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Key Points:
- Remote sensing shows that drainage increases forest cover, aboveground biomass, and canopy fuel loads, and all are higher near ditches
- Drainage caused changes to forest and peat properties contribute to increased peat burn severity, especially in drained margins
- A novel approach highlights areas of significant depth of burn using post-fire LiDAR and a topographic position index

Supporting Information:
Supporting Information may be found in the online version of this article.

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Fuel Loads and Peat Smoldering Carbon Loss Increase Following Drainage in a Forested Boreal Peatland

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Abstract We aimed to assess how peatland drainage altered the spatiotemporal variability in forest cover, aboveground biomass, and tree productivity and how these changes related to the spatial variability in peat burn severity. We studied a black spruce and birch dominated boreal peatland in Parkland County, Alberta, Canada, which was drained in 1987 and burned in 2021. Using remote sensing techniques (historical imagery and LiDAR), we determined that forest cover increased by 180% following drainage and aboveground tree biomass decreased from 26.1 kg m^{-2} adjacent to the nearest drainage ditch to 2.8 kg m^{-2} 95 m away from the nearest ditch. Field surveys and a LiDAR-based analysis were conducted to measure the spatial variability in peat burn severity. Drained peatland margins experienced the greatest peat burn severity with a mean depth of burn of 26.9 ± 12.6 cm (18.2 ± 10.1 kg C m^{-2}) compared to natural middles at 15.3 ± 6.2 cm (3.9 ± 2.1 kg C m^{-2}), where peat burn severity increased with proximity to ditches and greater aboveground biomass. We present a conceptual model outlining the increases in aboveground and peat fuel loads following drainage and suggest that the area around a ditch that is impacted by drainage, which is commonly assumed to be 30 m, likely increases through time in forested peatlands due to the afforestation feedback. Drained peatlands represent a severe fire risk for communities and fire management agencies. Peatland restoration should be integrated into fuel management strategies to reduce the risk that drained peatlands pose.

Plain Language Summary We studied the impacts of drainage in a forested boreal peatland in Parkland County, Alberta, Canada that burned in a 1,800 ha wildfire that occurred in 2021. We found that peatland drainage increased forest cover, aboveground biomass, and fuel loads. The drying and increased fuel loads caused by drainage led to increased organic peat soil combustion during the 2021 wildfire, specifically around the edges of peatlands, increasing ecological impacts, health risks to communities, and challenges for fire suppression efforts.

1. Introduction

Peatlands represent a vital store of terrestrial carbon, storing ~30% of the world's soil organic carbon while only covering ~3% of Earth's landmass (Yu et al., 2010). Much of this peatland carbon stock is stored in Canada's approximately 1.1 million km^2 of peatlands (the largest of any country in the world; Xu et al., 2018). Although the majority of these peatlands are located in the fire prone boreal region and are regularly impacted by fire, pristine peatlands are typically fire resistant and remain long-term carbon sinks accumulating more carbon during the fire return interval than what is typically lost through combustion during a fire (Ingram et al., 2019; Wieder et al., 2009). Burn severities in undrained boreal peatlands generally range from 5 to 10 cm depth of burn (DOB; e.g. Lukenbach et al., 2015) which represents a loss of ~1 kg C m^{-2} (Wilkinson et al., 2023), a relatively low burn severity compared to the ~10 kg C m^{-2} which some boreal peatlands can accumulate in soil organic carbon during the fire return interval of ~120 years within this region (Ingram et al., 2019; Turetsky et al., 2004). This relatively low burn severity is due to the shallow water tables and high near-surface moisture conditions maintained in peatlands due to a suite of autogenic ecohydrological feedbacks (Waddington et al., 2015). Although peatlands typically act as fire breaks and refugia on the landscape (e.g., Kuntzemann et al., 2023), there is mounting evidence that peatlands under certain conditions (e.g., in some hydrogeological settings, during extreme droughts, or post-drainage) can experience extreme combustion with peat carbon losses between 5 and 20 kg C m^{-2} (Hokanson et al., 2016; Wilkinson, Moore, Flannigan et al., 2018) threatening these vital carbon sinks (Ingram et al., 2019). These extreme burn severities present a significant challenge for fire managers as they are difficult to suppress (Rein & Huang, 2021), can result in smoldering overwintering fires which may lead to

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later reignition of flaming combustion (Scholten et al., 2021), and pose a threat to the health of surrounding communities through elevated smoke and PM2.5 emissions (Hu et al., 2018).

Forested peatlands in the North American boreal zone are often dominated by black spruce stands (*Picea mariana* Mill. BSP), which develop over the first ~80 years following a wildfire (Johnston et al., 2015; Mayner et al., 2024). These black spruce stands are characterized by stunted growth due to shallow peatland water tables maintained within the first few decimeters of the surface (Lieffers & Rothwell, 1987). After ~80 years following fire, peatland black spruce stands tend to reach and maintain a consistent stand density and fuel load until there is a subsequent stand replacing fire, restarting the post-fire successional cycle (Johnston et al., 2015). However, the drying of a peatland, either through meteorological drought or anthropogenic drainage, improves the growing conditions for trees and other vascular vegetation (Hillman & Roberts, 2006; Turetsky et al., 2011; Wilkinson, Moore, Flannigan et al., 2018), initiating a positive feedback mechanism through which the increased tree productivity results in further drying of the underlying peat through increased evapotranspiration (Waddington et al., 2015). This increased peatland drying and increasing growth of the forest stand, which continues to cause further increases in peatland drying through increased transpiration, result in a concomitant increase in the potential for elevated peat burn severities through four primary mechanisms. First, the increase in tree productivity results in a higher canopy fuel load (CFL) which in turn increases the intensity of a crown fire and thus the energy transferred to the peat surface during a fire (Thompson et al., 2015). Second, the increase in canopy cover and shading shifts the surface moss species from fire resistant *Sphagnum* mosses to more fire prone feather mosses (particularly *Pleurozium schreberi* and *Hylocomium splendens*; Bisbee et al., 2001; Thompson et al., 2020). Third, the decrease in peat moisture content enhances peat decomposition and consolidation resulting in denser peat which is able to sustain smoldering combustion at higher moisture contents (Benscoter et al., 2011). Finally, the overall drier conditions at the peat surface reduces the energy needed to ignite and sustain smoldering within the peat (Benscoter et al., 2011).

Previous studies have shown that peatlands drained for silviculture, which then subsequently burned, experienced significantly elevated burn severities with DOBs exceeding 1 m and, in some cases, burning down to the underlying mineral soil (Turetsky et al., 2011; Wilkinson, Moore, Flannigan et al., 2018). Carbon losses from combustion in these drained peatlands have been shown to exceed 20 kg C m^{-2} (Turetsky et al., 2011; Wilkinson, Moore, Flannigan et al., 2018). Additionally, peatland margins which tend to experience more variable water table fluctuations and have denser peat profiles, even in undrained peatlands (Wilkinson et al., 2019), are also prone to higher burn severities compared to the middles of the same peatlands (Hokanson et al., 2016). However, to date, there has been no explicit analysis of the combined effects of drainage and location within a peatland on aboveground fuel loads and the relation to peat burn severity. We address this research gap by quantifying the changes in forest cover, tree productivity, and aboveground biomass accumulation in a peatland complex which was partially drained in 1987 using a combination of remote sensing techniques (e.g., historical imagery and LiDAR). Using in-field measurements and a novel approach through LiDAR based remote sensing we then assess the impact of these fuel loads, drainage, and landscape position on peat burn severity from a fire which occurred in 2021.

2. Materials and Methods

2.1. Study Area

This study was conducted in two study sites in a portion of a partially drained peatland complex located near Tomahawk, AB. The primary study area is ~60 ha in size, which has been partially drained (from now on referred to as the primary study site; 53.38°N, 114.82°W; Figure 1) and a completely undrained site, ~44 ha in size, (from now on referred to as the control site; 53.39°N, 114.87°W). Both sites are comprised of peatlands dominated by black spruce and paper birch (*Betula papyrifera* Marshall) with upland mineral soil forests dominated by trembling aspen (*Populus tremuloides* Michx.) and a hybrid of jack and lodgepole pines (*Pinus banksiana* Lamb. and *Pinus contorta* Douglas, respectively). The surrounding landscape is dominated by land cleared for open grazing and agriculture. Two sections of the primary study site peatland were drained for peat harvesting in 1987, with additional ditches located in unharvested sections of the peatland to drain water away from the harvesting fields. Although we were unable to find information on the original ditch dimensions (i.e., width and depth) or the process used to create the ditches, the ditch dimensions at the study site in 2022 were ~1–1.5 m wide and 0.5–1 m deep at the peat harvesting fields and ~0.5–1 m wide and ~1 m deep throughout the forested (unharvested) areas.

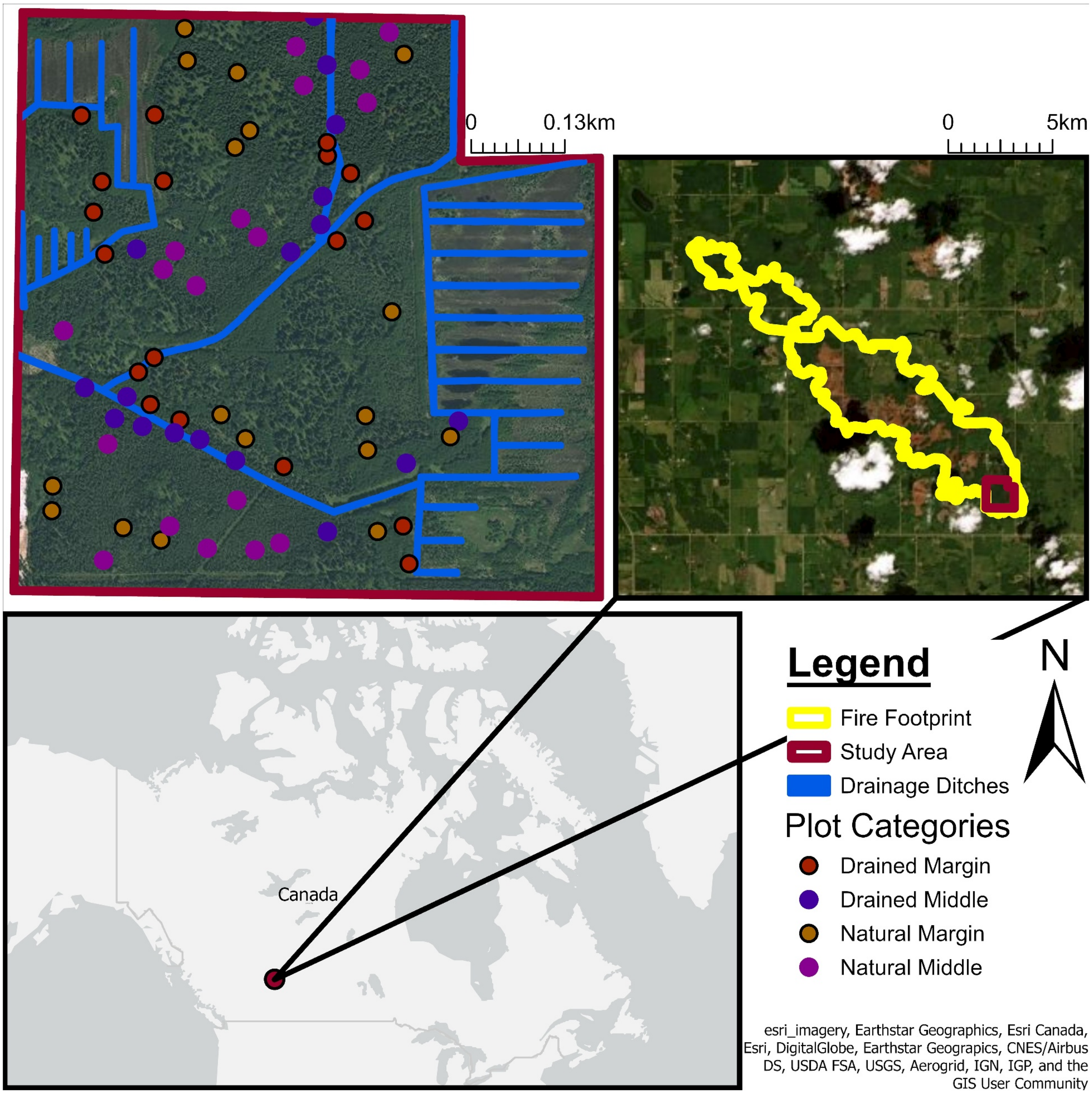

Figure 1. Map of the primary study site outlined in red (all maps) on the top left within the fire footprint outlined in yellow on the upper right map and the location in Canada indicated on the bottom map on the left. Measurement plots are marked with dots (with color indicating plot categories) and drainage ditches are marked in blue.

In May 2021 a fire ignited to the southeast of the primary study site which burned through the entirety of the primary study site along with ~1,800 ha of the surrounding landscape. The fire remained active for over a year with evidence of peat smoldering continuing through the 2021–2022 winter.

The control site is located ~3 km to the northwest of the primary site and is used as a comparison to the primary site for the analysis of forest cover changes through time (see Section 2.2 below). The control site is ~44 ha in size and has a similar landscape make up and forest cover prior to drainage at the primary site in 1987. The control site was not burned in the 2021 fire and is only used for the forest cover analysis and no other aspects of the study.

2.2. Forest Cover and Inventory

To assess the impact of drainage on peatland forest cover patterns, eight aerial photographs taken between 1949 and 2011 (four pre-drainage and four post-drainage) were obtained from the Alberta Air Photo Library (Government of Alberta, 2023). Images were georeferenced to world imagery in ArcGIS Pro (ArcGIS Pro, 2024) using maintained control points (i.e., roads and buildings). Each image was individually classified into two classes: canopy and open area, using the *Support Vector Machine* algorithm in ArcGIS Pro (ArcGIS Pro, 2024). Each image was classified separately using 100–200 training samples due to variations in spatial resolution and image sensors between photos. Due to large differences in the appearance of coniferous and deciduous trees in the image from 1949, the different tree types were classified independently, and then later combined into one single class, representing canopy cover. In all other photos the species were not radiometrically distinct, and as such only two classes were used. In post classification, all images were resampled to 1 m resolution, and filtered using a majority filter (*Majority Tool*) and a boundary filter (*Boundary Clean Tool*) to emphasize the boundaries between classes. This same analysis was conducted on the control site for 1949, 1966, and 1987 (pre-drainage years at the study site) and in 1990, 1994, and 2003 (following drainage at the study site) to determine if other environmental factors may have contributed to changes in forest cover observed at the study site. The accuracy of this methodology was tested using randomly sampled test pixels and confusion matrices, with accuracies of 0.79–0.93 and κ values ranging from 0.52 to 0.80 (Text S1 and Tables S1 and S2 in Supporting Information S1).

At the time of drainage at the study site (1987) a portion of the peatland not used for harvesting had no trees and is used here to assess the spatial impact of drainage (i.e., distance from ditch) on the accumulation of aboveground biomass (AGBM) and CFL without the influence of already established forest stands. Near Infrared LiDAR captured by an uncrewed aerial vehicle was collected in September 2022, with an average ground sampling distance of 1.5 cm (GreenLink Forestry Inc. 2022). Prior to analysis, outliers were removed using CloudCompare (CloudCompare, 2023). Using R (R Core Team, 2022), trees were delineated using the *Locate_Trees* function in the *LidR* package (Roussel et al., 2023) with a fixed window of 0.5 m, due to consistent crown sizes diameter of <25 cm. Trees under 1.5 m tall were removed from the data set. To account for trees that had fallen following the fire that may have been missed by the LiDAR, a classification of fallen trees was conducted using drone imagery captured by a Mavic DJI Mini 2 in August 2023. The imagery was captured at a resolution of 2.7 cm and was mosaicked using *Drone2Map* V2023.2. Fallen trees on the forest floor were easily identifiable in the imagery and were manually delineated as a linear feature class. In order to classify trees by species, trees identified in the LiDAR or imagery assessment were assigned to the dominant species in each 0.5-m pixel. Pixels were classified as black spruce or paper birch using *Support Vector Machine* classification in ArcGIS Pro on drone imagery captured in June 2021 (GreenLink Forestry Inc., 2021), as species were distinguishable based on color as black spruce canopies were completely consumed (appearing black), while birch either survived (appearing green) or only experienced minor impacts from the fire (appearing gray), as supported by our observations of the site following the fire. The accuracy of this was assessed using randomly sampled test pixels and a confusion matrix with an accuracy of 0.85 and a κ of 0.7 (Text S1 and Table S3 in Supporting Information S1).

Finally, the measured tree heights were used in allometric equations to calculate AGBM and CFL. For black spruce trees, diameter at breast height (DBH) was calculated from height using the model from Sharma and Zhang (2004) and then to basal diameter (BD) using plot data collected in the summer of 2022 and 2023 using a linear regression (Figure S1 in Supporting Information S1). For birch trees, DBH was calculated from height using an allometric equation derived from the Energy from the Forest database (Figure S2 in Supporting Information S1; Ung et al., 2017). CFL was calculated only for black spruce trees as birch tend not to contribute to fire behavior, and thus CFL models do not currently exist for birch species (de Groot et al., 2022). CFL for black spruce was calculated from BD using equations from (Johnston et al., 2015), AGBM for black spruce and paper birch were calculated from DBH using the models from (Ung et al., 2008). See (Text S2 in Supporting Information S1) for more detailed information on biomass and fuel load calculations.

2.3. Field Surveys

Peat burn severity, measured as a depth of burn (DOB), was assessed at the study site using a stratified random sampling survey of the unharvested peatland areas at the study site conducted in August 2022 and May 2023. Seventy 3 × 3 m plots were randomly placed throughout the study site with an equal number of plots (±one plot) falling within the four categories of natural middles, natural margins, drained middles, and drained margins. An area was considered drained if it was within 30 m of a ditch. The distinction between middle and margin was assessed within the field with margin plots being within 10 m of the nearest mineral soil upland. Although the effective distance away from a ditch for drainage is dependent on many factors, 30 m was chosen as the threshold based on previous studies (e.g., Belleau & Plamondon, 1992; Landry & Rochefort, 2012; Wilkinson, Moore, Flannigan et al., 2018). It is important to note that we largely excluded the peat harvesting fields from the sampling, apart from around some of the edges outside of perimeter ditches, as the peat fields did not experience any measurable loss of peat due to the fire. At each of the 70 plots, we measured DOB based on the adventitious root method (Kasischke et al., 2008), while additionally using clearly unburned reference surfaces where available (Lukenbach et al., 2015). A string was run taut between two reference surfaces to represent the pre-fire surface and then five measurements of DOB were made from the line to the surface of the remnant soil. This was repeated four times in each plot for a total of 20 measurements per plot and 1,400 individual DOB measurements across the study site. The depth of remnant peat (up to a maximum of 2 m) was measured using a soil auger in two locations within each plot and the DBH, BD, and species of each tree within the plot were measured. Each plot was georeferenced into ArcGIS FieldMaps using a Geode GNSS receiver (Juniper Systems Geode GNS2, Logan, UT; horizontal accuracy <30 cm) and then used to measure the distance from the nearest ditch in ArcGIS Pro (ArcGIS Pro, 2024).

2.4. Carbon Loss Estimates

Using data from a variety of studies on boreal peat properties (Granath et al., 2016; Silins & Rothwell, 1998; Turetsky et al., 2011; Wilkinson et al., 2019) we compiled an average bulk density for each 5 cm depth increment for natural middles, natural margins, and drained middles (Table S5 in Supporting Information S1). We were unable to find peat properties for drained margins and thus assumed that drained margin bulk density would be the highest of either drained middles or natural margins. Although the available data in most cases were only to a maximum depth of ∼60 cm, the greatest variation in bulk density occurs in near-surface peat (e.g., Price et al., 2023), also referred to as the acrotelm (e.g., Clymo, 1984; Morris et al., 2011), with changes at depths greater than 60–80 cm often being nonmonotonic (e.g., Price et al., 2023; Waddington et al., 2015). Given that many DOBs measured in this study exceeded those depths, we assumed that the remainder of the profile stayed at a constant bulk density matching the deepest available bulk density. Depth-dependent carbon content was then calculated by assuming a 5% ash content and 95% organic matter, which was assumed to have an organic carbon content of 51.7% (Gorham, 1991). We then converted our DOB measurements to peat carbon loss by multiplying the DOB by the depth-averaged carbon content for that respective depth from the appropriate profile based on the location of the field survey plot. It is important to note that our peat carbon loss estimates here do not account for the deposition of charcoal, or pyrogenic carbon, into the peat profile during combustion, which has been shown to make up an average of 13.5% of total soil carbon within northern peatlands (Leifeld et al., 2018).

2.5. Tree Ring Analysis

At all field survey plots (see Section 2.3 above), ∼3 cm thick cross-sections were sampled from the base of the trunk of two trees of the dominant species around the plot. Due to issues with ring visibility and sample size of other tree species only the cross sections from black spruce trees (n = 101) were used for the remainder of the analysis. Tree cross-sections were sanded with an orbital sander until tree rings were clearly visible and then scanned on a flatbed scanner at 1,200 dpi. The CooRecorder program (CooRecorder, 2022) was used to detect tree rings and generate coordinate files for four random transects (from edge to pith) of the cross section, which were then imported to the companion program CDendro (CDendro, 2022) for cross-dating and ring width generation (Maxwell & Larsson, 2021).

2.6. Remotely Sensed Peat Burn Severity

Using the post-fire LiDAR data, patterns in the burn severity of the study site were assessed using a topographic position index (TPI). A digital elevation model (DEM) of the post-fire bare ground surface was derived from the LiDAR data with a resolution of 25 cm. The DEM was used to calculate the average elevation of a 60 pixel (15 m) moving window using the *Focal Statistics* tool in ArcGIS Pro (ArcGIS Pro, 2024). The average elevation of the moving window for a given pixel was then subtracted from the elevation of that pixel to calculate a TPI (in m) for each 25 cm pixel of the entire study site. Thus, locations within the study site that experienced large DOBs would be identified as having significantly lower relative elevations compared to their moving window average. The TPI

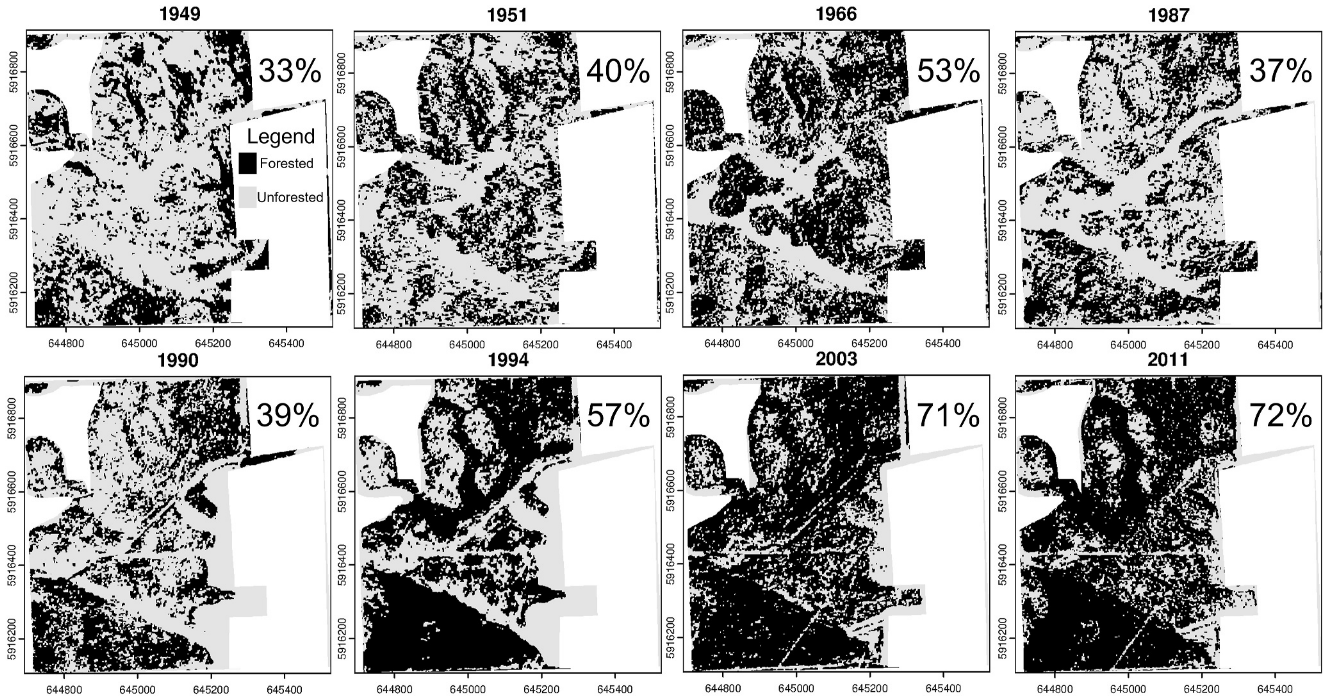

Figure 2. Forest cover maps from 1949 to 1987 (top row, pre-drainage) and from 1990 to 2011 (bottom row, post-drainage) determined from digitized historical air photos of the primary study site (Government of Alberta, 2023). Black, gray, and white pixels represent forested, unforested, and areas excluded from the analysis (i.e., peat harvesting), respectively. UTM coordinates displayed on map axes. Percentage values presented are the percent cover of forest in the study area for a given year. Peatland drainage occurred in 1987.

raster was then split between areas classified as natural and drained middles and margins, where drained areas were within a 30 m buffer of a ditch and margins were within a 10 m buffer of mineral soil upland hummocks, which were manually delineated based on aerial imagery and the DEM. Finally, positive values in the TPI rasters were removed as the purpose of this methodology was to identify areas with significant DOB. Two parameter Weibull probability density functions (PDFs; Equation 1) were fit to the TPI data using the MATLAB *fitdist* function (*MATLAB,* 2021) for each landscape classification, where only negative TPI values were used. Negative TPI values were transformed by a factor of negative one for the purposes of fitting distributions, but PDFs are presented with negative TPI values.

$$f(x \mid a,b) = \begin{cases} \frac{b}{a}(x/b)^{b-1} e^{-(x/a)^b}, & x \geq 0 \\ 0, & x < 0 \end{cases} \tag{1}$$

2.7. Statistical Analyses

Statistical analysis was conducted in MATLAB (MATLAB, 2021). Nonparametric *t*-tests (Kruskal–Wallis) with a correction for multiple comparisons (where applicable) were used to test for significant differences in DOB and peat carbon loss between plot categories. Linear and sigmoidal regressions and associated statistics were conducted using the *fit* and *fitlm* functions for the AGBM and CFL compared to distance from ditch analysis and for comparisons of DOB and peat carbon loss to AGBM (and other metrics shown in Supporting Information S1). Values presented in text are the arithmetic mean and standard deviation unless otherwise noted.

3. Results

3.1. Forest Cover

Forest canopy cover averaged 40% at the study site prior to drainage (1949–1987), ranging from 33% to 53% (Figure 2). Following drainage in 1990, there was limited change in forest cover at the study site relative to the

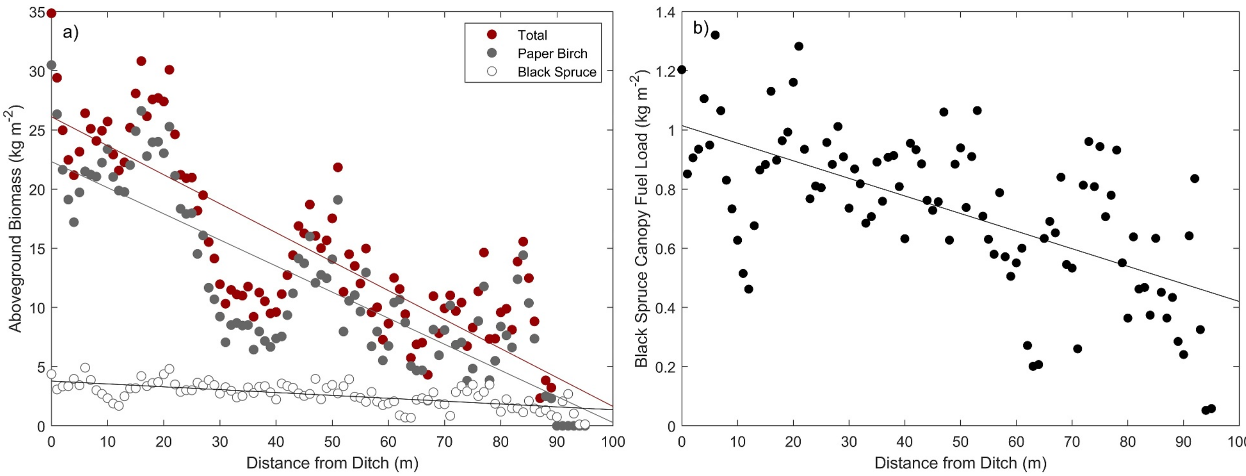

Figure 3. Distance from ditch impacts on forest inventory. (a) Aboveground biomass (AGBM) of trees with distance from nearest ditch (DFD) in areas that were not treed at the time of drainage, total tree AGBM in maroon (AGBM (kg m^{-2}) = −0.24 kg m^{-2} m^{-1} * DFD (m) + 26.11 kg m^{-2}); R^2 = 0.72), paper birch AGBM in gray (AGBM (kg m^{-2}) = −0.22 kg m^{-2} m^{-1} * DFD (m) + 22.66 kg m^{-2}; R^2 = 0.69), and black spruce AGBM in open circles (AGBM (kg m^{-2}) = −0.02 kg m^{-2} m^{-1} * DFD (m) + 3.79 kg m^{-2}; R^2 = 0.44). (b) Black spruce canopy fuel load (CFL) in areas that were not treed at the time of drainage with distance from nearest ditch (CFL (kg m^{-2}) = −0.006 kg m^{-2} m^{-1} * DFD (m) + 1.02 kg m^{-2}; R^2 = 0.40).

pre-drainage average, at 39% (the earliest post-drainage image available). However, from 1994 onwards, forest cover averaged 67%, reaching 71% by 2003, representing a 31% increase by area in forest cover or 1.8 times the forest coverage at the study site over 13 years (Figure 2). In the undrained control site, forest cover averaged 27% in both the years prior to drainage at the study site (1949–1987) and the years following drainage (1990–2003; Figure S3 in Supporting Information S1).

3.2. Drainage Impacts on Fuel Load and Biomass

In areas that were not treed prior to drainage we found that tree AGBM significantly increased with proximity to the nearest ditch. This relationship was most significant in total tree AGBM (paper birch and black spruce combined; slope = −0.24 kg m^{-2} m^{-1}, t = −15.7, df = 94, $p < 0.001$; Figure 3a), where paper birch AGBM was more strongly controlled by distance from the nearest ditch (slope = −0.22 kg m^{-2} m^{-1}, t = −14.5, df = 94, $p < 0.001$; Figure 3a) compared to black spruce. Although black spruce AGBM has a weaker relationship, it also decreased with increasing distance from the nearest ditch (slope = −0.02 kg m^{-2} m^{-1}, t = −8.6, df = 94, $p < 0.001$; Figure 3a). Additionally, CFL decreased with increasing distance from the nearest ditch (slope = −0.01 kg m^{-2} m^{-1}, t = −8.0, df = 94, $p < 0.001$; Figure 3b).

Tree productivity increased markedly in trees samples from drained plots following drainage compared to trees sampled from natural plots (Figure 4). The average ring width from years prior to drainage in drained and natural plots were 0.62 ± 0.15 and 0.67 ± 0.17 mm, respectively. Ring widths associated with years following drainage increased to a mean of 1.53 ± 0.33 mm in trees sampled from drained plots which was statistically significantly different (X^2 = 32.79, df = 1, $p < 0.001$) from trees sampled in natural plots with a mean of 1.04 ± 0.14 mm.

3.3. Peat Burn Severity

Depth of burn and peat carbon loss were significantly higher (DOB X^2 = 11.09, df = 1, $p < 0.001$; carbon loss X^2 = 23.59, df = 1, $p < 0.001$) in drained plots, with a mean DOB of 24.3 ± 11.6 cm (15.5 ± 8.9 kg C m^{-2}) compared to natural plots, where the DOB was 16.6 ± 5.8 cm (5.9 ± 3.4 kg C m^{-2}; Figures 5a and 5c). DOB and peat carbon loss were significantly different (DOB X^2 = 13.35, df = 3, p = 0.003; carbon loss X^2 = 30.6, df = 3, $p < 0.001$) between natural middles and drained margins when grouped by drainage and location, where natural middles had the lowest plot average mean DOB of 15.3 ± 6.2 cm (3.9 ± 2.1 kg C m^{-2}), followed by natural margins at 18.1 ± 5.2 cm (8.0 ± 3.2 kg C m^{-2}), then drained middles at 21.6 ± 10.2 cm (12.6 ± 6.5 kg C m^{-2}), and the greatest plot average DOB found in drained margins with a mean of 26.9 ± 12.6 cm (18.2 ± 10.1 kg C m^{-2}; Figures 5b and 5d). Peat carbon loss was also significantly different (X^2 = 30.6, df = 3, $p < 0.05$) between natural middles and drained middles and between natural margins and drained margins, but not between natural margins

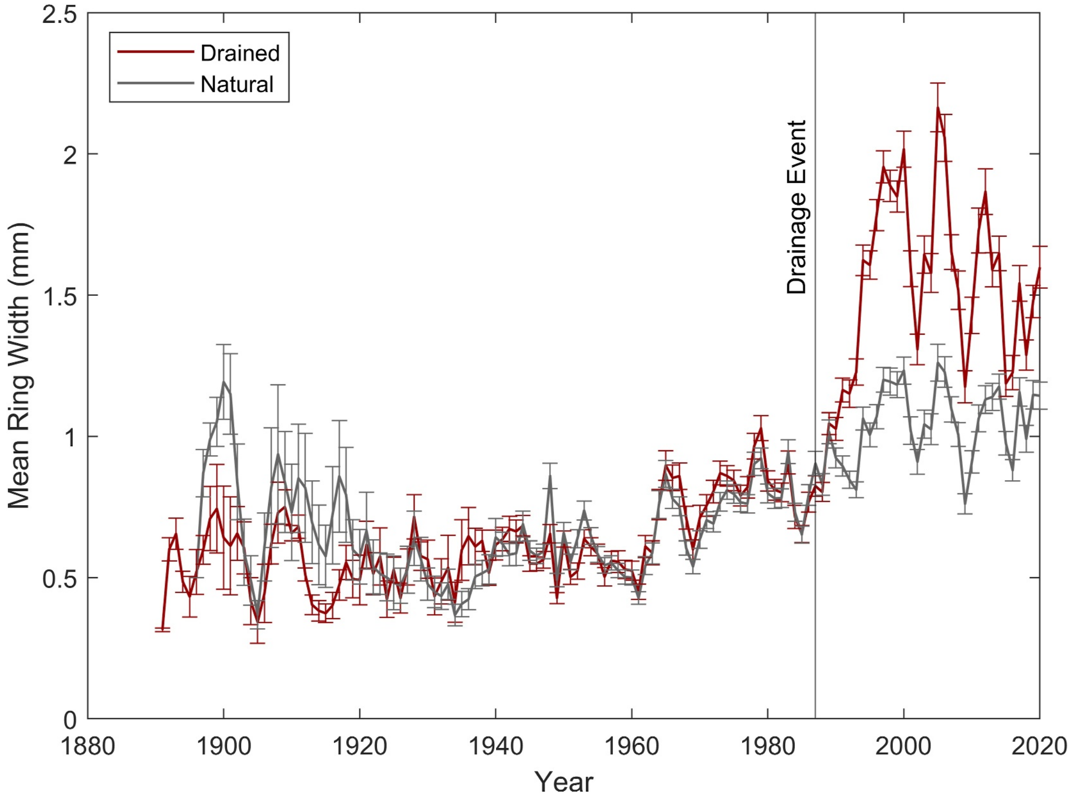

Figure 4. Annual mean tree ring widths from black spruce cross sections taken from drained (<30 m away from the nearest drainage ditch; maroon), and natural (>30 m away from the nearest drainage ditch; gray) plots. Error bars show standard error for each year of growth.

and drained middles or drained middles and drained margins. The maximum individual DOB measurements found in each category also follow the same pattern with maximum DOBs of 41 cm (14.4 kg C m^{-2}), 45.5 cm (32.3 kg C m^{-2}), 65 cm (40.6 kg C m^{-2}), and 94 cm (92.0 kg C m^{-2}), for natural middles, natural margins, drained middles, and drained margins, respectively. In some cases DOB was limited by the total amount of peat available to burn, as evidenced by situations where the peat column had been totally consumed, which was observed five times in this study (three times within drained margins and twice in natural margins). Two additional plots (one in each drained and natural margins) had less than 5 cm of peat remaining, and four additional plots had less than 10 cm of peat remaining (three in drained margins and one in a natural margin). In no case was DOB limited by the total amount of peat in either drained or natural middles.

Plots with the highest average DOBs and carbon loss were located closer to ditches, where the plot with the highest average DOB and carbon loss was ∼4 m from the nearest ditch (Figures 6a and 6c). All plots greater than 30 m from a ditch (i.e., natural plots) had a plot average DOB less than 30 cm and carbon loss estimates less than 15 kg C m^{-2}, while 10 plots within 30 m of the nearest ditch had plot average DOBs greater than 30 cm (Figure 6a) and 17 plots within 30 m of the nearest ditch had peat carbon losses greater than 15 kg C m^{-2} (Figure 6c). AGBM was also correlated with the plot average DOB and peat carbon loss where they increased with greater AGBM (Figures 6b and 6d). Similar trends were found when using plot basal area in place of AGBM (Figures S4 and S5 in Supporting Information S1).

3.4. Remotely Sensed Burn Severity Patterns

Our TPI analysis identified areas with significant peat loss as indicated by the darker areas in Figure 7. The mean TPI was lowest (most negative) in drained margins at −0.141 ± 0.121 m indicating the greatest overall burn severity. Natural middles had the highest TPI (least negative) at −0.048 ± 0.050 m. Further, PDFs of the TPI data show a higher probability of greater negative TPI values in drained margins and a much greater probability of TPI values near zero in natural middles (Table 1; Figure 7). This agrees with our field-based DOB measurements;

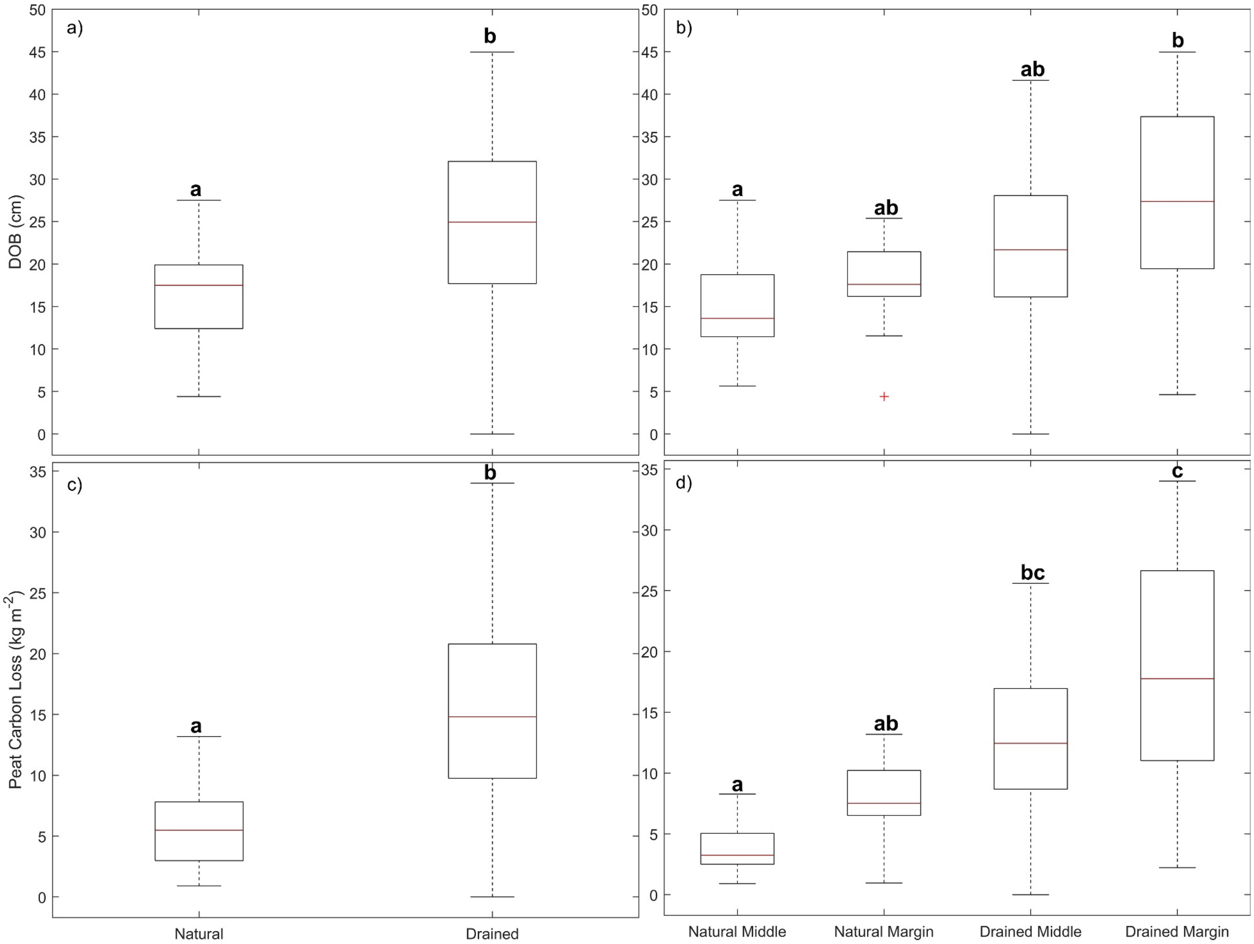

Figure 5. Boxplots of plot depth of burn measurements (a) and (b) and carbon loss estimates (c) and (d) grouped by (a) and (c) plot drainage condition, where drained plots were within 30 m of a ditch, and (b) and (d) drainage condition and landscape position (i.e., peatland middle and margin). Red lines indicate the median of the data, and letters indicate statistically significant differences according to a Kruskal-Wallis test, corrected for multiple comparisons in panels (b) and (d).

however, the TPI analysis showed that natural margins had a greater burn severity than drained middles which contradicts the field-based DOB surveys.

4. Discussion

4.1. Peatland Fuel Dynamics Following Drainage

Forest cover across the primary study site increased significantly in the years following drainage (Figure 2), whereas the forest cover at the undrained control site remained relatively constant pre- and post-drainage (Figure S3 in Supporting Information S1). Our results are similar to Pellerin et al. (2000) who also showed significant increases in forest cover in a drained peatland, although they found a slower overall rate of increase, albeit in a different climatic setting. In addition, in areas that were untreed at the time of drainage, we found a significant increase in AGBM and CFL closer to ditches. AGBM was greatest at ditch interfaces at 26.1 kg m^{-2}, decreasing to 2.8 kg m^{-2} at a distance of 95 m away from ditches (Figure 3a). Wilkinson, Moore, Flannigan et al. (2018), Wilkinson et al. (2018a) found a similar effect of drainage on forest stand biomass with values of 11.1, 3.2, and 1.2 kg m^{-2}, in heavily drained, moderately drained, and undrained portions of a black spruce dominated peatland, respectively.

In areas untreed at the time of drainage, we found low overall CFL values, with values ranging from 1.01 kg m^{-2} adjacent to ditches to 0.44 kg m^{-2} at a distance of 95 m away from ditches (Figure 3b). For comparison, typical CFL in natural boreal peatlands in late succession are ~1 kg m^{-2} (e.g., 0.9 kg m^{-2} in Johnston et al., 2015;

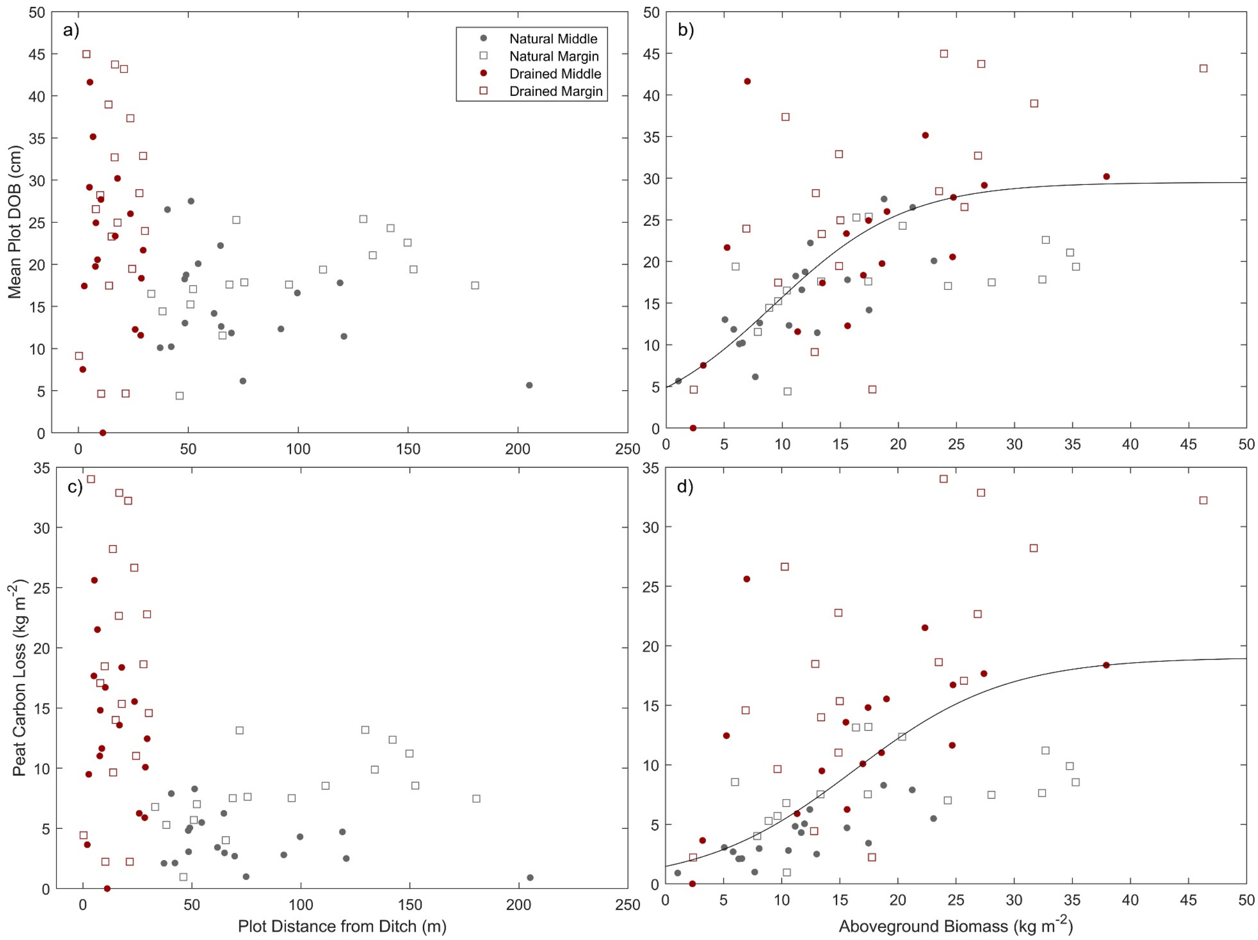

Figure 6. Mean plot depth of burn and peat carbon loss versus distance to the nearest ditch (a) and (c) and aboveground biomass (AGBM) of trees (c) and (d). Line of best fit in (b) has equation: DOB(cm) = 29.5/(1 + $e^{(-0.1757*\text{AGBM}(\text{kg m}-2)+1.626)}$; $R^2 = 0.30$. Line of best fit in (d) has equation: Carbon Loss (kg C m^{-2}) = 19.02/(1 + $e^{(-0.1534*\text{AGBM}(\text{kg m}-2)+2.485)}$; $R^2 = 0.24$. Data is grouped by drainage condition and landscape position.

1.3 kg m^{-2} in Thompson et al., 2020; and 1.2 kg m^{-2} in Wilkinson, Moore, Thompson et al., 2018). Moreover, the C-2 boreal spruce fuel type in the Canadian Forest Fire Danger Rating System is assigned a CFL value of 0.8 kg m^{-2}. In heavily drained peatlands with pre-existing (pre-drainage) black spruce stands, CFL values can reach as high as 3.2 kg m^{-2} (Wilkinson, Moore, Flannigan et al., 2018). The similar overall biomass values but significantly lower CFL values found in our study compared to other drained peatland studies are likely due to the high amounts of birch contributing to AGBM in our study, but not to the CFL, as birch are considered to not contribute significantly to crown fire behavior (de Groot et al., 2022). In addition, we selected for areas that had no trees at the time of drainage to eliminate the impacts of any pre-existing gradients of AGBM and CFL at the time of drainage, whereas areas with already established forest stands at the time of drainage likely would have greater AGBM and CFL values. Further, we did find that CFL values in some plots from the field surveys in drained black spruce dominated areas with forest cover prior to drainage to be >6 kg m^{-2}. These findings are further supported by the increase in tree ring width found in years following drainage (Figure 4). Our tree ring analysis results are similar to several other studies that found significant increases in tree ring width following drainage events in black spruce dominated peatlands (Hillman & Roberts, 2006; Turetsky et al., 2011; Wilkinson, Moore, Flannigan et al., 2018). The waterlogged conditions typical of boreal peatlands stunt the growth of large vascular vegetation by limiting rooting depth and by extension limiting AGBM and CFL (Johnston et al., 2015). Drainage, however, improves the growing conditions for large vascular vegetation, allowing deeper rooting (Lieffers & Rothwell, 1987) and increased AGBM and CFL. Higher AGBM and CFL can increase peat drying through increased transpiration (Kettridge et al., 2013; Waddington et al., 2015) and from a higher intensity of the crown fire phase (Thompson et al., 2015), increasing the risk of peat ignition and smoldering.

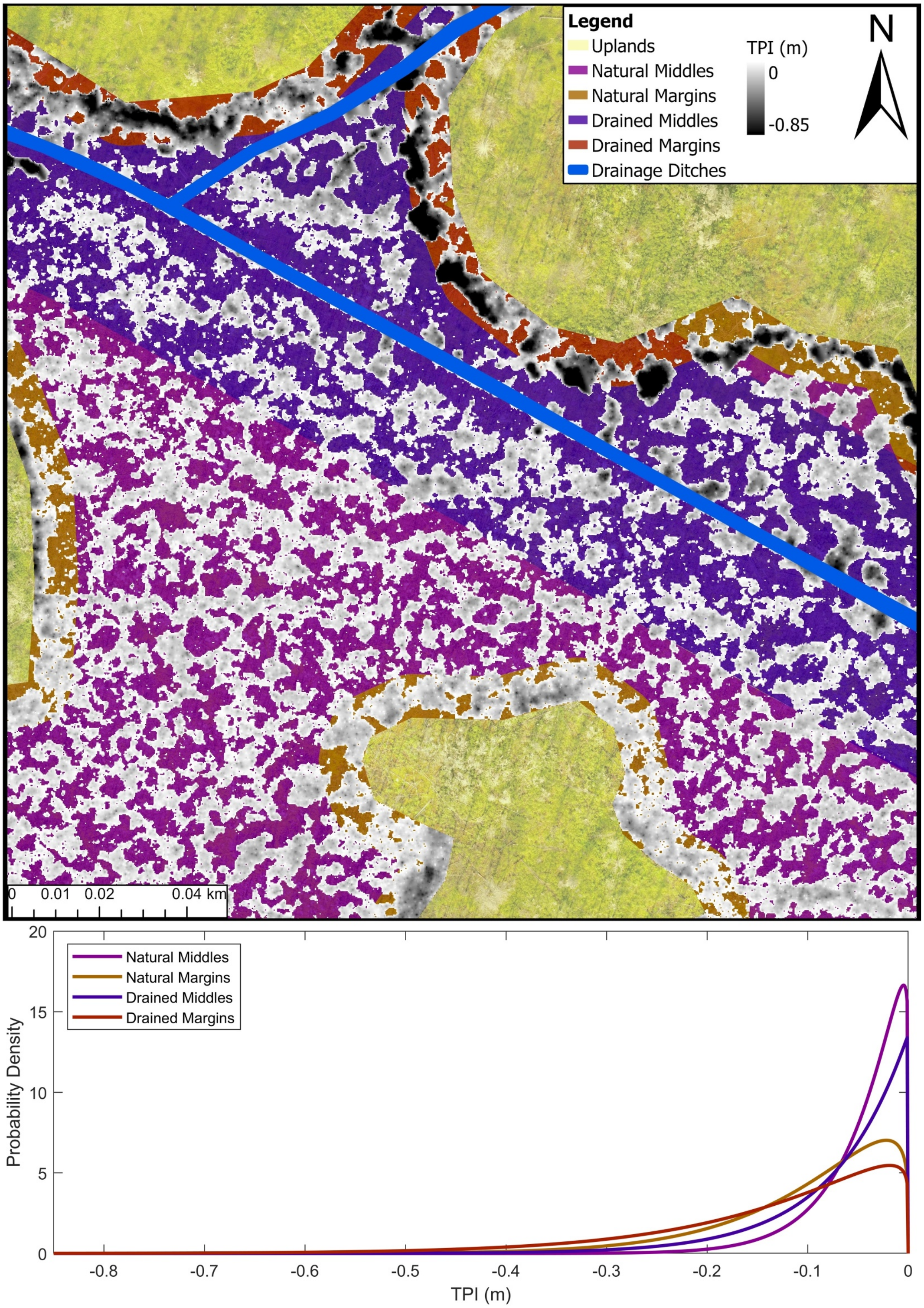

Figure 7. Example section of the study area showing negative topographic position index (TPI) values. Background colors indicate the drainage condition and landscape position categories and areas where the background colors are present and the TPI color scale are absent indicate areas where the TPI values were positive and removed (see Section 2.6). Mineral soil uplands were removed from the TPI analysis. Bottom shows probability density functions of negative TPI data for each of the drainage condition and landscape position categories.

Table 1
Summary Statistics (Mean and Standard Deviation) of Pixels Within the Topographic Position Index (TPI) Rasters and Parameter Values, a and b, for Probability Distribution Functions (Equation 1) fit to the TPI Raster Data for Each Drainage and Peatland Position Class

Landscape category	Mean (m)	Standard deviation (m)	Minimum (m)	*a*	*b*
Natural Middles	−0.048	0.050	−0.855	0.0496	1.0811
Drained Middles	−0.073	0.078	−0.823	0.0732	1.0020
Natural Margins	−0.103	0.087	−0.803	0.1084	1.1774
Drained Margins	−0.141	0.121	−0.824	0.1461	1.1114

The high amount of birch growth is likely due to the area being free of any trees at the time of drainage resulting in a lack of competition by black spruce trees, allowing for the establishment of paper birch in the drier conditions rather than black spruce which would typically dominate boreal peatlands. Although birch is considered a negligible contributor to crown fire activity (de Groot et al., 2022), its presence and increased growth in drained portions of this study site very likely contributed to the increased risk of deep smoldering following drainage. The increase in both black spruce and birch growth following drainage likely increases both the rate of transpiration (and thus drives further drying) while also increasing shading at the surface of the peatland. In addition, boreal broadleaves have been found to be less water conservative compared to conifers (Zha et al., 2010), and thus the increase in paper birch in this study is likely further increasing the drying effect caused by afforestation.

The drying of peat, both due to drainage itself as well as the increased forest water usage, causes higher rates of peat decomposition and consolidation (Waddington & Price, 2000), thus increasing peat bulk densities over time (Waddington et al., 2015). Previous studies in boreal peatlands have found significantly higher peat bulk densities in the top 20–30 cm of peat from drained peatlands compared to that from undrained peatlands (e.g., Minkkinen & Laine, 1998; Sherwood et al., 2013; Turetsky et al., 2011). This increase in the bulk density of near-surface peat is critical because high bulk density peat is able to maintain smoldering at higher gravimetric water contents, therefore increasing the likelihood of ignition and sustained smoldering (Benscoter et al., 2011). The increased shading due to higher canopy cover following drainage can cause shifts in surface vegetation composition. Although we were unable to document this transition at this study site due to all fieldwork being conducted post-fire, more shade-tolerant feather mosses (particularly *Pleurozium schreberi* and *Hylocomium splendens*) have been shown to begin to outcompete *Sphagnum* mosses in forested boreal peatlands as canopy cover increases (Bisbee et al., 2001; Kettridge et al., 2013). Feather mosses have lower moisture retention properties, due to their relatively loose structure, compared to *Sphagnum* species and are more prone to ignition and smoldering during peat fires (Deane et al., 2022; Thompson et al., 2020). Although an increase in paper birch in areas of the study site is likely to reduce crown fire activity, the higher AGBM and resulting peat drying and surface vegetation shifts are likely to contribute to an increase in the vulnerability to peat ignition and deep smoldering.

Here we present a conceptual model, based on the finding of this study and other literature in drained and pristine forested boreal peatlands, outlining an increase in what we refer to as the peat fuel load with time since drainage in boreal peatlands (Figure 8). We define the peat fuel load as the theoretical maximum amount of peat that could be consumed during a fire. Similar to a CFL, which represents all of the biomass within the canopy that could theoretically burn during a fire but excludes that which is unlikely to burn, even during the most extreme fires, the peat fuel load only includes the part of the peat profile that is likely to be consumed during the most extreme smoldering events. Further, just as the amount of canopy fuels actually consumed during a given fire is dependent on the fuel moisture conditions, fire weather, and ultimately fire behavior, and does not always result in the consumption of 100% of the CFL, peat fuel consumption will not always match the total peat fuel load as peat moisture conditions change in response to short (and long-term) meteorological conditions.

As outlined, the lowering of the WT following drainage and the concomitant increase in AGBM kickstarts the WTD-afforestation feedback (Waddington et al., 2015). This, in turn, increases the potential DOB (and peat carbon emissions) near the drainage ditches as well as the total area of the peatland that is likely to experience increased DOB compared to a natural peatland (e.g., Turetsky et al., 2011; Wilkinson, Moore, Flannigan et al., 2018). Prior to drainage, margins are the only parts of the peatland that are at a real risk for deep smoldering (Hokanson et al., 2016; Lukenbach et al., 2015), whereas the rest of the peatland remains relatively resistant due to

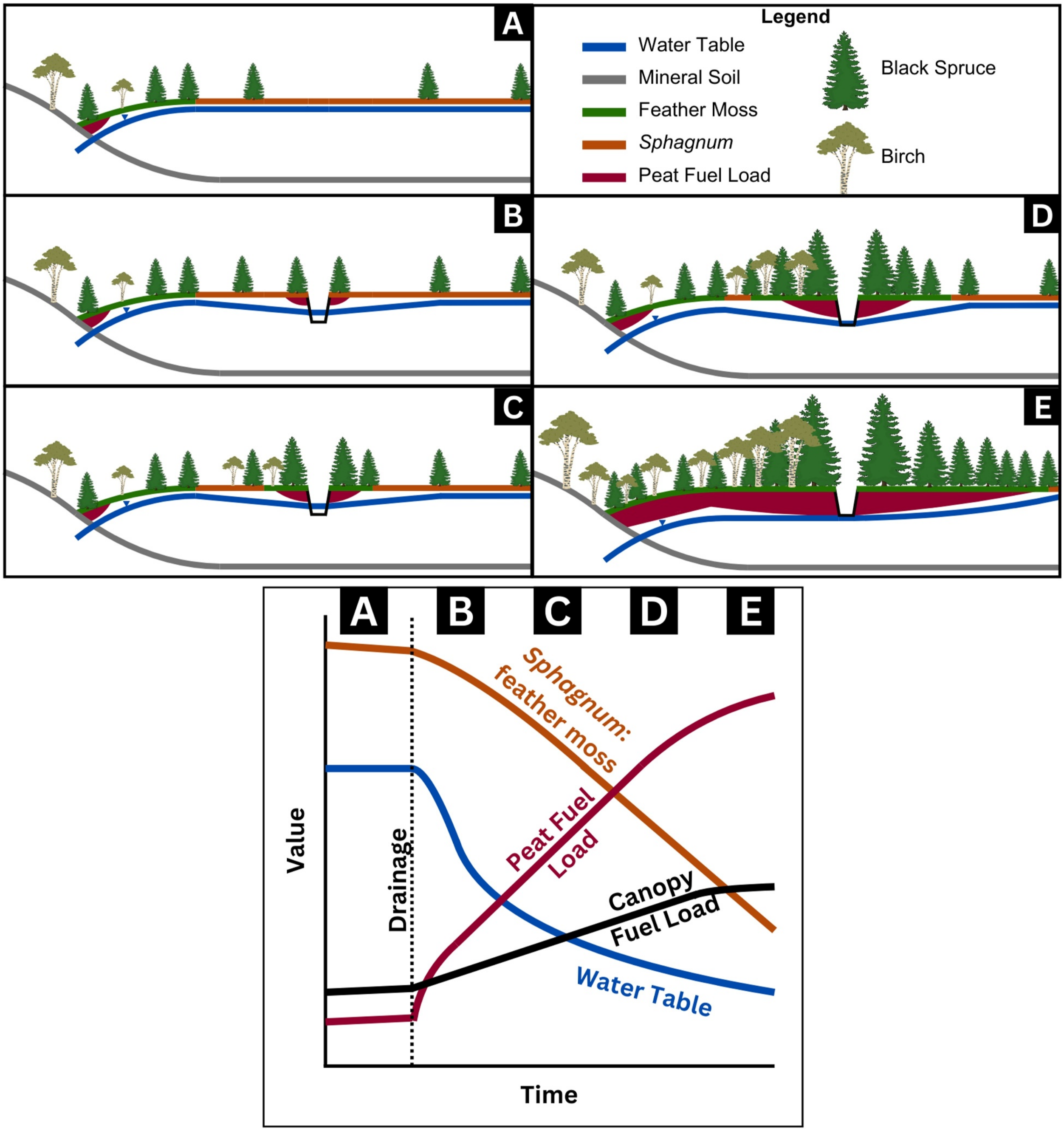

Figure 8. Conceptual diagram of the afforestation and evolution of the peat fuel load through time since drainage in boreal peatlands. Top shows cross sections of a hypothetical peatland showing various timesteps prior to (a) and following drainage (b)–(e). Bottom shows key peatland wildfire and smouldering potential metrics: water table position, canopy fuel load, the ratio between *Sphagnum* and feather moss cover, and the peat fuel load. Marked at the top of the graph are the corresponding letters associated with the timesteps in the top figure.

low CFL, a shallow WT, and *Sphagnum* dominance (Figure 8a). Initially following drainage there is an immediate drop in the WT and a sharp increase in the peat fuel load near ditches as the near-surface peat is left drier (Figure 8b). As time progresses, AGBM and CFL slowly increase due to the greater rooting depths allowing for increased productivity (Hillman & Roberts, 2006; Turetsky et al., 2011; Wilkinson, Moore, Flannigan et al., 2018). This, in turn, results in more shading and forest water use, lowering the *Sphagnum*:feather moss ratio (i.e., a shift to feather moss dominance; Bisbee et al., 2001; Kettridge et al., 2013) and further lowering the WT. As the WT lowers peat decomposition and consolidation occurs increasing bulk densities (e.g., Minkkinen &

Laine, 1998; Sherwood et al., 2013; Turetsky et al., 2011) and the potential for sustained smoldering (Benscoter et al., 2011). The lower WT allows for increased tree productivity thereby further increasing the AGBM and CFL (Figures 8c–8e) and causes peatland middles to begin exhibiting fire behavior more similar to peatland margins. All of this initiates at the ditch interface and radiates outward, ultimately extending beyond the theorized 30 m from ditch boundary (e.g., Belleau & Plamondon, 1992; Landry & Rochefort, 2012; Wilkinson, Moore, Flannigan et al., 2018) used in this study. Although the 30 m from ditch threshold used in this study is used quite extensively throughout the literature and in practice, we suggest that this threshold distance likely changes as time since drainage increases. As suggested by this conceptual model and evidenced by the increased DOBs found beyond the 30 m threshold in this study, there are very likely conditions in which the impact of drainage would be observed beyond this threshold, especially after some time has passed and positive feedbacks, such as the afforestation feedback, have initiated. We suggest that future studies should investigate this effect further.

4.2. Burn Severity

Peatland drainage has been shown to increase peat burn severity in forested boreal peatland middles. A large number of studies have shown that pristine peatland middles tend to experience DOBs of only ~5–10 cm (Hokanson et al., 2016; Lukenbach et al., 2015; Thompson et al., 2020; Turetsky et al., 2011; Wilkinson, Moore, Flannigan et al., 2018; Wilkinson, Moore, Thompson et al., 2018) and are therefore resilient to typical wildfire within the boreal forest of Canada as they are capable of recovering lost carbon (~1 kg C m^{-2}; Wilkinson et al., 2023) in the typical fire return interval of ~120 years (Ingram et al., 2019; Turetsky et al., 2004). Wilkinson, Moore, Flannigan et al. (2018), Wilkinson et al. (2018a) found that peat burn severity increased from 2.5 ± 3.5 cm (0.63 ± 0.93 kg C m^{-2}) in an undrained peatland to 6.4 ± 5.0 (1.65 ± 1.42 kg C m^{-2}) and 16.0 ± 10.2 cm (4.71 ± 3.63 kg C m^{-2}) in moderately and heavily drained portions of a peatland, respectively, whereas Turetsky et al. (2011) found that peat burn severity increased from 7 ± 1 cm (2.0 ± 0.5 kg C m^{-2}) in undrained plots to 19 ± 3 cm (16.8 ± 0.2 kg C m^{-2}) in drained plots. We found that undrained middles had higher than typical burn severities compared to previous studies at an average of 15.3 ± 6.2 cm (3.9 ± 2.1 kg C m^{-2}). This increased burn severity could be due to the impacts of drainage reaching beyond the 30 m from ditch threshold set in this analysis, as highlighted in our conceptual model (Figure 8), as AGBM was found to be elevated beyond 30 m from ditches. Further, weather conditions at the time of the wildfire were particularly dry, providing a potentially compounding effect on increased AGBM and drainage. This is supported by the higher burn severities compared to other studies found in drained middles at 21.6 ± 10.2 cm (12.6 ± 6.5 kg C m^{-2}; Figure 5b).

Of particular concern in this study was our analysis of peatland margins, where we found that drained margins experienced the greatest DOBs and peat carbon losses (Figures 5b and 5d). Previous research studies have shown that pristine boreal peatland margins can experience significantly higher burn severities compared to middles (Hokanson et al., 2016; Lukenbach et al., 2015). Lukenbach et al. (2015) found average DOBs in margins were 42 ± 2 cm (~27 kg C m^{-2}) and Hokanson et al. (2016) found average margin DOBs of 24.5 cm, both significantly greater than the DOBs found in middles. Here we found that natural peatland margins had a DOB of 18.1 ± 5.2 cm (8.0 ± 3.2 kg C m^{-2}), with a few locations having DOBs of ~50 cm (~36.85 kg C m^{-2}). However, no study to date has explicitly measured the impact of drainage in boreal peatland margins on peat burn severity. We found that drained margins experienced the greatest DOB, 26.9 ± 12.6 cm (18.2 ± 10.1 kg C m^{-2}), with some points having DOBs >90 cm (>87 kg C m^{-2}; Figures 5b and 5d). Peatland margins in the boreal plains experience the greatest WT fluctuations as WTs tend to go down in elevation as they move from peatlands into adjacent mineral soil uplands, particularly during water deficits (Hokanson et al., 2020), and thus margins tend to have higher peat bulk densities (Wilkinson et al., 2019) and higher amounts of AGBM (Mayner et al., 2024) compared to peatland middles. This combination leaves them at a greater risk for peat ignition and deep smoldering. Moreover, it is likely that the deeper WTs tend to leave peatland margins fuel-limited rather than moisture- (or energy-) limited, in contrast to peatland middles, that is, vertical smoldering tends to stop in peatland middles as the smoldering front encounters peat which has too much moisture and thus the energy released from smoldering peat is unable to overcome the energy demand of igniting adjacent peat layers (Benscoter et al., 2011; Hokanson et al., 2018). However, in peatland margins smoldering can continue propagating until the smoldering front encounters the underlying mineral soil after consuming all of the peat. In this study, at least five of the DOB measurements found in both natural and drained margin plots are limited because the entirety of the peat profile was consumed and smoldering was fuel-limited, not because smoldering was moisture-limited.

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4.3. Remotely Sensed Peat Burn Severity

Here we assessed a novel method for remotely assessing peat burn severity using drone-based LiDAR and a TPI. Previous research studies have attempted to use pre- and post-fire DEMs to assess the change in surface elevation as a direct measure of DOB (e.g., Nelson et al., 2022). Although this would be the ideal approach of remotely sensing peatland burn severity, the methodology presents challenges, particularly requiring the availability of accurate, high-resolution LiDAR taken within a reasonably short period of time prior to the fire for the particular area of concern and the challenges regarding the accuracy of elevation data from airborne LiDAR in peatland ecosystems (Nelson et al., 2022). Our TPI assessment using only post-fire LiDAR does not provide accurate measurements of the actual peat consumption or carbon lost during a fire, but as shown here can provide a relatively simple and fast approach to identifying areas within a peatland that have experienced the greatest burn severity. Here we show that, in general, our TPI assessment found that the greatest burn severities were in drained margins, and the lowest were found in natural peatland middles, corroborating our in-field assessments of DOB (Figure 7). In the event that pre-fire LiDAR is not available, but post-fire LiDAR can be acquired, this TPI-based burn severity assessment may provide a way for fire managers to identify areas most at risk for holdover smoldering fires and thus where targeted suppression should occur.

4.4. Implications for Peatland and Wildfire Management

High peat burn severity not only results in a high amount of carbon and particulate matter released to the atmosphere (Hu et al., 2018) and a potential shift in peatland carbon sink status (Ingram et al., 2019), but also the potential for further peatland ecosystem regime shifts. The complete loss of the peat profile in peatland margins represents a resetting of the ecosystem and may allow for the encroachment of mineral soil upland vegetation communities into areas previously dominated by peatland-adapted vegetation (e.g., Depante et al., 2019). Further, higher peat burn severity has been shown to shut off critical post-fire peatland ecohydrological feedbacks which prevent water loss and protect remnant peat carbon stores (Kettridge et al., 2019; Wilkinson et al., 2020).

Peatland margins represent the location on the landscape with the greatest risk for deep smoldering combustion and thus the largest challenge for fire management. However, peatland drainage clearly increases the occurrence of deep persistent smoldering, in both peatland middles and margins, with the overall peat fuel load increasing as time since drainage increases (Figure 8). Estimates of the area of peatlands disturbed vary; however, it is estimated that between ∼12,000 and 21,000 km^2 of peatlands have been disturbed in Canada alone, most of which involves drainage as a central component of the disturbance. Silviculture drainage, where forest cover is left intact, makes up ∼700 km^2 of that drainage (Harris et al., 2022; UNEP, 2022). Moreover, peatland drainage has occurred at much higher rates globally. Regional estimates of peatland drainage vary between 3% and 46% (UNEP, 2022) and it is estimated that up to 15% of all peatlands globally have been drained and that ∼12% of the total peatland area (∼580,000 km^2) has been disturbed to the point of no longer accumulating peat (UNEP, 2022). Fuel management strategies should be implemented in these disturbed peatlands to reduce the elevated biomass and CFL levels and mitigate the increase in fire behavior that occurs because of peatland drainage. The rewetting and restoration of peatlands should also be integrated into these fuel management strategies, and they should be considered a form of proactive fire management to reduce the burden that deep smoldering in disturbed peatlands presents to fire management agencies.

4.5. Limitations and Future Research

This study was conducted entirely post-fire within the study sites described, and there is little documentation, other than through the use of historical aerial photographs, of the land management processes occurring on the site prior to the study period (2021–2024). Therefore, although we do compare the changes in forest cover following drainage at our partially drained primary study site to another similar peatland area that is not drained (the control site), we are unable to fully confirm that the two sites are entirely representative of the same pre-drainage ecohydrological condition. Second, we limited our analysis of the AGBM and CFL to areas at the study site that had no trees at the time of drainage in order to avoid any pre-existing variability in forest structure impacting our analysis. However, this means that the forest stands in these areas likely have lower AGBM and CFL values compared to drained areas that did have trees at the time of drainage. Additionally, these untreed areas are likely inherently ecohydrologically distinct to areas with trees prior to drainage, and thus the effect of drainage may not be entirely comparable. Third, the 10 m distance from the edge of the peatland used to determine peatland margins is somewhat simplistic and may not fully account for the specific ecohydrological differences between middles and margins at this site. Finally, we selected a 30 m distance from nearest drainage ditch as a threshold to distinguish drained and undrained (natural) areas within the study site, based on previous literature (e.g., Belleau & Plamondon, 1992; Landry & Rochefort, 2012; Wilkinson, Moore, Flannigan et al., 2018). However, as suggested in our conceptual model, it may be the case that, due to the afforestation feedback, the area around a ditch that is impacted by drainage may expand through time in forested peatlands, and thus some of the plots that we have categorized as natural may in fact be influenced by drainage to some extent, impacting peat burn severity and our ring width analysis. We did not have access to other completely undrained peatland areas that were also within the 2021 fire footprint and thus could not compare our burn severity measurements to a fully unimpacted site. We suggest future research be conducted to explore the potential expansion of the area of drainage influence within drained forested peatlands.

Data Availability Statement

All data and code used in this research are available at (Verkaik et al., 2025). Historical airphotos are not included in this repository as they are under copyright by the Province of Alberta, but are available for purchase at https://www.alberta.ca/ordering-air-photo-products.

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References

ArcGIS Pro. (2024). *ArcGIS Pro (3.4.0)*. ESRI Inc.

Belleau, P., Plamondon, A. P., Lagacé, R., & Pépin, S. (1992). Hydrodynamique d'une pessière noire drainée. *Canadian Journal of Forest Research*, *22*(8), 1063–1070. https://doi.org/10.1139/x92-141

Benscoter, B. W., Thompson, D. K., Waddington, J. M., Flannigan, M. D., Wotton, B. M., de Groot, W. J., & Turetsky, M. R. (2011). Interactive effects of vegetation, soil moisture and bulk density on depth of burning of thick organic soils. *International Journal of Wildland Fire*, *20*(3), 418. https://doi.org/10.1071/WF08183

Bisbee, K. E., Gower, S. T., Norman, J. M., & Nordheim, E. V. (2001). Environmental controls on ground cover species composition and productivity in a boreal black spruce forest. *Oecologia*, *129*(2), 261–270. https://doi.org/10.1007/s004420100719

CDendro (9.8.1). (2022). Cybis Elektronik and data AB. Retrieved from https://www.cybis.se/forfun/dendro/

CloudCompare. (2023). CloudCompare (version 2.13) [GPL software]. Retrieved from http://www.cloudcompare.org/

Clymo, R. S. (1984). The limits to peat bog growth. *Philosophical Transactions of the Royal Society B*, *303*, 605. https://about.jstor.org/terms

CooRecorder (9.8.1). (2022). Cybis Elektronik and data AB. Retrieved from https://www.cybis.se/forfun/dendro/

Deane, P. J., Wilkinson, S. L., Verkaik, G. J., Moore, P. A., Schroeder, D., & Waddington, J. M. (2022). Peat surface compression reduces smouldering fire potential as a novel fuel treatment for boreal peatlands. *Canadian Journal of Forest Research*, *52*(3), 396–405. https://doi.org/10.1139/cjfr-2021-0183

de Groot, W. J., Hanes, C. C., & Wang, Y. (2022). Crown fuel consumption in Canadian boreal forest fires. *International Journal of Wildland Fire*, *31*(3), 255–276. https://doi.org/10.1071/WF21049

Depante, M., Morison, M. Q., Petrone, R. M., Devito, K. J., Kettridge, N., & Waddington, J. M. (2019). Hydraulic redistribution and hydrological controls on aspen transpiration and establishment in peatlands following wildfire. *Hydrological Processes*, *33*(21), 2714–2728. https://doi.org/10.1002/hyp.13522

Gorham, E. (1991). Northern peatlands: Role in the carbon cycle and probable responses to climatic warming. *Ecological Applications*, *1*(2), 182–195. https://doi.org/10.2307/1941811

Government of Alberta. (2023). Air photo library, minisity of environment and protected areas. Retrieved from https://www.alberta.ca/air-photos

Granath, G., Moore, P. A., Lukenbach, M. C., & Waddington, J. M. (2016). Mitigating wildfire carbon loss in managed northern peatlands through restoration. *Scientific Reports*, *6*(1), 1–9. https://doi.org/10.1038/srep28498

Harris, L. I., Richardson, K., Bona, K. A., Davidson, S. J., Finkelstein, S. A., Garneau, M., et al. (2022). The essential carbon service provided by northern peatlands. *Frontiers in Ecology and the Environment*, *20*(4), 222–230. https://doi.org/10.1002/FEE.2437

Hillman, G. R., & Roberts, J. J. (2006). Tamarack and black spruce growth on a boreal fen in central Alberta 9 years after drainage. *New Forests*, *31*(2), 225–243. https://doi.org/10.1007/s11056-005-6570-1

Hokanson, K. J., Lukenbach, M. C., Devito, K. J., Kettridge, N., Petrone, R. M., & Waddington, J. M. (2016). Groundwater connectivity controls peat burn severity in the boreal plains. *Ecohydrology*, *9*(4), 574–584. https://doi.org/10.1002/eco.1657

Hokanson, K. J., Moore, P. A., Lukenbach, M. C., Devito, K. J., Kettridge, N., Petrone, R. M., et al. (2018). A hydrogeological landscape framework to identify peatland wildfire smouldering hot spots. *Ecohydrology*, *11*(4), e1942. https://doi.org/10.1002/ECO.1942

Hokanson, K. J., Peterson, E. S., Devito, K. J., & Mendoza, C. A. (2020). Forestland-peatland hydrologic connectivity in water-limited environments: Hydraulic gradients often oppose topography. *Environmental Research Letters*, *15*(3), 034021. https://doi.org/10.1088/1748-9326/ab699a

Hu, Y., Fernandez-Anez, N., Smith, T. E. L., & Rein, G. (2018). Review of emissions from smouldering peat fires and their contribution to regional haze episodes. *International Journal of Wildland Fire*, *27*(5), 293–312. https://doi.org/10.1071/WF17084

Ingram, R. C., Moore, P. A., Wilkinson, S., Petrone, R. M., & Waddington, J. M. (2019). Postfire soil carbon accumulation does not recover boreal peatland combustion loss in some hydrogeological settings. *Journal of Geophysical Research: Biogeosciences*, *124*(4), 775–788. https://doi.org/10.1029/2018JG004716

Johnston, D. C., Turetsky, M. R., Benscoter, B. W., & Wotton, B. M. (2015). Fuel load, structure, and potential fire behaviour in black spruce bogs. *Canadian Journal of Forest Research*, *45*(7), 888–899. https://doi.org/10.1139/cjfr-2014-0334

Kasischke, E. S., Turetsky, M. R., Ottmar, R. D., French, N. H. F., Hoy, E. E., & Kane, E. S. (2008). Evaluation of the composite burn index for assessing fire severity in Alaskan black spruce forests. *International Journal of Wildland Fire*, *17*(4), 515–526. https://doi.org/10.1071/WF08002

Kettridge, N., Lukenbach, M. C., Hokanson, K. J., Devito, K. J., Petrone, R. M., Mendoza, C. A., & Waddington, J. M. (2019). Severe wildfire exposes remnant peat carbon stocks to increased post-fire drying. *Scientific Reports*, *9*(1), 3727. https://doi.org/10.1038/s41598-019-40033-7

Kettridge, N., Thompson, D. K., Bombonato, L., Turetsky, M. R., Benscoter, B. W., & Waddington, J. M. (2013). The ecohydrology of forested peatlands: Simulating the effects of tree shading on moss evaporation and species composition. *Journal of Geophysical Research: Biogeosciences*, *118*(2), 422–435. https://doi.org/10.1002/jgrg.20043

Kuntzemann, C. E., Whitman, E., Stralberg, D., Parisien, M. A., Thompson, D. K., & Nielsen, S. E. (2023). Peatlands promote fire refugia in boreal forests of northern Alberta, Canada. *Ecosphere*, *14*(5), e4510. https://doi.org/10.1002/ECS2.4510

Landry, J., & Rochefort, L. (2012). The drainage of peatlands: Impacts and rewetting techniques.

Leifeld, J., Alewell, C., Bader, C., Krüger, J. P., Mueller, C. W., Sommer, M., et al. (2018). Pyrgogenic carbon contributes substantially to carbon storage in intact and degraded northern peatlands. *Land Degradation and Development*, *29*(7), 2082–2091. https://doi.org/10.1002/ldr.2812

Lieffers, V. J., & Rothwell, R. L. (1987). Rooting of peatland black spruce and tamarack in relation to depth of water table. *Canadian Journal of Bottany*, *65*(5), 817–821. https://doi.org/10.1139/b87-111

Lukenbach, M. C., Hokanson, K. J., Moore, P. A., Devito, K. J., Kettridge, N., Thompson, D. K., et al. (2015). Hydrological controls on deep burning in a northern forested peatland. *Hydrological Processes*, *29*(18), 4114–4124. https://doi.org/10.1002/hyp.10440

MATLAB (9.10.0 (R2021a)). (2021). *MATLAB (9.10.0 (R2021a))*. The MathWorks Inc.

Maxwell, R. S., & Larsson, L.-A. (2021). Measuring tree-ring widths using the CooRecorder software application. *Dendrochronologia*, *67*, 1125–7865. https://doi.org/10.17632/r3v7236kkz.1

Mayner, K. M., Moore, P. A., Wilkinson, S. L., Gage, H. J. M., & Waddington, J. M. (2024). Differential post-fire vegetation recovery of boreal plains bogs and margins. *Wetlands*, *44*(44), 44. https://doi.org/10.1007/s13157-024-01794-8

Minkkinen, K., & Laine, J. (1998). Effect of forest drainage on the peat bulk density of pine mires in Finland. *Canadian Journal of Forest Research*, *28*(2), 178–186. https://doi.org/10.1139/x97-206

Morris, P. J., Belyea, L. R., & Baird, A. J. (2011). Ecohydrological feedbacks in peatland development: A theoretical modelling study. *Journal of Ecology*, *99*(5), 1190–1201. https://doi.org/10.1111/j.1365-2745.2011.01842.x

Nelson, K., Chasmer, L., & Hopkinson, C. (2022). Quantifying lidar elevation accuracy: Parameterization and wavelength selection for optimal ground classifications based on time since fire/disturbance. *Remote Sensing*, *14*(20), 5080. https://doi.org/10.3390/rs14205080

Pellerin, S., Lavoie, C., Pellerin, S., & Lavoie, C. (2000). Peatland fragments of southern quebec: Recent evolution of their vegetation structure. *Canadian Journal of Botany*, *78*(2), 255–265. https://doi.org/10.1139/b99-186

Price, J. S., McCarter, C. P. R., & Quinton, W. L. (2023). Groundwater in peat and peatlands. In *The Groundwater Project* (2nd ed.). https://doi.org/10.21083/978-1-77470-015-0

R Core Team. (2022). *R: A language and environment for statistical computing*. R Foundation for Statistical Computing.

Rein, G., & Huang, X. (2021). Smouldering wildfires in peatlands, forests and the arctic: Challenges and perspectives. *Current Opinion in Environmental Science and Health*, *24*, 100296. https://doi.org/10.1016/j.coesh.2021.100296

Roussel, J.-R., Goodbody, T. R., & Tompalski, P. (2023). LidR package. https://r-lidar.github.io/lidRbook/index.html

Scholten, R. C., Jandt, R., Miller, E. A., Rogers, B. M., & Veraverbeke, S. (2021). Overwintering fires in boreal forests. *Nature*, *593*(7859), 399–404. https://doi.org/10.1038/s41586-021-03437-y

Sharma, M., & Zhang, S. Y. (2004). Height-diameter models using stand characteristics for Pinus banksiana and Picea mariana. *Scandinavian Journal of Forest Research*, *19*(5), 442–451. https://doi.org/10.1080/02827580410030163

Sherwood, J. H., Kettridge, N., Thompson, D. K., Morris, P. J., Silins, U., & Waddington, J. M. (2013). Effect of drainage and wildfire on peat hydrophysical properties. *Hydrological Processes*, *27*(13), 1866–1874. https://doi.org/10.1002/hyp.9820

Silins, U., & Rothwell, R. L. (1998). Forest peatland drainage and subsidence affect soil water retention and transport properties in an Alberta peatland. *Soil Science Society of America Journal*, *62*(4), 1048–1056. https://doi.org/10.2136/sssaj1998.03615995006200040028x

Thompson, D. K., Schroeder, D., Wilkinson, S. L., Barber, Q., Baxter, G., Cameron, H., et al. (2020). Recent crown thinning in a boreal black spruce forest does not reduce spread rate nor total fuel consumption: Results from an experimental crown fire in Alberta, Canada. *Fire*, *3*(3), 28. https://doi.org/10.3390/fire3030028

Thompson, D. K., Wotton, B. M., & Waddington, J. M. (2015). Estimating the heat transfer to an organic soil surface during crown fire. *International Journal of Wildland Fire*, *24*(1), 120–129. https://doi.org/10.1071/WF12121

Turetsky, M. R., Amiro, B. D., Bosch, E., & Bhatti, J. S. (2004). Historical burn area in western Canadian peatlands and its relationship to fire weather indices. *Global Biogeochemical Cycles*, *18*(4), 1–9. https://doi.org/10.1029/2004GB002222

Turetsky, M. R., Donahue, W. F., & Benscoter, B. W. (2011). Experimental drying intensifies burning and carbon losses in a northern peatland. *Nature Communications*, *2*(1), 514. https://doi.org/10.1038/ncomms1523

UNEP. (2022). Global peatlands assessment: The state of the world's peatlands. Retrieved from https://www.unep.org/resources/global-peatlands-assessment-2022

Ung, C. H., Bernier, P., & Guo, X. J. (2008). Canadian national biomass equations: New parameter estimates that include British Columbia data. *Canadian Journal of Forest Research*, *38*(5), 1123–1132. https://doi.org/10.1139/X07-224

Ung, C.-H., Lambert, M. C., Raulier, F., Guo, J., & Bernier, P. Y. (2017). Biomass of trees sampled across Canada as part of the Energy from the Forest Biomass (ENFOR) Program. https://doi.org/10.23687/fbad665e-8ac9-4635-9f84-e4fd53a6253c

Verkaik, G. J., Eckert, M. G. K., Wilkinson, S. L., Moore, P. A., & Waddington, J. M. (2025). Fuel loads and peat smouldering carbon loss increase following drainage in a forested boreal peatland – Dataset (Version 2) [Dataset]. *Zenodo*. https://doi.org/10.5281/zenodo.15644161

Waddington, J. M., Morris, P. J., Kettridge, N., Granath, G., Thompson, D. K., & Moore, P. A. (2015). Hydrological feedbacks in northern peatlands. *Ecohydrology*, *8*(1), 113–127. https://doi.org/10.1002/eco.1493

Waddington, J. M., & Price, J. S. (2000). Effect of peatland drainage, harvesting, and restoration on atmospheric water and carbon exchange. *Physical Geography*, *21*(5), 433–451. https://doi.org/10.1080/02723646.2000.10642719

Wieder, R. K., Scott, K. D., Kamminga, K., Vile, M. A., Vitt, D. H., Bone, T., et al. (2009). Postfire carbon balance in boreal bogs of Alberta, Canada. *Global Change Biology*, *15*(1), 63–81. https://doi.org/10.1111/j.1365-2486.2008.01756.x

Wilkinson, S. L., Andersen, R., Moore, P. A., Davidson, S. J., Granath, G., & Waddington, J. M. (2023). Wildfire and degradation accelerate northern peatland carbon release. *Nature Climate Change*, *13*(5), 456–461. https://doi.org/10.1038/s41558-023-01657-w

Wilkinson, S. L., Moore, P. A., Flannigan, M. D., Wotton, B. M., & Waddington, J. M. (2018). Did enhanced afforestation cause high severity peat burn in the Fort McMurray Horse River wildfire? *Environmental Research Letters*, *13*(1), 014018. https://doi.org/10.1088/1748-9326/aaa136

Wilkinson, S. L., Moore, P. A., Thompson, D. K., Wotton, B. M., Hvenegaard, S., Schroeder, D., & Waddington, J. M. (2018). The effects of black spruce fuel management on surface fuel condition and peat burn severity in an experimental fire. *Canadian Journal of Forest Research*, *48*(12), 1433–1440. https://doi.org/10.1139/cjfr-2018-0217

Wilkinson, S. L., Moore, P. A., & Waddington, J. M. (2019). Assessing drivers of cross-scale variability in peat smoldering combustion vulnerability in forested boreal peatlands. *Frontiers in Forests and Global Change*, *2*. https://doi.org/10.3389/ffgc.2019.00084

Wilkinson, S. L., Verkaik, G. J., Moore, P. A., & Waddington, J. M. (2020). Threshold peat burn severity breaks evaporation-limiting feedback. *Ecohydrology*, *13*(1), e2168. https://doi.org/10.1002/eco.2168

Xu, J., Morris, P. J., Liu, J., & Holden, J. (2018). Peatmap: Refining estimates of global peatland distribution based on a meta-analysis. *Catena*, *160*, 134–140. https://doi.org/10.1016/J.CATENA.2017.09.010

Yu, Z., Loisel, J., Brosseau, D. P., Beilman, D. W., & Hunt, S. J. (2010). Global peatland dynamics since the last glacial maximum. *Geophysical Research Letters*, *37*(13), L13402. https://doi.org/10.1029/2010GL043584

Zha, T., Barr, A. G., van der Kamp, G., Black, T. A., McCaughey, J. H., & Flanagan, L. B. (2010). Interannual variation of evapotranspiration from forest and grassland ecosystems in western Canada in relation to drought. *Agricultural and Forest Meteorology*, *150*(11), 1476–1484. https://doi.org/10.1016/j.agrformet.2010.08.003

Erratum

The originally published version of this article contained errors. The fifth sentence of the Abstract has been corrected to the following: "Drained peatland margins experienced the greatest peat burn severity with a mean depth of burn of 26.9 ± 12.6 cm (18.2 ± 10.1 kg C m^{-2}) compared to natural middles at 15.3 ± 6.2 cm (3.9 ± 2.1 kg C m^{-2}), where peat burn severity increased with proximity to ditches and greater aboveground biomass." The second sentence of Section 3.3 has been corrected to the following: "DOB and peat carbon loss were significantly different (DOB $X^2 = 13.35$, df = 3, $p = 0.003$; carbon loss $X^2 = 30.6$, df = 3, $p < 0.001$) between natural middles and drained margins when grouped by drainage and location, where natural middles had the lowest plot average mean DOB of 15.3 ± 6.2 cm (3.9 ± 2.1 kg C m^{-2}), followed by natural margins at 18.1 ± 5.2 cm (8.0 ± 3.2 kg C m^{-2}), then drained middles at 21.6 ± 10.2 cm (12.6 ± 6.5 kg C m^{-2}), and the greatest plot average DOB found in drained margins with a mean of 26.9 ± 12.6 cm (18.2 ± 10.1 kg C m^{-2}; Figures 5b and 5d)." In the fourth sentence of the first paragraph of Section 4.2, the expression 8.3 ± 2.1 kg C m^{-2}" has been corrected to the following: 3.9 ± 2.1 kg C m^{-2}. In the last sentence of the same paragraph, the expression 25.6 ± 6.5 kg C m^{-2} has been corrected to the following: 12.6 ± 6.5 kg C m^{-2}. In the fourth sentence of the second paragraph of Section 4.2, the expression 13.2 ± 3.2 kg C m^{-2} has been corrected to the following: 8.0 ± 3.2 kg C m^{-2}. In the sixth sentence of the same paragraph, the expression 34.0 ± 10.1 kg C m^{-2} has been corrected to the following: 18.2 ± 10.1 kg C m^{-2}. This may be considered the authoritative version of record.