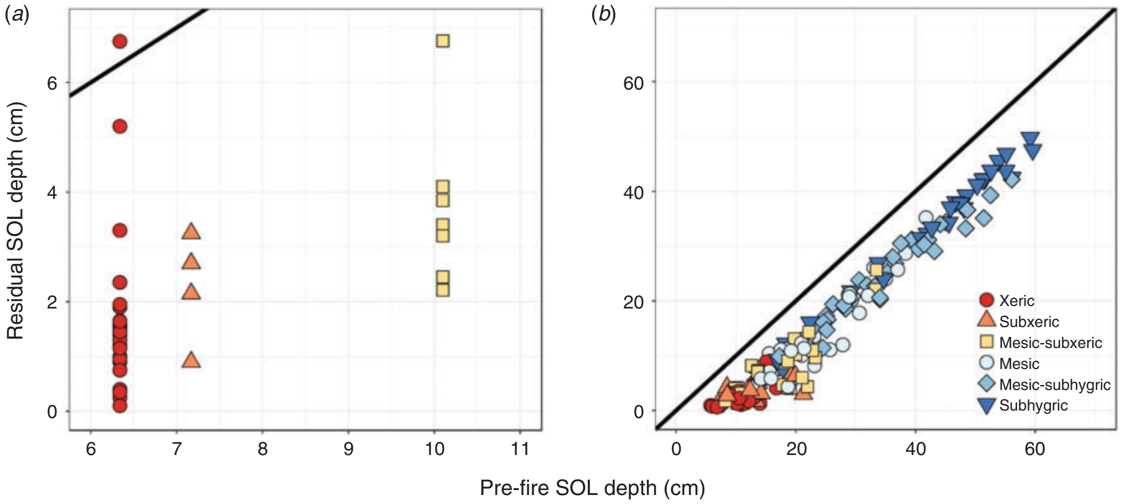

Fig. 5. Pre- *v.* post-fire soil organic layer (SOL) depth (cm) in (*a*) jack pine- and (*b*) black spruce-dominated stands. Black line represents 1 : 1 relationship.

ARH to mineral soil increased. The burned black spruce stands in the present study encompassed a large range in residual SOL, from nearly 0 to over 65 cm (Table 1). Using our calibration and the depth of adventitious roots in unburned stands (3.7 ± 0.7 cm), this results in adding anywhere from 3.73 to 5.85 cm to the ARH. We therefore suggest using the following calculation to estimate burn depth for black spruce stands in this region, as it is straightforward and will result in a better estimate of burn depth and pre-fire SOL:

$$\text{Burn depth} = \text{ARH} + 3.7 + 0.03 \times \text{SOL depth}$$

In both burned and unburned black spruce-dominated plots, the relationship between SOL depth measured at trees and random points is of similar direction and magnitude. In burned stands, the greater SOL depth recorded at trees compared with random points (mean difference = 0.56 cm) could be due to reduced organic combustion under trees, greater organic matter accumulation under trees or a combination of both. As the relationship is the same in unburned stands (mean difference = 0.49 cm), we believe that the greater SOL depth under trees is due to greater organic matter accumulation, not decreased combustion. Our results are similar to Kasischke *et al.* (2012), who found that SOL depths under trees were generally greater than SOL located across the sampling plot. These results are substantially different from previous findings in interior Alaska (Boby *et al.* 2010) and in the southern boreal forest of Canada (Miyanishi and Johnson 2002; Greene *et al.* 2007), where residual SOL measured at the base of trees was less than at random points in burned sites but there was no difference in unburned sites. The difference in burned stands was therefore attributed to enhanced combustion under trees (Boby *et al.* 2010). Because we observed greater SOL depths under trees in both unburned and burned stands, and only to a small extent, we believe that measurements of burn depth at trees is a valid representation of stand burn depth. As such, we suggest that it is unnecessary to account for differences in SOL between random points and tree points when estimating burn depth in black spruce-dominated stands in this study region.

Throughout the study region, there are large areas of jack pine dominated forest where black spruce is not present. We found marginal differences in SOL depths associated with moisture categories in such stands. These differences were based on SOL depths measured at systematic points in the plot irrespective of trees; however, unburned pine-dominated stands in the southern boreal forest of Canada had slightly thicker SOL depths near trees (Greene *et al.* 2007). We did not measure and therefore did not account for possible differences in SOL near the base of trees in jack pine stands, but we did assess if SOL varied with stand density and found no relationship. Thus, we believe our plot-level moisture classification and associated SOL measurements are representative of the stand mean. As such, when adventitious roots are not present, and the forest stand is dominated by jack pine, we suggest assessing plot-level moisture and determining burn depth based on measurements of residual SOL depth subtracted from estimates of unburned SOL depths that are specific to plot moisture categories (Table 2).

Previous estimates of burn depth in pine dominated boreal forests indicate that over 50% (~4 out of 7 cm) of the pre-fire SOL combusts (de Groot *et al.* 2009). Although burn depth is likely to depend to fire weather and climatic conditions, our results are similar in that we found a fairly consistent burn depth (~5 cm) and proportion of SOL combusted (~70%) across all moisture categories and ecozones for jack pine-dominated stands. The majority of the pre-fire organic layer (~7 cm) combusted, leaving very shallow or in some cases no residual SOL regardless of pre-fire stand characteristics. In black spruce plots, we found a mean burn depth of 9.4 cm. This estimate is considerably lower than similar studies in interior Alaska of 14.5 cm (Kasischke and Johnstone 2005), 19.2 cm (Rogers *et al.* 2014) and 19.6 cm (Kasischke *et al.* 2008). Our lower estimate could be due to the broader distribution of black spruce stands among moisture categories, occupying even the driest landscape positions, where it is often codominant with jack pine. In support of this, we found that burn depth increased with black spruce density and varied with plot moisture. The shallowest burning occurred in xeric and subhygric plots, presumably due to a lack of fuel and high soil moisture preventing deep burning, respectively.

Despite significant differences in burn depths associated with moisture, we found fairly consistent burn depths compared with residual SOL depths across moisture classes. Black spruce forests at dry and moderately well-drained landscape positions were most vulnerable to complete combustion of the SOL, whereas only a small proportion of the SOL combusted at wetter landscape positions. As such, pre-fire SOL depth strongly predicted residual SOL depth, particularly in black spruce-dominated plots. These results are similar to studies in black spruce forest of interior Alaska, where pre-fire SOL could explain over 50% of the variation in residual SOL depth (Johnstone *et al.* 2010*b*). Mean burn depths of 10–13 cm were reported in Alaska regardless of site drainage associated with topographic position (Kane *et al.* 2007; Hoy *et al.* 2016) but the proportion of organic layer combusted varied considerably with landscape position (Kane *et al.* 2007; Turetsky *et al.* 2011).

Changes to fire severity, specifically increasing burn depth, have the potential to alter the net ecosystem C balance (Harden *et al.* 2000), catalyse shifts in post-fire successional trajectories (Johnstone and Chapin 2006; Johnstone *et al.* 2010*a*), promote permafrost degradation (Shur and Jorgenson 2007; Nossov *et al.* 2013), change soil moisture regimes (Schuur *et al.* 2008), and decrease soil microbial biomass and respiration (Holden *et al.* 2013). The impacts of a changing fire regime of post-fire successional processes and function have been studied in black spruce forests of interior Alaska, and although it seems likely that the responses would be similar in the NWT, this has yet to be established, and there is even more uncertainty regarding the effects of varying fire severity in jack pine-dominated stands. Furthermore, estimating burn depth or the amount of SOL combusted is necessary to estimate C emissions in these forests. This will lead to better forecasts of how changes in fire severity contribute to the net ecosystem C balance in this region. The results we presented in our study should allow future research to develop improved estimates of burn depth, and assess the implications of deep burning on C stocks, successional trajectories and permafrost dynamics, and their associated feedbacks to longer term C storage in Canadian boreal forests.

Conflicts of interest

The authors confirm that they have no conflicts of interest.

Acknowledgements

This project was supported by funding awarded to M. C. Mack from National Science Foundation Division of Environmental Biology RAPID grant number 1542150, and from the NASA Arctic Boreal and Vulnerability Experiment (ABoVE) Legacy Carbon grant number Mack-01; NSERC Discovery Grant funding to J. F. Johnstone and M. R. Turetsky; Government of the Northwest Territories Cumulative Impacts Monitoring Program Funding project number 170 to J. L. Baltzer; and Polar Knowledge Canada's Northern Science Training Program funding awarded to Canadian field assistants. We thank our laboratory members at Northern Arizona University for their input and feedback at various stages of this manuscript. We also extend our appreciation to the numerous field and laboratory assistants and graduate students from Northern Arizona University, Wilfrid Laurier University and University of Guelph. We are grateful for the support provided by the Government of the Northwest Territories–Wilfrid Laurier University Partnership Agreement for important logistical support and access to laboratory space.

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