Variation in fuel structure of boreal fens

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Abstract.

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

Keywords: peatlands, wildfire, fuel type, forest biomass, fuel load
Introduction

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

The frequency and intensity of wildfire in the boreal region are important controls on C storage (Bond-Lamberty et al. 2007). Fires can be ignited within peatlands (Turetsky et al. 2004) or spread from adjacent upland areas (Zoltai et al. 1998). Wildfires burned an estimated 1470 ± 59 km² year⁻¹ of peatlands between 1980 and 1995 in continental western Canada (i.e., Manitoba, Saskatchewan, Alberta; Turetsky et al. 2002). Peatland fires can consume some portion of the aerial and understory fuel strata (e.g., trees, shrubs, herbs); however, surface (nonvascular plants, litter) and ground fuels (thick layers of duff, organic soils, root biomass) are more typically consumed through smouldering combustion that dominate peat fires (Zoltai et al. 1998; Benscoter and Wieder 2003; Rein et al. 2008). In many undisturbed peatlands, wet conditions that keep water tables near the peat surface limit wildfire frequency and the potential for deep organic matter consumption (Turetsky et al. 2011). However, projected warming is expected to cause drying as a result of increased evapotranspiration, despite potential increases in precipitation in some boreal regions. This will lower water table positions in peatlands and may increase the availability of peatland ground fuels for smouldering combustion.
(Waddington et al. 2012). Furthermore, smouldering combustion can be maintained at a higher moisture content than flaming combustion, thus allowing deeper ground fuels in these ecosystems to burn under conditions that may not support active flaming (Frandsen 1997).

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

The 16 benchmark fuel types of the Canadian Forest Fire Behaviour Prediction (FBP) System, a system used extensively by fire management agencies across Canada, do not include fuel complex characterization that would adequately describe the available fuels within peatland ecosystems; the boreal spruce model (C-2) explicitly excludes “spruce-Sphagnum bogs” (Forestry Canada Fire Danger Group 1992). The fire spread that may be exhibited in peatlands likely differs from that of uplands,
because fire behaviour is sensitive to fuel load, arrangement, connectivity and flammability of the fuel strata present. Continental peatlands of western Canada are typically forested. Ombrogenous bogs in this region are dominated by black spruce (*Picea mariana* (Mill) BSP.). Geogenous fens, on the other hand, vary more widely in canopy structure, and can be forested (either with black spruce or larch [*Larix laricina* (Du Roi) K. Koch]), or can lack a continuous tree canopy (Vitt 2000a). These differences in vegetation structure are partially attributed to differences in hydrology and minerotrophy. For example, mean growing season water table positions typically range from 10 cm above to 40 cm below the peat surface in fens, and from 40 to 60 cm below the peat surface in bogs (Vitt et al. 2000b). Together, variation in vegetation structure and organic layer moisture content will dictate fire danger (Wotton 2009), as dry wooded peatlands are more prone to burning than open or shrub dominated peatlands (Turetsky et al. 2002). Recently, Johnston et al. (2015) compared fuel loads and structure along a chronosequence of *Sphagnum*-dominated bogs in northern Alberta to better understand successional trends in fuel loading and structure over time. In general, they found that consistent surface fuel loads and a lack of fuel strata gap (typically <0.1 m) between the surface and the crowns could support crown fire initiation in all sites along their chronosequence. At ~60 years following fire, the canopy bulk density of black spruce was sufficient to support active crown fire, and at ~80 years it could support active crown fire on approximately 10-40% of days during a fire season. No studies to date have considered fuel structuring in fens, despite the fact that fens constitute more than 60% of peatland area in continental western Canada (Vitt et al. 2000a). In general, very little is known about the conditions needed to support widespread flame front propagation in fen ecosystems.

The purpose of this study was to identify and quantify fuel components available to support flame front spread through three fen types along a hydrological and vegetation gradient in northern Alberta, Canada. These fen types (open/sedge fens, shrub fens, and treed fens) are representative of the
cross-section of fens in continental Canada, reflecting the variation in the structure and type of fuel available to support burning. A second goal was to develop allometric equations for peatland larch that could be used, along with similar previously developed models for bog black spruce, to estimate overall available aerial fuels in treed peatlands.

Methods

Study site

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

Fuel load characterization

Sampling of each site involved characterization of aerial and surface fuel components. Sampling was performed at each site along a 100 m transect, with four 10 m x 10 m quadrats spaced evenly on
alternating sides of the transect. The transect was established with a random starting point and bearing, and a new bearing that was constrained to avoid sampling overlap was chosen at 50 m for the remainder of the transect to minimize potential sampling bias resulting from prevailing orientation of dead and down woody fuels. The focus of this study was to characterize fuels available to support combustion, but was constrained to the fuel strata present above the ground fuel layer. We did not sample deeper peat soils to reconstruct full peat profiles; however, we did measure peat thickness at the centre of each site using a soil depth probe.

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

Under some fuel descriptions, shrub fuels up to 2 m tall would be grouped generally with surface fuels (Keane 2015). Recent fuel layer classifications from Australia (Gould et al. 2007; Hines et al. 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 cm$^2$ 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, -
164 116.9166; Cold Lake, AB: 55.2852, -111.3210). Stand DBH and height were used to determine the
165 range and distribution of larch sizes present at each site, and individuals were selected to obtain an
166 approximately equal distribution of size classes for the five sites collectively, as each stem diameter size
167 was not present at every site. Basal diameter, DBH and total height were recorded for each individual
168 harvested. Trees were cut at the ground moss surface and the entire tree was divided into sections with a
169 chainsaw and branches were removed from the boles. All biomass from this process was placed in paper
170 bags and stored at the Meanook Biological Station until they were shipped to the University of Guelph
171 in September 2010. Biomass was quantified separately for each tree and sorted into the following
172 categories: branches, needles, stem (with bark attached) and cones. The branches were further divided
173 into size classes I-III, equating to roundwood diameters: < 0.5, 0.5-0.99, 1.0-2.99 cm, respectively
174 (McRae et al. 1979). Branchwood did not exceed a diameter of 3.0 cm. Samples were oven-dried at 95
175 degrees Celsius to a constant mass; the dry weight was recorded to the nearest 0.01 g. The total biomass
176 for each individual tree was determined by summing the weighed biomass of all categories. Available
177 branchwood fuel was determined by summing the weight of branch size classes I and II (i.e., < 1.0 cm
178 diameter) for an individual tree.

179 Two available fuel load equations were developed for larch representing the two components of
180 the crown that would consumed during the passage of a flaming front and contribute to fireline intensity,
181 foliage and branchwood <1 cm diameter. We created allometric equations to model oven-dried tree
182 biomass components as a function of tree diameter (e.g., Pastor et al. 1984; Crow and Schlaegel 1988;
183 Ter-Mikaelian and Korzukhin 1997). Graphical inspection of the relationship between tree biomass and
184 diameter (DBH or basal diameter) showed that these data did exhibit the typical power function form
185 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/m\(^2\)) was the sum of available branchwood and foliage for all trees, divided by the quadrat sampling area (100 m\(^2\)). Canopy bulk density (kg/m\(^3\)) 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 fen fuel types, we estimated fire intensity based on the classic equation presented by Byram (1959). Fireline intensity, $I$ (kW/m) was estimated as:

$$I = Hwr$$

(2)

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:

$$L = 0.0775 I^{0.46}$$

(3)
where $I$ is fireline intensity in kW/m (Alexander 1982). For the purpose of this discussion, 25 m/min rate of spread was assumed for comparison of fireline intensities between fen fuel types.

**Results**

**Fen fuel loading**

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

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

Downed woody debris (DWD) on the surface varied among the fen types ($p < 0.001$). Not surprisingly, DWD fuel loads were extremely low in the open sites and were highest in the treed sites (Table 2). In the treed fens, assuming that only the size class I and II fuels (<0.5 and 0.5-1.0 cm, respectively) would be available to contribute to flaming combustion, average DWD fuel loads ($0.021 \pm 0.005$ 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/m$^3$, which was similar to black-spruce dominated bogs that ranged from 0.166 to 0.543 kg/m$^3$ 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**
Biomass measurements from 47 trees sampled across several fens were combined to generate allometric equations for larch (Table 4). These trees ranged in basal diameter from 1.0 to 14.7 cm, DBH ranged from 0.3 to 11.5 cm, and total height ranged from 0.6 m to 8.5 m. Overall, stem weight was found to be the greatest contributor to total biomass for every individual, followed by branches with a diameter of <0.5 cm and then foliage. Models for total aboveground, stem (with bark), foliage, and branchwood (total, <0.5 cm, <1.0 cm) biomass were developed individually using Equation 1. Of all the measured tree attributes, diameter was the single strongest predictor of biomass; basal diameter was a slightly stronger predictor of total biomass than DBH ($r^2 = 0.984$ and $r^2 = 0.947$, respectively); however we developed separate models for both basal diameter and DBH because some studies, and many forest inventory methods, report only DBH. The power law model form (Equation 1) represented the best fit (Figure 5), with $r^2$ values exceeding 0.95. Variance in residuals across the range of diameters was relatively constant and did not exhibit any strong trends. Tree height was an additional significant predictor in a forward selection multiple regression model form but offered little meaningful improvement in predictive power. For example, once the effect of basal diameter was accounted for, the partial variance explained in total tree biomass due to height was $r^2 = 0.006$ ($p <0.0001$).

**Discussion**

*Fen fuel loading*

Despite representing a large fraction of land cover across many boreal regions, peatlands are rarely incorporated into fire behaviour prediction models. Johnston et al. (2015) characterized the fuel strata in black spruce bogs to estimate crown fire sustainability. Results from that study suggested that while torching would likely initiate at any site along their bog chronosequence, active crown fire would 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 ± 0.044 kg/m$^2$) is similar to those reported for bogs (0.396 ± 0.027 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 (0.36-0.77 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 ± 0.007 kg/m$^2$) was smaller than what has been reported for black-spruce bogs (0.186 ± 0.023 kg/m$^2$, Johnston et al. 2015) and upland fuel types (0.24-0.32 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 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 ~3200 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).
Given the presence of green vegetation in this open fen fuel complex, it is doubtful a fire could propagate at this intensity (Cruz et al. 2015). However, the presence of the low shrub layer complicates the projection of summer-time fire behaviour. If moisture levels in the live vegetation are low enough (<100% GMC), then propagation may be possible in areas with low densities of graminoids and other green (live) vegetation. While some grassland spread models have been found to work well in grasslands outside of Australia (Cheney et al. 1998, Kidnie and Wotton 2015), their predictive ability in this open fen type may be questionable and should be subject to further study.

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

Because the likelihood of canopy torching and crown fire occurrence increases with decreasing crown base height (Van Wagner 1977), we expect that the treed peatlands in this study would be prone to torching due to the very short crown base heights observed (Table 3). Van Wagner’s (1977) model, which is used worldwide, suggests the critical intensity for the ignition of black spruce canopy given an average CBH of 0.8 m and foliar moisture content at 100% would be 120 kW/m, which represents a low
intensity surface fire. Thus, if flaming propagation were possible, we expect that most of the black spruce in forested fens would experience torching. This torching would likely cause tree mortality where it occurred.

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

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


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.

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

*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.

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

Note: Superscript labels a, b, and c indicate significant differences (α = 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.

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

Note: Superscript labels a and b indicate significant differences (α = 0.05) in mean values across the fen fuel type classifications for a particular fuel element.
Table 4. Regression summary statistics for tree biomass relationships. Equations in the form \(\ln(Y)=\beta_0+\beta_1*\ln(diameter)\), where \(Y\) is fuel load (kg), and \(diameter\) is either basal diameter (cm) or DBH (cm). S.E. is standard error.

<table>
<thead>
<tr>
<th>Component</th>
<th>(n)</th>
<th>(\beta_1) (S.E.)</th>
<th>(\beta_0) (S.E.)</th>
<th>(r^2)</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Basal diameter models</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total Biomass</td>
<td>47</td>
<td>2.517 (0.048)</td>
<td>-3.394 (0.084)</td>
<td>0.984</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Stem (with bark)</td>
<td>47</td>
<td>2.639 (0.058)</td>
<td>-4.202 (0.101)</td>
<td>0.979</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Branches (&lt;0.5 cm)</td>
<td>47</td>
<td>2.141 (0.049)</td>
<td>-4.247 (0.086)</td>
<td>0.976</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Branches (&lt;1.0 cm)</td>
<td>47</td>
<td>2.330 (0.051)</td>
<td>-4.326 (0.090)</td>
<td>0.978</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Total Branches</td>
<td>47</td>
<td>2.388 (0.061)</td>
<td>-4.335 (0.106)</td>
<td>0.971</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Foliage</td>
<td>47</td>
<td>2.185 (0.067)</td>
<td>-4.980 (0.116)</td>
<td>0.960</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td><strong>DBH models</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total Biomass</td>
<td>39</td>
<td>1.635 (0.063)</td>
<td>-0.850 (0.098)</td>
<td>0.947</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Stem (with bark)</td>
<td>39</td>
<td>1.726 (0.069)</td>
<td>-1.604 (0.108)</td>
<td>0.943</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Branches (&lt;0.5 cm)</td>
<td>39</td>
<td>1.355 (0.064)</td>
<td>-2.033 (0.101)</td>
<td>0.921</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Branches (&lt;1.0 cm)</td>
<td>39</td>
<td>1.502 (0.069)</td>
<td>-1.964 (0.108)</td>
<td>0.925</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Total Branches</td>
<td>39</td>
<td>1.545 (0.070)</td>
<td>-1.917 (0.108)</td>
<td>0.928</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Foliage</td>
<td>39</td>
<td>1.357 (0.067)</td>
<td>-2.673 (0.104)</td>
<td>0.916</td>
<td>&lt;0.0001</td>
</tr>
</tbody>
</table>

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.

<table>
<thead>
<tr>
<th>Fen type</th>
<th>Rate of spread, $r$ (m/min)</th>
<th>Fuel consumed, $w$ (kg/m$^2$)</th>
<th>Intensity, $I$ (kW/m)</th>
<th>Flame length, $L$ (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Open (spring, cured)</td>
<td>25</td>
<td>0.426</td>
<td>3195</td>
<td>3.2</td>
</tr>
<tr>
<td>Open (summer, green)</td>
<td>25</td>
<td>0.050</td>
<td>375</td>
<td>1.2</td>
</tr>
<tr>
<td>Shrub</td>
<td>25</td>
<td>0.624</td>
<td>4680</td>
<td>3.8</td>
</tr>
<tr>
<td>Treed</td>
<td>25</td>
<td>0.734</td>
<td>5505</td>
<td>4.1</td>
</tr>
</tbody>
</table>
Treed fens

- T1, 9975 stems·ha⁻¹
- T2, 12600 stems·ha⁻¹
- T3, 11250 stems·ha⁻¹
- T4, 3525 stems·ha⁻¹
- T5, 9450 stems·ha⁻¹

Shrub fens

- S1, 2900 stems·ha⁻¹
- S2, 1075 stems·ha⁻¹
- S3, 600 stems·ha⁻¹
## Appendix

Table A-1. Mean and standard deviation of surface fuel load (kg/m$^2$) by fuel component for each fuel type.

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

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.

<table>
<thead>
<tr>
<th>Type</th>
<th>Site</th>
<th>&lt;0.5 cm</th>
<th>0.5-1.0 cm</th>
<th>1.0-3.0 cm</th>
<th>3.0-5.0 cm</th>
<th>5.0-7.0 cm</th>
<th>&gt;7 cm</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>SD</td>
<td>Mean</td>
<td>SD</td>
<td>Mean</td>
<td>SD</td>
<td>Mean</td>
<td>SD</td>
</tr>
<tr>
<td>Open</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>O1</td>
<td>0.000</td>
<td>(0.000)</td>
<td>0.000</td>
<td>(0.000)</td>
<td>0.000</td>
<td>(0.000)</td>
<td>0.000</td>
<td>(0.000)</td>
</tr>
<tr>
<td>O2</td>
<td>0.000</td>
<td>(0.000)</td>
<td>0.001</td>
<td>(0.000)</td>
<td>0.000</td>
<td>(0.000)</td>
<td>0.000</td>
<td>(0.000)</td>
</tr>
<tr>
<td>O3</td>
<td>0.000</td>
<td>(0.000)</td>
<td>0.000</td>
<td>(0.000)</td>
<td>0.000</td>
<td>(0.000)</td>
<td>0.000</td>
<td>(0.000)</td>
</tr>
<tr>
<td>All</td>
<td><strong>0.000</strong></td>
<td>(0.000)</td>
<td><strong>0.000</strong></td>
<td>(0.001)</td>
<td><strong>0.000</strong></td>
<td>(0.000)</td>
<td><strong>0.000</strong></td>
<td>(0.000)</td>
</tr>
<tr>
<td>Shrub</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>S1</td>
<td>0.004</td>
<td>(0.001)</td>
<td>0.012</td>
<td>(0.005)</td>
<td>0.005</td>
<td>(0.011)</td>
<td>0.000</td>
<td>(0.000)</td>
</tr>
<tr>
<td>S2</td>
<td>0.001</td>
<td>(0.000)</td>
<td>0.000</td>
<td>(0.000)</td>
<td>0.005</td>
<td>(0.011)</td>
<td>0.000</td>
<td>(0.000)</td>
</tr>
<tr>
<td>S3</td>
<td>0.003</td>
<td>(0.001)</td>
<td>0.001</td>
<td>(0.000)</td>
<td>0.003</td>
<td>(0.006)</td>
<td>0.000</td>
<td>(0.000)</td>
</tr>
<tr>
<td>All</td>
<td><strong>0.003</strong></td>
<td>(0.002)</td>
<td><strong>0.004</strong></td>
<td>(0.006)</td>
<td><strong>0.004</strong></td>
<td>(0.009)</td>
<td><strong>0.000</strong></td>
<td>(0.000)</td>
</tr>
<tr>
<td>Treed</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>T1</td>
<td>0.006</td>
<td>(0.004)</td>
<td>0.015</td>
<td>(0.009)</td>
<td>0.057</td>
<td>(0.034)</td>
<td>0.062</td>
<td>(0.113)</td>
</tr>
<tr>
<td>T2</td>
<td>0.008</td>
<td>(0.004)</td>
<td>0.033</td>
<td>(0.016)</td>
<td>0.141</td>
<td>(0.089)</td>
<td>0.042</td>
<td>(0.044)</td>
</tr>
<tr>
<td>T3</td>
<td>0.004</td>
<td>(0.001)</td>
<td>0.007</td>
<td>(0.008)</td>
<td>0.021</td>
<td>(0.011)</td>
<td>0.010</td>
<td>(0.023)</td>
</tr>
<tr>
<td>T4</td>
<td>0.003</td>
<td>(0.001)</td>
<td>0.008</td>
<td>(0.007)</td>
<td>0.008</td>
<td>(0.007)</td>
<td>0.000</td>
<td>(0.000)</td>
</tr>
<tr>
<td>T5</td>
<td>0.006</td>
<td>(0.006)</td>
<td>0.015</td>
<td>(0.018)</td>
<td>0.028</td>
<td>(0.038)</td>
<td>0.042</td>
<td>(0.044)</td>
</tr>
<tr>
<td>All</td>
<td><strong>0.005</strong></td>
<td>(0.000)</td>
<td><strong>0.016</strong></td>
<td>(0.001)</td>
<td><strong>0.051</strong></td>
<td>(0.000)</td>
<td><strong>0.031</strong></td>
<td>(0.000)</td>
</tr>
</tbody>
</table>

Note: Superscripted letters (a,b,c) indicate significantly different group means (α = 0.05) across the fen 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.

<table>
<thead>
<tr>
<th>Type</th>
<th>Site</th>
<th>Alder foliage</th>
<th>Alder branch</th>
<th>Bog birch foliage</th>
<th>Bog birch branch</th>
<th>Willow foliage</th>
<th>Willow branch</th>
<th>Shrub load (kg/m²)</th>
<th>Height (m)</th>
<th>Bulk density (kg/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Open</td>
<td>O1</td>
<td>0.000 (0.000)</td>
<td>0.000 (0.000)</td>
<td>0.005 (0.004)</td>
<td>0.000 (0.000)</td>
<td>0.000 (0.000)</td>
<td>0.000 (0.000)</td>
<td>0.005 (0.004)</td>
<td>1.0 (0.0)</td>
<td>0.005 (0.000)</td>
</tr>
<tr>
<td></td>
<td>O2</td>
<td>0.000 (0.000)</td>
<td>0.000 (0.000)</td>
<td>0.000 (0.000)</td>
<td>0.000 (0.000)</td>
<td>0.000 (0.000)</td>
<td>0.000 (0.000)</td>
<td>0.000 (0.000)</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td></td>
<td>O3</td>
<td>0.000 (0.000)</td>
<td>0.000 (0.000)</td>
<td>0.000 (0.000)</td>
<td>0.000 (0.000)</td>
<td>0.000 (0.000)</td>
<td>0.000 (0.000)</td>
<td>0.000 (0.000)</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td></td>
<td>All</td>
<td>0.000 (0.000)</td>
<td>0.000 (0.000)</td>
<td>0.002 (0.003)</td>
<td>0.000a (0.000)</td>
<td>0.000a (0.000)</td>
<td>0.002a (0.003)</td>
<td>1.0a (0.0)</td>
<td>1.0 -</td>
<td>0.002a (0.000)</td>
</tr>
<tr>
<td>Shrub</td>
<td>S1</td>
<td>0.000 (0.000)</td>
<td>0.000 (0.000)</td>
<td>0.029 (0.008)</td>
<td>0.333 (0.034)</td>
<td>0.005 (0.001)</td>
<td>0.030 (0.019)</td>
<td>0.397 (0.022)</td>
<td>1.2 (0.0)</td>
<td>0.324 (0.000)</td>
</tr>
<tr>
<td></td>
<td>S2</td>
<td>0.000 (0.000)</td>
<td>0.000 (0.000)</td>
<td>0.011 (0.003)</td>
<td>0.085 (0.051)</td>
<td>0.000 (0.000)</td>
<td>0.000 (0.000)</td>
<td>0.096 (0.054)</td>
<td>1.1 (0.1)</td>
<td>0.083 (0.000)</td>
</tr>
<tr>
<td></td>
<td>S3</td>
<td>0.000 (0.000)</td>
<td>0.000 (0.000)</td>
<td>0.003 (0.002)</td>
<td>0.026 (0.027)</td>
<td>0.006 (0.003)</td>
<td>0.023 (0.014)</td>
<td>0.057 (0.026)</td>
<td>1.2 (0.1)</td>
<td>0.049 (0.000)</td>
</tr>
<tr>
<td></td>
<td>All</td>
<td>0.000 (0.000)</td>
<td>0.000 (0.000)</td>
<td>0.014 (0.014)</td>
<td>0.148 (0.163)</td>
<td>0.004ab (0.003)</td>
<td>0.017ab (0.015)</td>
<td>0.183b (0.186)</td>
<td>1.2b (0.0)</td>
<td>0.152b (0.000)</td>
</tr>
<tr>
<td>Treed</td>
<td>T1</td>
<td>0.000 (0.000)</td>
<td>0.000 (0.000)</td>
<td>0.002 (0.002)</td>
<td>0.026 (0.027)</td>
<td>0.002 (0.002)</td>
<td>0.009 (0.010)</td>
<td>0.039 (0.041)</td>
<td>1.2 (0.1)</td>
<td>0.034 (0.000)</td>
</tr>
<tr>
<td></td>
<td>T2</td>
<td>0.000 (0.001)</td>
<td>0.018 (0.026)</td>
<td>0.001 (0.002)</td>
<td>0.009 (0.012)</td>
<td>0.022 (0.013)</td>
<td>0.160 (0.024)</td>
<td>0.210 (0.076)</td>
<td>2.0 (0.4)</td>
<td>0.113 (0.000)</td>
</tr>
<tr>
<td></td>
<td>T3</td>
<td>0.000 (0.000)</td>
<td>0.000 (0.000)</td>
<td>0.000 (0.000)</td>
<td>0.000 (0.000)</td>
<td>0.000 (0.000)</td>
<td>0.000 (0.000)</td>
<td>0.000 (0.000)</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td></td>
<td>T4</td>
<td>0.003 (0.005)</td>
<td>0.063 (0.101)</td>
<td>0.004 (0.005)</td>
<td>0.114 (0.132)</td>
<td>0.003 (0.004)</td>
<td>0.047 (0.071)</td>
<td>0.234 (0.032)</td>
<td>2.2 (0.5)</td>
<td>0.113 (0.000)</td>
</tr>
<tr>
<td></td>
<td>T5</td>
<td>0.000 (0.000)</td>
<td>0.000 (0.000)</td>
<td>0.000 (0.001)</td>
<td>0.003 (0.006)</td>
<td>0.008 (0.003)</td>
<td>0.053 (0.020)</td>
<td>0.065 (0.020)</td>
<td>1.7 (0.3)</td>
<td>0.039 (0.000)</td>
</tr>
<tr>
<td></td>
<td>All</td>
<td>0.001 (0.001)</td>
<td>0.016 (0.027)</td>
<td>0.001 (0.002)</td>
<td>0.030 (0.048)</td>
<td>0.007b (0.009)</td>
<td>0.054b (0.064)</td>
<td>0.110ab (0.105)</td>
<td>1.8b (0.4)</td>
<td>0.060ab (0.000)</td>
</tr>
</tbody>
</table>

Note: Superscripted letters (a,b) indicate significant differences (α = 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.

<table>
<thead>
<tr>
<th>Type</th>
<th>Site</th>
<th>Black spruce load (kg/m²)</th>
<th>Larch load (kg/m²)</th>
<th>Canopy fuel load (kg/m²)</th>
<th>Live crown base height (m)</th>
<th>Crown length (m)</th>
<th>Canopy bulk density (kg/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Foliage</td>
<td>Branch</td>
<td>Foliage</td>
<td>Branch</td>
<td>Foliage</td>
<td>Branch</td>
</tr>
<tr>
<td>Shrub</td>
<td>S1</td>
<td>0.000</td>
<td>(0.000)</td>
<td>0.000</td>
<td>(0.000)</td>
<td>0.037</td>
<td>(0.003)</td>
</tr>
<tr>
<td></td>
<td>S2</td>
<td>0.003</td>
<td>(0.004)</td>
<td>0.003</td>
<td>(0.005)</td>
<td>0.012</td>
<td>(0.012)</td>
</tr>
<tr>
<td></td>
<td>S3</td>
<td>0.006</td>
<td>(0.003)</td>
<td>0.004</td>
<td>(0.002)</td>
<td>0.000</td>
<td>(0.000)</td>
</tr>
<tr>
<td></td>
<td>All</td>
<td>0.003</td>
<td>(0.003)</td>
<td>0.002</td>
<td>(0.002)</td>
<td>0.017</td>
<td>(0.019)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>a</td>
<td>a</td>
<td></td>
<td>a</td>
</tr>
<tr>
<td>Treed</td>
<td>T1</td>
<td>0.190</td>
<td>(0.098)</td>
<td>0.173</td>
<td>(0.153)</td>
<td>0.010</td>
<td>(0.037)</td>
</tr>
<tr>
<td></td>
<td>T2</td>
<td>0.249</td>
<td>(0.098)</td>
<td>0.329</td>
<td>(0.144)</td>
<td>0.061</td>
<td>(0.011)</td>
</tr>
<tr>
<td></td>
<td>T3</td>
<td>0.129</td>
<td>(0.015)</td>
<td>0.157</td>
<td>(0.017)</td>
<td>0.069</td>
<td>(0.050)</td>
</tr>
<tr>
<td></td>
<td>T4</td>
<td>0.038</td>
<td>(0.048)</td>
<td>0.041</td>
<td>(0.072)</td>
<td>0.131</td>
<td>(0.019)</td>
</tr>
<tr>
<td></td>
<td>T5</td>
<td>0.084</td>
<td>(0.048)</td>
<td>0.138</td>
<td>(0.072)</td>
<td>0.043</td>
<td>(0.019)</td>
</tr>
<tr>
<td></td>
<td>All</td>
<td>0.138</td>
<td>(0.084)</td>
<td>0.168</td>
<td>(0.104)</td>
<td>0.063</td>
<td>(0.044)</td>
</tr>
</tbody>
</table>

Note: Superscripted letters indicate significant differences (α = 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.

<table>
<thead>
<tr>
<th>Type</th>
<th>Site</th>
<th>Black spruce</th>
<th></th>
<th></th>
<th>Larch</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Basal diameter (cm)</td>
<td>Height (m)</td>
<td>Density (stems/ha)</td>
<td>Basal diameter (cm)</td>
<td>Height (m)</td>
</tr>
<tr>
<td>Shrub</td>
<td>S1</td>
<td>NA</td>
<td>NA</td>
<td>0 (0)</td>
<td>3.7 (0.5)</td>
<td>2.5 (0.2)</td>
</tr>
<tr>
<td></td>
<td>S2</td>
<td>1.9 (1.4)</td>
<td>1.1 (0.8)</td>
<td>175 (96)</td>
<td>3.8 (0.8)</td>
<td>2.5 (0.3)</td>
</tr>
<tr>
<td></td>
<td>S3</td>
<td>1.9 (0.4)</td>
<td>1.2 (0.2)</td>
<td>575 (206)</td>
<td>2.4</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>All</td>
<td>1.9a (0.0)</td>
<td>1.1a (0.1)</td>
<td>250a (295)</td>
<td>3.3a (0.8)</td>
<td>2.3a (0.3)</td>
</tr>
<tr>
<td>Treed</td>
<td>T1</td>
<td>2.8 (0.2)</td>
<td>1.6 (0.1)</td>
<td>9125 (2074)</td>
<td>3.1 (0.2)</td>
<td>2.3 (0.2)</td>
</tr>
<tr>
<td></td>
<td>T2</td>
<td>3.6 (0.3)</td>
<td>4.3 (1.5)</td>
<td>8100 (6364)</td>
<td>3.2 (1.4)</td>
<td>4.2 (0.9)</td>
</tr>
<tr>
<td></td>
<td>T3</td>
<td>3.6 (1.0)</td>
<td>2.4 (0.3)</td>
<td>3300 (1556)</td>
<td>2.6 (0.1)</td>
<td>1.6 (0.0)</td>
</tr>
<tr>
<td></td>
<td>T4</td>
<td>5.4 (1.8)</td>
<td>3.3 (0.6)</td>
<td>600 (316)</td>
<td>5.5 (0.7)</td>
<td>6.0 (1.0)</td>
</tr>
<tr>
<td></td>
<td>T5</td>
<td>4.3 (1.2)</td>
<td>3.5 (1.1)</td>
<td>2225 (950)</td>
<td>2.4 (0.9)</td>
<td>1.9 (0.7)</td>
</tr>
<tr>
<td></td>
<td>All</td>
<td>4.0b (0.7)</td>
<td>3.0b (0.6)</td>
<td>4670b (2391)</td>
<td>3.4b (0.5)</td>
<td>3.2b (0.4)</td>
</tr>
</tbody>
</table>

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