1 **Variation in fuel structure of boreal fens**

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Draft

9 ***Abstract.***

10 Wildfire frequency and severity in boreal peatlands can be limited by wet fuel conditions, but increases
11 in burn severity can occur when lower water table positions cause drying of fuels. Most studies on
12 northern peatland fires to date have focused on ombrotrophic bogs. Though minerotrophic fens are the
13 most common type of peatland in North America, the influence of fuel structure and loading on potential
14 fire behaviour in boreal fens is poorly understood. To investigate the potential for widespread flame
15 front propagation across boreal fens, we quantified the fuel components present in three generalized
16 boreal fen types (open, shrub, and treed fens) in northern Alberta, Canada. The loadings of aerial fuels,
17 tall shrubs, and downed woody debris varied significantly among fen types. Fuel loads tended to be
18 smallest in the open fens and largest in the treed fens. Open and shrub fens had larger loads of total
19 surface fuels relative to treed fens, with short-statured shrubs being the dominant contributor to surface
20 fuel load. Based on our observations of available fuel loads, each of the fen types may support moderate
21 to high intensity fire following long-term drying, which may consume not only some fraction of the
22 aboveground biomass but also provides a substantial downward pulse of energy to initiate smouldering
23 in the organic layer.

24
25 Keywords: peatlands, wildfire, fuel type, forest biomass, fuel load

26 Introduction

27 Historically, boreal wildfire research has focused largely on upland forests, while peatlands have
28 received relatively little attention despite covering approximately 12% (1.136 million km²) of Canada's
29 land area (Tarnocai 2009). Boreal and subarctic peatlands represent a long-term net sink for
30 atmospheric carbon (C) because net primary productivity and input of organic matter to soils exceeds
31 soil C losses due to decomposition and disturbance such as combustion (Harden et al. 2000). Despite
32 their function as a net C sink, these ecosystems are prone to losses of C along with mercury and trace
33 gases via burning during wildfire. Smoke emissions associated with peat fires can pose significant
34 hazards to air quality and human health (Flannigan et al. 2009; Rappold et al. 2011; Johnston et al.
35 2012).

36 The frequency and intensity of wildfire in the boreal region are important controls on C storage
37 (Bond-Lamberty et al. 2007). Fires can be ignited within peatlands (Turetsky et al. 2004) or spread from
38 adjacent upland areas (Zoltai et al. 1998). Wildfires burned an estimated $1470 \pm 59 \text{ km}^2 \text{ year}^{-1}$ of
39 peatlands between 1980 and 1995 in continental western Canada (i.e., Manitoba, Saskatchewan, Alberta;
40 Turetsky et al. 2002). Peatland fires can consume some portion of the aerial and understory fuel strata
41 (e.g., trees, shrubs, herbs); however, surface (nonvascular plants, litter) and ground fuels (thick layers of
42 duff, organic soils, root biomass) are more typically consumed through smouldering combustion that
43 dominate peat fires (Zoltai et al. 1998; Benscoter and Wieder 2003; Rein et al. 2008). In many
44 undisturbed peatlands, wet conditions that keep water tables near the peat surface limit wildfire
45 frequency and the potential for deep organic matter consumption (Turetsky et al. 2011). However,
46 projected warming is expected to cause drying as a result of increased evapotranspiration, despite
47 potential increases in precipitation in some boreal regions. This will lower water table positions in
48 peatlands and may increase the availability of peatland ground fuels for smouldering combustion

49 (Waddington et al. 2012). Furthermore, smouldering combustion can be maintained at a higher moisture
50 content than flaming combustion, thus allowing deeper ground fuels in these ecosystems to burn under
51 conditions that may not support active flaming (Frandsen 1997).

52 The vulnerability of peatlands to burning under contemporary climate is still poorly understood
53 (Turetsky et al. 2015). Fire season duration, fire occurrence and annual area burned are predicted to
54 increase across northern forests as climate conditions become warmer and drier (Wotton and Flannigan
55 1993; Stocks et al. 1998; Flannigan et al. 2001, 2005; Wotton et al. 2010). While depth of burn in the
56 ground layer is typically thought to increase with the date of occurrence within the fire season, there was
57 no observed increase in late season burning in Alaskan peatlands, which was likely prevented by high
58 moisture content and surface permafrost present even during the late season burning period (Turetsky et
59 al. 2011). However, this trend may not apply to the large areas of peatland present south of the
60 discontinuous permafrost region. Particularly in these areas, a future warming trend is likely to result in
61 lower water tables and drier organic soils, potentially leading to deeper organic matter consumption
62 during burning and significant soil C losses (Turetsky et al. 2011). Because the vast majority of the
63 peatland C stocks reside belowground (only about 0.10 Pg C is aboveground biomass in continental
64 western Canada), this portion is of primary concern for C cycling (Vitt et al. 2000b). Under a scenario of
65 increasing wildfire activity, C emissions may very well exceed C uptake in these ecosystems, thus
66 diminishing the function of northern peatlands as a C sink (Wieder et al. 2009).

67 The 16 benchmark fuel types of the Canadian Forest Fire Behaviour Prediction (FBP) System, a
68 system used extensively by fire management agencies across Canada, do not include fuel complex
69 characterization that would adequately describe the available fuels within peatland ecosystems; the
70 boreal spruce model (C-2) explicitly excludes “spruce-*Sphagnum* bogs” (Forestry Canada Fire Danger
71 Group 1992). The fire spread that may be exhibited in peatlands likely differs from that of uplands,

72 because fire behaviour is sensitive to fuel load, arrangement, connectivity and flammability of the fuel
73 strata present. Continental peatlands of western Canada are typically forested. Ombrogenous bogs in
74 this region are dominated by black spruce (*Picea mariana* (Mill) BSP.). Geogenous fens, on the other
75 hand, vary more widely in canopy structure, and can be forested (either with black spruce or larch [*Larix*
76 *laricina* (Du Roi) K. Koch]), or can lack a continuous tree canopy (Vitt 2000a). These differences in
77 vegetation structure are partially attributed to differences in hydrology and minerotrophy. For example,
78 mean growing season water table positions typically range from 10 cm above to 40 cm below the peat
79 surface in fens, and from 40 to 60 cm below the peat surface in bogs (Vitt et al. 2000b). Together,
80 variation in vegetation structure and organic layer moisture content will dictate fire danger (Wotton
81 2009), as dry wooded peatlands are more prone to burning than open or shrub dominated peatlands
82 (Turetsky et al. 2002). Recently, Johnston et al. (2015) compared fuel loads and structure along a
83 chronosequence of *Sphagnum*-dominated bogs in northern Alberta to better understand successional
84 trends in fuel loading and structure over time. In general, they found that consistent surface fuel loads
85 and a lack of fuel strata gap (typically <0.1 m) between the surface and the crowns could support crown
86 fire initiation in all sites along their chronosequence. At ~60 years following fire, the canopy bulk
87 density of black spruce was sufficient to support active crown fire, and at ~80 years it could support
88 active crown fire on approximately 10-40% of days during a fire season. No studies to date have
89 considered fuel structuring in fens, despite the fact that fens constitute more than 60% of peatland area
90 in continental western Canada (Vitt et al. 2000a). In general, very little is known about the conditions
91 needed to support widespread flame front propagation in fen ecosystems.

92 The purpose of this study was to identify and quantify fuel components available to support
93 flame front spread through three fen types along a hydrological and vegetation gradient in northern
94 Alberta, Canada. These fen types (open/sedge fens, shrub fens, and treed fens) are representative of the

95 cross-section of fens in continental Canada, reflecting the variation in the structure and type of fuel
96 available to support burning. A second goal was to develop allometric equations for peatland larch that
97 could be used, along with similar previously developed models for bog black spruce, to estimate overall
98 available aerial fuels in treed peatlands.

99

100 **Methods**

101 *Study site*

102 We identified eleven fen sites in northern Alberta to examine inter-site variability in fuel
103 structure, composition and load (Figure 1; Table 1). Sites were identified using wildfire maps from the
104 Canadian Large Fires Database and the Canadian National Fire Database (Natural Resources Canada;
105 available from <http://cwfis.cfs.nrcan.gc.ca>) and were confirmed with aerial photography and ground
106 reconnaissance. All sites were representative of the continental boreal, and vegetation communities in
107 several of these sites are described in more detail by Miller et al. (2015). Our sites are located in the
108 Central Mixedwood Natural Subregion of the Boreal forest (Natural Regions Committee 2006). Each
109 site was categorized into one of three general categories: treed fen, shrub fen, or open fen. Open sites
110 were those consisting primarily of sedges (primarily *Carex* spp.) with infrequent small bog birch. Shrub
111 sites were dominated by taller shrubs (primarily *Betula pumila*) with some graminoids and sparse larch
112 or spruce trees. Treed sites were dominated by larch and/or black spruce with a shrub understory (Figure
113 2).

114

115 *Fuel load characterization*

116 Sampling of each site involved characterization of aerial and surface fuel components. Sampling
117 was performed at each site along a 100 m transect, with four 10 m x 10 m quadrats spaced evenly on

118 alternating sides of the transect. The transect was established with a random starting point and bearing,
119 and a new bearing that was constrained to avoid sampling overlap was chosen at 50 m for the remainder
120 of the transect to minimize potential sampling bias resulting from prevailing orientation of dead and
121 down woody fuels. The focus of this study was to characterize fuels available to support combustion, but
122 was constrained to the fuel strata present above the ground fuel layer. We did not sample deeper peat
123 soils to reconstruct full peat profiles; however, we did measure peat thickness at the centre of each site
124 using a soil depth probe.

125 The fuel load from downed woody debris was estimated using the line intersect (or planar
126 intercept) method (Van Wagner 1968, 1982; Brown 1974) along the entire 100 m transect. Woody
127 pieces under 7 cm were measured with a “go-no-go” gauge and tallied for the following diameter size
128 classes: <0.5, 0.5-1.0, 1.0-3.0, 3.0-5.0 and 5.0-7.0 cm (McRae et al. 1979). For pieces >7.0 cm, each
129 diameter was recorded individually. Size class specific coefficients for the load calculation were taken
130 from Nalder et al. (1999) for black spruce from central Alberta. For pieces >7 cm roundwood diameter,
131 we used methods described by Alexander et al. (2004) and specific gravity value of 0.427 g/cm³ from
132 Ter-Mikaelian et al. (2008). Surface fuels were destructively sampled using eleven 30 cm x 30 cm
133 quadrats spaced evenly along the 100 m transect. Fuels sampled were all graminoids, herbaceous plants,
134 lichen, litter, shrubs (bog birch and willow) and tree seedlings (black spruce and larch <0.5 m tall);
135 horsetail was excluded. All surface fuels that were rooted within the sampling quadrat were collected
136 down to the surface of the moss layer, placed in paper bags and transported to Meanook Biological
137 Research Station (formerly University of Alberta) for processing.

138 Under some fuel descriptions, shrub fuels up to 2 m tall would be grouped generally with surface
139 fuels (Keane 2015). Recent fuel layer classifications from Australia (Gould et al. 2007; Hines et al.
140 2010) have used visually distinguishable layers that could be associated with differing fire behaviour. In

these Australian classification systems, low shrubs would be considered ‘near-surface’ fuels (and thus in our summaries we have included them with the surface fuels), and the observed tall shrubs (>50 cm) would be described as ‘elevated’ fuel. We feel that grouping fuel layers as such creates a useful distinction for elements of the fuel complex that can significantly alter fire behaviour.

Stand structure parameters were inventoried within each 10 m x 10 m quadrat. All trees >0.5 m tall were recorded for: species, height (cm), live crown-base height (CBH, cm), diameter-at-breast height (DBH, cm) and basal diameter (cm). Crown base height (CBH) was measured from the moss surface to the lowest continuous branches of the tree. Basal diameter was measured above any root collar swelling to avoid a bias towards large stem diameters. Shrub fuels >0.5 m tall (bog birch, willow) were measured at the stem base to estimate biomass via foliage and stem allometric equations (Connolly and Grigal 1983).

In the laboratory, surface fuels were sorted, allowed to air cure, then oven-dried in a low humidity environment at 40 degrees Celsius to a constant mass. Dry weight was then recorded to the nearest 0.01 g. Within each site, fuels loads in each of the eleven 900 cm² quadrats were averaged by fuel category.

Tree and canopy fuel load modelling

The majority of trees in these fen types were either black spruce or larch. As allometric equations for bog black spruce had recently been developed for this same area (Johnston et al. 2015), we focused on destructive sampling of aboveground biomass in larch over the range of diameters observed in other recent studies in our study area (e.g., Miller et al. 2015). In July and August of 2010, we destructively harvested larch trees from fens within the general study area. Trees were sampled from three of the treed sites listed in Table 1 (T1, T2, T5) as well as two additional fens (McLennan, AB: 55.8724, -

116.9166; Cold Lake, AB: 55.2852, -111.3210). Stand DBH and height were used to determine the range and distribution of larch sizes present at each site, and individuals were selected to obtain an approximately equal distribution of size classes for the five sites collectively, as each stem diameter size was not present at every site. Basal diameter, DBH and total height were recorded for each individual harvested. Trees were cut at the ground moss surface and the entire tree was divided into sections with a chainsaw and branches were removed from the boles. All biomass from this process was placed in paper bags and stored at the Meanook Biological Station until they were shipped to the University of Guelph in September 2010. Biomass was quantified separately for each tree and sorted into the following categories: branches, needles, stem (with bark attached) and cones. The branches were further divided into size classes I-III, equating to roundwood diameters: < 0.5, 0.5-0.99, 1.0-2.99 cm, respectively (McRae et al. 1979). Branchwood did not exceed a diameter of 3.0 cm. Samples were oven-dried at 95 degrees Celsius to a constant mass; the dry weight was recorded to the nearest 0.01 g. The total biomass for each individual tree was determined by summing the weighed biomass of all categories. Available branchwood fuel was determined by summing the weight of branch size classes I and II (i.e., < 1.0 cm diameter) for an individual tree.

Two available fuel load equations were developed for larch representing the two components of the crown that would be consumed during the passage of a flaming front and contribute to fireline intensity, foliage and branchwood <1 cm diameter. We created allometric equations to model oven-dried tree biomass components as a function of tree diameter (e.g., Pastor et al. 1984; Crow and Schlaegel 1988; Ter-Mikaelian and Korzukhin 1997). Graphical inspection of the relationship between tree biomass and diameter (DBH or basal diameter) showed that these data did exhibit the typical power function form and increasing variance with increasing value seen in previous studies and thus should be log-

transformed. Linear regression was used on the transformed data to determine a line of best fit, using the form:

$$\ln(Y) = \ln(a) + b \ln(D)$$

where Y is the mass of the biomass component (kg) and D is the tree diameter, DBH or basal diameter (cm). Two sets of diameter-based models were created to accommodate differing user inputs; DBH is a common stand characteristic, although it would exclude smaller trees (<1.4 m tall) that contribute to total aerial fuel loads.

Canopy fuel load (CFL) and canopy bulk density (CBD) were calculated using the allometric equations and stand inventory data (following Alexander et al. 2004). Available branchwood (<1 cm) and foliage biomass were estimated for each individual tree surveyed in the four 10 m by 10 m quadrats. Canopy fuel load (kg/m²) was the sum of available branchwood and foliage for all trees, divided by the quadrat sampling area (100 m²). Canopy bulk density (kg/m³) was calculated by dividing canopy fuel load by mean crown length (m) (i.e. tree height minus live crown-base height).

Statistical analysis

Principal components analysis (PCA) was used to investigate differences in plot-level fuel loads among three fuel types: treed ($n = 16$), shrub ($n = 12$), open ($n = 10$). Fuel load values were standardized using the Hellinger-transformation (Legendre and Gallagher 2001). Each plot consisted of estimates of component fuel loads based on the 10 m x 10 m tree plot, the mean load of two surface fuel quadrats, and a 25 m segment of the line transect. Analyses were performed with R software (v3.1.2; R Core Team, 2015) using the ‘vegan’ and ‘BiodiversityR’ packages.

Additionally, we compared mean fuel load values across fuel types. The datasets failed a normality test (Shapiro-Wilk test, Q-Q plot), and therefore the non-parametric Kruskal-Wallis One Way ANOVA on Ranks ($\alpha = 0.05$) was applied to test for differences in loading of each fuel component within each fuel type and across the three fuel types; any significant differences were further investigated with non-parametric post-hoc testing using the Wilcoxon rank-sum test. Analyses were performed using R software (v3.1.2; R Core Team, 2015).

Potential fire behaviour

As a first approximation of potential fire behaviour in the three fuel types, we estimated fire intensity based on the classic equation presented by Byram (1959). Fireline intensity, I (kW/m) was estimated as:

$$(2) \quad I = Hwr$$

where H is the fuel low heat of combustion (18000 kJ/kg), w is the weight of the fuel layer consumed per unit area (kg/m^2), and r is the rate of spread (m/s). While there are a number of fire line intensity/flame length relationships in the literature, for the sake of consistency and the relative comparisons made herein, flame length, L (m), was also estimated by a relationship first developed by Byram (1959) as:

$$(3) \quad L = 0.0775 I^{0.46}$$

228 where I is fireline intensity in kW/m (Alexander 1982). For the purpose of this discussion, 25 m/min rate
229 of spread was assumed for comparison of fireline intensities between fen fuel types.

230

231 **Results**

232 *Fen fuel loading*

233 Mean total fuel load varied across the fen types, and were larger in the treed fen sites ($0.982 \pm$
234 0.098 kg/m^2) than in the open or shrub sites ($0.482 \pm 0.045 \text{ kg/m}^2$ and $0.686 \pm 0.073 \text{ kg/m}^2$,
235 respectively). Shrub and treed fens had similar mean peat depths, while open fens had shallower peat on
236 average (Table 1). Site-level fuel loading is summarized in the Appendix (Table A1-A5).

237 Total surface fuel load was overall consistent across the three fen types ($p > 0.05$), with similar
238 amounts of herbaceous, litter and graminoids in each of the fen types (Table 2). The dominant
239 contribution to total surface load came from the short-statured shrubs (<50 cm), consisting primarily of
240 short-statured bog birch, which comprised on average 66% of the total surface fuel load across all sites
241 (range = 30-84%). The contribution of tall shrub fuels (>50 cm) varied across fen types ($p < 0.001$;
242 Table 2). As expected, tall shrubs were mostly absent from the open sites. Shrub fen sites were
243 dominated by bog birch and a minor component of willow. The treed sites tended to have both willow
244 and bog birch, and alder was also present, though tall shrubs were completely absent from one of the
245 treed sites (site 'T3').

246 Downed woody debris (DWD) on the surface varied among the fen types ($p < 0.001$). Not
247 surprisingly, DWD fuel loads were extremely low in the open sites and were highest in the treed sites
248 (Table 2). In the treed fens, assuming that only the size class I and II fuels (<0.5 and 0.5-1.0 cm,
249 respectively) would be available to contribute to flaming combustion, average DWD fuel loads ($0.021 \pm$
250 0.005 kg/m^2) were a small fraction of the surface litter load (range: 13-64%) or of the total surface fuel

load (range: 4-18%). Thus, the contribution of down and dead woody material to flame front intensity is marginal. Coarse woody debris (>7 cm) was also present in four of the five treed sites, but was absent from the open and shrub sites.

Stand characteristics summarized from the surveyed quadrats show a variable mix of black spruce and larch composing the tree canopy (Table 3). The distribution of basal diameter from each of the treed and shrub fen sites (Figure 3) show large site-to-site variation in the proportion of black spruce and larch. Allometric equations for larch (described below) and black spruce bog (Johnston et al. 2015) were used with the tree density survey information to estimate overall average canopy fuel load and bulk density across sites (Table 4). Canopy bulk density in the treed fen sites ranged from 0.140 to 0.407 kg/m³, which was similar to black-spruce dominated bogs that ranged from 0.166 to 0.543 kg/m³ for sites that were approximately 30 to 110 years following fire (Johnston et al. 2015). Fireline intensity was modeled using the available component of fuels for each fen type, and the results are summarized in Table 5.

Principal component analysis identified two primary axes that together explained ~54% of the variability of the fuel load composition (first axis explained 36% of variation; the second axis explained an additional 18% of variation). A permuted multivariate analysis of variance (*Adonis* R package; 1000 permutations) suggested that the 'fen fuel type' classification was significant ($p < 0.001$) and explained 35% of variability in fuel loads. Sites clustered into these three fen categories along Axis 1, which primarily separated open from treed sites, while Axis 2 primarily separated treed from shrub fens (Figure 4). The abundance of surface shrubs (<0.5 m tall) was correlated with the open fen sites, whereas the abundance of larch fuels was correlated with the treed fen sites (Figure 4).

Larch allometric equations

274 Biomass measurements from 47 trees sampled across several fens were combined to generate
275 allometric equations for larch (Table 4). These trees ranged in basal diameter from 1.0 to 14.7 cm, DBH
276 ranged from 0.3 to 11.5 cm, and total height ranged from 0.6 m to 8.5 m. Overall, stem weight was
277 found to be the greatest contributor to total biomass for every individual, followed by branches with a
278 diameter of <0.5 cm and then foliage. Models for total aboveground, stem (with bark), foliage, and
279 branchwood (total, <0.5 cm, <1.0 cm) biomass were developed individually using Equation 1. Of all the
280 measured tree attributes, diameter was the single strongest predictor of biomass; basal diameter was a
281 slightly stronger predictor of total biomass than DBH ($r^2 = 0.984$ and $r^2 = 0.947$, respectively); however
282 we developed separate models for both basal diameter and DBH because some studies, and many forest
283 inventory methods, report only DBH. The power law model form (Equation 1) represented the best fit
284 (Figure 5), with r^2 values exceeding 0.95. Variance in residuals across the range of diameters was
285 relatively constant and did not exhibit any strong trends. Tree height was an additional significant
286 predictor in a forward selection multiple regression model form but offered little meaningful
287 improvement in predictive power. For example, once the effect of basal diameter was accounted for, the
288 partial variance explained in total tree biomass due to height was $r^2 = 0.006$ ($p < 0.0001$).

289

290 **Discussion**

291 ***Fen fuel loading***

292 Despite representing a large fraction of land cover across many boreal regions, peatlands are
293 rarely incorporated into fire behaviour prediction models. Johnston et al. (2015) characterized the fuel
294 strata in black spruce bogs to estimate crown fire sustainability. Results from that study suggested that
295 while torching would likely initiate at any site along their bog chronosequence, active crown fire would
296 only likely be supported when an adequate canopy bulk density was achieved within the stand, around

60 years since last fire (Johnston et al. 2015). The objective of our study was to characterize trends in fuel loading in boreal fens, given that fens are much more abundant on the landscape relative to bogs. Our results indicate that a simple classification of fens into open, shrub, and treed fens explains a significant amount of variation in fuel loading. For example, aerial fuels available to flaming combustion, tall shrub density, and downed woody debris all varied among fen types, and tended to be smaller in the open fens and largest in the treed fens (Table 2 and 3). On the other hand, total surface fuel load was relatively constant across the fen types, as were the density/abundance of short statured shrubs (<50 cm tall), which was the largest contributor to overall surface loads.

For some fuel components, our results in boreal fens compare reasonably well to those reported in the boreal forested-bog fuel type (Johnston et al. 2015) and to other upland forest types. For example, our mean estimate of the total surface fuel component in fens ($0.370 \pm 0.044 \text{ kg/m}^2$) is similar to those reported for bogs ($0.396 \pm 0.027 \text{ kg/m}^2$, Johnston et al. 2015), but lower than for coniferous/deciduous mixed upland forests (0.88 kg/m^2 , Hely et al. 2000b), and lodgepole pine-white spruce upland forests ($0.36\text{-}0.77 \text{ kg/m}^2$, Kiil et al. 1968). However, when only cured litter and ground lichens are considered (ignoring live, green and consequently very moist fuel on the surface and near surface), the mean fuel load across the fen types ($0.075 \pm 0.007 \text{ kg/m}^2$) was smaller than what has been reported for black-spruce bogs ($0.186 \pm 0.023 \text{ kg/m}^2$, Johnston et al. 2015) and upland fuel types ($0.24\text{-}0.32 \text{ kg/m}^2$, Kiil et al. 1968; 0.44 kg/m^2 , Hely et al. 2000b). This is an indication that fire in these sites would be most sustainable when this annual vegetation is in its cured state in the spring or late fall, or during a period of extended drought and low surface moisture.

The amount of dead and down woody material observed on the surface in the forested fens (Table 2) is much lower than what has been observed in upland stands (e.g., 2.5 kg/m^2 , Stocks 1987; 2.0 kg/m^2 Stocks 1989; 4.5 kg/m^2 , Hely et al. 2000a) but is similar to estimates from the northern boreal

spruce lichen woodland fuel type (0.38 kg/m^2 , Alexander et al. 1991), which is associated with low stem density. It seems likely that the smaller values of woody fuel loads in the boreal fens is because mosses grow quickly in these ecosystems and overtake and bury any downed woody biomass (Loisel et al. 2012). Downed woody debris loads in forested bogs in the same general study area were highly variable, ranging from virtually nothing to high values associated with a fresh deadfall (Johnston et al. 2015), but in general tended to be larger (1.470 kg/m^2) than what was observed in our study of boreal fens. Generally, only small diameter downed woody debris is expected to contribute to flaming combustion (Stocks et al. 2004); however, large dead woody fuels, and especially those that are buried or intermixed with the peat layer, can hold smouldering fire for extended periods of time (Brown et al. 2003).

To support investigations of canopy fuel dynamics, tree biomass equations have been established at multiple spatial scales in Canada (regional, provincial and national: e.g., Bond-Lamberty et al. 2002; Lambert et al. 2005; Case and Hall 2008), and there are a number of algorithms for upland boreal tree species. Relative to equations for upland forests, tree biomass algorithms for peatlands are relatively rare. Site conditions, in particular nutrient status and hydraulic regime, differ significantly between peatlands and uplands and result in characteristic differences in tree species' growth and stature, emphasizing the need for peatland-specific equations. The few published equations of tree allometry in peatlands have tended to focus on black spruce (Wieder et al. 2009; Johnston et al. 2015). Szumigalski and Bayley (1996) report an allometric relationship for larch; however, the equation was developed for larch $<1.9 \text{ m}$ tall and was based on a small sample size ($n = 6$). We compared published allometric equations from the literature with the models developed as part of this study (Figure 5). The relationships reported in Bond-Lamberty et al. (2002) consistently under-predicted tree biomass relative to our destructive measurements (Figure 5). We also compared our larch biomass equations with those

developed by Johnston et al. (2015) for bog black spruce (Figure 5). We found that, for a given diameter, larch sampled in our study have more available branchwood and less foliage than black spruce (Figure 5). Larch and black spruce may be contributing to aerial fuel loading differently, and this is an important consideration given that these species vary in percent composition and stem density across treed fens. We suggest that the equations for larch developed as part of this study (Table 4) together with the bog spruce equations presented in Johnston et al. (2015) will enhance the ability to characterize aboveground biomass and fuel loads in forested peatlands of boreal Canada.

Potential fire behaviour

Fuels loads were assessed in terms of their availability to support combustion and influence wildfire behavior. In the open and shrub fuel types, there was not enough available canopy biomass to support a crown fire. Agee (1996) suggested that a minimum canopy bulk density of 0.10 kg/m^3 was necessary to achieve active crown fire while Johnson (1992) suggested a minimum of 0.05 kg/m^3 . However, our estimates of surface and elevated fuel loads are large enough to support relatively high intensity surface fire based on estimated fireline intensity (Eqn 2; Table 5). In the open fens, if the full surface load were available for combustion in the spring before considerable green up of live vegetation, we estimate that 0.426 kg/m^2 could be consumed. A fire spreading at 25 m/min through the open fuel type would produce a fire-line intensity of $\sim 3200 \text{ kW/m}$, which would represent a moderate to high intensity fire (Table 5). However, in their green state, grasses typically do not readily support the spread of flame (Cheney et al. 1998, Cruz et al. 2015), given that the presence of very moist live vegetation acts as a large energy sink. If graminoids, herbs and shrubs are removed from the surface fuel complex as contributors to fire-line intensity, then the fuel load that remains (litter plus lichen) and consequently the potential intensity of combustion both drop significantly (0.05 kg/m^2 and 375 kW/m , respectively).

366 Given the presence of green vegetation in this open fen fuel complex, it is doubtful a fire could
367 propagate at this intensity (Cruz et al. 2015). However, the presence of the low shrub layer complicates
368 the projection of summer-time fire behaviour. If moisture levels in the live vegetation are low enough
369 (<100% GMC), then propagation may be possible in areas with low densities of graminoids and other
370 green (live) vegetation. While some grassland spread models have been found to work well in
371 grasslands outside of Australia (Cheney et al. 1998, Kidnie and Wotton 2015), their predictive ability in
372 this open fen type may be questionable and should be subject to further study.

373 The shrub fen sites, where fuel was vertically continuous from the ground up to heights of
374 around 1-1.5 m, would likely evolve higher intensity fires and longer flames than the open sites. Trees
375 were not present in sufficient quantity to support crown fire (apart from simple torching) and thus fire
376 spread in this type would be best characterized as surface fire. If the surface fuels, size class 1 and 2 of
377 the down and dead fuels, and fuels in the elevated layer (i.e., tall shrub branch and foliage) were
378 completely available for combustion (0.624 kg/m^2), the resultant fire (spreading again at 25 m/min)
379 would produce a fire-line intensity of $\sim 4700 \text{ kW/m}$. Tall shrub bulk densities observed in the shrub fen
380 fuel type ($\sim 0.15 \text{ kg/m}^3$) are on the low end of shrub fuels studied in other parts of the world ($0.1\text{--}6.1$
381 kg/m^3 , Anderson et al. 2015). It is likely the shrub fuel complex within fen systems is moister overall
382 than the mainly dry climate shrublands that dominated the Anderson et al. (2015) study; however their
383 model might be useful for providing an upper range of potential spread rate.

384 Because the likelihood of canopy torching and crown fire occurrence increases with decreasing
385 crown base height (Van Wagner 1977), we expect that the treed peatlands in this study would be prone
386 to torching due to the very short crown base heights observed (Table 3). Van Wagner's (1977) model,
387 which is used worldwide, suggests the critical intensity for the ignition of black spruce canopy given an
388 average CBH of 0.8 m and foliar moisture content at 100% would be 120 kW/m , which represents a low

389 intensity surface fire. Thus, if flaming propagation were possible, we expect that most of the black
390 spruce in forested fens would experience torching. This torching would likely cause tree mortality where
391 it occurred.

392 Van Wagner (1977) also established a widely used criterion for a minimum sustained crown fire
393 spread rate in a conifer stand. While the rate of spread of active crowning threshold was used by
394 Johnston et al. (2015) to discuss the increasing potential for sustainable crown fire and subsequent
395 potential for widespread organic consumption in black spruce bogs, the species mix in treed fens makes
396 these inferences more difficult. In most of our treed fen sites, the canopy was a mix of both black spruce
397 and larch. Annual foliage in larch contains much more moisture than older hardened off pine or spruce
398 foliage. Once established in late spring, the high moisture content in larch foliage should have more of a
399 moderating role in combustion. Conversely, larch needles senesce and dry out in early autumn, though
400 they remain attached to the branches for some time. That senesced component of aerial fuels, coupled
401 with curing surface fuels, may very well reinforce late-season vulnerability to burning. By late autumn
402 the larch needles are abscised and contribute the surface fuel strata.

403 The closest analogue this treed fen type in the Canadian FBP System is the boreal mixedwood
404 type (M-1/M-2), which is a blend of black spruce and aspen (a broadleaf deciduous) and in which
405 deciduous moderates spread rate through the spruce forest. While the black spruce component of canopy
406 fuel load in the treed fen sites is lower than observed in upland stands (e.g., Alexander et al. 2004), the
407 mean canopy bulk density of black spruce in our sites ($0.168 \pm 0.040 \text{ kg/m}^3$) is similar to those in
408 uplands, due to the short crown length in fens. Thus, in the absence of larch, black spruce would be able
409 to sustain active crown fire spread for values of spread rate greater than about 22 m/min (an easily
410 attainable fire spread rate with a moderate wind). A full crown fire in this fuel type in spring, spreading
411 at 25 m/min would produce a fireline intensity of $\sim 5500 \text{ kW/m}$ (based on total fuel consumed of 0.734

kg/m² assuming the larch needles are absent from the canopy and larch branchwood is a passive contributor that does not add to fire front energy). This would represent a high intensity fire that would be able to ignite smouldering combustion in the surface peat layers, depending on type and most importantly current moisture status (Thompson et al. 2015). However, during the summer, the moderating effect of moist larch foliage would reduce spread rates and consequently intensity.

Though peatland burning is generally dominated by smouldering combustion, the flaming and smouldering processes are linked, and fuels can transition from flaming to smouldering (i.e., residual smouldering combustion) and vice versa (Rein 2013). Thompson et al. (2015) showed that energy output from flame front propagation through surface and aerial fuels can ignite surface layers depending on the energy from the flame front itself, which depends on spread rate, fireline intensity, and the moisture in the surface organic layer. Thus with higher fuel loads and associated higher potential fire intensities, treed and shrub fen fuel types may be more prone to the ignition of the ground fuel layer, though deep burning would be moderated by moisture and oxygen. In terms of ground layer consumption across this range of fuel types, seasonal trends in the water table influences moisture content in organic layers, which is an important control of fuel consumption in peatland ground fuels (Benscoter et al. 2011; Huang et al. 2015). Waddington et al. (2012) linked the drying of surface moss in peatlands at several sites across Canada to water table depth and correlated this with the Canadian Drought Code of the Canadian Fire Weather Index System (Van Wagner 1987). Knowledge about the availability of fuels should enhance our assessments of the vulnerability of peatlands to burning, and might inform fire operations in assessing prolonged smouldering.

Conclusion

This is the first study to characterize the fuel environment for different types of boreal fens. We found that boreal fens tend to have somewhat similar amounts of surface and aerial fuel loads relative to boreal bogs; however, the deciduous nature of the larch present in treed fens is an important consideration for seasonal fuel load dynamics, fuel moisture and availability, and the types of fire that can be supported. Relative to uplands, both fens and bogs had smaller loads of downed woody debris. Based on the total available fuel loads, we conclude that boreal fens are susceptible to high intensity fires during certain periods of the fire season, such as early in the fire season when surface fuels have cured but new foliage has not emerged, or late in the fire season when the larch needle component has senesced and dropped from the aerial fuel strata to the surface.

Acknowledgements

Funding for this project was provided by a Natural Sciences and Engineering Research Council of Canada (NSERC) Strategic Grant to M.R.T., J.M. Waddington, and B.M.W. The authors also acknowledge the efforts of the PeatFire field crews from 2010 and 2012, in particular Abra Martin and Carolyn Gibson. We thank J.L.W. Ruppert for providing statistical advice. Dan C. Johnston (OMNRF) and Dan K. Thompson (Northern Forestry Centre-NRCAN) provided advice on field sampling and fens.

References

- Agee, J.K. 1996. The influence of forest structure on fire behavior. In: Proceedings of the 17th annual forest vegetation management conference, Redding, California, USA. January 16-18. pp52-68.
- Alexander, M. E. 1982. Calculating and interpreting forest fire intensities. *Can. J. Bot.* **60** (4): 349-357.
- Alexander, M.E., Stocks, B.J., and Lawson, B.D. 1991. Fire behavior in black spruce-lichen woodland: the Porter Lake project. For. Can. Inf. Rep. NOR-X-310. Northern Forestry Centre, Edmonton, Alberta, Canada.
- Alexander, M.E., Steffner, C.N., Mason, J.A., Stocks, B.J., Hartley, G.R., Maffey, M.E., Wotton, B.M., Taylor, S.W., Lavoie, N., and Dalrymple, G.N. 2004. Characterizing the Jack Pine – Black Spruce fuel complex of the International Crown Fire Modelling Experiment (ICFME). *Can. For. Serv. Rep. NOR-X 393*.
- Anderson, W.R., Cruz, M.G., Fernandes, P.M., McCaw, L., Vega, J.A., Bradstock, R.A., Fogarty, L., Gould, J., McCarthy, G., Marsden-Smedley, J., Matthews, S., Mattingley, G., Pearce, H.G., and van Wilgen, B.W. 2015. A generic, empirical-based model for predicting rate of fire spread in shrublands. *Int. J. Wildland Fire* **24**: 443-460. doi: 10.1071/WF14130.
- Benscoter, B.W., and Wieder, R.K. 2003. Variability in organic matter lost by combustion in a boreal bog during the 2001 Chisholm fire. *Can. J. For. Res.* **33**: 2509-2513. doi: 10.1139/x03-162.

- Benscoter, B.W., Thompson, D.K., Waddington, J.M., Flannigan, M.D., Wotton, B.M., de Groot, W.J., and Turetsky, M.R. 2011. Interactive effects of vegetation, soil moisture and bulk density on depth of burning of thick organic soils. *Int. J. Wildland Fire* **20**: 418-429. doi: 10.1071/WF08183.
- Bond-Lamberty, B., Wang, C., and Gower, S. 2002. Aboveground and belowground biomass and sapwood area allometric equations for six boreal tree species of northern Manitoba. *Can. J. For. Res.* **32**: 1441-1450. doi: 10.1139/x02-063.
- Bond-Lamberty, B., Peckham, S.D., Ahl, D.E., and Gower, S.T. 2007. Fire as the dominant driver of central Canadian boreal forest carbon balance. *Nature* **450** (7166): 89-92.
doi:10.1038/nature06272
- Brown, J.K. 1974. Handbook for inventorying downed woody material. USDA Forest Service General Technical Report No. INT-16.
- Brown, J.K., Reinhardt, E.D., and Kramer, K.A. 2003. Coarse woody debris: managing benefits and fire hazard in the recovering forest. USDA Forest Service General Technical Report RMRS-GTR-105.
- Byram, G.M. 1959. Combustion of forest fuels. In: Davis, K.P. (editor). *Forest fire: control and use*. New York, NY: McGraw-Hill.

- Case, B., and Hall, R. 2008. Assessing prediction errors of generalized tree biomass and volume equations for the boreal forest region of west-central Canada. *Can. J. For. Res.* **38**: 878-889. doi: 10.1139/x07-212.
- Cheney, N., Gould, J., and Catchpole, W. 1998: Prediction of fire spread in grassland. *Int. J. Wildland Fire* **8**: 1-13. doi:10.1071/WF9980001
- Connolly, B.J., and Grigal, D.F. 1983. Biomass estimation equations for wetland tall shrubs. Minnesota Forestry Research Notes No. 1866. St. Paul, Minnesota, USA.
- Crow, T.R., and Schlaegel, B.E. 1988. A guide to using regression equations for estimating tree biomass. *North. J. Appl. For.* **5**: 15-22.
- Cruz, M.G., Gould, J.S., Kidnie, S., Bessell, R., Nichols, D., and Slijepcevic, A. 2015. Effects of curing on grassfires: II. Effect of grass senescence on the rate of fire spread. *Int. J. Wildland Fire* **24**: 838-848. doi: 10.1071/WF14146.
- Flannigan, M.D., Campbell, I., Wotton, B.M., Carcaillet, C., Richard, P., and Bergeron, Y. 2001. Future fire in Canada's boreal forest: Paleoecology results, and general circulation model - regional climate model simulations. *Can. J. For. Res.* **31**: 854-864. doi: 10.1139/x01-010.
- Flannigan, M.D., Logan, K., Amiro, B., Skinner, W., and Stocks, B. 2005. Future area burned in Canada. *Clim. Change* **72**: 1-16. doi: 10.1007/s10584-005-5935-y.

- Flannigan, M.D., Stocks, B.J., Turetsky, M.R., and Wotton, B.M. 2009. Impacts of climate change on fire activity and fire management in the circumboreal forest. *Glob. Chang. Biol.* **15**: 549-560. doi: 10.1111/j.1365-2486.2008.01660.x.
- Forestry Canada Fire Danger Group. 1992. Development and structure of the Canadian Forest Fire Behaviour Prediction System. For. Can. Inf. Rep. ST-X-3. Ottawa, Ontario, Canada.
- Frandsen, W.H. 1997. Ignition probability of organic soils. *Can. J. For. Res.* **27**: 1471-1477. doi: 10.1139/x97-106.
- Gould, J.S., McCaw, W.L., Cheney, N.P., Ellis, P.F., Knight, I.K., and Sullivan, A.L. 2007. Project Vesta – fire in dry eucalypt forest: fuel structure, fuel dynamics and fire behavior. Ensis-CSIRO, ACT and Department of Environment and Conservation, Perth, WA.
- Harden, J.W., Trumbore, S.E., Stocks, B.J., Hirsch, A., Gowers, S.T., O'Neill, K.P., and Kasischke, E.S. 2000. The role of fire in the boreal carbon budget. *Global Change Biol.* **6**: 174-184. doi: 10.1046/j.1365-2486.2000.06019.x
- Hely, C., Bergeron, Y., Flannigan, M. 2000a. Coarse woody debris in the southeastern Canadian boreal forest: composition and load variations in relation to stand replacement. *Can. J. For. Res.* **30**: 674-687. doi: 10.1139/x99-256.

- Hely, C., Bergeron, Y., and Flannigan, M.D. 2000*b*. Effects of stand composition on fire hazard in mixed-wood Canadian boreal forest. *J. Veg. Sci.* **11**: 813-824. doi: 10.2307/3236551.
- Hines, F., Tolhurst, K.G., Wilson, A.A.G., and McCarthy, G.J. 2010. Overall Fuel Hazard Assessment Guide, 4th Edition. Report 82, Fire Management Branch, Department of Sustainability and Environment. Melbourne, Victoria, Australia.
- Huang, X., Rein, G., and Chen, H. 2015. Computational smoldering combustion: predicting the roles of moisture and inert content in peat wildfires. *Proceedings of the Combustion Institute* **35**: 2673-2681. doi: 10.1016/j.proci.2014.05.048.
- Johnson, E.A. 1992. Fire and vegetation dynamics. Cambridge University Press: Cambridge, UK.
- Johnston, D.C., Turetsky, M.R., Benscoter, B.W., and Wotton, B.M. 2015. Fuel load, structure and fire behaviour in forested boreal bogs. *Can. J. For. Res.* **45**: 888-899. doi: 10.1139/cjfr-2014-0334.
- Johnston, F.H., Henderson, S.B., Chen, Y., Randerson, J.T., Marlier, M., DeFries, R.S., Kinney, P., Bowman, D.M. and Brauer, M. 2012. Estimated global mortality attributable to smoke from landscape fires. *Environmental health perspectives* **120**(5): 695-701. doi: 10.1289/ehp.1104422.
- Keane, R.E. 2015. Wildland fuel fundamentals and applications. Springer: New York, USA. doi: 10.1007/978-3-319-09015-3.

- Kidnie, S., and Wotton, B.M. 2015. Characterization of the fuel and fire environment in southern Ontario's tallgrass prairie. *Int. J. Wildland Fire* 24: 1118-1128. doi: 10.1071/WF14214.
- Kiil, A. 1968. Weight of the fuel complex in 70-year-old Lodgepole pine stands of different densities. Canadian Department of Forestry and Rural Development. Departmental Publication No. 1228.
- Lambert, M.C., Ung, C.H., and Raulier, F. 2005. Canadian national tree aboveground biomass equations. *Can. J. For. Res.* **35**: 1996-2018. doi: 10.1139/X05-112.
- Legendre, P., and Gallagher, E.D. 2001. Ecologically meaningful transformations for ordination of species data. *Oecologia* **129**: 271-280. doi: 10.1007/s004420100716.
- Loisel, J., Gallego-Sala, A.V., and Yu, Z. 2012. Global-scale patterns of peatland Sphagnum growth driven by photosynthetically active radiation and growing season length. *Biogeosciences Discussions* **9**: 2169-2196. doi: 10.5194/bg-9-2737-2012
- McRae, D.J., Alexander, M.E., and Stocks, B.J. 1979. Measurement and description of fuels and fire behaviour on prescribed burns: a handbook. *Can. For. Serv. Rep.* 200-X-287.
- Miller, C.A., Benscoter, B.W., and Turetsky, M.R. 2015. The effect of long-term drying associated with experimental drainage and road construction on vegetation composition and productivity in boreal fens. *Wetlands Ecol. Manage.* **23**: 845-854. doi: 10.1007/s11273-015-9423-5.

Natural Regions Committee. 2006. Natural regions and subregions of Alberta. Compiled by D.J.

Downing and W.W. Pettapiece. Government of Alberta. Publication No. T/852.

Nalder, I.A., Wein, R.W., Alexander, M.E. and De Groot, W.J., 2000. Physical properties of dead and
downed round-wood fuels in the boreal forests of western and northern Canada. *Int. J. Wildland
Fire* **9**(2): 85-99. doi:10.1071/WF00008

Pastor, J., Aber, J.D., and Melillo, J.M. 1984. Biomass prediction using generalized allometric
regressions for some Northeast tree species. *For. Ecol. Manage.* **7**: 265-274. doi: 10.1016/0378-
1127(84)90003-3.

Rappold, A.G., Stone, S.L., Cascio, W.E., Neas, L.M., Kilaru, V.J., Carraway, M.S., Szykman, J.J.,
Ising, A., Cleve, W.E., Meredith, J.T., Vaughan-Batten, H., Deyneka, L., and Devlin, R.B. 2011.
Peat bog wildfire smoke exposure in rural North Carolina is associated with cardiopulmonary
emergency department visits assessed through syndromic surveillance. *Environmental health
perspectives* **119**(10):1415-1420. doi: 10.1289/ehp.1003206.

Rein, G. 2013. Smouldering fires and natural fuels. In *Fire phenomena and the earth system: an
interdisciplinary guide to fire science*. Edited by C.M. Belcher. John Wiley & Sons, Oxford. doi:
10.1002/9781118529539.ch2

Rein, G., Cleaver, N., Ashton, C., Pironi, P., and Torero, J.L. 2008. The severity of smouldering peat
fires and damage to the forest soil. *Catena* **74**: 304-309.

- Stocks, B.J. 1987. Fire behavior in immature jack pine. *Can. J. For. Res.* **17**: 80-86. doi: 10.1139/x87-014.
- Stocks, B.J. 1989. Fire behavior in mature jack pine. *Can. J. For. Res.* **19**: 783-790. doi: 10.1139/x89-119.
- Stocks, B.J., Foseberg, M.A., Lynham, T.J., Mearns, L., Wotton, B.M., Yang, Q., Jin, J-Z., Lawrence, K., Hartley, G.R., Mason, J.A., and McKenney, D.W. 1998. Climate change and forest fire potential in Russian and Canadian boreal forests. *Clim. Change* **38**: 1-13. doi: 10.1023/A:1005306001055.
- Stocks, B.J., Alexander, M.E., Wotton, B.M., Stefner, C.N., Flannigan, M.D., Taylor, S.W., Lavoie, N., Mason, J.A., Hartley, G.R., Maffey, M.E., Dalrymple, G.N., Blake, T.W., Cruz, M.G., and Lanoville, R.A. 2004. Crown fire behaviour in a northern jack pine-black spruce forest. *Can. J. For. Res.* **34**: 1548-1560. doi: 10.1139/X04-054
- Szumigalski, A., and Bayley, S. 1996. Net above-ground primary production along a bog-rich fen gradient in central Alberta, Canada. *Wetlands* **16**: 467-476. doi: 10.1007/BF03161336.
- Tarnocai, C. 2009. The impact of climate change on Canadian peatlands. *Can. Water Res. J.* **34**: 453-466. doi: 10.4296/cwrj3404453.

- Ter-Mikaelian, M.T., and Korzukhin, M.D. 1997. Biomass equation for sixty-five North American tree species. *For. Ecol. Manage.* **97**: 1–24. doi:10.1016/S0378- 1127(97)00019-4.
- Ter-Mikaelian, M.T., Colombo, S.J., and Chen, J. 2008. Amount of downed woody debris and its prediction using stand characteristics in boreal and mixedwood forests of Ontario, Canada. *Can. J. For. Res.* **38**: 2189-2197. doi: doi:10.1139/ X08-067.
- Thompson, D.K., Wotton, B.M., and Waddington, J.M. 2015. Estimating the heat transfer to an organic soil surface during crown fire. *Int. J. Wildland Fire* **24**: 120-129. doi: 10.1071/WF12121
- Turetsky, M.R., Weider, K., Halsey, L., and Vitt, D. 2002. Current disturbance and the diminishing peatland carbon sink. *Geophys. Res. Lett.* **29**: 1-4. doi:10.1029/ 2001GL014000.
- Turetsky, M.R., Amiro, B., and Bhatti, J. 2004. Peatland burning and its relationship to fire weather in western Canada. *Global Biogeochem. Cycles* **18**: GB4014.
- Turetsky, M.R., Kane, E.S., Harden, J.W., Ottmar, R.D., Manies, K.L., Hoy, E., Kasischke, E.S. 2011. Recent acceleration of biomass burning and carbon losses in Alaskan forests and peatlands. *Nat. Geosci.* **4**: 27-31. doi: doi:10.1038/ ngeo1027.
- Turetsky, M.R., Benscoter, B., Page, S., Rein, G., van der Werf, G.R., and Watts, A. 2015. Global vulnerability of peatlands to fire and carbon loss. *Nat. Geosci.* **8**: 11-14. doi: 10.1038/ngeo2325.

- Van Wagner, C.E. 1968. The line intersect method in forest fuel sampling. *For. Sci.* **14**: 20-26.
- Van Wagner, C.E. 1977. Conditions for the start and spread of crown fire. *Can. J. For. Res.* **7**: 23-34.
doi:10.1139/x77-004.
- Van Wagner, C.E. 1982. Practical aspects of the line intersect method. *Can. For. Serv. Inf. Rep.* PI-X-12.
- Van Wagner, C.E. 1987. Development and structure of the Canadian Forest Fire Weather Index System. Canadian Forest Service. *For. Techn. Rep.* 35. Ottawa, Canada.
- Vitt, D. H. 2000*a*. Peatlands: Ecosystems dominated by bryophytes. *Bryophyte Biology*. Edited by Shaw, A. J. and Goffinet, B. Cambridge University Press: Cambridge, England. pp 312-343.
- Vitt, D. H., Halsey, A., Bauer, I.E., and Campbell, C. 2000*b*. Spatial and temporal trends of carbon sequestration in peatlands of continental western Canada through the Holocene. *Can. J. Earth Sci.* **37**: 683-693. doi:10.1139/e99-097.
- Waddington, J.M., Thompson, D.K., Wotton, M., Quinton, W.L., Flannigan, M.D., Benscoter, B.W., Baisley, S.A., and Turetsky, M.R. 2012. Examining the utility of the Canadian Forest Fire Weather Index System in boreal peatlands. *Can. J. For. Res.* **42**: 47-58. doi:10.1139/x11-162.

- Wieder, K., Scott, K., Kamminga, K., Vile, M., Vitt, D., Bone, T., Xu, B., Benscoter, B., and Bhatti, J. 2009. Postfire carbon balance in boreal bogs of Alberta, Canada. *Global Change Biology* **15**: 63-81. doi:10.1111/j.1365-2486.2008.01756.x.
- Wotton, B.M. 2009. Interpreting and using outputs from the Canadian Forest Fire Danger Rating System in research applications. *Environ. Ecol. Stat.* **16**: 107-131. doi: 10.1007/s10651-007-0084-2.
- Wotton, B.M., and Flannigan, M.D. 1993. Length of the fire season in a changing climate. *For. Chron.* **69**: 187-192. doi: 10.5558/tfc69187-2.
- Wotton, B.M., Nock, C.A., and Flannigan, M.D. 2010. Forest fire occurrence and climate change in Canada. *Int. J. Wildland Fire* **19**: 253-271. doi: 10.1071/WF09002.
- Zoltai, S.C., Morissey, L.A., Livingston, G.P. and de Groot, W.J. 1998. Effects of fires on carbon cycling in North American boreal peatlands. *Environ. Rev.* **6**: 13-24. doi: 10.1139/a98-0

Figure Captions

Figure 1. Map of study region in northern Alberta, Canada. Circles indicate Open sites, triangles indicate Shrub sites, and stars indicate Treed sites. Note that the dark grey areas on the provincial map of Alberta show the Central Mixedwood subregion of the Boreal.

Figure 2. Photographs of three fen fuel types: (a) Open, (b) Shrub, (c) Treed.

Figure 3. Basal diameter frequency distribution for the Treed and Shrub sites.

Figure 4. Principal Components Analysis for fuel loads across sites.

Figure 5. Comparison of biomass and fuel loading relationships for larch and black spruce. Black lines show peatland-based allometric equations; grey lines show upland-based allometric equations; black dots are observations of destructively sampled larch trees obtained for this study. ^a Schiks et al. (current study); ^b Johnston et al. (2015); ^c Bond-Lamberty et al. (2002); ^d Case and Hall (2008); ^e Lambert et al. (2005).

Table 1. Location and general characteristics of the sites included in this study.

Date	Fen Type	Site Name	Age*	Latitude (° North)	Longitude (° West)	Elevation (m)	Mean Peat Depth (cm)
July 7, 2012	Open	O1	NA	55.83524	115.09275	650	382
July 30, 2012	Open	O2	NA	55.83256	115.11713	652	140
August 1, 2012	Open	O3	NA	55.84455	115.06783	649	305
July 3, 2012	Shrub	S1	30	55.08831	113.28215	671	108
July 31, 2012	Shrub	S2	21	55.83385	115.08279	654	186
August 2, 2012	Shrub	S3	20	55.82533	115.15935	655	153
July 6, 2012	Treed	T1	54	55.82959	115.09089	656	197
July 15, 2012	Treed	T2	44	55.216381	113.17079	504	100
June 29, 2012	Treed	T3	46	55.08357	113.11523	652	222
July 16, 2012	Treed	T4	NA	55.76789	113.42047	595	83
July 27, 2012	Treed	T5	60	55.79689	113.38596	564	122

*Age is the estimated time since last disturbance from fire when this could be determined via tree cores.

Table 2. Mean and standard deviation of fuel load (kg/m²) components by fuel type.

	Open		Shrub		Treed	
	mean	(SD)	mean	(SD)	mean	(SD)
<i>Surface fuels</i>						
Graminoid	0.033	(0.023)	0.033	(0.009)	0.032	(0.029)
Herbaceous	0.005 ^{ab}	(0.006)	0.007 ^a	(0.001)	0.009 ^b	(0.010)
Lichen	0.001	(0.001)	0.000	(0.000)	0.002	(0.002)
Litter	0.049	(0.005)	0.098	(0.033)	0.073	(0.009)
Shrub	0.338	(0.087)	0.294	(0.247)	0.191	(0.078)
Seedlings	0.000	(0.000)	0.002	(0.004)	0.003	(0.005)
Total	0.426	(0.076)	0.434	(0.259)	0.297	(0.075)
<i>Downed woody debris</i>						
<0.5 cm	0.000 ^a	(0.000)	0.003 ^b	(0.002)	0.005 ^c	(0.000)
0.5-1.0 cm	0.000 ^a	(0.001)	0.004 ^a	(0.006)	0.016 ^b	(0.001)
1.0-3.0 cm	0.000 ^a	(0.000)	0.004 ^a	(0.009)	0.051 ^b	(0.000)
3.0-5.0 cm	0.000 ^a	(0.000)	0.000 ^a	(0.000)	0.031 ^b	(0.000)
5.0-7.0 cm	0.000 ^a	(0.000)	0.007 ^a	(0.027)	0.062 ^b	(0.000)
>7.0 cm	0.000 ^a	(0.000)	0.000 ^a	(0.000)	0.095 ^b	(0.000)
Total	0.000 ^a	(0.001)	0.018 ^b	(0.033)	0.261 ^c	(0.001)
<i>Tall shrubs</i>						
Alder foliage	0.000	(0.000)	0.000	(0.000)	0.001	(0.001)
Alder branch	0.000	(0.000)	0.000	(0.000)	0.016	(0.027)
Bog birch foliage	0.000	(0.000)	0.014	(0.014)	0.001	(0.002)
Bog birch branch	0.002	(0.003)	0.148	(0.163)	0.030	(0.048)
Willow foliage	0.000 ^a	(0.000)	0.004 ^{ab}	(0.003)	0.007 ^b	(0.009)
Willow branch	0.000 ^a	(0.000)	0.017 ^{ab}	(0.015)	0.054 ^b	(0.064)
Total	0.002 ^a	(0.003)	0.183 ^b	(0.186)	0.110 ^{ab}	(0.105)

Note: Superscript labels a, b, and c indicate significant differences ($\alpha = 0.05$) in mean values across the fen fuel type classifications for a particular fuel element.

Table 3. Mean and standard deviation of stand and aerial fuel characteristics by fuel type.

	Shrub		Treed	
	mean	(SD)	mean	(SD)
<i>Black spruce</i>				
Basal diameter (cm)	1.9 ^a	(0.0)	4.0 ^b	(0.7)
Height (m)	1.1 ^a	(0.1)	3.0 ^b	(0.6)
Density (stems/ha)	250 ^a	(295)	4670 ^b	(2391)
Foliage fuel load (kg/m ²)	0.003 ^a	(0.003)	0.138 ^b	(0.084)
Branch fuel load (kg/m ²)	0.002 ^a	(0.002)	0.168 ^b	(0.104)
<i>Larch</i>				
Basal diameter (cm)	3.3 ^a	(0.8)	3.4 ^b	(0.5)
Height (m)	2.3 ^a	(0.3)	3.2 ^b	(0.4)
Density (stems/ha)	1275 ^a	(1474)	4690 ^b	(1504)
Foliage fuel load (kg/m ²)	0.017 ^a	(0.019)	0.063 ^b	(0.044)
Branch fuel load (kg/m ²)	0.040 ^a	(0.045)	0.185 ^b	(0.126)
<i>Total</i>				
Canopy fuel load (kg/m ²)	0.062 ^a	(0.059)	0.554 ^b	(0.192)
Live crown base height (m)	0.3 ^a	(0.1)	0.8 ^b	(0.5)
Crown length (m)	1.6 ^a	(0.6)	2.2 ^b	(1.2)
Canopy bulk density (kg/m ³)	0.032 ^a	(0.026)	0.287 ^b	(0.096)

Note: Superscript labels a and b indicate significant differences ($\alpha = 0.05$) in mean values across the ten fuel type classifications for a particular fuel element.

Table 4. Regression summary statistics for tree biomass relationships. Equations in the form $\ln(Y) = \beta_0 + \beta_1 \ln(\text{diameter})$, where Y is fuel load (kg), and *diameter* is either basal diameter (cm) or DBH (cm). S.E. is standard error.

Component	<i>n</i>	β_1 (S.E.)	β_0 (S.E.)	r^2	p-value
<i>Basal diameter models</i>					
Total Biomass	47	2.517 (0.048)	-3.394 (0.084)	0.984	<0.0001
Stem (with bark)	47	2.639 (0.058)	-4.202 (0.101)	0.979	<0.0001
Branches (<0.5 cm)	47	2.141 (0.049)	-4.247 (0.086)	0.976	<0.0001
Branches (<1.0 cm)	47	2.330 (0.051)	-4.326 (0.090)	0.978	<0.0001
Total Branches	47	2.388 (0.061)	-4.335 (0.106)	0.971	<0.0001
Foliage	47	2.185 (0.067)	-4.980 (0.116)	0.960	<0.0001
<i>DBH models</i>					
Total Biomass	39	1.635 (0.063)	-0.850 (0.098)	0.947	<0.0001
Stem (with bark)	39	1.726 (0.069)	-1.604 (0.108)	0.943	<0.0001
Branches (<0.5 cm)	39	1.355 (0.064)	-2.033 (0.101)	0.921	<0.0001
Branches (<1.0 cm)	39	1.502 (0.069)	-1.964 (0.108)	0.925	<0.0001
Total Branches	39	1.545 (0.070)	-1.917 (0.108)	0.928	<0.0001
Foliage	39	1.357 (0.067)	-2.673 (0.104)	0.916	<0.0001

Note: Mean and range of individually harvested stems are as follows: basal diameter = 6.3 cm (1.0-14.7); DBH = 4.8 cm (0.3-11.5); Height = 3.9 m (0.65-8.5); Total Biomass = 6.7 kg (0.04-31.7).

Table 5. Byram's fireline intensity (Eqn 2) and flame length (Eqn 3) results for the fen fuel types.

Fen type	Rate of spread, r (m/min)	Fuel consumed, w (kg/m ²)	Intensity, I (kW/m)	Flame length, L (m)
Open (spring, cured)	25	0.426	3195	3.2
Open (summer, green)	25	0.050	375	1.2
Shrub	25	0.624	4680	3.8
Treed	25	0.734	5505	4.1

Draft

(a)

(b)

(c)

Treed fens

Shrub fens

Axis 2

Axis 1

Appendix

Table A-1. Mean and standard deviation of surface fuel load (kg/m²) by fuel component for each fuel type.

Fen Type	Site	Graminoid		Herbaceous		Lichen		Litter		Shrub		Seedlings		Total	
		Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Open	O1	0.008	(0.008)	0.012	(0.016)	0.002	(0.005)	0.055	(0.037)	0.411	(0.587)	0.000	(0.000)	0.488	(0.618)
	O2	0.052	(0.042)	0.001	(0.002)	0.000	(0.000)	0.046	(0.040)	0.242	(0.352)	0.000	(0.000)	0.341	(0.358)
	O3	0.040	(0.031)	0.001	(0.001)	0.002	(0.007)	0.046	(0.044)	0.360	(0.578)	0.000	(0.000)	0.450	(0.636)
	All	0.033	(0.023)	0.005^{ab}	(0.006)	0.001	(0.001)	0.049	(0.005)	0.338	(0.087)	0.000	(0.000)	0.426	(0.076)
Shrub	S1	0.038	(0.040)	0.007	(0.007)	0.000	(0.000)	0.061	(0.046)	0.093	(0.101)	0.000	(0.000)	0.196	(0.140)
	S2	0.038	(0.029)	0.005	(0.007)	0.000	(0.000)	0.125	(0.062)	0.220	(0.342)	0.007	(0.024)	0.396	(0.333)
	S3	0.023	(0.017)	0.008	(0.014)	0.000	(0.000)	0.109	(0.109)	0.569	(0.470)	0.000	(0.000)	0.710	(0.426)
	All	0.033	(0.009)	0.007^a	(0.001)	0.000	(0.000)	0.098	(0.033)	0.294	(0.247)	0.002	(0.004)	0.434	(0.259)
Treed	T1	0.029	(0.031)	0.002	(0.004)	0.003	(0.004)	0.078	(0.049)	0.294	(0.322)	0.000	(0.000)	0.406	(0.334)
	T2	0.005	(0.007)	0.003	(0.004)	0.004	(0.012)	0.064	(0.046)	0.155	(0.120)	0.000	(0.000)	0.232	(0.143)
	T3	0.010	(0.009)	0.002	(0.003)	0.000	(0.000)	0.078	(0.058)	0.211	(0.091)	0.000	(0.000)	0.293	(0.109)
	T4	0.079	(0.055)	0.023	(0.021)	0.000	(0.001)	0.083	(0.081)	0.084	(0.153)	0.012	(0.039)	0.226	(0.219)
	T5	0.038	(0.046)	0.015	(0.015)	0.001	(0.001)	0.063	(0.055)	0.212	(0.169)	0.001	(0.002)	0.330	(0.205)
	All	0.032	(0.029)	0.009^b	(0.010)	0.002	(0.002)	0.073	(0.009)	0.191	(0.078)	0.003	(0.005)	0.297	(0.075)

Note: Superscripted letters (a,b,c) indicate significantly different group means ($\alpha = 0.05$) across the fen fuel type classification for each surface fuel component. Graminoid includes grasses, cotton grass and horsetail. Shrub includes bog birch and willow (<0.5 m tall). Seedlings include larch and spruce (<0.5 m tall).

Table A-2. Mean and standard deviation of down woody debris (kg/m²) by size class for each fuel type.

Type	Site	<0.5 cm		0.5-1.0 cm		1.0-3.0 cm		3.0-5.0 cm		5.0-7.0 cm		>7 cm		Total	
		Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Open	O1	0.000	(0.000)	0.000	(0.000)	0.000	(0.000)	0.000	(0.000)	0.000	(0.000)	0.000	(0.000)	0.000	(0.000)
	O2	0.000	(0.000)	0.001	(0.001)	0.000	(0.000)	0.000	(0.000)	0.000	(0.000)	0.000	(0.000)	0.001	(0.001)
	O3	0.000	(0.000)	0.000	(0.000)	0.000	(0.000)	0.000	(0.000)	0.000	(0.000)	0.000	(0.000)	0.000	(0.000)
	All	0.000^a	(0.000)	0.000^a	(0.001)	0.000^a	(0.000)	0.000^a	(0.000)	0.000^a	(0.000)	0.000^a	(0.000)	0.000^a	(0.001)
Shrub	S1	0.004	(0.001)	0.012	(0.005)	0.005	(0.011)	0.000	(0.000)	0.000	(0.000)	0.000	(0.000)	0.021	(0.015)
	S2	0.001	(0.001)	0.000	(0.000)	0.005	(0.011)	0.000	(0.000)	0.021	(0.046)	0.000	(0.000)	0.027	(0.058)
	S3	0.003	(0.001)	0.001	(0.001)	0.003	(0.006)	0.000	(0.000)	0.000	(0.000)	0.000	(0.000)	0.006	(0.005)
	All	0.003^b	(0.002)	0.004^a	(0.006)	0.004^a	(0.009)	0.000^a	(0.000)	0.007^a	(0.027)	0.000^a	(0.000)	0.018^b	(0.033)
Treed	T1	0.006	(0.004)	0.015	(0.009)	0.057	(0.034)	0.062	(0.113)	0.041	(0.093)	0.074	(0.166)	0.256	(0.395)
	T2	0.008	(0.004)	0.033	(0.016)	0.141	(0.089)	0.042	(0.044)	0.062	(0.057)	0.059	(0.132)	0.345	(0.258)
	T3	0.004	(0.001)	0.007	(0.008)	0.021	(0.011)	0.010	(0.023)	0.062	(0.093)	0.164	(0.169)	0.268	(0.257)
	T4	0.003	(0.001)	0.008	(0.007)	0.008	(0.007)	0.000	(0.000)	0.021	(0.046)	0.000	(0.000)	0.039	(0.047)
	T5	0.006	(0.006)	0.015	(0.018)	0.028	(0.038)	0.042	(0.044)	0.124	(0.113)	0.180	(0.165)	0.395	(0.141)
	All	0.005^c	(0.000)	0.016^b	(0.001)	0.051^b	(0.000)	0.031^b	(0.000)	0.062^b	(0.000)	0.095^b	(0.000)	0.261^c	(0.001)

Note: Superscripted letters (a,b,c) indicate significantly different group means ($\alpha = 0.05$) across the ten fuel type classifications for each fuel size class component.

Table A- 3. Mean and standard deviation of shrub fuel load (kg/m²), shrub height (m) and shrub fuel bulk density (kg/m³) for each fuel type.

Type	Site	Alder foliage		Alder branch		Bog birch foliage		Bog birch branch		Willow foliage		Willow branch		Shrub load (kg/m ²)		Height (m)		Bulk density (kg/m ³)	
		Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Open	O1	0.000	(0.000)	0.000	(0.000)	0.000	(0.000)	0.005	(0.004)	0.000	(0.000)	0.000	(0.000)	0.005	(0.004)	1.0	(0.0)	0.005	(0.000)
	O2	0.000	(0.000)	0.000	(0.000)	0.000	(0.000)	0.000	(0.000)	0.000	(0.000)	0.000	(0.000)	0.000	(0.000)	NA	NA	0.000	(0.000)
	O3	0.000	(0.000)	0.000	(0.000)	0.000	(0.000)	0.000	(0.000)	0.000	(0.000)	0.000	(0.000)	0.000	(0.000)	NA	NA	0.000	(0.000)
	All	0.000	(0.000)	0.000	(0.000)	0.000	(0.000)	0.002	(0.003)	0.000^a	(0.000)	0.000^a	(0.000)	0.002^a	(0.003)	1.0^a	-	0.002^a	(0.000)
Shrub	S1	0.000	(0.000)	0.000	(0.000)	0.029	(0.008)	0.333	(0.034)	0.005	(0.001)	0.030	(0.019)	0.397	(0.022)	1.2	(0.0)	0.324	(0.000)
	S2	0.000	(0.000)	0.000	(0.000)	0.011	(0.003)	0.085	(0.051)	0.000	(0.000)	0.000	(0.000)	0.096	(0.054)	1.1	(0.1)	0.083	(0.000)
	S3	0.000	(0.000)	0.000	(0.000)	0.003	(0.002)	0.026	(0.027)	0.006	(0.003)	0.023	(0.014)	0.057	(0.026)	1.2	(0.1)	0.049	(0.000)
	All	0.000	(0.000)	0.000	(0.000)	0.014	(0.014)	0.148	(0.163)	0.004^{ab}	(0.003)	0.017^{ab}	(0.015)	0.183^b	(0.186)	1.2^b	(0.0)	0.152^b	(0.000)
Treed	T1	0.000	(0.000)	0.000	(0.000)	0.002	(0.002)	0.026	(0.027)	0.002	(0.002)	0.009	(0.010)	0.039	(0.041)	1.2	(0.1)	0.034	(0.000)
	T2	0.000	(0.001)	0.018	(0.026)	0.001	(0.002)	0.009	(0.012)	0.022	(0.013)	0.160	(0.024)	0.210	(0.076)	2.0	(0.4)	0.113	(0.000)
	T3	0.000	(0.000)	0.000	(0.000)	0.000	(0.000)	0.000	(0.000)	0.000	(0.000)	0.000	(0.000)	0.000	(0.000)	NA	NA	0.000	(0.000)
	T4	0.003	(0.005)	0.063	(0.101)	0.004	(0.005)	0.114	(0.132)	0.003	(0.004)	0.047	(0.071)	0.234	(0.032)	2.2	(0.5)	0.113	(0.000)
	T5	0.000	(0.000)	0.000	(0.000)	0.000	(0.001)	0.003	(0.006)	0.008	(0.003)	0.053	(0.020)	0.065	(0.020)	1.7	(0.3)	0.039	(0.000)
	All	0.001	(0.001)	0.016	(0.027)	0.001	(0.002)	0.030	(0.048)	0.007^b	(0.009)	0.054^b	(0.064)	0.110^{ab}	(0.105)	1.8^b	(0.4)	0.060^{ab}	(0.000)

Note: Superscripted letters (a,b) indicate significant differences ($\alpha = 0.05$) in group means across the fen fuel type classification.

Table A-4. Mean and standard deviation for aerial fuels in the shrub and treed fuel types.

		Black spruce load (kg/m ²)				Larch load (kg/m ²)						Live crown base height		Crown length (m)		Canopy bulk density (kg/m ³)	
Type	Site	Foliage		Branch		Foliage		Branch		Canopy fuel load (kg/m ²)		(m)					
Shrub	S1	0.000	(0.000)	0.000	(0.000)	0.037	(0.003)	0.089	(0.007)	0.126	(0.010)	0.5	(0.2)	2.0	(0.0)	0.062	(0.005)
		(0.004)	(0.004)	(0.005)	(0.005)	(0.012)	(0.012)	(0.031)	(0.030)	(0.040)	(0.040)	0.3	(0.1)	1.9	(0.4)	0.025	(0.017)
	S2	0.003	(0.003)	0.003	(0.002)	0.012	(0.000)	0.031	(0.001)	0.050	(0.005)	0.3	(0.1)	1.9	(0.4)	0.025	(0.005)
		(0.003)	(0.003)	(0.002)	(0.002)	(0.000)	(0.000)	(0.001)	(0.001)	(0.005)	(0.005)	0.2	(0.1)	1.0	(0.3)	0.011	(0.005)
	S3	0.006	(0.003)	0.004	(0.002)	0.000	(0.000)	0.000	(0.001)	0.010	(0.005)	0.2	(0.1)	1.0	(0.3)	0.011	(0.005)
All		0.003^a	(0.003)	0.002^a	(0.002)	0.017^a	(0.019)	0.040^a	(0.045)	0.062^a	(0.059)	0.3^a	(0.1)	1.6^a	(0.6)	0.032^a	(0.026)
Treed	T1	(0.034)	(0.034)	(0.016)	(0.016)	(0.020)	(0.020)	(0.049)	(0.049)	(0.046)	(0.046)	0.3	(0.2)	1.4	(0.3)	0.295	(0.092)
		0.190	(0.098)	0.173	(0.153)	0.010	(0.037)	0.025	(0.022)	0.399	(0.192)	1.0	(0.2)	2.9	(0.6)	0.310	(0.134)
	T2	(0.098)	(0.098)	(0.329)	(0.144)	(0.061)	(0.011)	(0.216)	(0.085)	(0.856)	(0.146)	1.0	(0.2)	2.9	(0.6)	0.310	(0.101)
		0.249	(0.098)	0.329	(0.144)	0.061	(0.011)	0.216	(0.085)	0.856	(0.146)	1.0	(0.2)	2.9	(0.6)	0.310	(0.101)
	T3	(0.098)	(0.098)	(0.157)	(0.017)	(0.069)	(0.050)	(0.217)	(0.146)	(0.571)	(0.199)	0.4	(0.1)	1.4	(0.0)	0.407	(0.027)
		0.129	(0.015)	0.157	(0.017)	0.069	(0.050)	0.217	(0.146)	0.571	(0.199)	0.4	(0.1)	1.4	(0.0)	0.407	(0.027)
	T4	(0.015)	(0.015)	(0.041)	(0.072)	(0.131)	(0.019)	(0.358)	(0.058)	(0.568)	(0.150)	1.6	(0.1)	4.1	(0.9)	0.140	(0.145)
		0.038	(0.048)	0.041	(0.072)	0.131	(0.019)	0.358	(0.058)	0.568	(0.150)	1.6	(0.1)	4.1	(0.9)	0.140	(0.145)
	T5	0.084	(0.048)	0.138	(0.072)	0.043	(0.019)	0.111	(0.058)	0.376	(0.150)	0.8	(0.4)	1.4	(0.3)	0.284	(0.145)
All		0.138^b	(0.084)	0.168^b	(0.104)	0.063^b	(0.044)	0.185^b	(0.126)	0.554^b	(0.192)	0.8^b	(0.5)	2.2^b	(1.2)	0.287^b	(0.096)

Note: Superscripted letters indicate significant differences ($\alpha = 0.05$). The statistical testing did include the Open type, though all of those values were 0, or NA in the case of live crown base height.

Table A-5. Mean and standard deviation for stand characteristics of treed and shrub fuel types.

Type	Site	Black spruce						Larch					
		Basal diameter (cm)		Height (m)		Density (stems/ha)		Basal diameter (cm)		Height (m)		Density (stems/ha)	
Shrub	S1	NA	NA	NA	NA	0	(0)	3.7	(0.5)	2.5	(0.2)	2900	(990)
	S2	1.9	(1.4)	1.1	(0.8)	175	(96)	3.8	(0.8)	2.5	(0.3)	900	(804)
	S3	1.9	(0.4)	1.2	(0.2)	575	(206)	2.4	-	2.0	-	25	(50)
	All	1.9 ^a	(0.0)	1.1 ^a	(0.1)	250 ^a	(295)	3.3 ^a	(0.8)	2.3 ^a	(0.3)	1275 ^a	(1474)
Treed	T1	2.8	(0.2)	1.6	(0.1)	9125	(2074)	3.1	(0.2)	2.3	(0.2)	850	(1634)
	T2	3.6	(0.3)	4.3	(1.5)	8100	(6364)	3.2	(1.4)	4.2	(0.9)	4500	(3536)
	T3	3.6	(1.0)	2.4	(0.3)	3300	(1556)	2.6	(0.1)	1.6	(0.0)	7950	(3748)
	T4	5.4	(1.8)	3.3	(0.6)	600	(316)	5.5	(0.7)	6.0	(1.0)	2925	(793)
	T5	4.3	(1.2)	3.5	(1.1)	2225	(950)	2.4	(0.9)	1.9	(0.7)	7225	(4291)
	All	4.0 ^b	(0.7)	3.0 ^b	(0.6)	4670 ^b	(2391)	3.4 ^b	(0.5)	3.2 ^b	(0.4)	4690 ^b	(1504)

Note: Superscripted letters (a,b) indicate significant differences ($\alpha = 0.05$) in group means across the fen fuel type classification.