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Effects of snow and climate on soil temperature and frost development in forested peatlands in minnesota, USA

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ABSTRACT

Black spruce (*Picea mariana*) peatlands play important ecologic and economic roles in the temperate-boreal region of North America, providing a valuable timber resource while also performing important ecosystem functions. Climate models project decreases in the amount of snowfall received throughout the temperate-boreal region by 2100, as average wintertime temperatures increase. We used a paired-plot experimental design to assess the effect of snow removal on soil temperature and frost development at six forested peatland sites in northern Minnesota, USA, during the three winters from 2017 to 2020. Treatments consisted of 1) removal of snow throughout the winter, or 2) ambient snow cover conditions. During the three years of the study, there was a significant effect of snow removal by mid-winter that continued into late winter and spring, where removal of snow increased soil frost depth compared to plots with ambient snow cover treatment. Soil temperatures in the removal plots were highly responsive to air temperature fluctuations to depths of 20 cm or more, whereas the ambient snow cover soils exhibited little fluctuation and maintained temperatures near or above 0° C for much of the winter season. We found that each cumulative freezing degree day resulted in an average of 0.36 cm of soil frost development in snow removal plots, as compared to 0.07 cm depth in the ambient treatment plots. Soils were significantly colder through much of the summer growing season in the removal treatment compared to the ambient treatment, with detectable soil frost in the soil profile as late as mid- to late-June. These results indicate that predicted changes in wintertime precipitation may result in increased development of soil frost in forested peatland systems, although some of this effect may be offset by predicted concurrent increases in air temperature. We did not measure indicators of biological activity, but the large and prolonged reduction in soil temperature with snow removal is likely to depress biological activity throughout the growing season and the many ecosystem functions it influences. Because of the role that soil temperature and frost play on the hydrologic and ecological processes of peatlands, as well as the crucial role of soil frost in peatland forest management, findings of this study provide important insight into the potential effects of altered winter conditions on these expansive and ecologically important ecosystems.

1. Introduction

Forested peatlands are a defining landform of the boreal region, providing important ecosystem services such as carbon storage, fiber supply, and habitat for rare flora and fauna. Peatlands cover more than four million km^2 of the earth's terrestrial surface, with most known peatlands concentrated in the boreal regions of Canada, Scandinavia, Russia, and northern portions of the United States (such as Alaska and the Lake States) (Frolking et al., 2011; Xu et al., 2018). Minnesota alone contains over 24,000 km^2 of peatlands, over 10% of the state's total land area (Wright et al., 1992). The boreal region has historically experienced long winter seasons with cold air temperatures, deep snow accumulation, and seasonal soil frost development. Changes to these winter conditions could have cascading effects on peatland hydrology and decomposition, factors strongly related to the ability of peatlands to store and sequester carbon (Dunn et al., 2007; Frolking et al., 2011; Gorham, 1991; Groffman et al., 1999, 2001; Huang et al., 2017; Joosten et al., 2012; Xu et al., 2018; Yu et al., 2011). Changes in the winter season conditions also have potential to severely constrain fiber supply from peatlands and associated economic benefits, as forest harvesting

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can occur only when sufficient soil frost is present to support harvest equipment (Shoop, 1995).

Because of their location at the southern edge of the boreal zone, Minnesota's peatlands are considered a useful "bellwether" of potential climate change effects on peatlands in the larger boreal region (Wright et al., 1992; Handler et al., 2014). In this region, climate change is expected to increase winter air temperatures and decrease snowfall and snowpack, as more precipitation is expected to fall as rain rather than snow (Kellomäki et al., 2010; Handler et al., 2014). The disproportionately warmer winter temperatures predicted by many climate models could have drastic impacts on the development of soil frost; by the end of this century, model simulations estimate a drop in the average number of days with soil frost (~30) and decreased total frost depth (up to 40%) in this region (Henry, 2008; Kellomäki et al., 2010; Handler et al., 2014). These anticipated changes are supported by observations over the past several decades which have shown increased warming of air temperatures (0.7 °C per decade since 1961) during the winter months and a lengthening of the growing season due to earlier spring thaw (Sebestyen et al., 2011; Dymond et al., 2014).

The effects of climate-related changes to winter snow conditions on ecosystem processes has been well-established across ecosystems types, with observations in forest, tundra, wetland, and grassland systems, emphasizing the important role of winter climate conditions on ecosystem function (Sanders-DeMott et al., 2017). For instance, altered snow cover patterns in the Arctic have resulted in effects on ecosystem productivity, changes in flowering phenology, and species abundance and richness (Wipf and Rixen, 2010). In temperate ecosystems, the potential decrease in snow cover extent and length of season may cause an increase in fine root mortality, counteracting the potential benefit of shorter and warmer winters on plant overwintering success and longer growing season (Tierney et al., 2001; Cleavitt et al., 2008; Kreyling, 2010). Some studies have investigated the effects of snow cover manipulation in bog and other wetland environments (Robroek et al., 2013; Huang et al., 2017), but there is much uncertainty on how a decrease in snow cover might affect the vast forested peatlands of the northern temperate and boreal region.

Snow cover extent has decreased in the Northern Hemisphere over the past several decades, and this trend is expected to continue in all but the coldest climates (Derksen and Brown, 2012; Hernández-Henríquez et al., 2015; Thackeray et al., 2019). One method by which researchers have attempted to study the impact of changing winter conditions on ecosystem processes is by using snow removal techniques, simulating a future with less snow cover. Snow manipulation studies have been found to be an effective method to evaluate the effects of climate change on ecosystem processes (Wipf and Rixen, 2010). Of the snow removal studies conducted to date, most have been completed in upland hardwood forest sites with mineral soils (Decker et al., 2003; Groffman et al., 1999, 2001; Hardy et al., 2001; Hart and Lull, 1963). These studies found that decreased snow cover results in colder soils and increased depth of soil frost, which is associated with changes in carbon and nutrient cycling (Decker et al., 2003; Groffman et al., 2001; Hardy et al., 2001; Hart and Lull, 1963). However, because these studies were conducted in temperate ecosystems with mineral soils, their applicability to boreal peatland systems is unclear due to the colder and wetter conditions common to peatlands, factors that can have implications for frost development due to the thermal conductivity of water in saturated organic soils.

This study aimed to provide a better understanding of the effects of snow cover and winter air temperature on soil temperature and frost, variables which have large influence on peatland functions including carbon storage, hydrologic function, and fiber production. In this study, we assessed how changing winter conditions may affect soil frost development in peatlands by using snow removal in a paired plot experimental design. This research design was based on similar studies conducted on upland forest sites (Decker et al., 2003; Groffman et al., 1999, 2001; Hardy et al., 2001; Hart and Lull, 1963). The main objective of this study was to understand the relationships among air temperature, snow cover, soil temperature, and soil frost depth in forested peatland systems. We also explored techniques by which soil frost depth may be estimated from easily measurable proxy variables, such as air temperature and cumulative freezing days. We hypothesized that removal of snow cover would result in colder soils and deeper soil frost development than in plots with ambient snow cover conditions, consistent with the results of previous studies. Determining the factors which moderate the development of soil frost in peatlands will be important to better understand how these relationships may be affected by climate change, and in turn influence ecosystem services including carbon storage and fiber supply.

2. Methods

2.1. Site description

The study was conducted over the course of three winter seasons, 2018, 2019, and 2020, in Minnesota, USA, at six replications (sites) across three locations: the Cloquet Forestry Center (CFC), Hubachek Wilderness Research Center (HWRC), and Marcell Experimental Forest (MEF) (Fig. 1). These research forests are all located in the northeastern region of Minnesota and compose an ecosystem gradient, with CFC containing a mixture of boreal and temperate tree species, while MEF and HWRC are dominated by boreal vegetation. The region has a moist and cool climate, with average annual precipitation of 71 to 81 cm and mean annual temperatures of 2.8 to 4.4 °C across the region (Minnesota Department of Natural Resources, 2017). About one-third of the total annual precipitation in northern Minnesota falls as snow, with a common snow accumulation season of November to April (Sebestyen et al., 2011). Meteorological winter (Dec. – Feb.) average temperatures range from −12.8 to −10.6 °C (Minnesota Department of Natural Resources, 2017). Soils are all classified as Histosols that are greater than 1 m deep which formed on glacial moraines or outwash and Lake plains (Table 1).

For the purposes of this study, winter was defined as Oct. – Apr. of each study year, reflecting the typical onset and conclusion of freezing air temperatures in the study region. Conditions were generally slightly colder (~1–2 ℃) than average during the first two winters of the study and slightly warmer (~1–1.5 ℃) than average during the third winter (when compared to 30-Year Normal temperature records) (Table S1). All three years of the study had average to high snowfall amounts, when compared to 30-Year Normal snowfall records (Minnesota State Climatology Office, 2019) (Table S2). On average, snowfall amounts were 23% higher, 9% higher, and equal to the 30-Year Normal at CFC, HWRC, and MEF, respectively. Across all sites, snowfall was approximately 10% higher than Normal during the study period.

3. Experimental design

A paired-plot experimental design was utilized for this study, with two sites at each of the three study locations. Each site contained two 4x4 m plots: a snow removal treatment plot and ambient snow cover treatment plot which served as control. Previous studies have shown that manipulation of snow cover via snow removal provides a reasonable, if inexact, proxy of climate change-influenced decreases in snow cover (Groffman et al., 1999, 2001; Hardy et al., 2001; Decker et al., 2003; Freppaz et al., 2008; Wipf & Rixen, 2010; Robroek et al., 2013). Plots were all in forested peatlands but were situated in tree canopy openings such that few or no trees were present within the boundaries of the study plots, as pictured in Fig. 2. The plots were delineated in an east/west orientation and randomly assigned to a treatment. For snow removal treatments, lengths of aluminum window screening were laid on the ground surface to operate as a snow removal mechanism and as a barrier to capture snowfall prior to it reaching the ground (Fig. 2). The use of aluminum window screening did not inhibit gas exchange from the snow removal plots and resulted in negligible blocking of sunlight,

Fig. 1. Research site locations in Northern Minnesota. The dark grey areas on the expanded forest maps are the approximate areas of the peatland systems in which the research sites were installed, with stars marking plot locations within the peatlands. Area a) Hubachek Wilderness Research Center (UMN), b) Marcell Experimental Forest (USFS Chippewa National Forest), and c) Cloquet Forestry Century (UMN).

Table 1
Measured site characteristics. Peat depth and depth to water table are shown plus or minus one standard deviation of the mean. Depth to water table is shown as depth below the soil surface and was measured via water table wells installed at each research site.

	Site	Average Peat Depth (cm)		2018 Avg. Depth to Water-Table (cm) (May 21 - Oct. 10)		2019 Avg. Depth to Water-Table (cm) (May 21 - Oct. 10)		Avg. Basal Area (m^2 per hectare)	Soil Series[1]
Cloquet Forestry Center (CFC)	CFC-1	56	± 6	4.5	±5.1	3.4	±4.3	102	Loxley muck
	CFC-2	181	±43	4.8	±2.0	7.2	±4.9	106	Moose Lake mucky peat
Hubachek Wilderness Research Center (HWRC)	HWRC-1	221	±7	4.9	±1.9	13.5	±5.1	98	Rifle soils, spooner catena
	HWRC-2	137	±32	1.9	±1.9	3.1	±4.6	128	Rifle soils, spooner catena
Marcell Experimental Forest (MEF)	MEF-1	225	±9	8.5	±3.1	20.9	±5.3	54	Loxley muck
	MEF-2	146	±38	4.8	±1.7	12.8[2]	±2.1[2]	84	Mooselake and Lupton soils

[1] Soil series name is from the USDA Natural Resources Conservation Service official series descriptions https://www.nrcs.usda.gov/wps/portal/nrcs/detail/soils/survey/geo/?cid = nrcs142p2_053587.
[2] Data for May 21, 2019 – August 19, 2019 due to data logging error following Aug. 19, 2019.

while providing an effective surface for the interception and removal of snowfall. This allowed for almost complete removal of snow with minimal disturbance to the *Sphagnum sp.* moss layer and soft organic soils. The ambient snow cover treatment plots were not covered with screening (Fig. 2). On the snow removal plots, snow was removed by lifting the screen and shaking snow off the plot or via shovel across the screen surface. Snow was removed from the treatment plots within 24 h or one business day following a snowfall event of 5 cm or more. If no snowfall event exceeding 5 cm occurred in a week, the plots were checked once per week, snow depth measured on ambient treatment plots, and removal treatment plots cleared of incidental snow.

3.1. Field measurements

Soil temperature was measured via Decagon 5TM temperature/moisture sensors (+/−1.0 °C, +/−0.03 m^3/m^3; METER Group, Pullman WA) installed at depths 5, 10, 15, 20, 40, and 60 cm in each ambient snow cover plot and at 5, 10, 15, and 20 cm in each snow removal plot. The soil temperature at depths 40 and 60 cm of the snow removal plots was measured via Thermochron® iButton sensors (+/−0.5 °C; model DS1921Z; Maxim Integrated Products, Inc., Sunnyvale CA) housed in water-tight casings. Measurement interval for the 5TM sensors was 15 min, while the iButton sensors recorded temperature at 180 min intervals, due to constraints in sensor memory. Measurements were initiated on Oct. 20, 2017 and continued until Apr. 25, 2020. In 2019, data at 40 and 60 cm depths was not obtained during the late-winter, a)

b)

Fig. 2. Paired research plot during the autumn of experiment installation (a) and the winter of 2018 (b). In (a), the screening system for snow removal is visible on the snow removal plot (pink markers). The ambient snow cover plot does not have screening coving it and is delineated with blue markers. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

spring, and early summer periods (Table S3) due to a data recording error. In addition, during the summer of 2018, several weeks contained no measurements at 40 and 60 cm depths due to a delay in replacing iButton sensors that had reached full memory capacity.

Depth of soil frost was recorded within the treatment plots at each site to validate the use of soil temperature as a proxy for soil frost and for additional analyses. The protocol utilized in this study for measuring the frost depth was previously developed at the MEF and was implemented without major modification (USDA Forest Service, 2007). In this protocol, soil frost was measured utilizing a hand-held power drill fitted with a 1 m long drill bit, which was drilled into the soil until breakthrough of the frost layer occurred. Any snow cover depth over the soil was recorded and subtracted from the resulting total depth measurement. Soil frost thickness was recorded to the nearest inch, and measurements occurred at all sites a minimum of once per week throughout the winters of 2019 and 2020, as well as the later part of the winter of 2018 at the CFC and MEF sites.

Air temperature was measured at each site with either HOBO temperature and relative humidity sensors (+/−0.21 °C, +/−2.5%; model U23 Pro v2, Onset Computer Corporation, Bourne MA) or Thermochron® iButton sensors (+/−0.5 °C; model DS1921G, Maxim Integrated Products, Inc., Sunnyvale CA).

Additional site characteristics, including depth to water table, peat depth, and basal area, were measured during the course of the study (Table 1). Depth to water table was measured during both intervening summers of the study. Peat depth was measured using a manual depth probe during the summer of 2018. Basal area measurements were conducted on variable radius plots using a 10-factor wedge prism.

3.2. Data analyses

Statistical analyses were completed using R statistical software (R Core Team 2018). Soil and air temperature data were first averaged by day and then by week (Wickham et al., 2019). Soil temperature and frost measurements were also compared to determine if soil temperature is an appropriate proxy for soil frost development. Linear regression was used to compare observed frost depth measurements taken during the months of Dec. – Feb. in the winters of 2019 and 2020 with the depth where soil temperature was interpolated to be 0 °C, indicating the estimated extent of soil frost development (Fig. 4). Outliers and cases in which no frost was detected via manual measurement were removed prior to conducting this regression.

Treatment effects on weekly mean soil temperature were assessed with a mixed effects model with repeated measures analysis, with location and site-within-location as random variables, and treatment, week, sensor depth, and their interactions modeled as fixed effects (Pinheiro et al., 2017). To calculate the appropriate covariance matrices to account for correlation among sensor depths and among measurement weeks, the weekly-averaged soil temperature data were divided into six discreet time periods each year (each approximately 8 weeks in length, Table S3). The three winters of the study were broken into three discreet periods: early winter (approx. late Oct. – mid-Dec.), mid-winter (mid-Dec. – mid-Feb.), and late winter (mid-Feb. – late April). When significant treatment effects were found ($p < 0.05$), least-squared means analyses with Tukey adjustment were used to identify weeks and depths where significant differences existed between snow removal and ambient treatments across all sites (Lenth, 2016).

Linear regression was used to assess relationships between frost depth and cumulative freezing degree days (FDDs) and cumulative freezing temperatures across all sites during the 2019 and 2020 winter seasons. Cumulative FDDs were calculated as the running total of days in which average daily air temperature was equal to or less than 0 °C. Cumulative freezing temperatures were the sum of daily average temperatures that were equal to or less than 0 °C during the winter, beginning at the defined start of each winter period (Table S3). We also conducted analysis of covariance (ANCOVA) to test for site-specific effects on the relationship between frost depth and FDDs using alternative models allowing for 1) different intercepts and slopes among sites, 2) different intercepts among sites, 3) different slopes among sites, and 4) no difference in slopes or intercepts among sites. AIC was used to identify the best of these alternative models.

4. Results

4.1. Relationship between soil temperature and soil frost

Average daily soil temperature was assumed to have a linear relationship between successive measurement depths, allowing us to interpolate the depth below the soil surface at which the soil temperature reached 0 °C, representing frost extent. The average R^2 for the linear relationship between soil depth and average daily temperature was ~ 0.95 for the selected dates, supporting this assumption.

During the months of Dec. – Feb. of each study year, a total of 208 frost measurements were conducted that resulted in measurable soil frost. For the purposes of the frost depth interpolation, 130 of these measurements were deemed appropriate. Of the measurements removed, 75 were removed because, although frost was measured, soil temperatures were not recorded below 0 °C (but typically less than 1 °C), prohibiting interpolation of frost depth. These instances largely occurred in the ambient snow cover plots (62 of 75 cases), where soil temperature rarely dropped below 0 °C, even at shallow soil depths. An additional 3 measurements were removed because we were unable to interpolate frost depth due to insufficient soil temperature data.

There was a significant relationship between the observed frost depths and interpolated depths at which 0 °C occurred ($p < 0.0001$; $R^2 = 0.73$) (Fig. 3). However, the estimated slope was less than 1 with many of the points falling above the 1:1 ($y = x$), indicating that measured frost depth tended to be greater than interpolated frost depth based on soil temperature. When forcing the intercept through 0 to account for the reality that soil frost cannot occur above soil depths of 0 cm (ground surface), the equation of best fit for the data is $y = 1.11x$ with $R^2 = 0.89$. These results would indicate that soil temperature is an appropriate, if conservative, proxy for soil frost development. This is further supported by the number of instances where soil frost was detected but the average daily soil temperature did not drop below 0 °C (n = 75, see description above).

4.2. Treatment effects on soil temperature

During all three winters of the study, soil temperature in the snow removal treatment became significantly colder than soils in the ambient treatment (Fig. 5). Soils in the snow removal treatment plots also remained colder during the spring and summer months, before largely recovering in the late summer and autumn (Fig. 4). Weekly average soil temperatures as low as −7.9 °C were observed in the snow removal treatment plots (predominantly at shallow depths); by contrast, soil temperatures in ambient snow cover plots rarely dropped below freezing throughout the study period, with the coldest weekly average soil temperature recorded at −0.5 °C.

In general, soil temperatures were significantly colder in the snow removal treatment by mid-winter and remained colder throughout the late winter period with soil temperatures recorded well below 0 °C. There was a significant 3-way interaction among treatment, soil depth, and week during the mid- and late-winter time periods in all three winters of the study (Tables S4–S6). During each mid-winter period, the average difference between treatments decreased with depth, ranging from relatively large differences of 3.3 °C, 2.9 °C, and 2.4 °C (during each consecutive winter season) at 5 cm and relatively small differences of 1.0 °C, 0.9 °C, and 0.9 °C at 60 cm. Interestingly, during the mid-winter periods, the soils under the ambient snow cover treatment became increasingly warmer under each subsequent winter of the study, while the soils that received the snow removal treatment were colder with each successive year. For example, average soil temperatures under the ambient snow cover treatment increased by approximately 30% and 60% at 10 cm depth for winters 2019 and 2020, respectively, relative to the 2018 winter, and decreased by 12% and 43% in the same years for the snow removal treatment. Similar patterns were observed at 5 cm and 15 cm depths for both ambient and removal treatments (data not shown).

During the later-winter period of all three study winters there was significant interaction among treatment, week, and depth (Tables S4–S6). In the upper 20 cm of the soil profile, the mean weekly difference between treatments ranged from 1.1 to 1.2 °C during the late-winter of 2018, from 1.2 to1.4 °C during the late-winter of 2019, and was 1.4 °C across all depths during the late-winter of 2020. Like the mid-winter period, soil temperatures in the upper soil profile during the late-winter warmed year-over-year under the ambient snow cover treatment while they cooled under the snow-removal treatment. Between the first and third late-winter periods of the study, the average soil temperatures under the ambient snow cover treatments increased by 66%, 70%, 51%, and 31% at depth of 5, 10, 15, and 20 cm (respectively), while they decreased by 33%, 34%, 41%, and 46% under the snow removal treatment.

In addition to developing colder soils, soil temperatures in snow removal treatment plots tended to mirror fluctuations in air temperature during the winter season, as is visually evident during all three winters of the study to depths of 20 cm or greater (Fig. 5). By comparison, soil temperature in the ambient treatment plots tended to level-off at or near freezing (0 °C) during the mid- and late-winter periods and did not respond to changes in air temperature, even when air temperatures dropped drastically below 0 °C (Fig. 5). The fluctuations in soil

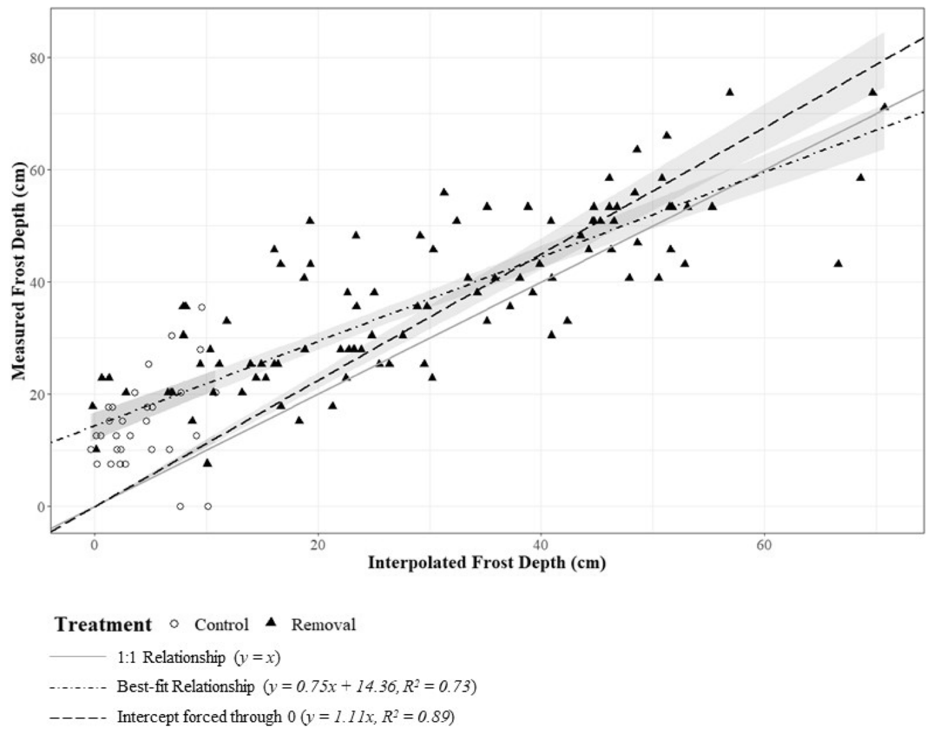

Fig. 3. Frost depth interpolated from soil temperature measurements versus measured frost depth for the months of Dec. – Feb. of each study year. The 1:1 relationship line (y = x) is shown as a solid line, while the best-fit linear regression line (y = 0.75x + 14.36) for the data is represented by a dot-dashed line and the regression with intercept forced through 0 (y = 1.11x) is depicted by a dashed line. The shaded regions of these lines represents the 95% confidence interval for the regressions.

temperature in the snow removal plots in response to changes in air temperature tended to occur only once the soil reached freezing temperature. Prior to the soil reaching a mean temperature of 0 °C, the soils under the snow removal and ambient snow cover treatments responded similarly to changes in air temperature, even for large fluctuations to nearly −10 °C.

4.3. Relationship between frost depth and freezing degree days

Based on manual measurements of soil frost during the winters of 2019 and 2020, frost was found to develop to significantly greater depths under snow removal treatment conditions as compared to the ambient snow cover treatment (Fig. 6). The maximum extent of measured frost development during the study period was also much greater under snow removal conditions: 71 cm as compared to 30 cm under the ambient snow cover treatment in the winter of 2019 and 53 cm as compared to 20 cm in the winter of 2020. In addition, frost was found to persist much longer into the growing season under snow removal treatment conditions than were observed in the ambient snow cover treatment plots. Detectable frost was measured in snow removal plots as late as mid-July, over two months later than frost-out occurred on adjacent ambient plots. The soil frost appeared to thaw primarily from the surface, leaving frost present in the deeper soil profile under a layer of thawed peat.

There was a significant ($p < 0.05$) and positive relationship between soil frost depth and cumulative freezing degree days (FDDs) for both snow removal and ambient snow cover treatments, with R^2 values of 0.74 and 0.21, respectively (Fig. 7). Based on the slope coefficients (0.371 +/- 0.016 for snow removal and 0.077 +/- 0.011 for ambient snow cover treatments), frost developed about 5x faster under snow removal conditions than under the ambient snow cover treatment.

4.4. Site-by-site comparison of the relationship between frost depth and FDDs

Comparison of regression lines among sites indicated that a model allowing for a fixed intercept and variable slopes (by site) provided a better fit to the data then the global model (AIC of 1321.96 versus 1334.92 for the snow removal data and AIC of 1132.66 versus 1161.99 for the ambient snow cover data) (Fig. S2).

Pairwise comparisons of the variable slope model indicated that for the snow removal plots, site CFC-1 (slope = 0.42) was significantly different than sites HWRC-1 (slope = 0.34) and HWRC-2 (slope = 0.35), but not significantly different than sites CFC-2 (slope = 0.37), MEF-1 (slope = 0.38), or MEF-2 (slope = 0.41). For the ambient snow cover treatment plots, a pairwise comparison by site of the random intercepts model indicated that site MEF-2 (slope = 0.13) was significantly different than sites CFC-1 (slope = 0.08), CFC-2 (slope = 0.06), HWRC-1 (slope = 0.04), and HWRC-2 (slope = 0.06), but not different than site MEF-1 (slope = 0.10). Site HWRC-1 was also significantly different than sites CFC-1, MEF-1, and MEF-2, but not CFC-2 or HWRC-2.

5. Discussion

5.1. Soil temperature and frost development

The removal of snow cover in this study resulted in colder soils, deeper soil frost, and more persistent soil frost during the seasonal thaw. This corroborates trends that have been observed across a range of ecosystems, including in forested, alpine, and meadow environments, and extends them to forested peatlands (Decker et al., 2003; Cleavitt et al., 2008; Freppaz et al., 2008; Iwata et al., 2010). Several previous studies noted increased variability in soil temperature following snow removal such that soil temperature more closely tracks fluctuations in air temperature when snow is removed, especially at shallow soil depths (Groffman et al., 1999, 2001; Hardy et al., 2001; Decker et al., 2003;

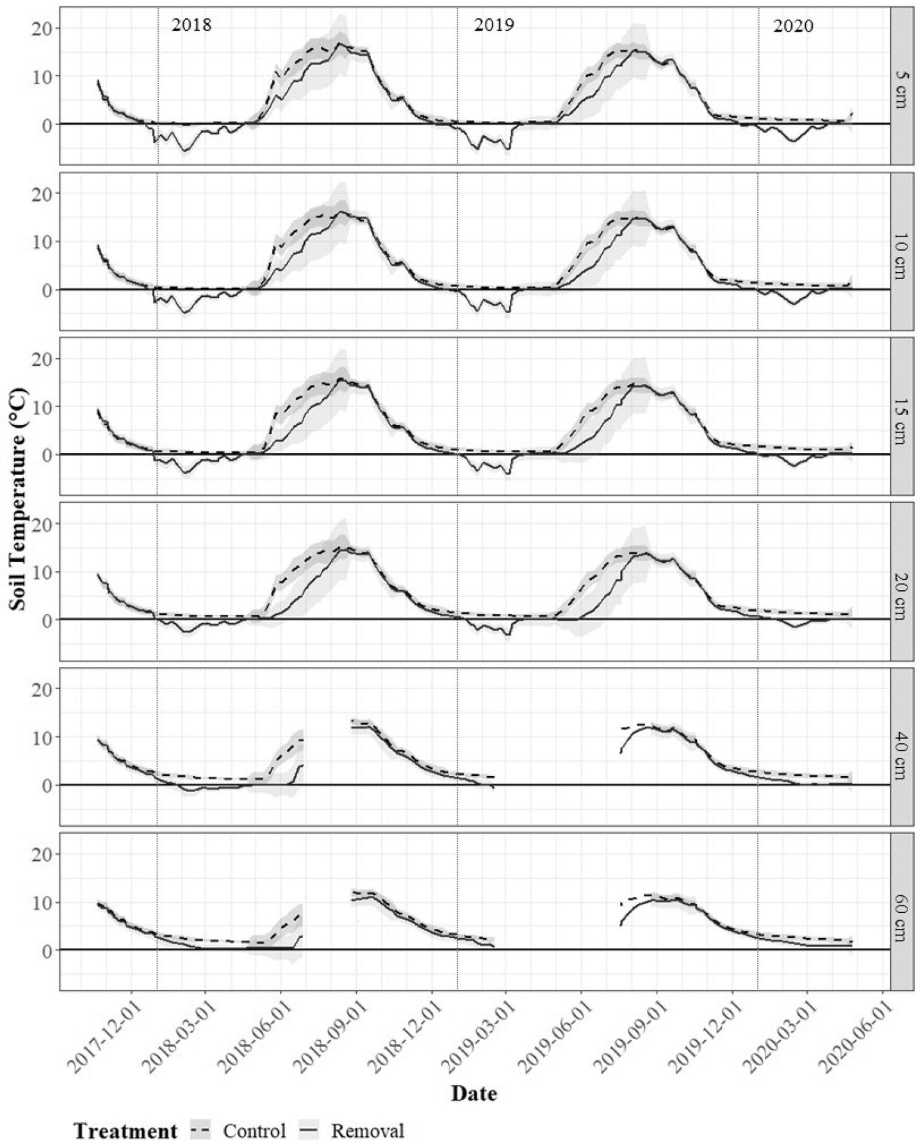

Fig. 4. Least-square mean soil temperatures across all sites for ambient snow cover (control) plots and snow removal plots, faceted by sensor depth. The winter seasons of the study will be examined in closer detail in Fig. 4.

Freppaz et al., 2008; Iwata et al., 2010). This is consistent with observations of soil temperature made in this study.

We found that soil temperature does offer an appropriate, if conservative, proxy for soil frost development, particularly in the snow removal treatment. Comparison of interpolated frost depth from soil temperature with actual soil frost measurements indicates that the extent of frost estimated from soil temperature tended to be shallower than the measured value (Fig. 3). There could be several reasons for this difference. The 5TM soil temperature sensors have an error rate of +/−1 °C, which could influence the interpolated frost depth from those temperature data. In addition, error associated with the manual frost measurement process and the location within the plot where frost was measured could also account for some of the difference between the measured and estimated frost depth. However, the relatively good fit of the linear regressions for both the best-fit relationship ($r^2 = 0.73$) and regression forced through 0 ($r^2 = 0.89$) between measured and interpolated frost depth indicate that despite these differences, soil temperature does tend to provide an appropriate proxy for frost development in peatland soils.

Although the general trends in soil temperature and frost we observed are similar to previous work, the magnitude of this effect appears to be larger in organic soil peatlands compared to mineral soils (Groffman et al., 1999, 2001; Hardy et al., 2001; Decker et al., 2003). For example, Decker et al. (2003) observed that soil temperature under snow-free conditions was responsive to changes in air temperature at depths up to 15 cm, which is much shallower than the fluctuations in soil temperature we observed at depths as deep as 40 cm (Fig. 5). Similarly, our measured frost depths tended to be greater than those recorded in mineral soil environments (Groffman et al., 2011; Hardy et al., 2001). The maximum frost depth measured under the ambient snow cover treatment was 30.5 cm during the winter of 2019 and 20.3 cm during the winter of 2020; snow removal conditions resulted in maximum frost depths of 71.1 and 53.3 cm in the winters of 2019 and 2020, respectively. By comparison, maximum frost extent values typically ranged from 0 to 20 cm and 20–50 cm in previous studies under ambient snow cover and snow removal conditions, respectively (Groffman et al., 2011; Hardy et al., 2001). Though some of these differences may be explained by variation in climate between this study and other studies, the magnitude of the difference in soil response does not appear to be fully accounted for by differences in air temperature. Several previous studies have been conducted in regions with average wintertime air temperatures similar or slightly warmer than those observed in the current

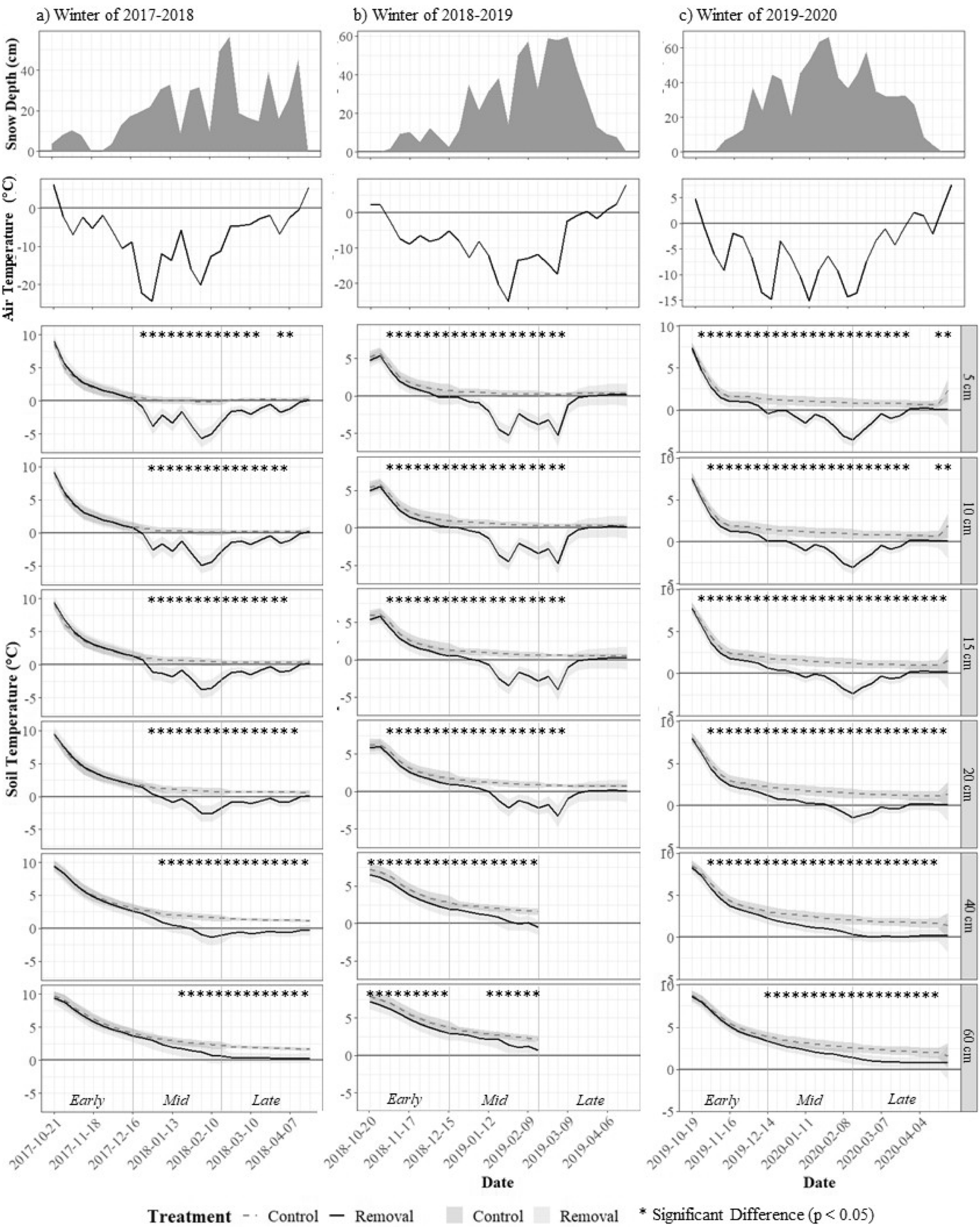

Fig. 5. Weekly average snow depth, air temperature, and least-square mean soil temperatures across all sites during the three winters of the study a) Oct. 21, 2017 – Apr. 21, 2018, b) Oct.20, 2018 – Apr. 20, 2019, and c) Oct. 19, 2019 – Apr. 25, 2020. Asterisks indicate significantly different soil temperatures between treatments ($p < 0.05$), based on pairwise comparison of least-square mean temperature.

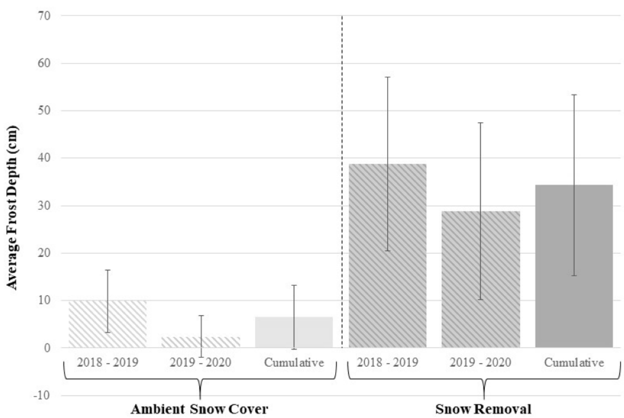

Fig. 6. Average soil frost depth during the winters of 2018–2019 and 2019–2020 and cumulative across these two winters of the study, as measured via manual frost depth process. Error bars are +/− one standard deviation of the mean. Frost depths under snow removal conditions were found to be significantly deeper than those under ambient snow cover conditions during both winters in which frost depth was manually measured.

study. While the average air temperature across study sites and years in our study was approx. −6.2 °C +/−9.6 for the period from Oct. – April, other work observed average temperatures during the period from Dec. – April between −1.9 to −4.8 °C (Hardy et al., 2001; Decker et al., 2003).

While variation in climate and methodology may explain some of the differences in frost and soil temperature between our study and other work, it is likely that the more pronounced treatment effect we observed is related to the unique properties of peatland organic soils. One of the defining characteristics of peatlands are that they are fully or nearly fully saturated throughout the year (Frolking et al., 2011; Gorham, 1991). This is reflected by the average water table level observed at our study sites, where the average water table was often within 15 cm of the peat surface, and frequently within 5 cm of the peat surface (Table 1). These saturated conditions likely allowed for the development of concrete frost across the soil profile and to deep soil depths. It has long been recognized that wet peat requires less soil frost thickness than frozen dry peat to bear the same weight (e.g., 35–50 cm frozen depth for dry peat to hold a 10-ton truck, as compared to 25–40 cm frozen depth for saturated peat) (Shoop, 1995). This points to the strong, concrete nature of frost layers in frozen peatland soils under saturated conditions, as were observed across the research sites in this study.

In addition to creating a strong concrete frost layer in saturated soils, soil water is also a strong heat sink, and peatland organic soils have low thermodynamic conductivity compared with mineral soils (Edwards and Cresser, 1992; O'Donnell et al., 2009). Low thermal conductivity would inhibit soil temperature changes and allow the deeper soil profile to remain colder throughout much of the growing season after snow removal, despite warm summertime air temperatures (O'Donnell et al., 2009). Indeed, during this study, frozen layers of peat were observed in the deep soil profile of snow removal plots as late as mid-July. The wintertime fluctuations in soil temperature observed under snow removal conditions in response to air temperature changes can be attributed to the fact that ice, or in this case, frozen saturated soil, has a higher thermal conductivity than does liquid water (Bonales et al., 2017). By comparison, the soil frost observed in previous studies conducted in mineral soil environments was not described as concrete in nature and persisted only until March or April following the seasonal thaw (Groffman et al., 2001; Hardy et al., 2001; Decker et al., 2003).

5.2. *Effect of snow as an insulator*

Although much of the previous literature agrees with our observations, there are some exceptions. Notably, Robroek et al. (2013) found that removal of snow cover in Swiss mountain peatlands was associated with warmer soils and earlier thaw, compared with sites where snow cover was added or not manipulated. This difference may be attributable to the importance of the timing of snowfall and its role as an insulator of

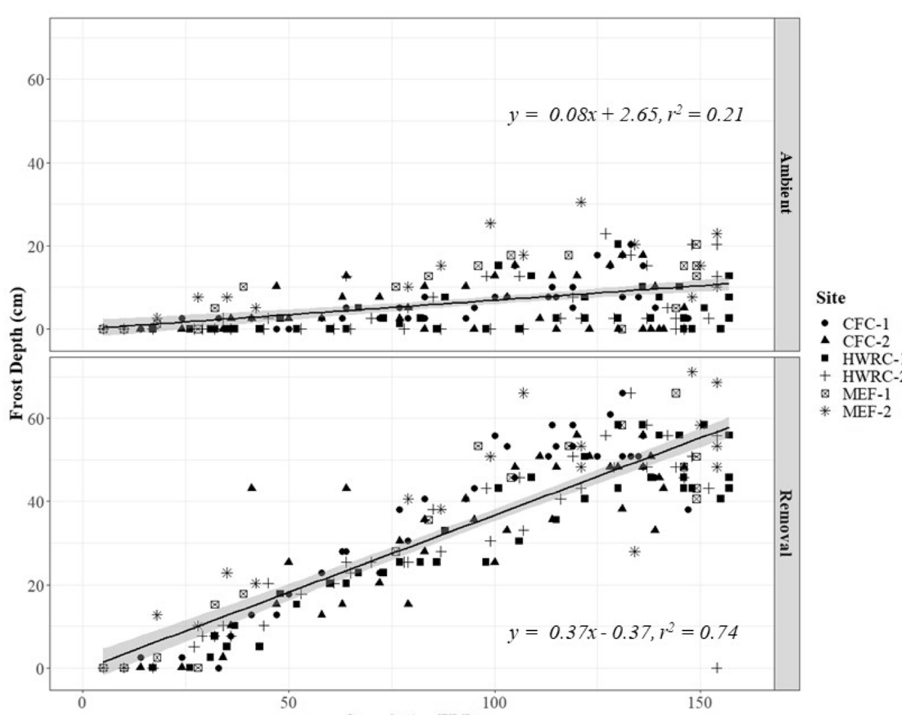

Fig. 7. Measured frost depth by cumulative freezing degree days (FDDs), separated by treatment. Each study site is represented by point shape. The linear regression lines for snow removal and ambient snow cover plots are also included, with the variance represented by the shaded region.

soil temperature to air temperature changes. The region studied by Robroek et al. (2013) experienced a comparable snow accumulation season and comparable or slightly less snow cover depth to that observed in the current study. However, in the Robroek et al. (2013) study, snow removal did not begin until early February, after snow had accumulated for several months, and the average air temperature during the snow removal period was considerably higher than that observed in our study, with air temperatures regularly recorded above freezing during the manipulation period. Previous work has established that when snowpack depth reaches 25–30 cm, it acts to insulate the soil from extreme fluctuations in air temperature, as was observed in this and many previous studies (Seppälä, 1990; Groffman et al., 1999; Decker et al., 2003; Hirota et al., 2006; Cleavitt et al., 2008; Freppaz et al., 2008; Iwata et al., 2010). Here, we observed maximum snow depths of approximately 66 cm during the 2018 winter season, 76 cm during the 2019 season, and 79 cm during the 2020 on the ambient snow cover plots, well above the 25–30 cm threshold reported in previous work to be necessary to insulate the soil. It is possible that if extreme cold temperatures occur prior to establishment of snow cover, subsequent snow cover may maintain those colder temperatures in the soil, while snow-free soils may warm in the presence of warmer air temperatures (Robroek et al., 2013).

During the first two winter seasons of our study, snow cover did not accumulate to a depth of greater than 25 cm until the mid-winter period. The lack of insulating snow cover allowed for cooling of the soil at similar rates between treatments during the early winter period during these two winters, minimizing treatment differences. In the third winter of the study (2020), deep snowfall greater than 25–30 cm occurred earlier in the season, resulting in warmer temperatures and less frost development in the ambient snow cover treatment plots and an earlier effect of snow removal treatment, with significant differences in least-square mean soil temperature between treatments at 5 cm depth occurring 1–4 weeks earlier than other study years (Fig. 5). Further, the average weekly soil temperature under ambient snow cover treatment conditions at 5 cm was 0.99 °C during the winter of 2020, as compared to colder temperatures of 0.05 °C and 0.37 °C during 2018 and 2019, respectively, and the average frost depth in these plots across the winter of 2020 was 2.4 cm as compared to 9.8 cm in 2019 (Fig. 6). Had the study occurred during winters with less snowfall, the magnitude of the difference in soil temperature and frost depth between treatments would likely have been much less. This inference is supported by the results found in our comparison of frost depth by FDD. While frost depth did increase throughout the 2019 and 2020 winter seasons in the ambient snow cover treatment plots, the rate of increase was much slower compared to snow removal treatment conditions (Fig. 7), even as air temperatures dramatically decreased during the mid-winter and into the late winter.

It is likely that a combination of snow cover and air temperature resulted in the year-over-year trends in soil temperature observed in this study, with ambient snow cover treatment plots warming and snow removal plots cooling on average over the course of the study. Though total snowfall did not increase uniformly across the three winters of the study (Table S2), maximum measured snow depth did increase year-over-year during each subsequent winter, which may explain the year-over-year warming trend observed in the ambient snow cover plots. Comparatively, average air temperature at each study location decreased year-over-year during the months of Dec. – Feb., while the minimum daily average air temperature varied across the study period (−28.8 °C in 2018, −31.7 °C in 2019, and −25.7 °C in 2020). The year-over-year decrease in soil temperature in the snow removal plots may therefore not be fully explained by air temperature only. It is possible that some lingering effect of treatment affected soil temperatures during the second and third winters of the study, resulting in colder soils during those winters. Differing year-to-year soil moisture conditions (e.g., depth to water table) may have also contributed to the observed response. Summer water tables were generally deeper in 2019 compared to 2018, but it is unknown if those differences persisted into fall and winter.

5.3. Site-to-Site variations

There were some site-to-site variations in frost development, but differences were modest. Exceptions include the ambient snow cover treatment plots at sites MEF-2 and HWRC-2, and the snow removal plot at site CFC-1, all of which had significantly different rates of frost development than at least two other sites (Fig. S2). We found when using a variable slope model for the relationship between cumulative FDD and frost depth that the plot at MEF-2 had a significantly higher slope (0.13) than the other ambient snow cover treatment plots, excluding the plot at site MEF-1. This indicates that, on average, frost depths at MEF-2 under ambient snow cover conditions were deeper than those found in other ambient treatment plots. A potential explanation for the difference observed at MEF-2 is that, while most of the research sites for this study were forested ombrotrophic bogs, site MEF-2 is a forested groundwater fen. A previous study has found that fens tend to have thicker frost layers than bogs, likely due to differing hydrologic conditions, including generally higher water tables and enhanced groundwater interaction in fens, compared to bogs (FitzGibbon, 1981). The ambient snow cover plot at site HWRC-1 had a significantly lower rate of frost accumulation (0.04 cm per day) than three other sites. This may be because of site-specific conditions at HWRC-1, including a thick *Sphagnum sp.* moss layer (a trait shared with site CFC-2) and similar air temperature and snow fall conditions to those experienced at site HWRC-2. The snow removal plot at site CFC-1 had a significantly higher rate of frost accumulation than the plots at sites HWRC-1 and HWRC-2, indicating that this site accumulated soil frost at a faster rate than did the HWRC sites, possibly because of shallow peat depth and relatively thin *Sphagnum sp.* moss layer at CFC-1 (Table 1).

Despite the above, the response to treatment was relatively consistent across all sites, and the observed results likely provide a good indication of how peatlands across the temperate-boreal forest transition zone in northern Minnesota could respond to decreased snow cover under climate conditions similar to those observed in this study. The consistent response across sites to snow removal – colder soils, increased frost depth, greater persistence of frost – indicate that the results observed here may be generally applicable across peatland ecosystems in northern Minnesota and similar temperate-boreal transition zones.

5.4. Implications for ecology & management

The persistent and deep soil frost and colder soils that were observed during the summers of 2018 and 2019 in the snow removal plots (Fig. 4) may have further ecological implications considering the fundamental role that temperature has on biological activity (Dunn et al., 2007). Conditions such as those observed in this study under snow removal conditions – where soil temperatures decrease well-below 0 °C and remain cold for prolonged periods – may result in decreased microbial activity throughout the growing season, affecting carbon cycling and methane production from peatlands (Edwards and Cresser, 1992; Robroek et al., 2013). Increased soil frost can also impede snowmelt infiltration and increase springtime runoff and water table height (Hayashi, 2013; Hardy et al., 2001), which have been found to have important control on carbon exchange from peatland ecosystems (Dunn et al., 2007; Frolking et al., 2011; Gorham, 1991; Limpens et al., 2008). Given the above, it is likely that changes in winter processes in peatland soils associated with changes in snow accumulation will have large influence on summertime carbon fluxes of both methane and carbon dioxide (Dunn et al., 2007; Edwards and Cresser, 1992; Frolking et al., 2011; Gorham, 1991; Limpens et al., 2008; Robroek et al., 2013).

In addition to the potential ecological impacts described above, our findings have important implications for forest management activities. Forest harvesting in peatlands occurs almost exclusively under frozen ground conditions. Previous work has found that to support a 10-ton truck, a conservative estimate of 30–50 cm of peatland soil frost is necessary (Shoop, 1995). The regression of frost depth to cumulative FDDs indicates that under snow removal conditions, about 83 FDDs would be necessary for the formation of 30 cm of soil frost (Fig. 7). This number of cumulative FDDs tended to occur around mid-January across all sites. In contrast, even though the winters of this study experienced air temperatures equal to or slightly colder than average, frost depth of 30 cm or greater was rarely observed at any site under ambient snow cover conditions (Fig. 6). In practice, many foresters currently use machinery to compact the snow layer prior to operations, a process that likely produces soil freezing intermediate to the observed depths in this study by reducing the insulating effect of snow.

The results of this study indicate that under climatic conditions with reduced snow cover, peatlands may develop colder soils and increased depth of soil frost, as compared with current conditions. While most climate models have estimated that by the end of this century, soil frost days will decrease as a result of increasing wintertime air temperatures (Venäläinen et al., 2001; Balland et al., 2006; Kellomäki et al., 2010; Sinha and Cherkauer, 2010; Handler et al., 2014; Huang et al., 2017), there may still be sufficient freezing temperatures for the development of peatland soil frost. In particular, if early winter season snowfall decreases and rainfall increases (as is predicted) (Handler et al., 2014), the increase in saturated soil conditions and reduction in insulating snowpack may increase soil frost, should sufficient cumulative below-freezing air temperatures occur. There is still a high level of uncertainty in the modeled projections on peatland hydrology, particularly in predicting soil frost depth (Balland et al., 2006; Huang et al., 2017). Because of the intrinsic relationship between peatland hydrology and the ecologic functions and economic services they provide, it is imperative that additional study is conducted to better understand how forested peatlands may react to a changing climate.

6. Conclusion

Understanding the relationship(s) among winter conditions including air temperature, snow cover, and soil temperature/frost development are essential to understanding how these peatland ecosystems might be affected by a changing climate. In this study, we found that removal of snow cover from peatlands results in significantly colder soils during mid- and late winter (approx. 2℃ and 1.4℃, respectively), deeper soil frost development (approx. 37.5 cm on average versus 8.5 cm under the ambient snow cover treatment; Fig. 6), and faster frost development (approx. 0.4 cm/FDD versus less than 0.1 cm/FDD under ambient conditions; Fig. 7).

While our results indicate that under conditions of decreased snow cover (a predicted climate change outcome in Minnesota), soil temperature may decrease and frost depth increase, we did not account for any influence of increased air temperature that is predicted to occur concurrently under future climate conditions. Additional studies are needed to understand how changing frost dynamics may affect the ecological functioning of peatlands, including carbon storage and nutrient cycling. Also, changing winter conditions and soil frost will have implications on the time available to harvest peatland forests. Soil temperature and the presence of soil frost play an important role on soil, hydrologic, and ecological processes, as well as forest management. Understanding the effects of colder soils and deeper, more persistent soil frost (as observed in our study) is an essential next step in understanding the influence of changing winter conditions on peatlands.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.geoderma.2021.115015.

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