LETTER

Did enhanced afforestation cause high severity peat burn in the Fort McMurray Horse River wildfire?

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OPEN ACCESS

RECEIVED
5 October 2017
REVISED
11 December 2017
ACCEPTED FOR PUBLICATION
13 December 2017
PUBLISHED
17 January 2018

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Keywords: peatland, afforestation, wildfire, tipping point, land management, Sphagnum, burn severity

Supplementary material for this article is available online

Abstract

Climate change mediated drying of boreal peatlands is expected to enhance peatland afforestation and wildfire vulnerability. The water table depth–afforestation feedback represents a positive feedback that can enhance peat drying and consolidation and thereby increase peat burn severity; exacerbating the challenges and costs of wildfire suppression efforts and potentially shifting the peatland to a persistent source of atmospheric carbon. To address this wildfire management challenge, we examined burn severity across a gradient of drying in a black spruce dominated peatland that was partially drained in 1975–1980 and burned in the 2016 Fort McMurray Horse River wildfire. We found that post-drainage black spruce annual ring width increased substantially with intense drainage. Average (±SD) basal diameter was 2.6 ± 1.2 cm, 3.2 ± 2.0 cm and 7.9 ± 4.7 cm in undrained (UD), moderately drained (MD) and heavily drained (HD) treatments, respectively. Depth of burn was significantly different between treatments (p < 0.001) and averaged (±SD) 2.5 ± 3.5 cm, 6.4 ± 5.0 cm and 36.9 ± 29.6 cm for the UD, MD and HD treatments, respectively. The high burn severity in the HD treatment included 38% of the treatment that experienced combustion of the entire peat profile, and we estimate that overall 51% of the HD pre-burn peat carbon stock was lost. We argue that the HD treatment surpassed an ecohydrological tipping point to high severity peat burn that may be identified using black spruce stand characteristics in boreal plains bogs. While further studies are needed, we believe that quantifying this threshold will aid in developing effective adaptive management techniques and protecting boreal peatland carbon stocks.

Introduction

Boreal peatlands represent a globally important long-term carbon sink with the majority of the carbon stock residing in peat where primary production has exceeded losses from decomposition and combustion throughout the Holocene (Vitt et al 2000). These boreal peatlands also represent a large wildfire fuel source on the landscape in boreal sub-humid regions (e.g. Canada’s Boreal Plains ecozone (BP)). BP peatlands generally experience low severity peat burn during wildfire, with depth of burn (DOB) ranging from 5–10 cm and releasing 2–3 kg C m⁻² (e.g. Hokanson et al 2016). Black spruce (Picea mariana) dominated peatlands, common to the BP landscape, are generally resilient to low burn severity wildfire, returning to an annual net carbon sink within ~20 years post-fire (Wieder et al 2009). However, with enhanced drying, black spruce dominated peatlands in the BP can experience severe smouldering combustion with high DOB (>20 cm) releasing 10–85 kg C m⁻² (Turetsky et al 2011, Lukenbach et al 2015). These high burn severity peat fires are costly and challenging for fire suppression operations and often cause potentially hazardous air quality (Flannigan et al 2009, Shaposhnikov et al 2014). These fires also demand extra resources due to prolonged smouldering and the subsequent ‘mop-up’, exemplified by the Fort McMurray Horse River
wildfire that was not considered extinguished until 456 days after ignition due to such smouldering (Alberta Agriculture and Forestry 2017). Moreover, these fires can trigger an ecosystem regime shift causing the loss of keystone Sphagnum mosses and recruitment of vascular vegetation, resulting in a long-term change in peatland ecohydrological structure and function. This shift is sustained by a low intensity, high frequency wildfire regime that leads to further degradation of the peat reserve (Kettridge et al 2015). Given that the areal extent, frequency and severity of peatland drying (Granath et al 2016) and boreal wildfires (Flannigan et al 2005, 2013) are predicted to increase due to climate change, there is an urgent need to gain a better understanding of the processes controlling high severity peat burns, including the influence of peatland drying and the associated enhanced afforestation.

Previous research suggests that the loss of peatland ecohydrological resilience due to high severity peat burns likely occurs when an ecosystem structure and function threshold (i.e. tipping point, see Scheffer 2009) is exceeded (Kettridge et al 2015). Tipping points, known as catastrophic bifurcations in ecological theory, have been identified in a number of important ecosystems (Scheffer 2009), and while they have received little attention in peatland studies (Hilbert et al 2000), peatland ecosystems have tightly-coupled ecological and hydrological processes that are precursors of threshold behaviour (Scheffer 2009). As such, the response of peatlands to wildfires is the result of both pre-fire ecohydrological conditions and numerous ecohydrological feedbacks (Thompson et al 2015, Waddington et al 2015). The majority of these are negative feedbacks which are centred around key traits of the peat-forming moss genus, Sphagnum (Waddington et al 2015). Undecomposed or partially decomposed Sphagnum mosses have high porosity, providing a high specific yield which regulates water table (WT) fluctuations (Waddington et al 2015). Low moss bulk density (fuel density), together with high surface moisture content, enables Sphagnum to act as an energy sink during wildfire (e.g. Shetler et al 2008). However, positive feedbacks can alter peatland ecohydrological conditions and increase wildfire vulnerability.

One such feedback is the water table depth (WTD)—afforestation feedback, which can exacerbate drying and negatively impact the peatland water balance (Waddington et al 2015). As WTD increases (due to drying or peatland drainage), black spruce net above-ground productivity increases resulting in greater tree heights, basal diameters, and stand density (Liefers and Rothwell 1986), and a concomitant increase in transpiration and rainfall interception (Price et al 1997), further increasing WTD (Waddington et al 2015). This increase in above-ground fuel load also increases the potential for sustaining high-intensity crown fires (Johnston et al 2015). Moreover, because feather moss has been shown to out-compete Sphagnum under low light conditions as afforestation increases (Bisbee et al 2001), and tends to be drier than Sphagnum under field conditions (Lukenbach et al 2015), peatland afforestation may also increase smouldering ignition potential and peat burn severity (Thompson et al 2015). Because enhanced afforestation has been associated with deep burning in temperate peatlands (Davies et al 2013), we suggest that quantifying stand characteristics may provide an opportunity to identify peatlands at high risk of exceeding an ecohydrological tipping point and thereby potentially help reduce wildfire management challenges and costs.

As a first step towards identifying a deep burning tipping point through drying and enhanced afforestation this study capitalises on a multi-decadal peatland drainage experiment that burned in the 2016 Horse River wildfire. We use a gradient of peatland drainage as a proxy for climate-mediated drying with measurements of depth of burn to assess peat burn severity.

Methodology

Study site

The research site is a 14 ha section of black spruce dominated (>95%) peatland located 11 km south of Fort McMurray, Alberta (56.732°N, 111.376°W) that burned in the 602 000 ha Horse River wildfire (MWF-009) in 2016. As part of a silviculture experiment, a portion of the peatland was drained between 1975 and 1980 (Hillman 1987). Drainage was initiated by clearing and scarification of the black spruce canopy along a ditch network in 1975–1976, and in 1979–1980 the drainage ditch network was expanded with 0.76–1.06 m deep, 3 m wide, ditches spaced 9 m or 18 m apart (Hillman 1987). The southern portion of the peatland remained undrained, with regional flow being roughly south to north. We classified the peatland into three treatments along a pre-fire ecohydrological gradient based on drainage ditch density: (i) undrained (UD) being >30 m from drainage ditches; (ii) moderately-drained (MD) with ditch spacing every 18 m; and (iii) heavily-drained (HD) with ditch spacing every 9 m. Three 50 m² plots were randomly located in each treatment and used to assess tree productivity pre- and post-drainage, stand characteristics, as well as peat burn severity.

The peatland experienced a crown fire between 5–6 May 2016, with below-ground smouldering continuing from this date (Newman 2016). The Drought Code (DC), calculated using the Canadian Fire Weather Index system, represents the moisture content of mesic and humic organic layers (Van Wagner 1987). On the days of the crown fire the DC value averaged 452 which is greater than 88% of the DC values during the fire season (May–October) over the last 50 years. Fire-fighting efforts were required to control and extinguish peat smouldering in some areas of the HD treatment due to the proximity of the peatland to important transportation infrastructure. Hence, our
plots were chosen to avoid these heavily disturbed fire suppression areas.

**Peat burn severity**

Peat burn severity, was estimated by making 900 DOB measurements using the adventitious root method (see Kasischke et al. 2008) five months post fire. DOB was estimated as the vertical distance between the burned surface and the datum provided by the adventitious roots between tree pairs. Average DOB per tree pair was based on five equally spaced measurements. In each 50 m² plot (three per treatment), average DOB was estimated for five clusters of four tree pairs (i.e. 15 clusters/treatment). DOB could not be assessed in an area within the HD treatment using the adventitious root method due to the complete smouldering consumption of the peat profile, resulting in exposure of mineral soil, and complete tree fall. In the burned-to-mineral portion of HD, we took DOB to be equal to the estimated pre-fire peat depth. The average and standard deviation of DOB for the entire HD treatment was derived from a weighted random resampling of measured DOB and estimated residual peat depth, with weighting based on the proportional cover of the two areas within the treatment. Measurements of post-fire peat depth were taken at nine random locations in each 50 m² plot by auguring to mineral soil. Pre-fire peat depths in each treatment were estimated to be the sum of DOB and post-fire (residual) peat depth. Mean and standard deviation of pre-fire peat depth were derived by random resampling of the measured DOB and residual peat depth (see the supplementary material available at stacks.iop.org/ERL/13/014018/mmedia). Post-fire ground-cover was assessed using 15 randomly located 0.6×0.6 m quadrats in one plot of each treatment.

Carbon loss from peat smouldering was estimated using DOB at each measurement location, depth-dependent average bulk density and average ash content from the Zoltai database (Zoltai et al. 2000). As a lower and upper estimate of average depth-dependent bulk density, we used values for *Sphagnum* and sylvic peat, respectively. Average ash content for *Sphagnum* and sylvic peat were taken to be 5% and 12%, respectively, and organic matter was assumed to have an organic carbon content of 51.7% (Gorham 1991) (i.e. peat C-content of ~49% and 46%). Estimated carbon loss in the burned-to-mineral section of the HD treatment used estimated pre-fire peat depth (see supplementary material) and average bulk density for the corresponding depth from the Zoltai et al. (2000) database. The same approach was used to estimate total pre-fire peat carbon content.

**Stand characteristics**

Stand characteristics were assessed by measuring the basal diameter (BD), diameter at breast height (for trees > 1.3 m), and tree species for all trees in each plot. Stand biomass and carbon/fuel loadings were then calculated using standard allometric equations (e.g. Bond-Lamberty et al. 2002, Johnston et al. 2015). Canopy closure was estimated using the relationship defined in Housman (2017) based on total above-ground stand biomass in black spruce dominated BP peatlands (supplementary material). In each plot, five trees were randomly chosen and 2–3 cm thick discs of the tree trunk were cut just above the root collar, hereafter referred to as ‘tree cookies’. Tree cookies were used to measure annual tree ring widths (RWs) in order to estimate annual above-ground tree net productivity. Prior to measuring RWs, tree cookies were smoothed with sandpaper of progressively finer grit until all annual rings were clearly visible. Tree cookies were digitized using a flatbed scanner at 1200 dpi. RW were subsequently measured using the R package digitizeR (Poisot 2011). To account for non-uniform radial growth of the tree trunk, RW was measured in four quadrats of each tree cookie, and averaged on an annual basis.

**Statistical analyses**

All statistical analyses were conducted using R (R Core Team 2013) and results presented are means and standard deviation unless stated otherwise. DOB measurements were rank transformed due to being non-normally distributed based on the Shapiro–Wilk test (*shapiro.test* function—R). A one-way ANOVA (*aov* function—R), followed by a Tukey–HSD post-hoc test was used to determine significant differences in DOB and BD with treatment. A Spearman rank correlation test (*cor.test* function—R) was used to assess correlation between DOB and treatment level stand characteristics. A linear mixed effects model (*lmer* function—R) was used to evaluate treatment differences in annual RW.

**Results**

**Peat burn severity**

DOB was significantly different between treatments (*F* = 439.2, *p* < 0.001) (figure 1). DOB was 2.5 ± 3.5, 6.4 ± 5.0, and 16.0 ± 10.2 cm for UD, MD, and HD treatments, respectively. Measurements from the HD treatment (figure 1) exclude the burned-to-mineral portion (38%) of the HD treatment. Given that the estimated pre-fire peat depth in the HD treatment (see supplementary material) was 70.9 ± 16.4 cm (median = 70 cm), average DOB across the HD treatment was calculated to be 36.9 ± 29.6 cm.

Negligible DOB (≤0.5 cm) occurred in 46% and 14% of the UD and MD treatment plots, respectively, indicating ground cover was unburned or singed. In contrast, the HD treatment had no areas of negligible DOB recorded. Correspondingly, spatial surveys of ground cover showed that singed *Sphagnum* hummocks were present in both the UD and MD treatments but not in the HD treatment (supplementary...
Table 1. Estimated peat carbon (C) loss (mean ± SD) based on measured depth of burn, depth-dependent estimates of average peat bulk density, and estimated C-content for Sphagnum and sylvic peat in western boreal Canada from the Zoltai database (Zoltai et al 2000). Sphagnum and sylvic peat are used as rough analogues for undrained and drained peat bulk density, respectively.

| Treatment | Peat depth (cm) | Peat carbon loss ($\text{kg C m}^{-2}$) | Peat carbon loss (% of pre-fire peat carbon stock) |
|-----------|----------------|----------------------------------------|--------------------------------------------------|
|           | Pre-fire       | Sphagnum peat                          | Sphagnum peat                                    |
| UD        | 68.9 ± 11.3    | 0.63 ± 0.93                            | 0.92 ± 0.34                                      | 2.8 %  2.9 % |
| MD        | 83.5 ± 13.5    | 1.65 ± 1.42                            | 2.40 ± 2.01                                      | 5.7 %  6.1 % |
| HD        | 70.9 ± 16.4    | 4.71 ± 3.63                            | 6.74 ± 5.21                                      | 20.4 % 20.4 % |
| HD*       | 11.70          | 16.75                                  | 50.6 %                                           | 50.6 %  |

* Weighted average C-loss including 38% of HD site which burned to mineral soil.

![Figure 1.](image) Measured depth of burn (DOB) across the undrained (UD), moderately drained (MD), and heavily drained (HD) treatments. Median DOB and 95% confidence interval of the median is represented by the horizontal red line and notch, respectively. Outliers are presented as red dots. Letters indicate a significant difference in DOB between treatments, using a significance level of 0.05.

Material). Peat carbon loss from the three treatment areas was estimated to be greatest from the HD treatment, followed by MD, and UD (Table 1). When assessed as a percent of estimated pre-fire peat carbon stock, this loss equates to 2.8%, 5.7% and 20.4% (50.6% when burned-to-mineral included) in the UD, MD and HD treatments, respectively (Table 1).

**Pre-fire peatland stand characteristics**

The apparent increase in tree productivity post-drainage relative to the UD baseline, was much greater at the HD versus MD treatment, based on average annual measured RW (Figure 2). A linear mixed effects model was used to evaluate average annual RW, with drainage treatment and tree sample as fixed and random effects, respectively. Drainage treatment was shown to have a significant effect on average annual RW ($F = 87.86, p < 0.001$) where post-drainage UD, MD and HD RW were $0.22 ± 0.07$, $0.32 ± 0.07$ and $0.84 ± 0.17$ mm, respectively (Figure 2). Maximum average annual ring width was $1.22$ mm for the HD treatment, $0.45$ mm for the MD and $0.43$ mm for the UD treatment. Peak annual RW occurs after a three-year time lag since drainage in the MD treatment compared to nine years in the HD treatment (Figure 2). Differences in tree productivity result in treatment stands with significantly different basal diameters ($F = 106.9, p < 0.001$). Stem density was greatest in the MD treatment compared to the UD treatment and HD treatment. However, due to the proportionally larger basal diameters, basal area was greatest in the HD treatment, followed by the MD and UD treatments. Correspondingly, crown fuel load, total stand biomass and canopy closure follow the trend HD > MD > UD (Table 2).

An ANOVA showed that BD varied significantly with treatment ($F_{2,6} = 41.83, p < 0.001$) with a linear model showing a significant effect of local drainage density (ditch area ha$^{-1}$) on plot level BD ($F_{1,7} = 14.65, p = 0.006$). The corresponding average ditch spacing for MD and HD treatments are $16.5$ m and $9.5$ m on centre, respectively. Conversely, within treatment, a two-way ANOVA with treatment, distance to ditch, and their interaction as factors, shows that distance to ditch has no significant effect on the BD of individual trees ($F = 1.85, p = 0.158$). A correlation matrix containing treatment average DOB, stem density, basal area and drainage density shows that all pairwise combinations excluding stem density have a Spearman rank correlation equal to one. Pearson correlations are similarly high ($r > 0.86$), but with only three treatments, the correlations are generally not considered significant ($p > 0.05$). Finally, using all treatments together, there was a strong linear correlation between the average DOB measured at tree clusters ($n = 15$ per treatment—see methods), and the median basal diameter of the tree cluster (Figure 3).

**Discussion**

WTD—afforestation feedback and peat burn severity

Our results demonstrate that experimental drainage substantially increased above-ground tree productivity at the HD treatment compared to MD treatment (Figure 2) where HD average annual RW was approximately double that of MD and UD 20 years after drainage. We suggest that above-ground tree productivity at the MD and HD treatments was affected by post-drainage enhancement of the WTD-afforestation feedback (Waddington et al 2015). With higher above-ground biomass, not only is canopy fuel load higher, but there has likely been a decrease in Sphagnum moss
cover (Bisbee et al. 2001) and near-surface peat moisture content (Lukenbach et al. 2015) at MD and HD treatments, resulting in enhanced peat burn severity during the wildfire.

The enhanced afforestation increased canopy fuel loads at both the MD and HD treatments (approximately two and five times higher than the UD treatment, respectively; table 2), which increases the capability and likelihood of sustaining a high-intensity crown fire and the probability of widespread surface ignition and potential smouldering (Johnston et al. 2015). The burning of greater crown fuel loads provides more energy to supply the downward propagation of smouldering combustion (Thompson et al. 2015). While there are many complexities to the ignition and propagation of smouldering peat fire (Benscoter et al. 2011), it is worth noting that the total stand biomass estimate in both the MD and HD treatments is greater than measurements from an undisturbed BP peatland 108 years since fire (Johnston et al. 2015) despite maximum tree age being <64 years.

Differences in above-ground tree productivity corresponded with canopy development, resulting in canopy closure estimates of 20, 30, and 70% for the UD, MD and HD treatments, respectively. As canopy closure (and shading) increases, the competitive advantage of Sphagnum moss declines (Bisbee et al. 2001) and shade-tolerant feather moss becomes the dominant moss cover, usually after 60–80 years post-fire (Benscoter and Vitt 2008, Housman 2017). The importance of moss moisture content as an energy sink means that Sphagnum mosses can limit carbon losses from peat fires given their superior moisture retention traits (Shetler et al. 2008, Thompson et al. 2015). The poor water retention properties of feather moss exacerbate low surface moisture conditions and is likely responsible for the greater DOB associated with its ground cover (Thompson et al. 2015). Indeed, DOB was greatest where feather moss was likely the dominant moss cover, in the HD treatment (with highest canopy closure estimate) followed by the MD treatment, and DOB was smallest in the UD, which contained a much higher proportion of Sphagnum cover compared to the other treatments (supplementary material).

Stand density and leaf area index are the primary predictors of the bulk rates of transpiration from peatlands (Waddington et al. 2015) indicating that transpiration water losses increase with afforestation. However, Kettridge et al. (2013) suggest that changes in evapotranspiration are insensitive to afforestation until very high foliage densities (as observed at the HD treatment). Nevertheless, this positive feedback is
amplified further by the increased levels of interception (Price et al. 1997) with higher foliage density. Water intercepted by the canopy is lost directly via evaporation, reducing the net input of water to the peatland and decreasing surface moisture content, an important variable for smouldering potential (Thompson et al. 2015). The complex interactions of the WTD–afforestation feedback likely progressed the HD treatment to exceed a tipping point resulting in high peat burn severity.

Exceeding a tipping point to high peat burn severity

Our results suggest the exceedance of an ecohydrological tipping point to high peat burn severity in the HD treatment of the study site as the HD and MD treatments experienced significantly different peat burn severity (figure 1). While average DOB in the UD treatment (2.5 ± 3.5 cm) is comparable to the shallow peat burns common to BP peatlands (e.g. Hokanson et al. 2016), we attribute the increased DOB at the MD (6.4 ± 5.0 cm) and HD (36.9 ± 29.6 cm—includes area burned-to-mineral) treatments to drainage and enhanced afforestation, similar to other northern and temperate peatlands (Turetsky et al. 2011, Davies et al. 2013). By defining the tipping point as carbon loss in excess of the product of long-term carbon accumulation rate and average fire return interval we find that the HD treatment has surpassed the tipping point. Moreover, the HD treatment was the greatest resource draw on fire suppression efforts (Newman 2016), and we speculate that the high depth greatest resource draw on fire suppression efforts ping point. Moreover, the HD treatment was the find that the HD treatment has surpassed the tip-accumulation rate and average fire return interval we find that the HD treatment has surpassed the tipping point as previously defined has been surpassed.

Conversely, a loss of 6% and 3% of peat carbon at the MD and UD treatments, represents ∼80–120 and 30–50 years worth of average carbon accumulation, respectively. Given the current fire return interval and residual peat depths of 68.9 ± 11.3 cm and 83.5 ± 13.5 cm in the UD and MD treatments respectively, it appears that moderate drainage may not impact long-term carbon storage. We suggest that the original function is maintained in the UD and MD treatments primarily by the presence of Sphagnum moss, associated with singed ground cover and negligible DOB, because it is the keystone moss species that promotes fast recovery and the re-initiation of carbon accumulation (Shetler et al. 2008, Waddington et al. 2015). In contrast, there is no evidence of low burn severity Sphagnum in the HD treatment. Sphagnum moss promotes the redevelopment of peatland negative feedbacks such as the WTD–moss productivity feedback and WTD–moss surface resistance feedback (see Waddington et al. 2015). With natural post-fire recovery and establishment of Sphagnum, peatland ecohydrological conditions return to a state which promotes moss productivity and carbon accumulation (Waddington et al. 2015).

Implications for peatland and wildfire management

Average tree basal diameter and stand basal area may provide easily measurable indices of proximity to the ecohydrological tipping point surpassed in the HD

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| Treatment stand characteristic | UD    | MD    | HD    |
|--------------------------------|-------|-------|-------|
| Average basal diameter (cm)    | 2.6 ± 1.2 | 3.2 ± 2.0 | 7.9 ± 4.7 |
| Stem density (stems ha$^{-1}$) | 16 100 | 20 300 | 9000  |
| Basal area (m$^2$ ha$^{-1}$)   | 10.0  | 16.5  | 60.3  |
| Crown fuel load (kg ha$^{-1}$) | 6668  | 13 778 | 32 269 |
| Total stand biomass (kg ha$^{-1}$) | 12 025 | 31 554 | 110 903 |
| Canopy closure (%)             | 20    | 30    | 70    |
treatment. The tipping point identified in this study is bounded between the MD and the HD basal diameters of 3.2 ± 2.0 and 7.9 ± 4.7 cm, and basal area estimates of 16.5 and 60.3 m² ha⁻¹, respectively. Although there are many confounding variables that influence fire severity and energy input to the peat surface (Thompson et al. 2015), we suggest that the identification of this bounded tipping point is a useful and practical guide to identify peatlands that are vulnerable to high severity peat burns in moderate–extreme fire weather. This is especially valuable as fire management in the sub-humid region of Canada’s boreal is approaching a critical threshold of effectiveness, and enhancement of the fire regime due to climate change will only add stress to the system (Flannigan et al. 2009).

Climate change is predicted to increase the incidence and areal extent of high/extreme fire weather across central western Canada (Flannigan et al. 2005) with longer drought periods and fire weather index values, such as the Drought Code, likely to increase (Collins et al. 2013, Flannigan et al. 2016). The drying of northern peatlands leading to WT-drawdown will enhance the effects of the WTD–afforestation feedback, increase peat burn severity (Flannigan et al. 2013), and potentially increase the likelihood of peatlands exceeding ecohydrological tipping points to high severity peat burn. Although there is much research needed to quantify more specific effects of afforestation on peat burn severity, we suggest that the concept of ecohydrological tipping points to high severity peat burn should be incorporated into fire and land management techniques. By managing peatlands to remain below ecohydrological tipping points through fuel load management and potential Sphagnum moss propagation, fire management challenges and costs could be reduced and the carbon stock of boreal peatlands further sustained.

Acknowledgments

We thank C McCann for assistance with field research and laboratory analysis. We also thank Dr D Thompson for provision of fire weather index data. Funding was provided by a NSERC Discovery Grant (289514) to JMW. We would also like to thank and acknowledge suggestions made by three anonymous reviewers on an earlier version of the manuscript.

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