



Assessing Drivers of Cross-Scale Variability in Peat Smoldering Combustion Vulnerability in Forested Boreal Peatlands

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Wildfire represents the largest areal disturbance of forested boreal peatlands and the spatial variability in the severity of these peat fires is both a leading source of uncertainty in boreal wildfire carbon emissions and a major challenge for regional wildfire management. Peat smoldering can emit large quantities of carbon and smoke to the atmosphere, and therefore can contribute to hazardous air quality. The wildland-industry interface and wildland-urban interface are both extensive across the sub-humid boreal plains (BP) ecozone where one-third of the area is covered by peatlands. As such, there is a growing research need to identify drivers of variability in smoldering combustion. This study uses hydrophysical peat properties to assess the drivers of cross-scale variability in peat smoldering combustion vulnerability in forested peatlands across the BP. Using a space-for-time chronosequence across the 120 year fire return interval and three main hydrogeological settings, and by incorporating hummock, hollow and margin locations, cross-scale variability is studied. We find that, based on peat properties such as specific yield (Sy) and gravimetric water content, forested peatland margins represent areas of high peat smoldering vulnerability, and that this is exacerbated with an increasing time-since-fire (stand-age). Although increasing Sy with time-since-fire in peatland middles may buffer water table drawdown, when accounting for increases in canopy fuel load, transpiration, and feather moss dominance forested peatland middles also become more vulnerable to smoldering combustion with time-since-fire. Moreover, the interaction of peatland margins with coarse- and heterogeneous-grained hydrogeological settings leads to lower Sy and higher density margin peat than in fine-grained settings, further increasing smoldering vulnerability. We estimate that forested peatland margins are vulnerable to combustion throughout their entire profile i.e., burn-out, under moderate-high water deficits in the BP. Furthermore, we identify peatland margin: total area ratio as a driver of smoldering vulnerability where small peatlands that are periodically disconnected from regional groundwater systems are the most vulnerable to high total peat carbon loss. We suggest that these drivers of cross-scale variability should be incorporated into peatland and wildfire management strategies, especially in areas near the wildland-industry and wildland-urban interface.

Keywords: peat properties, carbon, organic soil, moisture retention, specific yield, wildfire

INTRODUCTION

Peatland ecosystems store approximately one-third of the world's organic soil carbon (C) pool (Gorham, 1991) and they are most abundant in northern latitudes (above 45°N) where they store approximately 455–547 Pg C (Yu et al., 2010). Carbon is stored in organic soil (peat) when long term production exceeds losses, where losses are primarily through decomposition and combustion. Forested peatlands also accumulate substantial above-ground fuels, consisting mainly of black spruce in the Canadian boreal, making them highly susceptible to wildfire (Johnston et al., 2015; Thompson et al., 2017, 2019). In fact, wildfire represents the largest disturbance of forested boreal peatlands (Turetsky et al., 2002) and the spatial variability in the severity of these peat fires [i.e., depth of burn (DOB)] is both a leading source of uncertainty in boreal wildfire carbon emissions (de Groot et al., 2009) and a major challenge for regional wildfire management (Flannigan et al., 2013, 2016). For example, during wildfire disturbance, the ignition of surface moss/peat can lead to minimal DOB (Shetler et al., 2008), can undergo smoldering combustion to depths up to 1 m (Lukenbach et al., 2015a; Walker et al., 2019), or can consume the entire peat profile exposing the underlying mineral soil (Wilkinson et al., 2018). As such, the variability in peat carbon loss from forested boreal peatlands has been shown to span two orders of magnitude, from <1 to 85 kg C m⁻² (Turetsky et al., 2011; Lukenbach et al., 2015a; Hokanson et al., 2016). Given that this smoldering combustion variability also impacts the severity of smoke and particulate matter emission associated with hazardous air quality (Shaposhnikov et al., 2014) there is a growing research need to assess the drivers of this spatial variability. By characterizing peat hydrophysical properties, two important factors that influence peat smoldering vulnerability are evaluated; (1) the response of the water table to a water deficit i.e., specific yield (Sy), and (2) the ability of peat to retain water under a change in water table depth i.e., moisture retention. Using these vulnerability metrics we address the research need by assessing cross-scale variability in peat smoldering combustion vulnerability in forested peatlands across the Boreal Plains (BP) ecozone of northern Alberta (Table 1).

Peat typically burns via smoldering combustion rather than flaming combustion (Frandsen, 1987; Rein et al., 2008). The propagation of smoldering and the ability to be sustained in oxygen-depleted conditions causes considerable challenges for wildfire managers as smoldering can persist for several months to years (Rein et al., 2008). The hydrophysical properties of peat are fundamental to the thermodynamic reaction of smoldering combustion (Frandsen, 1987, 1997) and are controlling factors on DOB (Miyaniishi and Johnson, 2002; Benschoter et al., 2011). The propagation of smoldering combustion is controlled by the ratio of energy sink to fuel source, where for peat this can be approximated by the ratio of volumetric water content to peat bulk density [i.e., gravimetric water content (GWC) g g⁻¹] (Benschoter et al., 2011). However, bulk density is not often linearly related to GWC because bulk density has been shown to be positively correlated to water retention on a volumetric basis (Sherwood et al., 2013; Moore et al., 2014). Because of

TABLE 1 | Summary of acronyms used throughout the manuscript.

Terminology	Acronym
Boreal Plains	BP
Carbon	C
Depth of burn	DOB
Gravimetric water content	GWC
Hydrogeological setting	HS
Specific yield	Sy
Time since fire	TSF
Volumetric water content	VWC
Water table depth	WTD

the complex interactions between increasing moisture retention and increasing fuel density, threshold values of combustion-critical GWC have been shown to increase with bulk density (e.g., Frandsen, 1997; Rein et al., 2008). Hence, high density peat can smolder at a GWC of up to 2.95 g g⁻¹ (Benschoter et al., 2011) whereas low density peat has a lower combustion-critical GWC (~1.5 g g⁻¹) (Frandsen, 1997; Benschoter et al., 2011).

Specific yield is defined as the amount of water required to raise or lower the water table by one unit length (Freeze and Cherry, 1979). Peat with a lower Sy has a more “flashy” water table, where a water deficit causes a larger increase in water table depth below the ground surface (WTD) and a lower soil-water pressure compared to peat with high Sy (Price, 1996; Lukenbach et al., 2015a). For a given soil-water pressure peat with poorer moisture retention and/or higher bulk density will have a lower GWC and consequently be more vulnerable to smoldering combustion. Therefore, estimations of soil-water pressure are useful to better assess peat smoldering variability across the landscape. WTD is commonly used to approximate soil-water pressure in the unsaturated zone by assuming hydrostatic equilibrium (e.g., Thompson and Waddington, 2013). Although equilibrium conditions are a simplification of real-world processes, linear equations have been shown to accurately predict soil-water pressure using WTD (Lindholm and Markkula, 1984), where the slope and intercept of these relationships differ with bulk density (and/or microform and species) (Lukenbach et al., 2015a).

The variation in peat hydrophysical properties, in particular bulk density, between hummock and hollow microforms that make up the interior of peatlands (middles) has been well-evidenced (Branham and Strack, 2014). However, peatland margins have only recently been objectively identified as both a common and distinct feature of forested boreal peatlands (Mayner et al., 2018). In the Boreal Plains (BP) ecozone, peat at the edge of peatlands (margins) has been shown to have higher bulk density compared to peatland middles (Ingram et al., 2019) and margins tend to experience greater DOB (Lukenbach et al., 2015a; Hokanson et al., 2016). These margins tend to be dominated by a black spruce—deciduous swamp species mix, and leaf litter and feather moss (e.g., *Pluerozium schreberi*) at the ground surface (Dimitrov et al., 2014; Housman, 2017). The mix of vegetation inputs into the peat profile and higher bulk

density, suggest that margin peat will have lower S_y compared to hummock and hollow peat, since bulk density correlates to the approximated pore-size distribution (Boelter, 1968).

Forested boreal peatlands become more susceptible to high-intensity crown fire as fuel load increases with time-since-fire (TSF) (Johnston et al., 2015). Thompson et al. (2015) examined the variability of modeled crown fire heat transfer to the peat surface and determined that peatland surface ignition varied by soil water deficit and peat hydrophysical properties, however, the interaction of TSF and peat hydrophysical properties has not previously been assessed. Peat properties in the near-surface may change due to the succession of moss species from *Sphagnum*—dominated to feather moss dominated (Benscoter and Vitt, 2008), as well as through peat and surface fuel accumulation (Wieder et al., 2009; Ingram et al., 2019). Forested peatlands in the BP have developed in a range of hydrogeological settings (HS) (e.g., glaciofluvial/coarse, heterogeneous fine-grained/moraine, glaciolacustrine/fine) resulting from the deposition of deep glacial sediment after deglaciation (Fenton et al., 2013). The interaction between peatland ecosystems and HS results in varying degrees of connectivity with regional-scale groundwater systems (Devito et al., 2005, 2012; Hokanson et al., 2018). For example, peatlands in glaciofluvial and heterogeneous fine-grained HS are often (ephemerally) perched i.e., experience (periodic) isolation from larger groundwater systems (Hokanson et al., 2016; James, 2017). In such circumstances margins can undergo large water table fluctuations and have been associated with extreme smoldering combustion “hotspots” (>1 m DOB) (Hokanson et al., 2016).

As discussed, there has been much research into the influence of individual factors on peat smoldering combustion (Frandsen, 1987, 1997; Rein et al., 2008; Benscoter et al., 2011; Lukenbach et al., 2015a; Hokanson et al., 2016). However, the spatial variability across the BP cannot be adequately explained without assessing these factors throughout the landscape and considering their interactions across scales. By characterizing key peat hydrophysical properties and evaluating chosen smoldering vulnerability metrics we assess cross-scale variability in peat smoldering combustion in forest peatlands of the BP, with particular focus on the interaction between within-peatland location, TSF and HS. We hypothesize that peat smoldering vulnerability will be greatest; (1) in margins due to higher bulk density and lower S_y peat, (2) in near-surface peat under increasing TSF, and (3) in peatlands in glaciofluvial and heterogeneous HS that are subject to repeated water table drawdown.

METHODS

Study Sites and Research Design

The BP ecozone has a sub-humid climate whereby potential evapotranspiration generally exceeds precipitation, with long term mean values of ~520 and 480 mm, respectively (Devito et al., 2012). As such, peatlands exist at the edge of their climatic limit where the region often experiences long- and short-term water deficits resulting in annual water deficits of up to ~200 mm (Devito et al., 2012). Approximately one-third of the BP land area

TABLE 2 | Summary of forested black spruce peatlands in each space-for-time chronosequence category based on hydrogeological setting and time-since-fire, where time-since-fire categories are 0–20, 21–80, and 81–120 years.

Chronosequence category	Sites (n)
Coarse–0–20	2
Coarse–21–80	3
Coarse–81–120	1
Fine–0–20	3
Fine–21–80	3
Fine–81–120	3
Moraine–0–20	4
Moraine–21–80	3
Moraine–81–120	4

is covered by peatlands (Vitt et al., 2000), where the majority of peatlands are classified as treed or forested and black spruce (*Picea mariana* Mill. BSP) is a dominant stand species [(Alberta Biodiversity Monitoring Institute (ABMI), 2016)]. As such, BP peatlands are susceptible to stand-replacing wildfire, with a current average fire return interval of 120 years (Turetsky et al., 2004; Wieder et al., 2009) resulting in a mosaic of peatlands of differing stand-ages between 0 and 120+ years on the landscape.

Twenty-six black spruce forested peatlands were selected in a space-for-time chronosequence, spanning the current average fire return interval for BP peatlands (~120 years, Turetsky et al., 2004) (Table 2). TSF is separated in three categories based on the early-, mid- and late-successional stages identified by Benscoter and Vitt (2008). Peatlands in the Central Mixedwood Natural Subregion of north central Alberta, Canada, were mapped using Ducks Unlimited Wetland Inventories. The Canadian National Fire Database (Canadian Forest Service, 2011) and Alberta Surficial Geology map (Fenton et al., 2013) were used to shortlist peatlands across a range of fire years and HS. Aerial photographs (1940–2016) (Government of Alberta, 2016) were used to aid the assessment of peatland type (black spruce dominated; bog) and confirm disturbance by wildfire (see Mayner et al., 2018). Peatlands were finally selected for detailed study based on their level of accessibility. Selected peatlands were preliminarily visited in May–June 2016 to confirm HS classification by soil texturing (see Ingram et al., 2019). HS are grouped into glaciofluvial/coarse, heterogeneous fine-grained/moraine, and glaciolacustrine/fine. The selected peatlands (middle) were found to follow the general vegetation recovery trajectory outlined by Benscoter and Vitt (2008) and (Housman, 2017). The peatland margins were characterized by swamp-type vegetation with some black spruce, and a lack of hummock-hollow microtopography (Housman, 2017).

Peat Hydrophysical Properties

At each of the 26 peatlands, peat cores were taken from a representative hummock, hollow and margin location. The peatland margin ecotone (the transition from peatland proper to upland) was delineated in the field based on vegetation community and the core was taken from a central position. Cores

(0.1 m diameter PVC) were taken to 0.6 m depth in the middle of the peatland and to mineral soil in the margin ecotone where peat depths were usually <0.6 m (Mayner et al., 2018). Peat cores were then frozen and sub-sectioned into 0.05 m increments using a band saw. Peat samples were enclosed at one end using cheese cloth, thawed, and then slowly saturated from below with deaired water for 48 h to prevent entrapped gas. Moisture retention was measured by placing samples on a saturated Soil Moisture Equipment Corp (Goleta, CA) ceramic plate with an air-entry pressure of 1 bar. The wet surface of the ceramic plate and the cheese cloth form an uninterrupted connection between the sample and plate (Klute, 1986), to which a negative pressure was applied using a central vacuum. Pressure steps of -10 , -20 , -50 , and -200 hPa were used to measure water retention. Samples were kept at a pressure step for ~ 24 h or until mass was unchanging, and sample volume changes were accounted for in volumetric water content calculations.

Specific yield was estimated using the water yield from the first pressure step ($\psi = -10$ hPa) and was calculated for each 0.05 m peat core increment according to:

$$S_y = \theta_{sat} - \theta_{\psi=-10 \text{ hPa}} \quad (1)$$

where θ_{sat} is the volume of water at saturation and $\theta_{\psi=-10 \text{ hPa}}$ is the volume of water at the first pressure step. A value closer to zero represents a water table that is more sensitive to the addition or removal of water, and a value closer to one represents a more stable water table. Porosity of the peat samples was calculated using a particle density of 1.48 g cm^{-3} for *Sphagnum* peat (Redding and Devito, 2006), and saturated water content was calculated as equal to porosity, assuming no entrapped gas. Bulk density was calculated from sample dry weight after oven drying at 65°C for 48 h or until mass was unchanging.

Water Table Drawdown

The response of the water table in the middle of the peatland is regulated by the average response of hummock and hollow peat in the saturated zone, and the spatial proportion of such microforms. Hence, for water deficit analyses, hummock and hollow peat profiles were combined, accounting for an average hummock height of 30 cm and a 1:1 ratio of hummock: hollow microforms (*data not shown*). A linear regression of the natural log of mean S_y with depth was done for each peat profile, where “profile” refers to the specific within-peatland location and TSF category combination, to determine potential water table drawdown under water deficit. Water deficit values were constrained based on literature-derived values where water deficit can be up to ~ 200 mm in the study region (Devito et al., 2012).

Peat Smoldering Vulnerability Metrics

The ratio of volumetric water content (VWC) to peat bulk density [i.e., gravimetric water content (GWC) g g^{-1}], was used to describe the ratio of energy sink to fuel source and hence the smoldering combustion vulnerability of peat. GWC and VWC at a soil-water pressure of -200 hPa, hereafter referred to as GWC_{-200} and VWC_{-200} , were chosen as common

metrics to compare between peat profiles. Soil-water pressures of < -100 hPa lead to the draining of the hollow hyaline cells in key peat-forming *Sphagnum* mosses (Hayward and Clymo, 1982) consequently, we used -200 hPa to represent peat under “dry” conditions (once hyaline cells had begun to drain). Moreover, we used the modeled WTD to calculate soil-water pressure in the near-surface using WTD- soil-water pressure relationships from Lindholm and Markkula (1984) for higher density peat. Linear relationships were found to adequately represent the changes in soil-water pressure at WTD between 0 and 0.8 m ($R^2 = 0.77$). Similarly, Lukenbach et al. (2015a) measured near-equilibrium soil-water pressure for undisturbed peat to WTD of 0.7 m. At greater WTD non-linear behavior was observed, suggesting that our estimates of soil-water pressure are conservative. We calculated the necessary WTD required to reach the combustion-critical GWC associated with vulnerability to smoldering combustion for each peat profile (Benscoter et al., 2011). Combining the water table drawdown values, the WTD required to reach combustion-critical GWC, and the average margin depths across the BP (Mayner et al., 2018), we estimate water deficit amounts that correspond to peat smoldering combustion vulnerability in the near-surface, and entire average margin peat profiles across all HS.

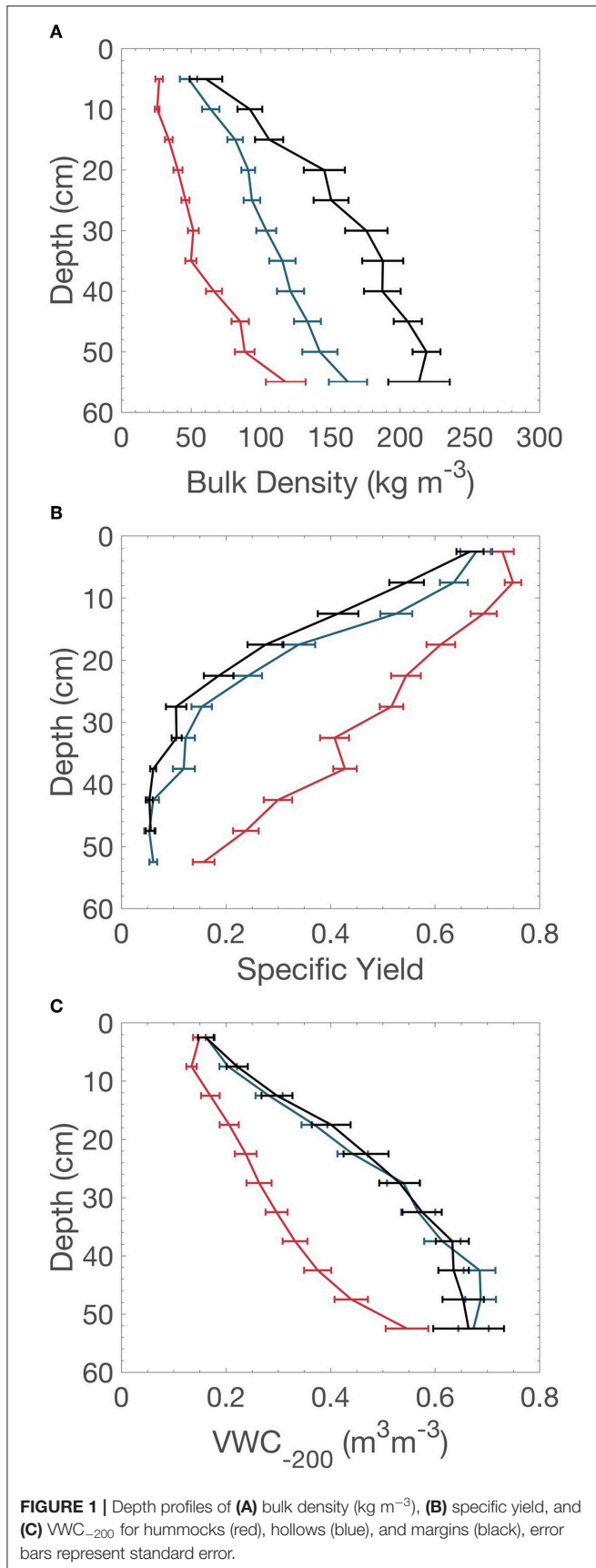
Statistical Analyses

Non-parametric statistics are used as the data don’t tend to follow a normal distribution. A series of un-paired non-parametric *t*-tests (Mann Whitney), and ANOVA (Kruskal Wallis) tests were performed in Matlab (2017) to test for significant differences in bulk density, S_y , VWC, and GWC for within-peatland location, time-since-fire category and their interaction. We used the same methodology to compare depth-integrated peat properties between location—HS combinations. *Post-hoc* tests were conducted using non-parametric Tukey’s HSD (Steel-Dwass) tests where alpha was set at 0.05 unless otherwise stated. We report arithmetic means and standard deviations unless otherwise stated.

RESULTS

Peat Hydrophysical Property Variability Within Peatland Location

Mean bulk density, specific yield (S_y) and VWC_{-200} were significantly different for within-peatland locations where bulk density followed the trend hummock < hollow < margin, and S_y and VWC_{-200} followed the opposite trend (**Supplementary Material**). Bulk density, S_y and VWC_{-200} showed strong depth-dependency (**Figure 1**). S_y decreased with depth for all within-peatland locations where values were 0.73 ± 0.13 , 0.68 ± 0.18 , and 0.67 ± 0.16 at the surface (top 0.05 m) of hummocks, hollows and margins, respectively, and 0.24 ± 0.15 , 0.05 ± 0.06 , and 0.06 ± 0.05 at the deepest points measured (0.5–0.55 m) (**Figure 1B**). Conversely, bulk density and VWC_{-200} increased with depth for all locations (**Figures 1A,C**). Bulk density was a good predictor of S_y [$r^2 = 0.62, 0.45, 0.70$ for hummocks, hollows and margins, respectively (linear fit, *F* test *p*



< 0.01)], and also a good predictor of VWC_{-200} [$r^2 = 0.66, 0.49, 0.78$ for hummocks, hollows and margins, respectively (linear fit, F test $p < 0.01$)].

Hydrogeological Setting

For margins, depth-integrated bulk density was higher and S_y was significantly lower in heterogeneous hydrogeological setting (HS) compared to glaciofluvial and glaciolacustrine HS ($F = 2.92, p < 0.1$) (Figure 2). VWC_{-200} was significantly higher in margins in heterogeneous HS compared to glaciolacustrine ($F = 5.99, p < 0.1$) while VWC_{-200} for margins in glaciofluvial HS was not significantly different to any other HS (Supplementary Material).

Time-Since-Fire

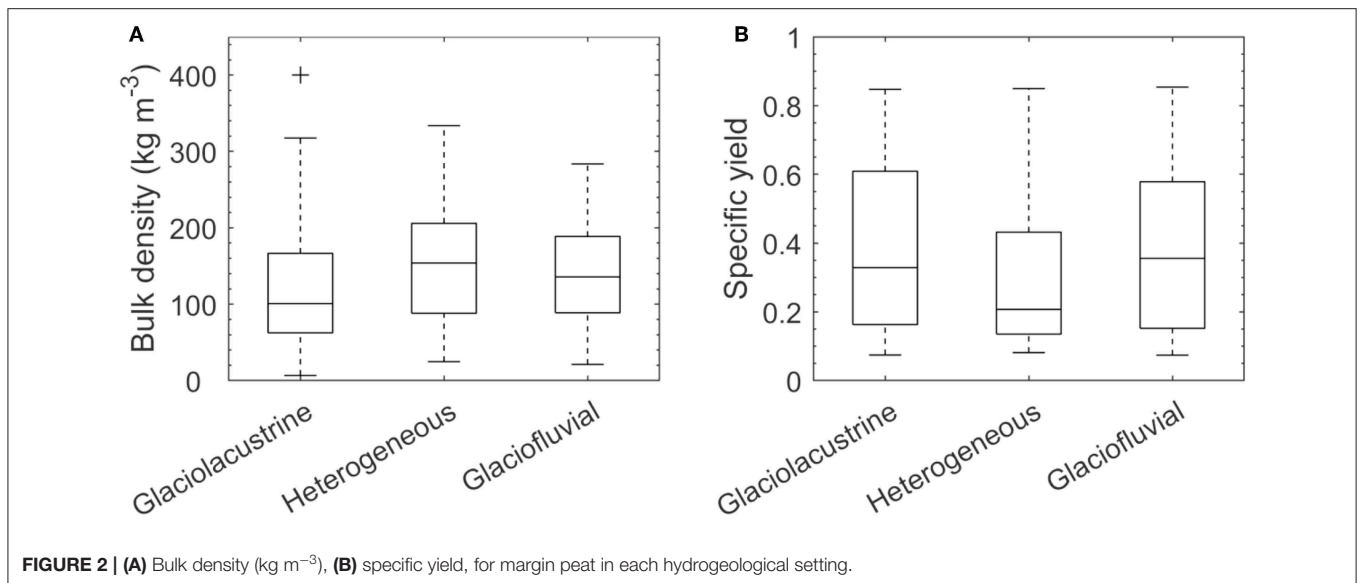
Analyses of depth profiles by TSF category found that S_y in hummocks tended to shift toward increasing values with TSF (Figure 3A), where there was a significant difference between near-surface (upper 0.25 m) S_y in the 0–20 and 81–120 year TSF categories (Table 3). Hollows and margins also shifted to higher values of S_y (Figures 3B,C), however, this change was mainly achieved in the first 80 years since fire, and the difference was confined to the upper 0.15 m of the peat profile (Table 3).

Sensitivity to Water Table Drawdown

Using S_y depth relationships for the TSF category peat profiles for middle (hummock and hollow combined) and margin (Supplementary Material), we calculated potential water table drawdown values as water deficit increases (Figure 4). Based on average measured peat properties, water table depth (WTD) in peatland middles is decreasingly responsive to water deficit with TSF (less change in WTD for a given water deficit) whereas margin WTD is most responsive in early- and late-successional phases, 0–20 and 81–120+ years since fire, respectively. In isolation from other water inputs, on average, margin peat would require >80 mm of water deficit to reach a WTD of 0.4 m at 21–80 years since fire, whereas <50 mm would be required at >80 years since fire (initial WTD of 0.05 m). Comparatively, middle peat would require >150 mm water deficit in all TSF categories (initial WTD of 0.1 m). Margin WTD is more sensitive to water deficit than middle WTD across all TSF categories and margins tend to show an increase in expected water table response at around 0.4 m WTD, whereas the middle only becomes more responsive at WTD >0.7 m (Figure 4).

Combined Effects on Peat Smoldering Combustion

When accounting for bulk density in moisture retention analysis, gravimetric water content (GWC; g g^{-1}) at a given soil-water pressure follows the trend hummocks > hollows > margins (Figure 5). Median GWC with decreasing soil-water pressure shows that margin GWC crosses the critical threshold of 2.95 g g^{-1} at $\sim 200 \text{ hPa}$ whereas hollow and hummock median GWC is ~ 5 and 6 g g^{-1} , respectively (Figure 5). The relationship between mean S_y and mean GWC_{-200} differed between within-peatland locations (Figure 6). In hummock profiles, GWC_{-200} stayed near constant with depth ($4.6\text{--}5.5 \text{ g g}^{-1}$) and mean S_y tended to be higher than in hollows and margins. In hollows, GWC_{-200} ranged from 6.0 to 3.5 g g^{-1} across the range of mean S_y , where



lower GWC₋₂₀₀ values corresponded with higher Sy in the near-surface. Although Sy values were similar for a given depth in margins and hollows, margins retain relatively less water on a gravimetric basis. Margin GWC₋₂₀₀ was lower than hummock and hollow GWC₋₂₀₀ regardless of mean Sy and values were close to the critical 2.95 g g⁻¹ threshold over the entire depth and range of mean Sy.

Soil-water pressure of -200 hPa corresponded to the critical GWC in margin peat. Using this benchmark, we estimated the average WTD for each peat profile where soil-water pressure would fall below -200 hPa. We found that a WTD in excess of the calibrated range (i.e., >2 m) would be required to reach critical GWC in middle peat profiles, whereas WTD of ~1.1 m was required in margins (**Supplementary Material**). Applying this to the estimated water table drawdown values, we approximate the water deficit required to lower GWC to critical values in the near-surface (lower water deficit) and entire margin peat profile (upper water deficit; **Figure 7**). This suggests that margins are vulnerable to smoldering combustion throughout their entire peat profile, hereafter referred to as “burn-out,” when water deficit exceeds ~130 mm and 100 mm in 21–80 and 81–120+ years since fire, respectively (**Figure 7**).

DISCUSSION

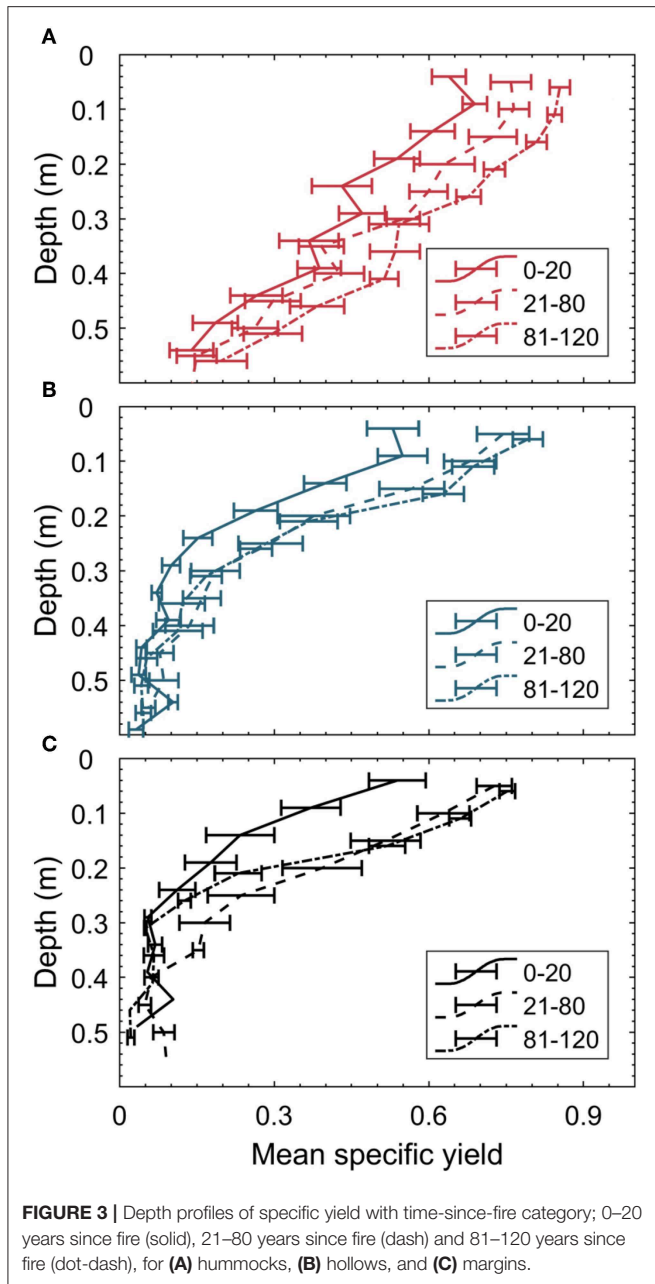
Variability in Peat Hydrophysical Properties

Peat hydrophysical properties were found to vary significantly depending on location within the peatland, depth below ground, time-since-fire (TSF) and hydrogeological setting (HS). Hummocks, hollows and margins showed distinct profiles of bulk density, specific yield (Sy) and moisture retention (**Figure 1**) likely due to their composition of different moss species (e.g., *Sphagnum fuscum* dominates hummocks, and *Sphagnum angustifolium* dominates hollows; Housman, 2017). Moss species has been shown to affect peat recalcitrance, whereby *S. fuscum*

is resistant to decomposition, often having lower bulk density than other species under similar environmental conditions (Turetsky et al., 2008). Moreover, using bulk density as a proxy for pore-size distribution (Boelter, 1968), it corresponds that hummocks have a greater Sy than hollows and margins. Although Sy and volumetric water content (VWC) are similar with depth in margins and hollows, margin bulk density generally exceeds hollows, which can be attributed to the different peat composition in the margins i.e., the input of deciduous leaf litter and a higher quantity of woody roots (Housman, 2017; Ingram et al., 2019).

TSF was found to have a significant effect on Sy in the uppermost 0.15–0.2 m of the peat profiles (**Figure 3; Table 3**). In black spruce dominated peatlands, hummocks are rarely inundated, and the water table resides at or below the surface of hollows for most of the growing season (Lukenbach et al., 2015b, 2017). Hence the change in Sy will have relatively less impact on the WTD response in the middle, compared to in the margins which frequently experience flooding (Lukenbach et al., 2017). Margin WTD response is far greater than middles [generally twice as responsive (**Figure 4**)], especially at low TSF, when the uppermost, least decomposed, peat is burned away exposing denser peat at the surface (Sherwood et al., 2013; Thompson et al., 2015; Ingram et al., 2019). Margin WTD becomes more responsive to water deficit between mid- and late-succession (21–80 and 81–120+ years) which supports our original hypothesis. Comparatively, middle WTD becomes slightly less responsive due to increasing Sy (**Figure 4**).

The trends found between within-peatland locations were consistent across HS, however, the differences between margins and middles are amplified in glaciofluvial and heterogeneous HS compared to fine HS due to greater bulk density and lower Sy (**Figure 2**). This supports our hypothesis that the large WTD fluctuations experienced in glaciofluvial and heterogeneous peatland margins (Hokanson et al., 2018) causes increased

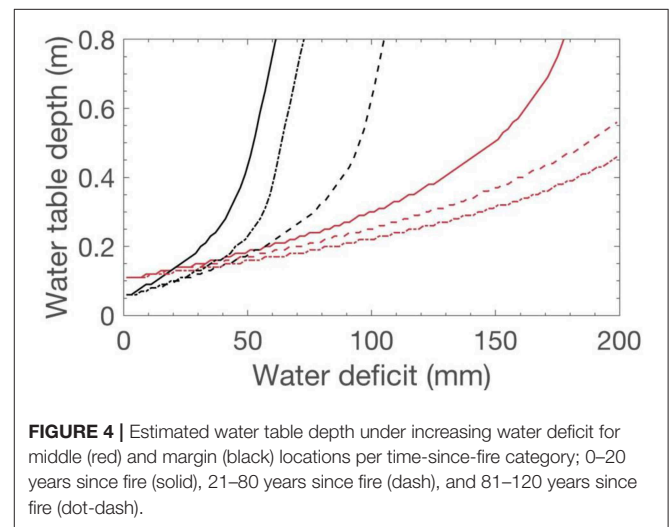


decomposition and lower Sy. In addition to the large-scale hydrological control of HS, the WTD-Sy feedback also impacts margin peat properties (Waddington et al., 2015); a positive feedback when initiated, whereby peat with low Sy more frequently experiences water table fluctuation leading to increased rates of decomposition and increasingly lower Sy. However, this positive feedback on decomposition is likely regulated by the build-up of decomposition by-products and decreasing sources of labile carbon (Moore and Basiliko, 2006). Moreover, high density margin peat may also act to buffer WTD response in the peatland middle by reducing lateral water loss (Lapen et al., 2005), as peat bulk density

TABLE 3 | Subset of significant differences of within-peatland location depth-increments by time-since-fire category (TSFcat); 0–20, 21–80, and 81–120 years.

Location	Depth mid-point (cm)	TSFcat 1	TSFcat 2	Specific yield p-Value	Specific yield significance
Hummock	2.5	0–20	81–120	0.025	**
Hummock	7.5	0–20	81–120	0.025	**
Hummock	12.5	0–20	81–120	0.030	**
Hummock	17.5	0–20	81–120	0.050	**
Hummock	22.5	0–20	81–120	0.023	**
Hollow	2.5	0–20	81–120	0.049	**
Hollow	2.5	0–20	21–80	0.039	**
Hollow	7.5	0–20	21–80	0.083	*
Hollow	12.5	0–20	81–120	0.050	**
Margin	2.5	0–20	81–120	0.074	*
Margin	2.5	0–20	21–80	0.038	**
Margin	7.5	0–20	81–120	0.017	**
Margin	7.5	0–20	21–80	0.021	**
Margin	12.5	0–20	21–80	0.039	**

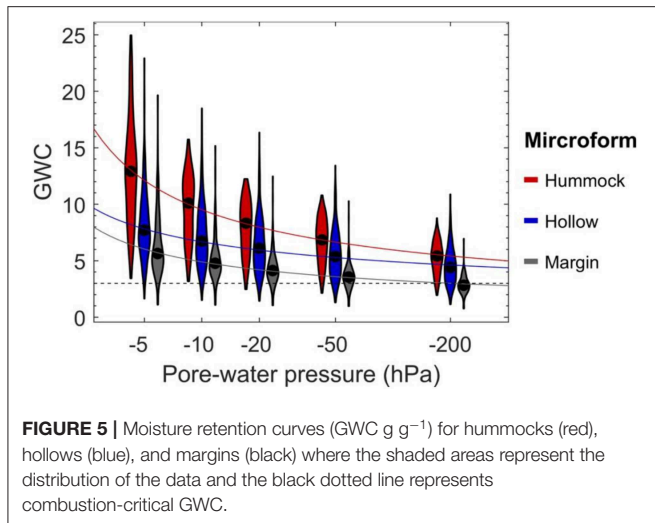
*, **, *** corresponds to $p < 0.1$, $p < 0.05$, $p < 0.01$, respectively.



is negatively correlated with saturated hydraulic conductivity (Branham and Strack, 2014). Negative feedbacks such as this will be critical to the resilience of peatlands to wildfire disturbance given the increasing intensity and severity of the boreal wildfire regime expected due to climate change (Wang et al., 2014; Wotton et al., 2017).

Implications for Peat Smoldering Vulnerability

Margins and hollows have lower Sy than hummocks, such that WTD will be more responsive to water deficit, and more peat will be exposed to drying. However, WTD in peatland middles is buffered by the response of combined hummock and hollow peat due to small hydraulic gradients



between microforms (Malhotra et al., 2016), leading to less severe water table drawdown (Figure 4). Under decreasing soil-water pressure (i.e., increasing WTD) GWC is lowest in margins, and therefore smoldering combustion vulnerability is highest, followed by hollows and hummocks (Figure 5). Median GWC falls below the combustion-critical GWC ($2.95\ g\ g^{-1}$) at much higher (less negative) soil-water pressure in margins than in hummocks or hollows (corresponding to shallower WTD). Although mean S_y with depth is similar between margin and hollow peat (Figure 1B), the greater bulk density of margins (Figure 1A), and the buffering of middle WTD (Figure 4) result in margins being vulnerable to smoldering combustion throughout their entire profile at soil-water pressures $\sim -200\ hPa$ (Figure 6). Comparatively, hollows have their lowest GWC values in the surface peat (upper 0.1 m) where S_y is highest (Figure 6). This supports the observed heterogeneity of actual depth of burn (DOB) measurements in the BP. Where margin DOB was approximately four times greater than middles (mean margin DOB = 0.25 m and mean middle DOB = 0.06 m; Lukenbach et al., 2015a) and middle DOB was dominated by hollows because hummock DOB is generally minimal (Benscoter and Wieder, 2003; Hokanson et al., 2016).

Applying Ecosystem—Landscape Scale Context

The abundance and species of both above-ground and surface vegetation also have an effect on vulnerability to wildfire (Johnston et al., 2015) and peat smoldering (Benscoter et al., 2015; Thompson et al., 2015, 2019). The potential for the propagation of surface and crown fire with TSF (analogous to stand-age) has been documented for BP black spruce forested peatlands (Johnston et al., 2015). Low intensity surface fire can be supported after just 10 years following wildfire, whereas the canopy fuel load necessary for high-intensity crown fire requires a stand-age of ~ 80 years (Johnston et al., 2015). For margins

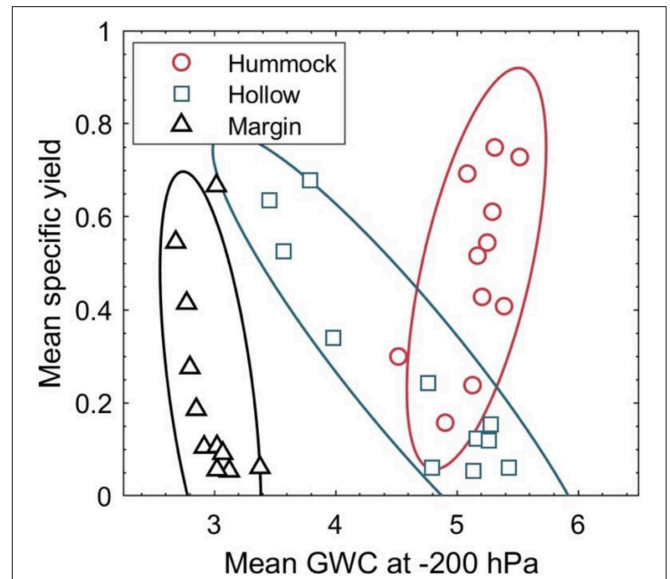


FIGURE 6 | Mean specific yield for each depth interval and mean GWC_{-200} for hummocks (red), hollows (blue), and margins (black) where the cluster denotes 90% confidence interval.

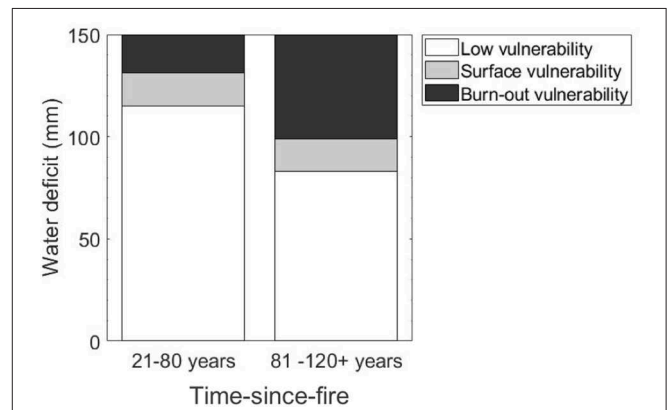
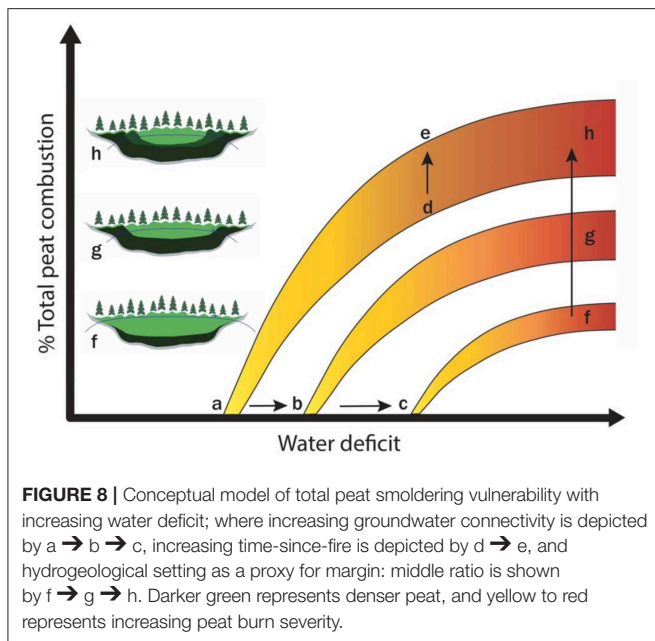


FIGURE 7 | Estimated water deficit required to lower GWC to combustion-critical value for margins of 21–80 (left) and 81–120+ (right) years since fire, where levels of peat smoldering vulnerability correspond to: low (white), near-surface (light gray), and full profile “burn-out” (black).

specifically, above-ground biomass has been found to accumulate quickly post-fire, and biomass generally exceeds that of black spruce forested peatland middles (Housman, 2017), although some above-ground biomass in margins comprises deciduous species that are generally less susceptible to wildfire (Hély et al., 2001). Overall, peat smoldering vulnerability increases with TSF due to the accumulation of above-ground fuels. Moreover, increased canopy cover contributes to increased rates of transpiration, that, in some cases, can outweigh reductions in surface evaporation and increase peatland water deficit (Kettridge et al., 2014). Increased canopy cover increases shading of the ground surface, reducing evaporation as



mentioned, but also increasing the competitive advantage of feather moss species over *Sphagnum* species (Bisbee et al., 2001). Feather mosses are more susceptible to combustion than *Sphagnum* and begin to dominate margin and middle ground cover at ~60 (Housman, 2017) and 80 years post-fire (Benscoter and Vitt, 2008), respectively. In combination with an increasingly responsive WTD in the margin with TSF, we highlight forested peatlands margins at >60 years since fire as areas extremely vulnerable to peat smoldering combustion. In fact, since mean margin depths are only 0.4–0.6 m across the range of HS in the BP, we expect that they are vulnerable to smoldering combustion throughout their entire profile i.e., “burn-out” under water deficits of 100–130 mm and above (Figure 7).

We find that, in general, peat smoldering vulnerability is much greater in forested peatland margins than middles, and since groundwater connectivity (Hokanson et al., 2018) and the ratio of margin to total area (Mayner et al., 2018; Ingram et al., 2019), varies by HS, we expect differences in total peat smoldering vulnerability to vary by HS as presented in a conceptual model (Figure 8). In conjunction with topographic position (relative elevation in the landscape), HS determines interactions with regional groundwater systems in the BP (Devito et al., 2005). Peatlands located in glaciolacustrine HS (on the clay plain) tend to be more expansive (Mayner et al., 2018) and can create their own larger scale flow regimes (Devito et al., 2012). Conversely, peatlands located in glaciofluvial/coarse and heterogenous/moraine HS at mid-upper topographic position can be periodically (or fully) disconnected from regional groundwater systems, resulting in hydrological regimes that are susceptible to climatic water deficits (Hokanson et al., 2016, 2018; James, 2017). Because these peatlands tend to be smaller in areal extent,

margins constitute a larger proportion of their total carbon store (Housman, 2017; Ingram et al., 2019) and thus have greater total peat smoldering vulnerability. Consequently, we further identify small peatlands in the mid-upper topographic reaches of glaciofluvial and heterogeneous HS as areas of the greatest peat smoldering vulnerability, within our conceptual model (Figure 8).

CONCLUSIONS

Peat hydrophysical properties show considerable variability across the BP leading to different responses to water deficit. In combination with ecosystem—landscape scale variability in the potential for wildfire disturbance and exposure to climatic water deficits, we find that peat hydrophysical properties can act to buffer or exacerbate peat smoldering combustion (Figure 8). A slight decrease in WTD responsiveness with TSF may decrease peat smoldering vulnerability in peatland middles. However, this is likely outweighed by increases in feather moss dominance, transpiration, above-ground fuel density, and energy transfer during crown fire. Margins are expected to be more vulnerable than middles across all HS, however, less connectivity with regional groundwater, greater margin area, and greater margin WTD sensitivity in glaciofluvial and heterogeneous HS, will amplify peat smoldering vulnerability in these areas when subjected to climatic water deficit (Figure 8).

In light of these findings and the increasing severity of the boreal wildfire regime we suggest that future research should focus on developing adaptive wildfire management strategies for black spruce forested peatlands, especially those at the wildland-industry-interface and/or wildland-urban-interface. Wildfire management strategies should consider TSF as well as HS whilst taking a multi-faceted approach, incorporating above-ground, surface, and below-ground fuels, to manage the detrimental effects of peat smoldering combustion across the BP ecozone of northern Alberta. We suggest the development of identification tools to help guide resource deployment by wildfire managers to areas of high peat smoldering combustion vulnerability highlighted by this work, and the continued research into the propagation of fire-resistant *Sphagnum* mosses on the landscape.

DATA AVAILABILITY STATEMENT

The data supporting the conclusions of this manuscript will be made available by the authors, without undue reservation, to any qualified researcher.

AUTHOR CONTRIBUTIONS

Funding was secured by JW. Research was designed by SW, PM, and JW. Data analysis was undertaken by SW and assisted by PM. Writing was conducted by SW, PM, and JW.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: <https://www.frontiersin.org/articles/10.3389/ffgc.2019.00084/full#supplementary-material>

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Conflict of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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