

LETTER • **OPEN ACCESS**

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

To cite this article: S L Wilkinson *et al* 2018 *Environ. Res. Lett.* **13** 014018

View the [article online](#) for updates and enhancements.

## Environmental Research Letters



## LETTER

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

## OPEN ACCESS

## RECEIVED

5 October 2017

## REVISED

11 December 2017

## ACCEPTED FOR PUBLICATION

13 December 2017

## PUBLISHED

17 January 2018

Original content from this work may be used under the terms of the [Creative Commons Attribution 3.0 licence](#).

Any further distribution of this work must maintain attribution to the author(s) and the title of the work, journal citation and DOI.

S L Wilkinson<sup>1,4</sup> , P A Moore<sup>1</sup>, M D Flannigan<sup>2</sup> , B M Wotton<sup>3</sup> and J M Waddington<sup>1</sup> <sup>1</sup> School of Geography and Earth Sciences, McMaster University, 1280 Main Street West, Hamilton, ON, L8S 4K1, Canada<sup>2</sup> Faculty of Agricultural, Life and Environmental Sciences, University of Alberta, 116 St. and 85 Ave., Edmonton, AB, T6G 2R3, Canada<sup>3</sup> Faculty of Forestry, University of Toronto, 33 Willcocks St. Toronto, ON, M5S 3B3, Canada<sup>4</sup> Author to whom any correspondence should be addressed.E-mail: [wilkisl@mcmaster.ca](mailto:wilkisl@mcmaster.ca)**Keywords:** peatland, afforestation, wildfire, tipping point, land management, *Sphagnum*, burn severitySupplementary 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 ( $\pm$ SD) basal diameter was  $2.6 \pm 1.2$  cm,  $3.2 \pm 2.0$  cm and  $7.9 \pm 4.7$  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 ( $\pm$ SD)  $2.5 \pm 3.5$  cm,  $6.4 \pm 5.0$  cm and  $36.9 \pm 29.6$  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<sup>-2</sup> (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<sup>-2</sup> (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 wildfire 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 (Lieffers 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 m<sup>2</sup> 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 m<sup>2</sup> 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 m<sup>2</sup> 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](https://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

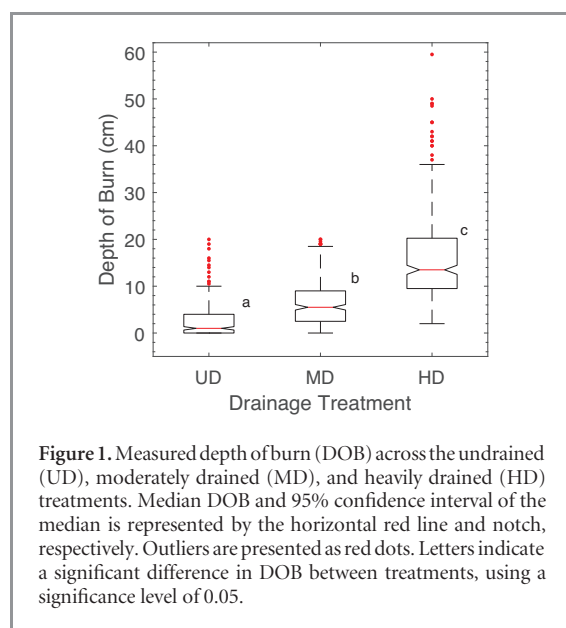
DOB was significantly different between treatments ( $F = 439.2$ ,  $p < 0.001$ ) (figure 1). DOB was  $2.5 \pm 3.5$ ,  $6.4 \pm 5.0$ , and  $16.0 \pm 10.2$  cm for UD, MD, and HD treatments, respectively. Measurements from the HD treatment (figure 1) exclude the burned-to-mineral portion (38%) of the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

Negligible DOB ( $\leq 0.5$  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  $\pm$  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		Peat carbon loss		
	(cm)	(kg C m <sup>-2</sup> )	(% of pre-fire peat carbon stock)		
	Pre-fire	<i>Sphagnum</i> peat	Sylvic peat	<i>Sphagnum</i> peat	Sylvic peat
UD	68.9 $\pm$ 11.3	0.63 $\pm$ 0.93	0.92 $\pm$ 0.34	2.8 %	2.9 %
MD	83.5 $\pm$ 13.5	1.65 $\pm$ 1.42	2.40 $\pm$ 2.01	5.7 %	6.1%
HD	70.9 $\pm$ 16.4	4.71 $\pm$ 3.63	6.74 $\pm$ 5.21	20.4 %	20.4%
HD <sup>a</sup>		11.70	16.75	50.6 %	50.6%

<sup>a</sup> Weighted average C-loss including 38% of HD site which burned to mineral soil.



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  $0.22 \pm 0.07$ ,  $0.32 \pm 0.07$  and  $0.84 \pm 0.17$  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

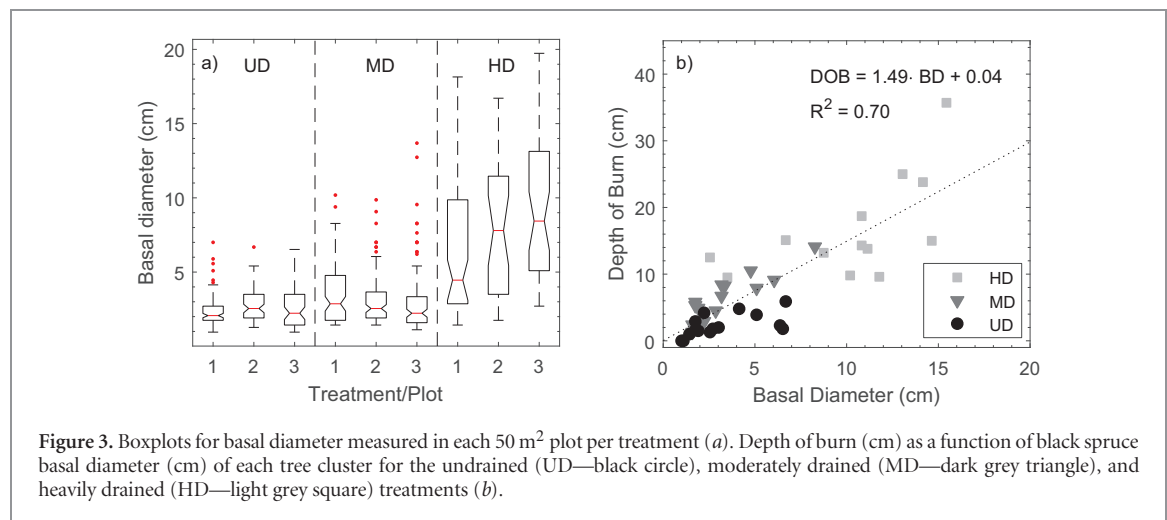
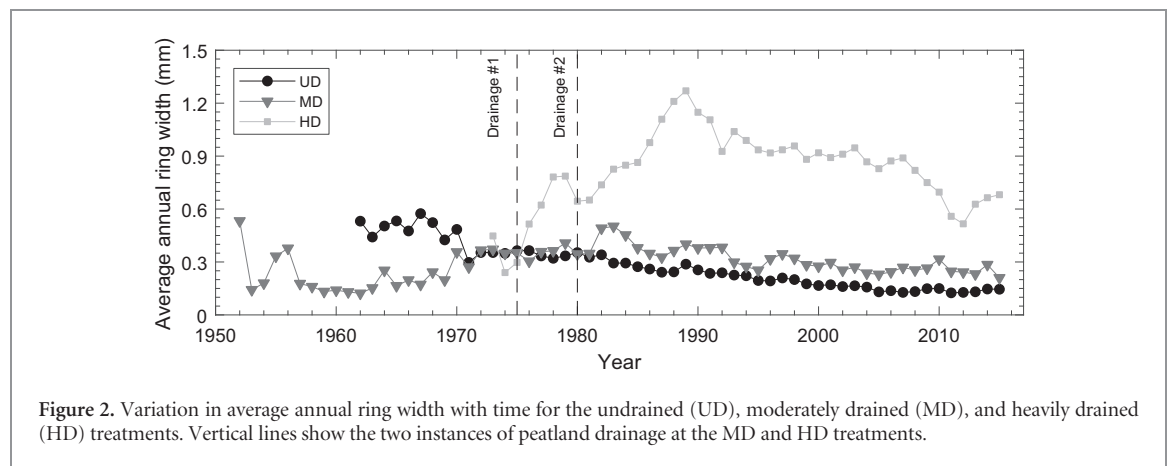
treatment stands with significantly different basal diameters ( $F = 106.9$ ,  $p < 0.001$ ). Stem density was greatest in the MD treatment compared to the UD treatment and HD treatment. However, due to the proportionally larger basal diameters, basal area was greatest in the HD treatment, followed by 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<sup>-1</sup>) 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 ( $F_2 = 1.85$ ,  $p = 0.158$ ). 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

**Table 2.** Treatment level black spruce stand characteristics. Crown fuel load and total stand biomass calculated using empirical equations from Bond-Lamberty *et al* (2002) and Johnston *et al* (2015). Values include  $\pm$  one standard deviation.

Treatment stand characteristic	UD	MD	HD
Average basal diameter (cm)	$2.6 \pm 1.2$	$3.2 \pm 2.0$	$7.9 \pm 4.7$
Stem density (stems ha <sup>-1</sup> )	16 100	20 300	9000
Basal area (m <sup>2</sup> ha <sup>-1</sup> )	10.0	16.5	60.3
Crown fuel load (kg ha <sup>-1</sup> )	6668	13 778	32 269
Total stand biomass (kg ha <sup>-1</sup> )	12 025	31 554	110 903
Canopy closure (%)	20	30	70

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 ( $2.5 \pm 3.5$  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 ( $6.4 \pm 5.0$  cm) and HD ( $36.9 \pm 29.6$  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 of burn and partial exposure of mineral soil may increase the recruitment of vascular vegetation, potentially leading to a regime shift. In the case of a shift to shrub/grassland, the new vegetation community is likely to be sustained by higher frequency, low intensity fires, resulting in the degradation of residual carbon stocks (Kettridge *et al* 2015).

Our estimated peat carbon loss of  $\sim 5\text{--}7$  kg C m<sup>-2</sup> in the HD treatment (excluding the area burned-to-mineral) is double that of a typical peat fire in this region ( $2\text{--}3$  kg C m<sup>-2</sup>) (e.g. Hokanson *et al* 2016). However, when the burned-to-mineral portion of the HD treatment is included, peat carbon loss ( $\sim 12\text{--}17$  kg C m<sup>-2</sup>) is an order of magnitude greater than UD, and also exceeds carbon losses of other drained BP peatlands (Turetsky *et al* 2011, Kettridge *et al* 2015). We suggest that this is due to the relatively high drainage density in the HD treatment and the strengthening of the

WTD–afforestation feedback, allowing for prolonged drying-enhanced tree growth (figure 2) (Waddington *et al* 2015). Moreover, this is supported by a strong linear correlation between basal diameter and DOB (figure 3). Of greatest concern is the percent of peat carbon lost due to smouldering combustion; this equates to 20% in the HD treatment (51% including burned-to-mineral area) but only 6% in the MD treatment, and 3% in the UD treatment. With an average carbon accumulation rate of continental western Canadian peatlands over the last 1000 years of  $0.0194$  kg C m<sup>-2</sup> yr<sup>-1</sup> (Vitt *et al* 2000), the extensive carbon loss from the HD treatment equates to  $\sim 240\text{--}350$  years of carbon accumulation ( $\sim 600\text{--}860$  years when the area burned-to-mineral is included). It is unlikely that enough carbon will be accumulated within a typical fire return interval (100–120 years) to retain a carbon sink status (Turetsky *et al* 2002), hence we argue 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  $\sim 80\text{--}120$  and  $30\text{--}50$  years worth of average carbon accumulation, respectively. Given the current fire return interval and residual peat depths of  $68.9 \pm 11.3$  cm and  $83.5 \pm 13.5$  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

treatment. The tipping point identified in this study is bounded between the MD and the HD basal diameters of  $3.2 \pm 2.0$  and  $7.9 \pm 4.7$  cm, and basal area estimates of 16.5 and 60.3 m<sup>2</sup> ha<sup>-1</sup>, 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.

## ORCID iDs

S L Wilkinson  <https://orcid.org/0000-0002-4043-6277>

M D Flannigan  <https://orcid.org/0000-0002-9970-5363>

J M Waddington  <https://orcid.org/0000-0002-0317-7894>

## References

- Alberta Agriculture and Forestry 2017 Wildfire Status Map—Fort McMurray Area (Accessed: 8 February 2017) (<http://wildfire.alberta.ca/wildfire-status/status-map.aspx>)
- Benscoter B W and Vitt D H 2008 Spatial patterns and temporal trajectories of the bog ground layer along a post-fire chronosequence *Ecosystems* **11** 1054–64
- Benscoter B W, Thompson D K, Waddington J M, Flannigan M D, Wotton B M, De Groot W J and Turetsky M R 2011 Interactive effects of vegetation, soil moisture and bulk density on depth of burning of thick organic soils *Int. J. Wildland Fire* **20** 418–29
- Bisbee K E, Gower S T, Norman J M and Nordheim E V 2001 Environmental controls on ground cover species composition and productivity in a boreal black spruce forest *Oecologia* **129** 261–70
- Bond-Lamberty B, Wang C and Gower S T 2002 Aboveground and belowground biomass and sapwood area allometric equations for six boreal tree species of northern Manitoba *Can. J. Forest Res.* **32** 1441–50
- Collins M *et al* 2013 Long-term climate change: projections, commitments and irreversibility *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* ed T F Stocker, D Qin, G-K Plattner, M Tignor, S K Allen, J Boschung and P M Midgley (Cambridge: Cambridge University Press)
- Davies G M, Gray A, Rein G and Legg C J 2013 Peat consumption and carbon loss due to smouldering wildfire in a temperate peatland *Forest Ecol. Manage.* **308** 169–77
- Flannigan M D, Cantin A S, De Groot W J, Wotton M, Newbery A and Gowman L M 2013 Global wildland fire season severity in the 21st century *Forest Ecol. Manage.* **294** 54–61
- Flannigan M D, Logan K A, Amiro B D, Skinner W R and Stocks B J 2005 Future area burned in Canada *Clim. Change* **72** 1–16
- Flannigan M D, Stocks B, Turetsky M and Wotton M 2009 Impacts of climate change on fire activity and fire management in the circumboreal forest *Glob. Change Biol.* **15** 549–60
- Flannigan M D, Wotton B M, Marshall G A, de Groot W J, Johnston J, Jurko N and Cantin A S 2016 Fuel moisture sensitivity to temperature and precipitation: climate change implications *Clim. Change* **134** 59–71
- Gorham E 1991 Northern peatlands: role in the carbon cycle and probable responses to climatic warming *Ecol. Appl.* **1** 182–95
- Granath G, Moore P A, Lukenbach M C and Waddington J M 2016 Mitigating wildfire carbon loss in managed northern peatlands through restoration *Sci. Rep.* **6** 28498
- Hilbert D W, Roulet N and Moore T 2000 Modelling and analysis of peatlands as dynamical systems *J. Ecol.* **88** 230–42
- Hillman G R 1987 Improving wetlands for Forestry in Canada *Informative Report NOR-X-288* (Northern Forestry Centre, Edmonton, Alberta: Canadian Forestry Service)
- Hokanson K J, Lukenbach M C, Devito K J, Kettridge N, Petrone R M and Waddington J M 2016 Groundwater connectivity controls peat burn severity in the boreal plains *Ecohydrology* **9** 574–84
- Housman K 2017 Post-fire chronosequence analysis of peatland bog vegetation communities across hydrogeological settings *MSc Thesis* McMaster University, Hamilton, ON
- Johnston D C, Turetsky M R, Benscoter B W and Wotton B M 2015 Fuel load, structure, and potential fire behaviour in black spruce bogs *Can. J. Forest Res.* **45** 888–99
- Kasischke E S, Turetsky M R, Ottmar R D, French N H F, Hoy E E and Kane E S 2008 Evaluation of the composite burn index for assessing fire severity in Alaskan black spruce forests *Int. J. Wildland Fire* **17** 515–26
- Kettridge N, Thompson D K, Bombonato L, Turetsky M R, Benscoter B W and Waddington J M 2013 The ecohydrology of forested peatlands: simulating the effects of tree shading on moss evaporation and species composition *J. Geophys. Res. Biogeosci.* **118** 422–35

- Kettridge N, Turetsky M R, Sherwood J H, Thompson D K, Miller C A, Benscoter B W, Flannigan M D, Wotton B M and Waddington J M 2015 Moderate drop in water table increases peatland vulnerability to post-fire regime shift *Sci. Rep.* **5** 1–4
- Lieffers V J and Rothwell R L 1986 Effects of depth of water table and substrate temperature on root and top growth of *Picea mariana* and *Larix laricina* seedlings *Can. J. Forest Res.* **16** 1201–6
- Lukenbach M C, Hokanson K J, Moore P A, Devito K J, Kettridge N, Thompson D K, Wotton B M, Petrone R M and Waddington J M 2015 Hydrological controls on deep burning in a northern forested peatland *Hydrol. Process.* **29** 4114–24
- Newman M 2016 Fire Manager personal communication
- Poisot T 2011 The digitize package: extracting numerical data from scatterplots *R Journal* **3** 25–6
- Price A G, Dunham K, Carleton T and Band L 1997 Variability of water fluxes through the black spruce (*Picea mariana*) canopy and feather moss (*Pleurozium schreberi*) carpet in the boreal forest of northern Manitoba *J. Hydrol.* **196** 310–23
- R Core Team 2013 *R: A Language and Environment for Statistical Computing* (Vienna: R Foundation for Statistical Computing) ([www.R-project.org/](http://www.R-project.org/))
- Scheffer M 2009 *Critical Transitions in Nature and Society* (Oxford: Princeton University Press)
- Shaposhnikov D *et al* 2014 Mortality related to air pollution with the Moscow heat wave and wildfire of 2010 *Epidemiology* **25** 359–64
- Shetler G, Turetsky M R, Kane E and Kasischke E 2008 Sphagnum mosses limit total carbon consumption during fire in Alaskan black spruce forests *Can. J. Forest Res.* **38** 2328–36
- Thompson D K, Wotton B M and Waddington J M 2015 Estimating the heat transfer to an organic soil surface during crown fire *Int. J. Wildland Fire* **24** 120–9
- Turetsky M R, Donahue W F and Benscoter B W 2011 Experimental drying intensifies burning and carbon losses in a northern peatland *Nat. Commun.* **2** 514–9
- Turetsky M, Wieder K, Halsey L and Vitt D 2002 Current disturbance and the diminishing peatland carbon sink *Geophys. Res. Lett.* **29** 1526–9
- Van Wagner C E 1987 Development and Structure of the Canadian Forest Fire Weather Index System *Forestry Technical Report* 35 (Ottawa: Canadian Forestry Service)
- Vitt D H, Halsey L A, Bauer I E and Campbell C 2000 Spatial and temporal trends in carbon storage of peatlands of continental western Canada through the Holocene *Can. J. Earth Sci.* **37** 683–93
- Waddington J M, Morris P J, Kettridge N, Granath G, Thompson D K and Moore P A 2015 Hydrological feedbacks in northern peatlands *Ecohydrology* **8** 113–27
- Wieder R K, Scott K D, Kamminga K, Vile M A, Vitt D H, Bone T, Xu B I N, Benscoter B W and Bhatti J S 2009 Postfire carbon balance in boreal bogs of Alberta, Canada *Glob. Change Biol.* **15** 63–81
- Zoltai S C, Siltanen R M and Johnson J D 2000 A wetland data base for the western, subarctic, and arctic regions of Canada *Information Report NOR-X-368* (Edmonton, Alberta: Natural Resources Canada, Canadian Forest Service) p 28