The effects of combined throughfall reduction and snow removal on soil physical properties across a drainage gradient in aspen forests of northern Minnesota, USA

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Abstract

Climate change is projected to alter precipitation patterns across northern latitudes, with decreased snow accumulation and summer rainfall predicted. These changes may alter soil physical properties such as soil strength, which would have implications for the feasibility of forest management activities. Reductions in summer and winter precipitation were simulated using a paired-plot design with throughfall reduction and snow removal as treatments across four soil drainage classes (well, moderately well, somewhat poor, and poorly drained) at each of three locations in northern Minnesota, USA. Snow removal caused large reductions in soil temperature and significantly deeper penetration of frost that varied by drainage class, where frost depth decreased with decreasing (wetter) drainage. There was a positive relationship between air freezing index and frost depth, where the rate of frost development was much higher in the snow removal treatment compared to the control (Treatment - r^2 = 0.8, slope =

0.093, $p < 0.001$; Control - $r^2 = 0.18$, slope = 0.012, $p < 0.001$). Throughfall reduction had limited effects on soil water content (SWC) and inconsistent effects on soil strength; relationships between SWC and strength were positive, negative, or non-existent. Based on these findings, changes in soil physical properties with altered precipitation are likely to manifest primarily in winter. Drainage class and air freezing index may be used to predict when sufficient soil frost is present for forest management activities to occur without detrimental effects to soil functions.

Introduction

Soil strength, the amount of shear stresses that a soil can resist, determines the operability of soil for forest management activities (Grigal, 2000). Soil operability is defined as the ability of a soil to withstand the physical stresses from equipment used during forest harvesting with limited impacts on soil properties (NCASI, 2004). A key impact of concern is soil compaction which can negatively affect soil health by increasing bulk density and reducing macropore space, resulting in concurrent decreases in water availability, gas exchange, and root growth (Greacen & Sands, 1980; Grigal, 2000; Horn et al., 2007; McNabb et al., 2001; Tan et al., 2005). Long-term effects of soil compaction have major implications for stand growth (Cambi et al. 2015), and recovery can take decades to occur (Curzon et al. 2021). Thus, avoiding compaction is crucial in maintaining long-term productivity since forest soils are unlikely to recover from compaction in the short-term (Greacen & Sands, 1980; von Wilpert & Schäffer, 2006; Powers et al., 1990). When soil operability is optimal, risks of soil compaction are greatly reduced.

Current climate change models for northern latitudes predict an overall decrease in summer precipitation but with more extreme precipitation events (Handler et al., 2014). More winter precipitation will occur as freezing rain rather than snow due to warmer winter temperatures, resulting in an overall decrease in snowpack depth (Handler et al., 2014). Since soil strength is influenced by soil moisture and frost depth, future changes in precipitation will likely affect forest soil operability during the summer and winter harvesting seasons, which has major economic and ecological implications (Uusitalo et al., 2019; McNabb et al., 2001; Shoop, 1995; Horn et al., 2007; Kok & McCool, 1990).

The feasibility of harvesting on soils during the summer will likely be impacted by the timing and amount of precipitation (Uusitalo et al., 2019). High bulk density and low water content are characteristics of high strength soils, which have a low compaction risk (Uusitalo et al., 2019; McNabb et al., 2001). Thus, altered soil moisture dynamics arising from changes in summer precipitation patterns may affect summer operability of forest soils. For example, a study by McNabb et al. (2001), which investigated the effects of skidding and soil water content (SWC) on compaction, found that decreases in SWC were directly related to increases in effective shear strength. Given this relationship, there is a need to quantify changes in soil strength associated with reductions in precipitation, and to quantify the relationships between SWC and soil strength across a range of soil types.

Winter harvesting is more common in northern latitudes because the risk of soil compaction is reduced when soils are frozen (Blinn et al. 2015). Frozen soils can withstand higher shear stresses (*e.g.,* heavy harvesting equipment) compared to nonfrozen soils of the same texture (Kok & McCool, 1990; Shoop, 1995). However, changes in winter precipitation and frost dynamics may also affect the compaction risk of forest soils due to the role of snowpack in frost development. Snowpack acts as an insulative layer over the soil surface due to its high albedo and low thermal conductivity, so frost does not develop under a thick snowpack to the same extent as a thin snowpack (Zhang, 2005). Changes in the type of winter precipitation and warming temperatures may decrease the period between soil freeze and thaw when operators may harvest forest stands with minimal soil disturbance. There is a need to understand how changing climate change will alter winter soil operability in the future.

Drainage class, which can be easily measured in the field and mapped, may be an important modifier of soil strength. Soil water content, texture, and porosity are all related to drainage class, and drainage class may be useful when categorizing site compaction risk (Briggs & Lemin, 1994; McNabb et al., 2001; Uusitalo et al., 2019; Veneman et al., 1998). For example, soil water content increases as drainage worsens due to a change in landscape position and increase in clay content (Veneman et al., 1998). Soil temperature also tends to be higher during the winter in poorly-drained soils due to the low thermal diffusivity of soils with a high soil water content (Arkhangelskaya & Lukyashchenko, 2018). As a result, soil drainage class is likely to have a large influence on soil strength and frost development, but such an effect has not yet been quantified.

We investigated the influence of a combined throughfall reduction and snow removal treatment on soil strength, frost depth, moisture, and temperature across a gradient of soil drainage classes using a paired-plot design. Our objectives were to quantify the effect of the throughfall reduction and snow removal treatment, and drainage class on soil water content and soil strength during the summer growing season, and soil temperature and frost during the winter. The purpose of this study was to provide information for forest managers and operators who plan timber harvests to identify when soil operability is optimal, and the risk of soil compaction is minimal.

Methods

Study area

The study included three sites in the Laurentian Mixed Forest Province (LMFP) of northeastern Minnesota. Two sites were located within state-managed forests (Solana and George Washington State Forests), and the third was located on county-owned land. Soils in this region span a range from fine to coarse textured with glacial parent material from the last glacial retreat 12,000 years ago (Handler et al., 2014). Quaking aspen (*Populus tremuloides*) is a large part of the LMFP, composing 30% of Minnesota's forest land and is most concentrated in the LMFP (Handler et al., 2014).

All sites were dominated by upland quaking aspen in the forest canopy with beaked hazel (*Corylus cornuta*), willow (*Salix* spp.), or speckled alder (*Alnus incana*) in the understory. Mean summer (June – August) temperature for this region is 18˚C and winter temperature averages -12˚C (Handler et al., 2014). Average precipitation during the summer is 305 mm, and average accumulated snowfall ranges from 1,016 mm to 1,778 mm (Handler et al, 2014).

Site characteristics

Mature quaking aspen (40-60 years of age) was the dominant tree species at all sites. Soils at each site were predominantly loams occurring on relatively flat topography (less than 10% slope) (Table 1). Plot locations with the target drainage classes (well-drained through poorly drained) were identified based on depth to redoximorphic features. Drainage classes were defined as >102 cm to redoximorphic features (well-drained, WD), 51-101 cm (moderately well drained, MWD), 26-50 cm (somewhat-poorly drained, SPD), and 0-25 cm (poorly drained, PD; Soil Science Division Staff, 2017).

Table 1: Description of soil series and textures for each drainage class within the three sites (county) determined from soil survey information. Soil survey information from National Cooperative Soil Survey (NRCS)**.**

Site	Coordinates	Soil unit	Soil texture	Bulk density (g cm^{-3})
Site 1	46.361908, -93.236416	Milaca-Millward complex	Fine sandy loam	1.03 - 1.21
Site 2	47.688509, -93.546264	Warba-Menahga complex	Fine sandy loam	1.24 - 1.31
		Morph very fine sandy loam	Very fine sandy loam	1.31 - 1.32
		Baudette silt loam	Silt loam	1.27 - 1.36
Site 3	47.182644, -92.104667	Aldenlake-Pequaywan complex	Sandy loam	1.02 - 1.22
		Brimson stony fine sandy loam	Stony fine sandy loam	0.84 - 0.93

Experimental design and treatment implementation

The study occurred from May 2018 until May 2022 using a paired-plot, factorial (4 x 2) experimental design with Factor 1 being drainage class and Factor 2 being the throughfall reduction and snow removal treatment. Treated plots were replicated across sites (n = 3), with each site containing eight plots (an unmanipulated control and treatment plot in each of the four drainage classes). Paired treatment and control plots were 4x4 m in size and located adjacent to each other. Snow was removed from treatment plots during the winter (Supplemental Materials Figure 1), and throughfall was reduced during the growing season (Supplemental Materials Figure 2).

Snow was removed from treatment plots during the winter according to the method defined by Friesen et al. (2021). To allow for snow removal without impacting the soil surface, gray aluminum window screening (Phifer Incorporated, Tuscaloosa AL) was placed over the entire treatment plot area prior to the first snowfall. Screens were not placed within the control plots. Shrubs and other woody stems were cut prior to screen placement in both the control and treatment. Snow was cleared manually and was always cleared and deposited away from the control plot to limit any possible disturbance. Snow was cleared after every storm of 2.5 cm or more, or at least weekly.

Throughfall reduction shelters were installed during the growing season to simulate a 50% reduction in throughfall similar to the design implemented by Yahdjian & Sala (2002). The shelters were guttered with 10.2 cm wide, U-shaped white vinyl gutters that extended 40 cm past the 4 x 4 m plot boundary. The ridgeline of the A-frame shelter ran along a north-south transect so that panels were situated on an east-west transect to avoid greenhouse effects created by a south-facing panel. To assess treatment efficacy, the volume of throughfall in plots was measured biweekly during the growing season of 2021 using 20.3 cm funnels attached to glass jars that were placed in each quadrant of MWD plots at each site (n = 4 collectors per plot and site). The biweekly average throughfall volume for control plots was 648.6 mL (± 54.44 mL; 2.15 cm ± 0.18 cm) and was 305.5 mL (± 108.41 mL; 1.01 cm ± 0.36 cm) for treatment (reduction) plots.

Soil water content, soil temperature, and air temperature measurements

Soil temperature and moisture were measured every 15 minutes at depths of 10, 20, 30, 40, and 60 cm via Decagon 5TM sensors (± 0.1˚C, ± 0.08% SWC; METER Group, Pullman, Washington). Sensors were installed in a cluster at the center of each plot (Supplemental Materials Figures 1, 2) and connected to EM50 data loggers (METER Group). Air temperature was recorded at control plots every 90 minutes by Thermochron iButton sensors (± 0.5˚C; Maxim Integrated Products, Inc., Sunnyvale, California) enclosed in a PVC solar shield.

Soil frost measurements

Soil frost depth was measured weekly between November and April of the winter of 2019/20, between October and May of the winter of 2020/21, and between November and May of the winter of 2021/22. Frost tubes were constructed by Northern Frost Tubes (Brian Hahn, Oconomowoc, Wisconsin). Frost tubes were installed to a depth of 1.5 m in the soil profile and were filled with a solution of water and color-changing indicator dye. The solution turned clear when frozen, indicating the depth of frost. Frost depth was measured to the nearest 2.5 cm in all plots.

Soil strength measurements

Soil strength measurements were collected biweekly between June and September of 2020, and monthly between May and September of 2021. Soil strength was measured via a dual-mass dynamic cone penetrometer (Humboldt Mfg. Co., Elgin, Illinois). Strength measurements followed the protocol of the Minnesota Department of Transportation (MNDOT, n.d.). At least two full penetrometer runs to a depth of 45 cm were conducted per plot in two random quadrants.

Data analysis

Analyses focused on soil water content during the growing season (May – September/October 2019 – 2021), and soil temperature during the winter (October/November – April/May 2018 – 2022). Soil water content and temperature, as well as air temperature were first averaged by day and then by week using the “lubridate” package in R (Grolemund & Wickham, 2011). Frost depths were grouped into time periods (week) based on measurement dates from each site, since observations occurred at different days across sites.

Repeated measures, linear mixed effect models were used to evaluate the influence of drainage class, treatment, and time on soil strength, frost depth, moisture, and temperature. Site (block) was included as a random effect in all models, and each year of measurement was run independently. A mixed effects model with year and drainage class modeled as fixed effects, and site as a random effect, was used to analyze differences in snow depth among years and drainage classes. The R package “nlme” (Pinheiro et al., 2021) was used to run the models. Autocorrelation matrices (corAR1 function) were included in models to account for temporal correlation in the data (Pinheiro et al., 2021). Least square means analysis with the Tukey p-value adjustment was performed when significant effects were found by using the “lsmeans” R package (Lenth, 2021).

Plots of standardized residuals and quantile-quantile plots were used to validate the assumptions of normality, linearity, constant variance, and independence. Soil strength was transformed using a natural logarithm to correct for non-normality. Frost depth was transformed as the logarithm of frost depth + 1 to avoid using the logarithm of zero in 2020 to correct for non-normality. Quantile-quantile plots and plots of standardized residuals were used to identify the best transformation of the dependent variable. All least square means and confidence intervals were presented in original, non-transformed units for interpretation in figures.

Linear regression was used to determine the correlation between frost depth and the air freezing index (AFI) for control and treatment plots (Erlingsson et al., 2020). Air freezing index was calculated as the sum of the mean daily air temperatures below freezing (0˚C). Regression lines were compared to assess the effect of drainage class on the relationship between AFI and frost depth in control and treatment plots. Analysis of covariance (ANCOVA) was used to test alternative models (variable intercepts and slopes between drainage classes, variable intercepts between drainage classes, or no difference in intercepts or slopes).

We also used linear regression to determine relationships between soil strength (bearing capacity) and SWC (%). Depth per blow (DPB) was used to calculate the California Bearing Ratio (Equation 1; Black, 1962) and bearing capacity (Equation 2) in pounds per square inch (psi). Runs for each plot were averaged to create a plot-level soil strength estimate.

Equation 1

$$CBR\ (\%) = \frac{292}{DPB^{1.12}}$$

Equation 2

$$BC\ (psi) = 4.5915 \times CBR^{0.6105}$$

Results

Effects of snow removal

There were significant differences in winter air temperature and ambient snow depth among study years (Table 2). Mean air temperature was significantly higher and snow depth significantly lower in 2020/21 compared to 2019/20. Mean air temperature was significantly lower with greater snow depth in 2021/22 compared to the two prior winters of the study.

Table 1: Least square mean weekly air temperature and snow depth during the winters of 2019/20, 2020/21, and 2021/22 between November 1st and April 30th. Values within a column containing different letters are significantly different.

Year	Air temperature (°C)			Snow depth (cm)
	Mean	Max	Min	Mean
2019-20	-5.4^{a}	5.7	-15.3	36.7^{a}
2020-21	-4.1^{a}	8.7	-27.6	13.6^{b}
2021-22	-7.5^{b}	3.8	-10.5	29.2^{c}

There was a significant three-way interaction among drainage, treatment, and week for soil temperature in all three years ($p < 0.001$; Supplemental Materials Table 1; Figure 1a). Soil temperature increased from WD to PD, likely a result of the higher water content of the PD plots (Figure 1a, Supplemental Materials Figure 5). Additionally, more rapid changes in air temperatures occurred in the WD plots compared to the PD plots, which showed slower warming during the spring period.

Soil temperature was consistently lower in the treatment plots throughout the three winters (Figure 1a). Minimum soil temperature in snow removal plots occurred during late February or early March, depending on the year, with minimum mean weekly soil temperatures of -7.3˚C, -13˚C, and -9.2˚C in the winters of 2019/20, 2020/21, and 2021/22, respectively. There was a significant three-way interaction among treatment, week, and soil depth during the winters of 2020/21, and 2021/22 ($p = 0.01$, $p < 0.001$, $p < 0.001$, respectively; Supplementary Materials Table 1; Figure 1b). The interaction manifested as more pronounced differences between treatments at shallow depths with decreasing differences as soil depth increased. For example, in the winter of 2021/22, mean soil temperatures in the snow removal treatment were lower than ambient conditions by 2.4˚C, 2.2˚C, 2.0˚C, 1.9˚C, and 1.7˚C for depths 10 cm, 20 cm, 30 cm, 40 cm, and 60 cm, respectively.

Soil temperature increased as depth increased, with soil temperature at 60 cm rarely reaching sub-freezing temperatures and showing little variability, compared to 10-40 cm depths, which reached sub-freezing soil temperatures during all three winters with high temporal variability that mirrored changes in air temperature (Figure 1b; Supplemental Materials Figure 3). Under ambient conditions, differences in mean soil temperature between 10 cm and 60 cm ranged from 0.7˚C and 1.1˚C depending on year, and between 1.0˚C and 3.5 ˚C with snow removal.

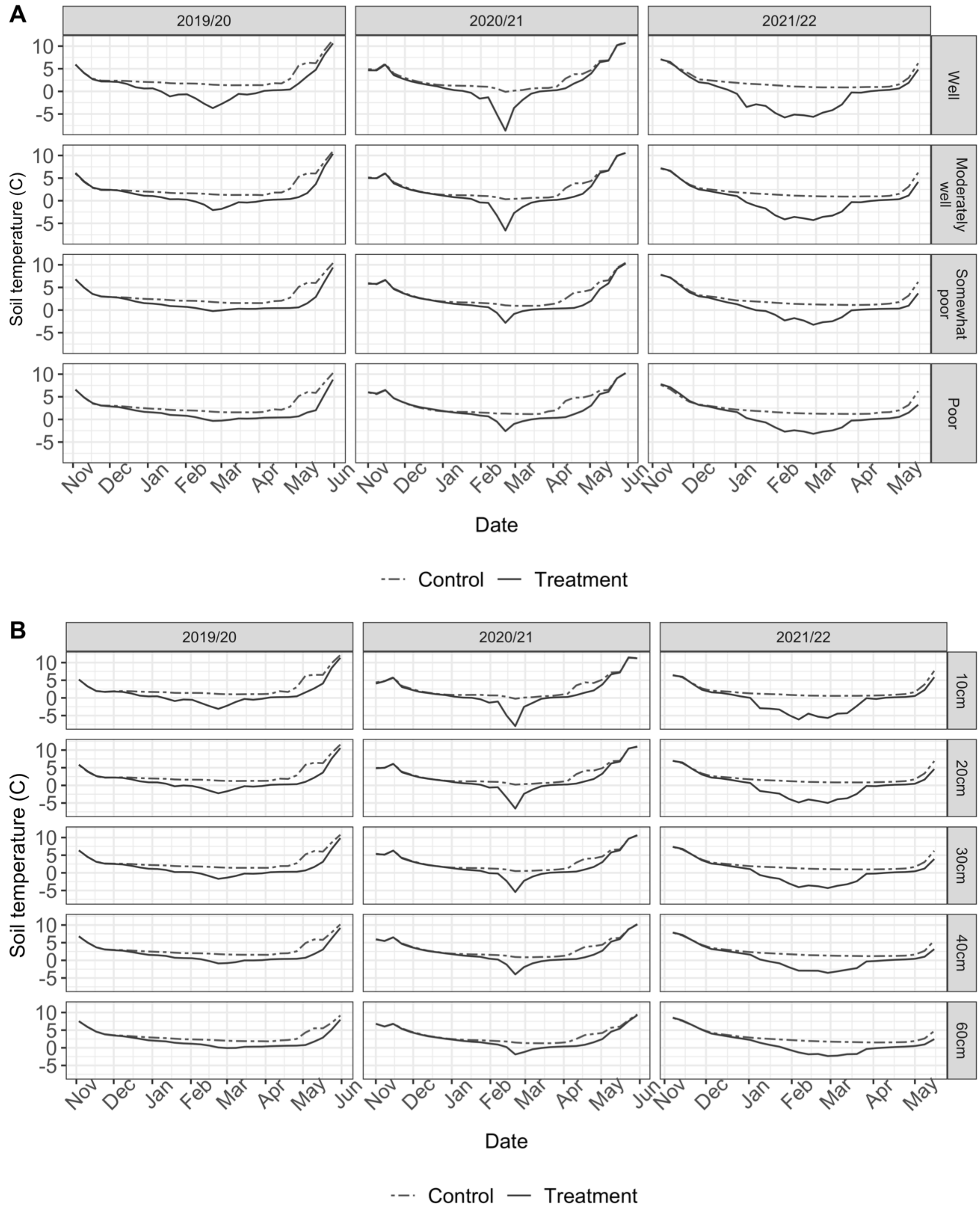

Figure 1: Mean weekly soil temperature by treatment and drainage class (panel A) and mean weekly soil temperature by treatment and depth (panel B) during the three winters of the study.

There was a significant interaction between treatment and week ($p < 0.001$) in all three years on soil frost (Supplemental Materials Table 2). Frost depth in the snow removal treatment across all drainage classes was 0.9 – 59 cm, 0.7 – 55 cm, and 3 – 91 cm deeper compared to the control in 2019/20, 2020/21, and 2021/22, respectively (Figure 1). There was a significant interaction between drainage and treatment ($p = 0.001$) in 2019/20 for the effect on soil frost. Snow removal caused significantly deeper penetration of frost but the difference between treatments decreased as drainage class became progressively wetter (*e.g.*, 31.0 cm in the WD class versus 19.2 cm in the PD class in 2019/20; Supplemental Materials Figure 4). In 2020/21 and 2021/22 ($p < 0.001$), there was a main effect of drainage class on frost depth, where the drier drainage classes froze to a deeper depth compared to the wetter drainage classes (Figure 3; Supplemental Materials Figure 4). For example, mean frost depth in the WD class was 16 cm and 12 cm deeper compared to the PD class in 2020/21 and 2021/22 (Figure 3, $p < 0.001$).

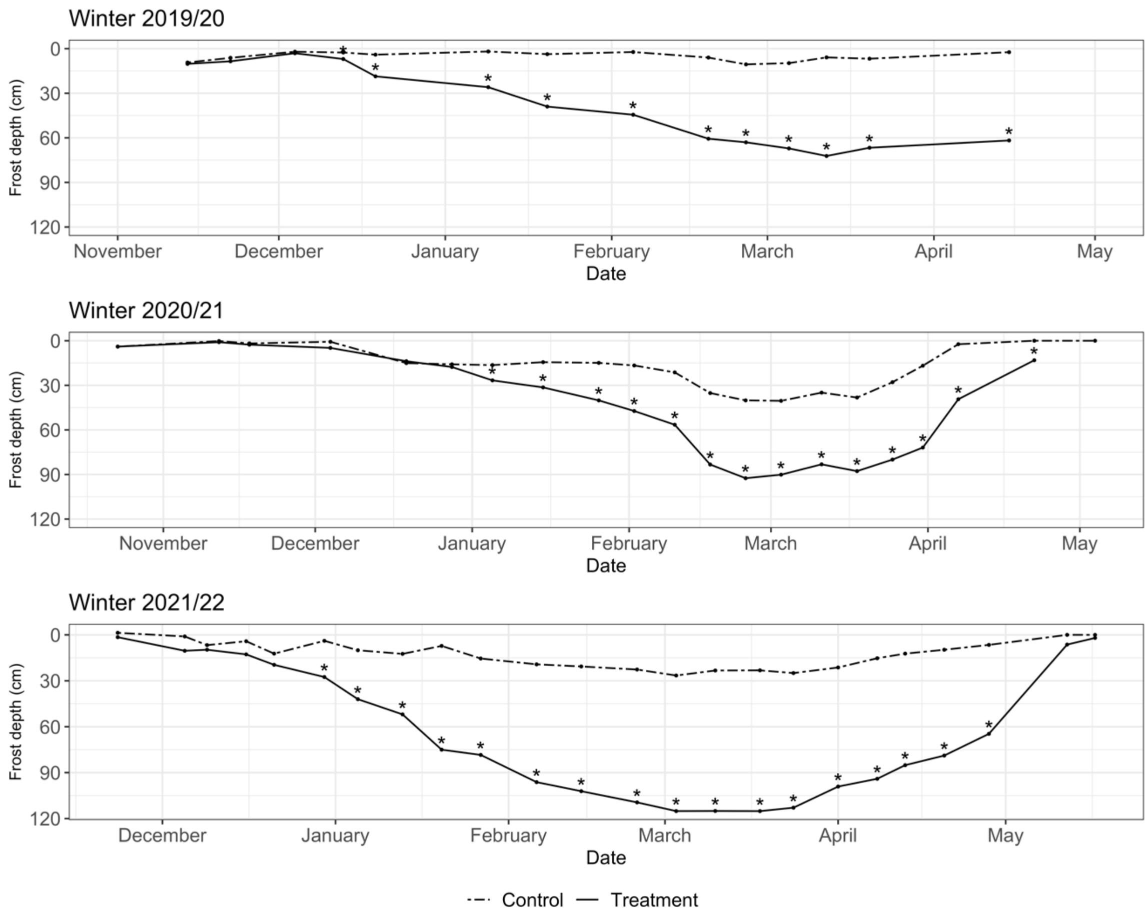

Figure 2: Least square means of soil frost depth during the winters of 2019/20, 2020/21, and 2021/22 for the significant interaction between treatment and date. Asterisks indicate time periods where there was a significant difference in soil frost depth between treatments.

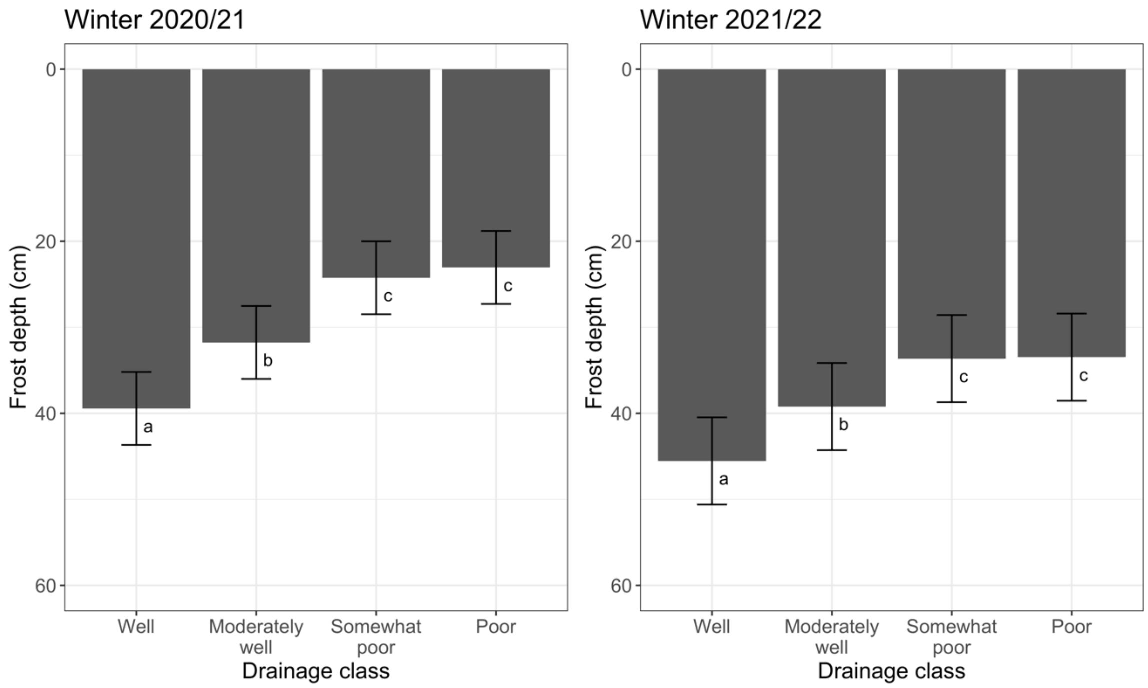

Figure 3: Least square mean frost depth by drainage class during the winters of 2020/21 and 2021/22. Bars with different letters indicate significant differences between means (p-value < 0.05). Error bars represent standard error.

There was a significant positive relationship between AFI and frost depth for both control and treatment plots across all three winters. However, the relationship was stronger in the treatment plots ($r^2 = 0.80$, $p < 0.001$; Figure 4b) compared to the control plots ($r^2 = 0.18$, $p < 0.001$; Figure 4a). Comparison of the regression slopes indicated that the rate of frost development was approximately 68% higher in the treatment plots compared to the control plots.

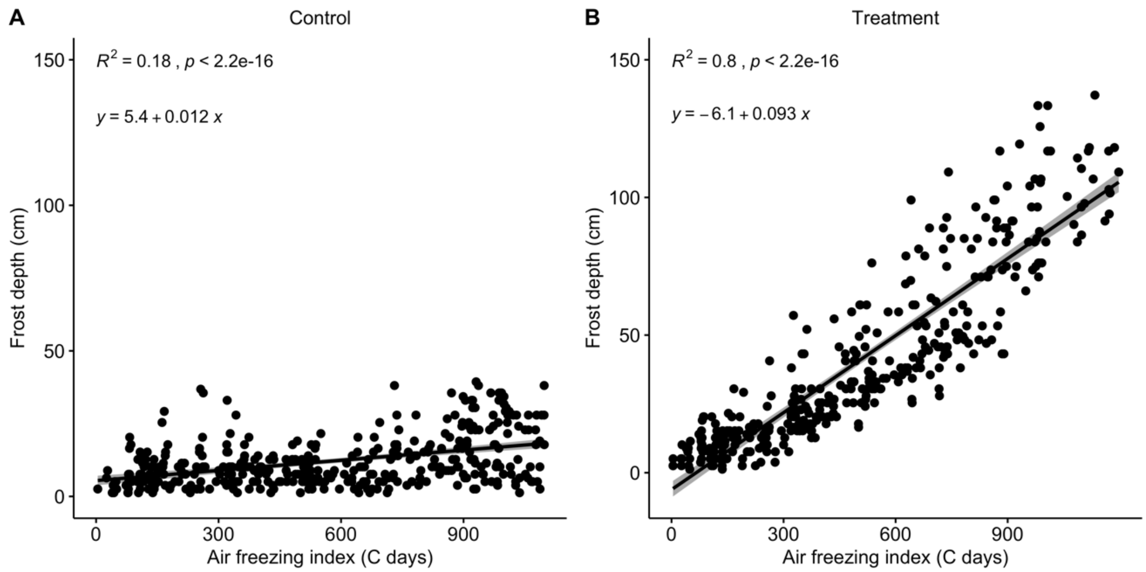

Figure 4: Linear regressions between Air Freezing Index and frost depth in control (panel A) and treatment (panel B) plots during all three winters of the study. Confidence limits (shading around the line) are 95% confidence intervals.

The pairwise comparison of the estimated intercepts and slopes by drainage class shows that the intercepts and slopes decreased as drainage decreased (*e.g.*, well-drained had the highest intercept and slope, followed by MWD, SPD, and PD; Table 5). Intercepts in WD in the control were significantly different from MWD (difference of 1.6

cm), SPD (3.7 cm), and PD (4.8 cm), and slopes in WD in the treatment were significantly different from SPD (0.03 cm/˚C day) and PD (0.031 cm/˚C day; Table 5).

Table 5: Results of intercept and slope comparisons for the relationship between frost depth and AFI. Regression intercepts are shown for control plots and slopes are shown for treatment plots for all three years. Superscript letters indicate significant differences between means of each drainage class within each treatment (p-value < 0.05). Intercepts are in units of depth (cm). Slopes are in units of depth/˚C day.

	Control		**Treatment**	
Drainage class	**Intercept**	**Standard error**	**Slope coefficient**	**Standard error**
WD	7.69^{a}	1.15	0.102^{a}	0.004
MWD	6.12^{b}	1.04	0.082^{a}	0.004
SPD	4.00^{c}	1.12	0.072^{b}	0.004
PD	2.91^{c}	1.15	0.069^{b}	0.004

Effects of throughfall reduction

There was a significant interaction among drainage class, treatment, and depth on SWC in all three years (p < 0.001; Supplemental Materials Table 3, Figure 5). No differences in SWC existed between treatments at 0-20 cm (except for 10-20 cm depth for PD during 2020 and 2021); differences in SWC between control and treatment primarily occurred for depths 30-60 cm during all three years (Figure 5).

However, the treatment plots were not consistently drier than the control plots. For example, the treatment plots were drier than the control for the WD class at 40cm during 2019 and 2020 (difference of -0.05 and -0.04, respectively, but no difference (p = 0.15) during 2021. The SPD class followed a similar trend at 30 cm and 60 cm during

2019 (Figure 7). In contrast, the treatment plots in the MWD class had significantly higher SWC than the control plots at 30 and 60 cm during all three years of the study with differences ranging from 0.04 m^3m^{-3} to 0.06 m^3m^{-3}. The PD class showed a similar trend at 60cm during 2019, 20 cm and 60 cm during 2020, and 20cm during 2021.

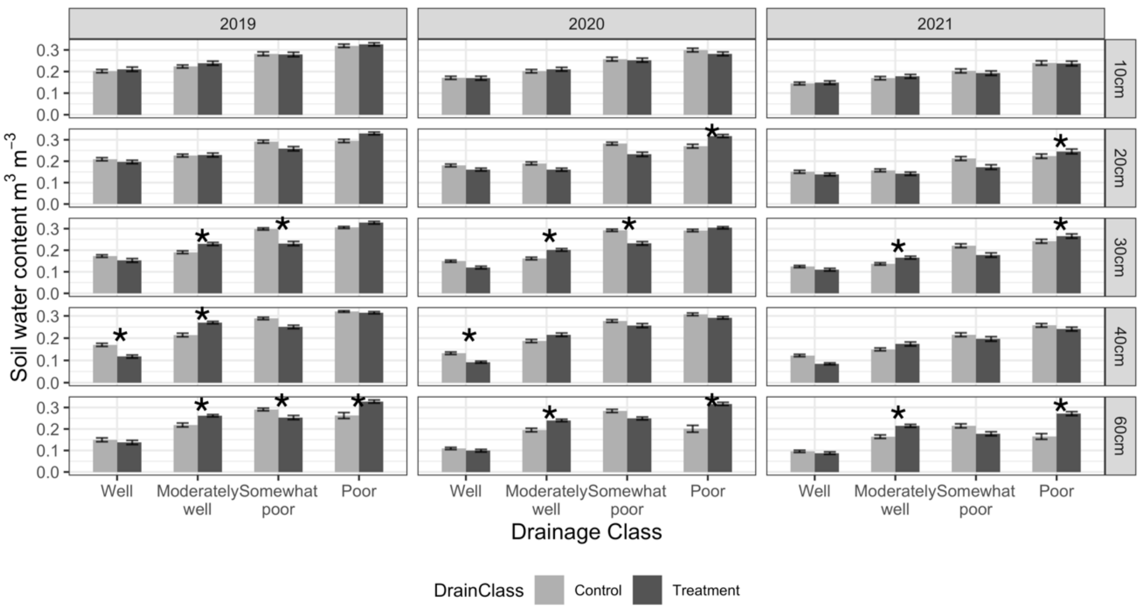

Figure 5: Mean soil water content by treatment, drainage class, and soil depth for the three years of the study. Soil depth in centimeters is shown on the right y-axis. Asterisks indicate significant differences (p-value < 0.05) between control and treatment within a drainage class for a given depth.

Treatment effects on soil strength (bearing capacity) were limited. There was a significant interaction between drainage class and treatment, but only at 60 cm during the growing season of 2020 (see Supplemental Materials Table 4 for p-values, Figure 8). Measurement date had no effect on soil strength, and percent clay was not a significant covariate in the models. Pairwise comparisons of drainage class by treatment means in 2020 show that the mean bearing capacity for the SPD class in the treatment plots (SPD treatment) was significantly lower than the WD treatment (p = 0.02, difference of 16.2

psi) and MWD treatment ($p = 0.005$, difference of 18.4 psi, Figure 8). SPD treatment was also significantly lower than MWD control ($p = 0.005$, difference of 18.5 psi) and SPD control (0.04, difference of 13.2 psi; Supplemental Materials Figure 6).

Linear regression show relationships between soils strength (bearing capacity) and soil water content were also limited. All relationships were weak ($r^2 < 0.30$) and inconsistent in direction across drainage classes (Supplemental Materials Figures 7, 8, 9, 10). For example, there was a significant positive relationship between soil strength and SWC in the WD class at 30 cm in 2020 ($r^2 = 0.25$, $p = 0.002$), as well as the PD class at 60 cm in 2021 ($r^2 = 0.30$, $p = 0.005$). On the other hand, there was a significant negative relationship between soil strength and SWC in the MWD class at 30 cm in 2020 ($r^2 = 0.18$, $p = 0.011$) and the PD class at 60 cm in 2020 ($r^2 = 0.17$, $p = 0.0013$).

Discussion

Changes in winter and summer precipitation under climate change will have implications for forest soil operability, since frost depth (as influenced by changes in snow cover) and soil moisture have been shown to influence soil strength (Greacen & Sands, 1980; McNabb et al., 2001; Uusitalo et al., 2019). Drainage class was a strong indicator of soil temperature and soil moisture throughout the study. The snow removal treatment significantly increased frost depth which varied by drainage class and year and there was a strong relationship across drainage classes between frost depth and air freezing index (AFI) when snow was removed. In contrast, there were limited effects of throughfall reduction on soil moisture during the growing season and limited effects on soil strength. Relationships between soil strength and soil moisture were generally weak and inconsistent across and within drainage classes. We explore these key findings in more detail below.

Effects of snow removal

Our findings clearly show that snow removal significantly decreased soil temperature (Figure 1) and increased frost depth (Figure 2). These results are consistent with previous literature that has shown soil temperature is significantly decreased under snow removal treatments (Decker et al., 2003; Groffman et al., 2001; Hardy et al., 2001). Decker et al. (2003) found similar trends in soil temperature under snow removal compared to ambient snow treatments, where the temperature variation in soil decreased with depth and when snow was retained. Additionally, snow cover was found to be a strong regulator of soil temperature during the winter by Hardy et al. (2001). Soil temperature was attenuated as drainage worsened, which mirrors the soil moisture results in that warmer soil temperatures correlate with higher soil water content due to the low thermal diffusivity of wet soils (Arkhangelskaya & Lukyashchenko, 2018). In this study, soil temperature increased from WD to PD in both the control and snow removal treatments during winter months. Even when snow was removed, temperature effects did not occur at the same depth in the wetter drainage classes compared to the drier drainage classes, and wetter drainage classes had a slower rate of warming in the spring due to low thermal diffusivity. A drainage class gradient has not been utilized in previous snow removal studies, so these results add novel insight on frost development under changing precipitation regimes across a range of soil moisture conditions.

Given the established relationship between soil temperature and soil wetness, it is not surprising that soil frost development was also dependent on treatment and drainage class, where snow removal caused significantly deeper frost development that was further influenced by drainage class (Figure 3). Snow removal studies at the Hubbard Brook Experimental Forest in New Hampshire showed that snow removal can cause deeper frost penetration across a range of landscape positions and aspects (Cleavitt et al., 2008; Hardy et al., 2001). However, the frost depths observed with snow removal in this study were deeper than those observed at Hubbard Brook, which may be due to the consistently colder winter temperatures of northern MN compared to NH, where the 30-year average air temperature observed was -4.7˚C (Cleavitt et al., 2008; Hardy et al., 2001). Drainage class regulated soil frost depth, where frost did not develop to the same depth in wetter drainage classes since soil temperature did not reach sub-freezing temperatures at the same depths as drier drainage classes.

Frost depth increased with AFI, and the slope of this relationship was higher in the snow removal treatment compared to the control. Even when the coldest air temperatures were reached (maximum AFI), frost depth in the control remained relatively shallow compared to the snow removal treatment (Figure 4). The differences in these relationships across drainage classes reflect the influence of drainage class on soil moisture and how that affects the change in soil temperature. The well-drained class, under both snow removal and ambient conditions, had the highest estimated intercept and slope, respectively, in the regression of frost depth on AFI. Estimated intercepts and slopes decreased from WD to PD, representing the decline in frost depth in wetter drainage classes. Differences in frost between the control and treatment emphasize the importance of snow cover as a regulator of soil temperature and frost depth in mineral soils.

The results of the intercept and slope regression comparison support the findings of the soil temperature and frost depth models, which also reflect the strong regulation of temperature and frost depth by drainage class (in a three-way interaction with treatment and week, as well as another three-way interaction with treatment and depth). Across the drainage classes, however, snow removal caused an increase in the rate of frost development with AFI. The positive relationship between frost depth and AFI suggests that mineral soils across drainage classes will respond relatively consistently to a decrease in winter snowpack, as predicted by current climate change models (Handler et al., 2014). The magnitude of frost depth differs across drainage classes, but the positive relationship between frost depth and AFI remains consistent regardless of drainage class, which makes this relationship a potential tool for forest managers when planning winter harvests.

Effects of throughfall reduction

Effects of throughfall reduction, drainage class, and depth on soil moisture were often inconsistent and unexpected. Notably, there was no difference in soil water content at the soil surface (10 cm) between the control and throughfall reduction treatments, which is where we expected a reduction effect would be most apparent. Additionally, some of the treatment plots often had higher SWC than the control plots across the drainage classes even though the treatment plots were receiving less than half the volume of throughfall compared to the control during 2021 (Figure 7; see methods for throughfall volume measurements). For example, SWC was higher in the throughfall reduction treatment compared to the control treatment in MWD at 30 cm, 40 cm, and 60 cm (2019-

2021), and PD at 60 cm (2019-2021). In contrast, SWC was higher in the control in WD at 40 cm (2019, 2020) and SPD at 30 cm (2019, 2020) and 60 cm (2019). This trend in soil moisture, which was inconsistent with our expectations, suggests that either the treatment was not modifying soil moisture or that another variable was negating the throughfall reduction. Soil water content consistently increased from WD to PD (Figure 7) which aligns with the expected relationship between drainage class and soil moisture (Briggs & Lemin, 1994; Henninger et al., 1976; Veneman et al., 2008).

Potential artifacts exist when designing and implementing throughfall reduction treatments, especially in forested ecosystems with one level of precipitation manipulation (Beier et al., 2012; Hoover et al., 2018). For example, the relatively small plot size ($16m^2$) may have limited the ability of the throughfall reduction shelters to modify the soil microenvironment. As plot size decreases, the risk of edge effects increases, meaning that precipitation could enter the plot via other routes other than vertical interception (Beier et al., 2012; Fay et al., 2000). Additionally, the plots in this study were not trenched, which may have resulted in lateral flow or influence from tree roots outside the plot boundaries. Increased gradients in total water potential in treatment plots may have caused differences in capillary rise, which may have also contributed to the unclear trends in soil moisture (Romero-Saltos et al., 2005). Manipulations of precipitation may also alter near surface evaporation, which could affect the amount of water infiltrating into the soil (Beier et al., 2012). Finally, heterogeneity in soil moisture content (and its measurement) may have masked differences between control and treatment plots within a drainage class. Although the cause of the inconsistent treatment effect is unclear, the results highlight the need to give careful thought in the design of throughfall reduction studies.

The lack of any effect of throughfall reduction on soil strength aligns with the lack of treatment effect on SWC (Supplemental Materials Table 3). There were also inconsistent effects of drainage class on soil strength (Figure 8, Supplemental Materials Table 4). The lack of significant differences among drainage classes may have been due to differences in soil texture. However, the results overall contrast with many studies that have shown that soil strength decreases as soil water content increases (Cambi et al., 2015; Greacen & Sands, 1980; McNabb et al., 2001; Uusitalo et al., 2019). Few studies, however, have investigated the effect of experimental throughfall reduction on soil strength in forest ecosystems. Yang et al. (2019) constructed throughfall reduction shelters over 20 x 20m plots in subtropical planted forests in China and found that throughfall reduction significantly reduce SWC and soil aggregate stability.

Compared to laboratory measurements, the *in situ* measurement of soil strength has the potential for high variability, especially in soils with glacial heterogenous parent material and high rock content like those in Minnesota. Contact with a belowground root or coarse fragment could alter the angle of the dynamic penetrometer, which reduces the accuracy of the measurement (Minnesota Department of Transportation, n.d.). Previous studies have suggested that the dynamic penetrometer is sensitive to differences in soil moisture and texture, especially in heterogenous soils (Herrick & Jones, 2002). Therefore, much difficulty still exists when using a dynamic penetrometer in highly heterogenous soils with a high concentration of tree roots and coarse fragments.

Implications for management

The increase in frost development that occurred with snow removal may have implications for future accessibility of forest stands during the winter, potentially increasing the period in which those stands could be harvested with limited impacts to the soil if predicted reduction in snowfall occurs. The maximum frost depths reached in the snow removal treatment would sufficiently support harvesting equipment since previous work has recommended at least 15 cm of frost for heavy equipment (Stone, 2002). However, equipment weights may have increased over time; Stone (2002) did not report equipment weights, but a similar study by McNabb et al. (2001) reported that the empty weight of skidders used in the study was between 14 and 17 Mg and capable of carrying 4 to 6 Mg of timber. An example of a modern wheeled grapple skidder from John Deere weighs approximately 19 Mg unloaded.

Also, current climate change models have simulated warming winter temperatures, which would result in a decline in the total number of freezing days and possibly negate the effect of reduced snow cover (Handler et al., 2014). While this study suggests that winter frost depths will increase with reduced snow cover, there will be interactions between the effects of reduced snow cover and warmer winter temperatures on frost development in northern climates such as Minnesota. Current climate change models predict that mean winter temperatures in northern Minnesota will increase by 2100 (PCM B1: 2.2˚C; GFDL A1FI: 3.0˚C) but are expected to still remain below freezing in the winter (Handler et al., 2014). So even with the predicted warming, sub-freezing temperatures with reduced snowpack would likely still result in increased frost development assuming minimal changes in the total number of freezing degree days per season. Regardless, future research on frost regimes under a changing climate could include the addition of a warming treatment to simulate warmer winter air temperatures.

Further study is required to quantify the effects of reduced precipitation on soil strength in forest ecosystems during the summer. Understanding the operability of forest soils under climate change is crucial in maintaining sufficient yield from summer timber harvests with minimal impacts to the soil. The relationship between soil strength and soil moisture has been reported in previous studies, so the predicted declines in summer precipitation (in addition to an increase in extreme precipitation events) will likely have a tangible effect on soil operability in northern Minnesota (Greacen & Sands, 1980; Handler et al., 2014; McNabb et al., 2001; Uusitalo et al., 2019). Future studies should aim to quantify soil strength under reduced precipitation scenarios across cover types and drainage classes for improved prediction of the operability of forest soils under climate change.

A key finding from this study is that drainage class was a strong predictor of soil moisture, temperature, and frost development. Drainage class is easily mapped and measured, such as with widely available NRCS data products, and thus may be an important metric for forest managers when determining the feasibility of harvesting in the winter. Managers may be able to rely on drainage class, and the relationship between AFI and frost, to identify the harvesting periods which will minimize negative impacts to soil. The relationships we identified between AFI and frost depth by drainage class can be used to approximate the winter operability of a site, based on the approximate required frost depth needed to support harvesting equipment. Drainage class can help managers to identify sites that may take longer to freeze and to determine approximately how many days would be required to reach sufficient frost depth to sustain heavy equipment. Operators should also be encouraged to compact snow with low ground pressure equipment to increase its thermal conductivity several days prior to initiating harvesting activities to encourage increased frost development. Timing snow compaction efforts to occur soon before an extended drop in air temperature will help accelerate frost development. Use of metrics such as the palmer Drought Severity Index or Standardized Precipitation Index to estimate relative soil moisture levels prior to a winter harvest season.

Conclusions

The results of this study provide critical insight to managers on the long-term operability of forest soils under a changing climate. We applied a novel methodology by combining throughfall reduction and snow removal treatments across a gradient of drainage class in aspen forests of northern Minnesota, USA. Based on current climate change models, northern latitudes are expected to experience decreased growing season precipitation and winters with reduced snow cover, which would have major implications for the operability of forest soils. We found that throughfall reduction during the growing season had minimal impacts on soil moisture and soil strength. The snow removal treatment during the winter significantly increased frost development and decreased soil temperature across drainage classes. Drainage class was a strong indicator of soil moisture, temperature, strength, and frost development. These results demonstrate the utility of using drainage class as a metric when inferring soil moisture and temperature when determining harvesting periods.

Acknowledgments

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SUPPLEMENTAL MATERIALS

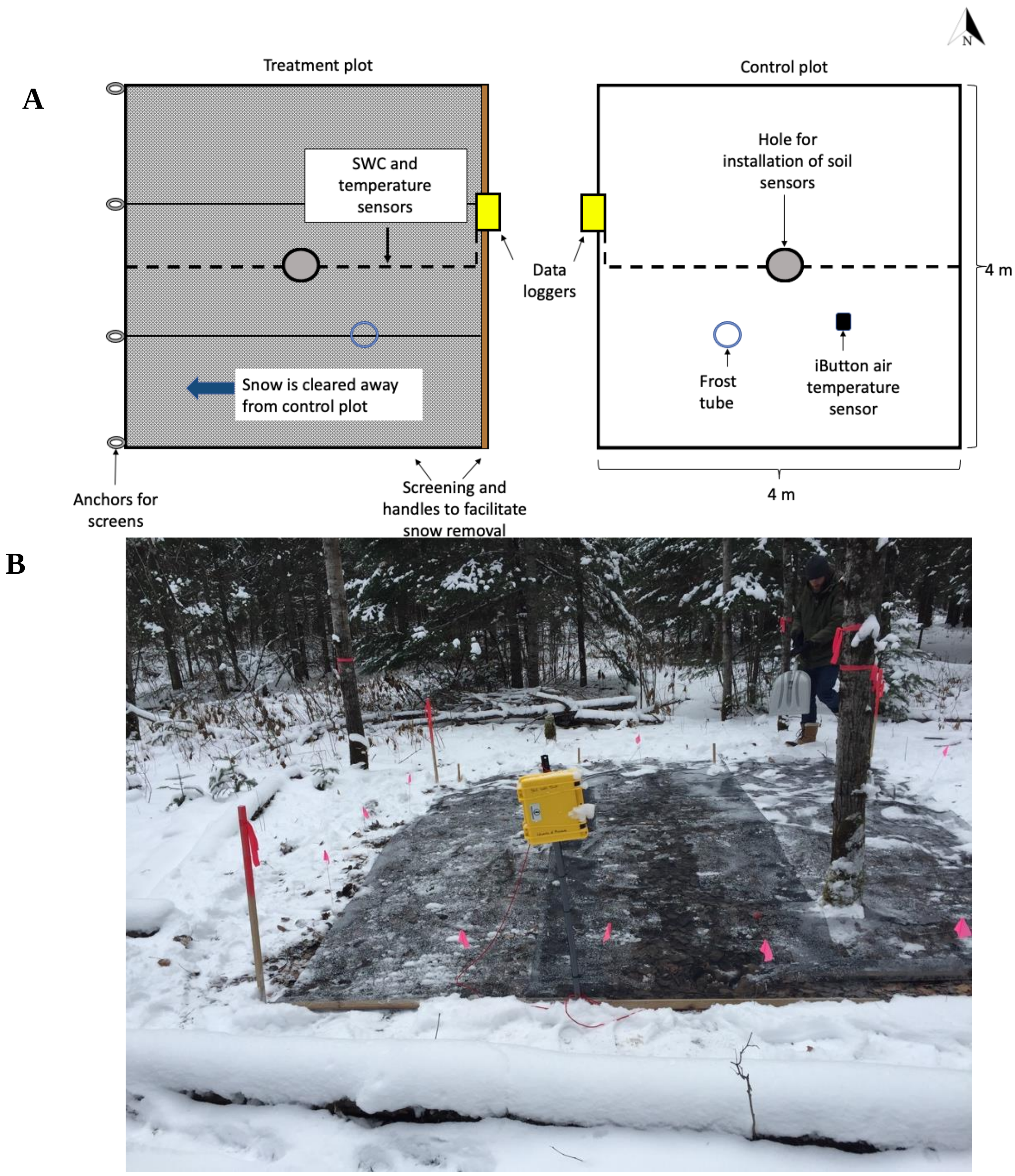
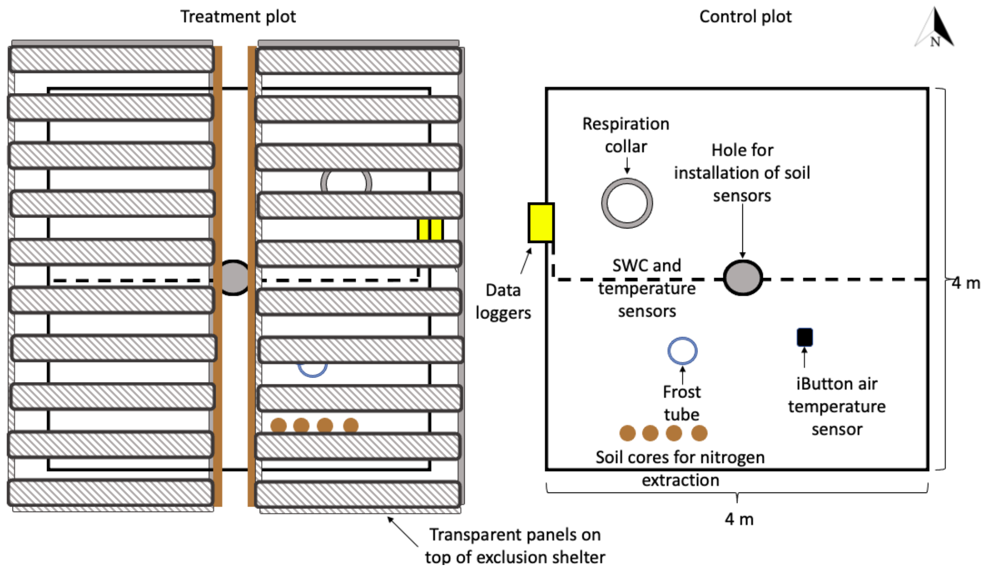


Figure 1: Paired-plot design schematic (panel A) and field photo (panel B) with snow removal treatment during the winter. (Photo credit: Alan Toczydlowski, University of Minnesota)

A



B

Figure 2: Paired-plot design with throughfall reduction treatment during the growing season is shown in panel A. All plots and transparent roof panels were oriented on an east-west transect, with the shelter ridgeline running north-south. Precipitation reduction shelters were designed to exclude 50% of throughfall. Plots that received treatment were randomized in each pair. Panel B shows the throughfall exclusion shelter on a treatment plot during the growing season. (Photo credit: Alan Toczydlowski)

Table 0: ANOVA summary for soil temperature models for the winters of 2018/19, 2019/20, 2020/21, and 2021/22. Numerator degrees of freedom and model coefficient p-values are shown. Bolded values indicate a significant result (p-value < 0.05).

	2018/2019 2018/11/04 - 2019/05/26		**2019/2020** 2019/11/03- 2020/05/31		**2020/2021** 2020/11/01 - 2021/05/31		**2021/2022** 2021/11/07 - 2021/05/15	
Model term	**Degrees of freedom**	**p-value**	**Degrees of freedom**	**p-value**	**Degrees of freedom**	**p-value**	**Degrees of freedom**	**p-value**
Intercept	1	**<0.001**	1	**<0.001**	1	**<0.001**	1	**<0.001**
Drainage	3	**<0.001**	3	**<0.001**	3	**<0.001**	3	**<0.001**
Treatment	1	**<0.001**	1	**<0.001**	1	**<0.001**	1	**<0.001**
Week	29	**<0.001**	30	**<0.001**	30	**<0.001**	27	**<0.001**
Depth	4	**<0.001**	4	**<0.001**	4	**<0.001**	4	**<0.001**
Drainage:Treatment	3	**<0.001**	3	**<0.001**	3	**<0.001**	3	**<0.001**
Drainage:Week	87	**<0.001**	90	**<0.001**	90	**<0.001**	81	**<0.001**
Treatment:Week	29	**<0.001**	30	**<0.001**	30	**<0.001**	27	**<0.001**
Drainage:Depth	12	0.276	12	**0.008**	12	**0.002**	12	**<0.001**
Treatment:Depth	4	**<0.001**	4	**<0.001**	4	**<0.001**	4	**<0.001**
Week:Depth	116	**<0.001**	120	**<0.001**	120	**<0.001**	108	**<0.001**
Drainage:Treatment:Week	87	**<0.001**	90	**<0.001**	90	**<0.001**	81	**<0.001**
Drainage:Treatment:Depth	12	0.897	12	0.050	12	0.649	12	0.205
Drainage:Week:Depth	348	1.000	360	1.000	360	1.000	324	1.000
Treatment:Week:Depth	116	**0.010**	120	0.272	120	**<0.001**	108	**<0.001**
Drainage:Treatment:Week:Depth	348	1.000	360	1.000	360	1.000	324	1.000

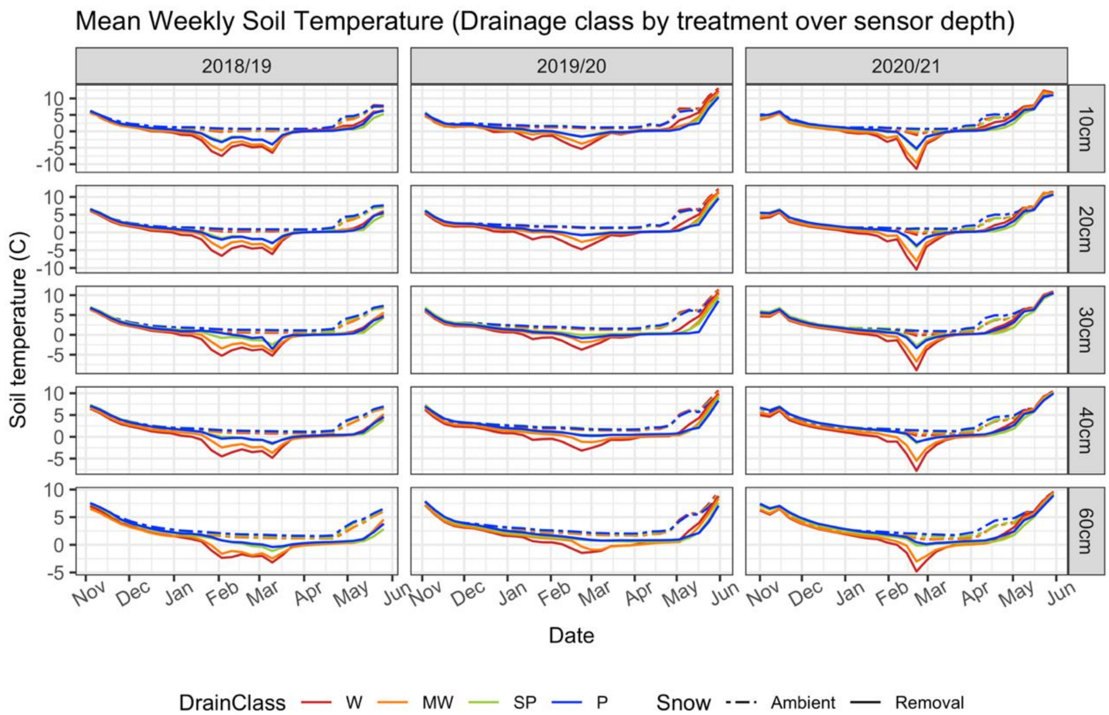


Figure 3: Mean weekly soil temperature during the winters of 2018/19, 2019/20, and 2020/21 across drainage class, treatment, depth, and week.

Table 2: Three-way ANOVA results summary for the soil frost models for winters 2019/20, 2020/21, and 2021/22. Numerator degrees of freedom and model coefficient p-values are shown. Bolded values indicate a significant result (p-value < 0.05).

	2019/2020		**2020/2021**		**2021/2022**	
	2019/11/14 - 2019/04/15		2020/10/23 - 2021/05/04		2021/11/23 - 2022/05/17	
Model term	**Degrees of freedom**	**p-value**	**Degrees of freedom**	**p-value**	**Degrees of freedom**	**p-value**
Intercept	1	**<0.001**	1	**<0.001**	1	**<0.001**
Drainage	3	**<0.001**	3	**<0.001**	3	**<0.001**
Treatment	1	**<0.001**	1	**<0.001**	1	**<0.001**
Date	13	**<0.001**	20	**<0.001**	22	**<0.001**
Drainage:Treatment	3	**0.001**	3	0.183	3	0.071
Drainage:Date	39	0.985	60	0.230	66	0.999
Treatment:Date	13	**<0.001**	20	**<0.001**	22	**<0.001**
Drainage:Treatment:Date	39	0.994	60	0.963	55	1

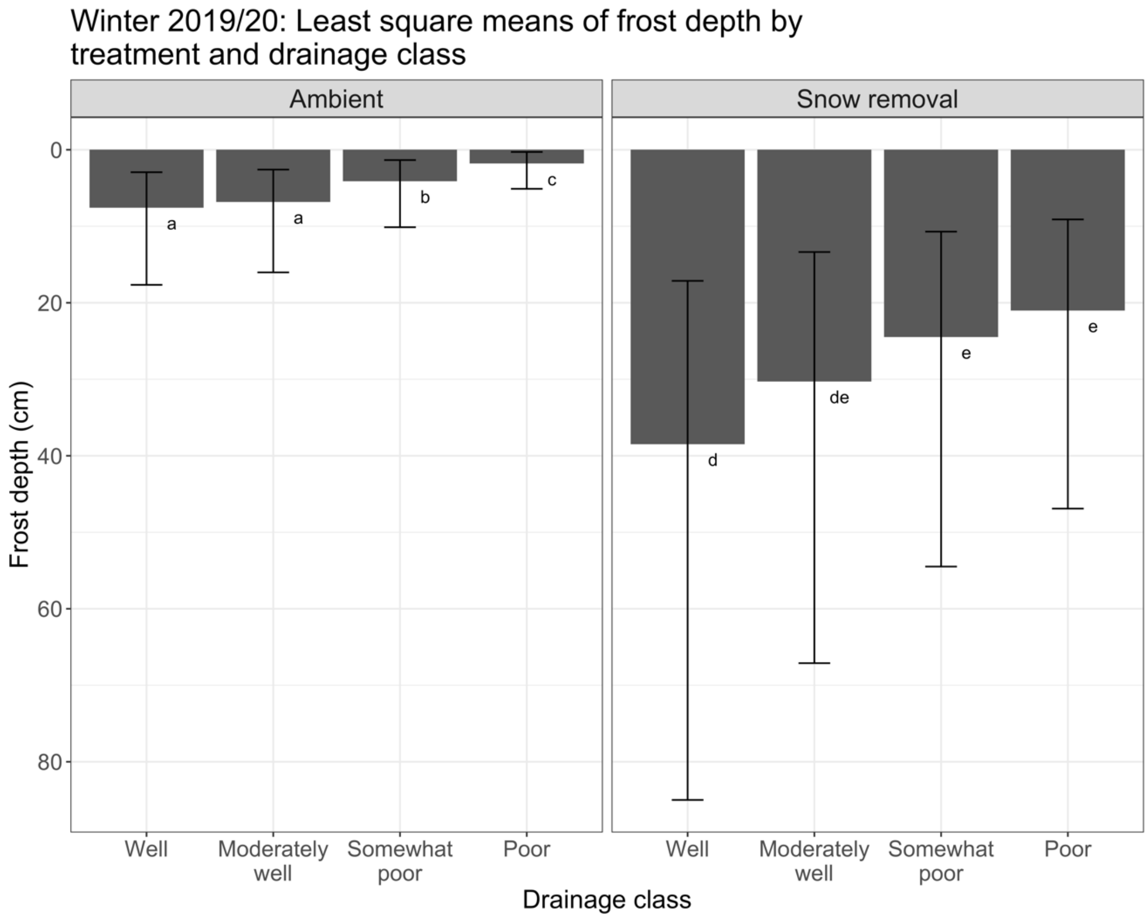


Figure 4: Least square means of frost depth by treatment and drainage class during the winter of 2019/20. Bars with different letters indicate significant differences between the means (p-value < 0.05). Error bars represent 95% confidence intervals.

Table 3: Four-way ANOVA summary for soil water content models for the growing seasons of 2019, 2020, and 2021. Model coefficient p-values are shown. Bolded values indicate a significant result (p-value < 0.05).

	2019	**2020**	**2021**
Model term	**p-value**	**p-value**	**p-value**
Intercept	**<0.001**	**<0.001**	**<0.001**
Drainage	**<0.001**	**<0.001**	**<0.001**
Treatment	0.976	0.338	**<0.001**
Week	**<0.001**	**<0.001**	**<0.001**
Depth	**<0.001**	**<0.001**	0.220
Drainage:Treatment	**<0.001**	**<0.001**	**<0.001**
Drainage:Week	0.114	0.941	**<0.001**
Treatment:Week	0.001	0.650	0.399
Drainage:Depth	**<0.001**	**<0.001**	**<0.001**
Treatment:Depth	**0.002**	**<0.001**	**<0.001**
Week:Depth	1.000	1.000	0.974
Drainage:Treatment:Week	1.000	1.000	1.000
Drainage:Treatment:Depth	**<0.001**	**<0.001**	**<0.001**
Drainage:Week:Depth	1.000	1.000	1.000
Treatment:Week:Depth	1.000	1.000	1.000
Drainage:Treatment:Week:Depth	1.000	1.000	1.000

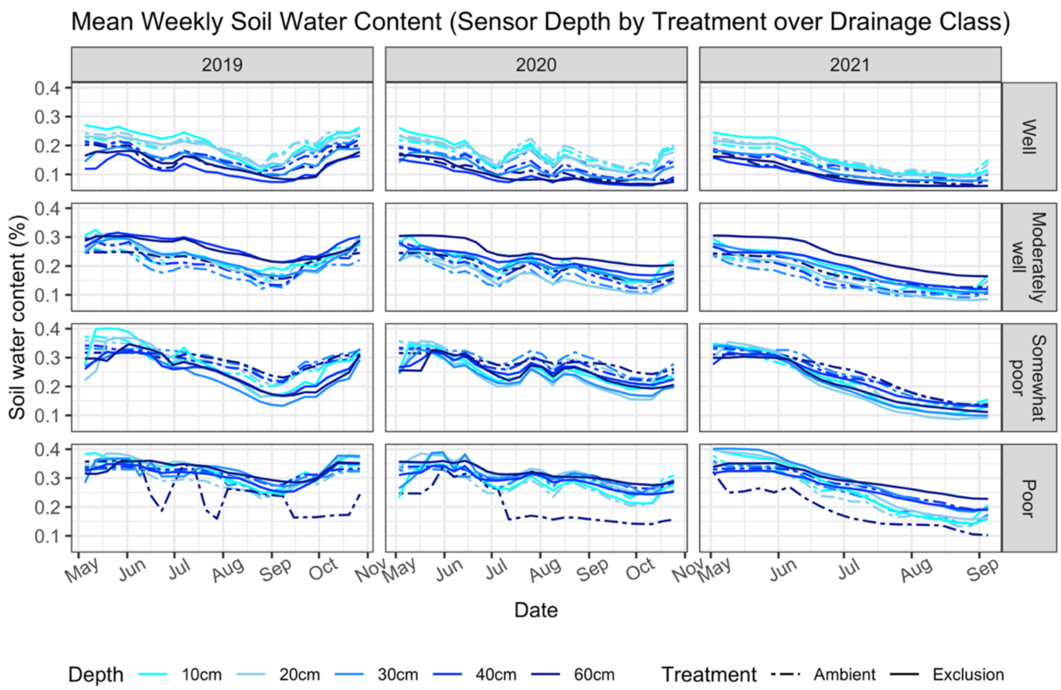


Figure 5: Mean weekly soil water content during the growing seasons of 2019, 2020, and 2021 by drainage class, treatment, and depth.

Table 4: Three-way ANOVA results summary for the soil strength models for 2020 and 2021. Bolded values indicate a significant result (p-value < 0.05).

	2020		**2021**	
	30 cm depth	60 cm depth	30 cm depth	60 cm depth
Model term	**p-value**	**p-value**	**p-value**	**p-value**
Intercept	**<0.001**	**<0.001**	**<0.001**	**<0.001**
Drainage	0.888	**0.034**	0.891	0.716
Treatment	0.262	0.253	0.647	0.351
Date	0.779	0.943	0.551	1.000
Percent clay	0.245	0.502	0.025	0.183
Drainage:Treatment	0.242	**0.014**	0.688	0.555
Drainage:Date	0.990	0.999	0.864	0.915
Treatment:Date	0.872	0.999	0.778	0.636
Drainage:Treatment:Date	0.997	1.000	0.967	0.942

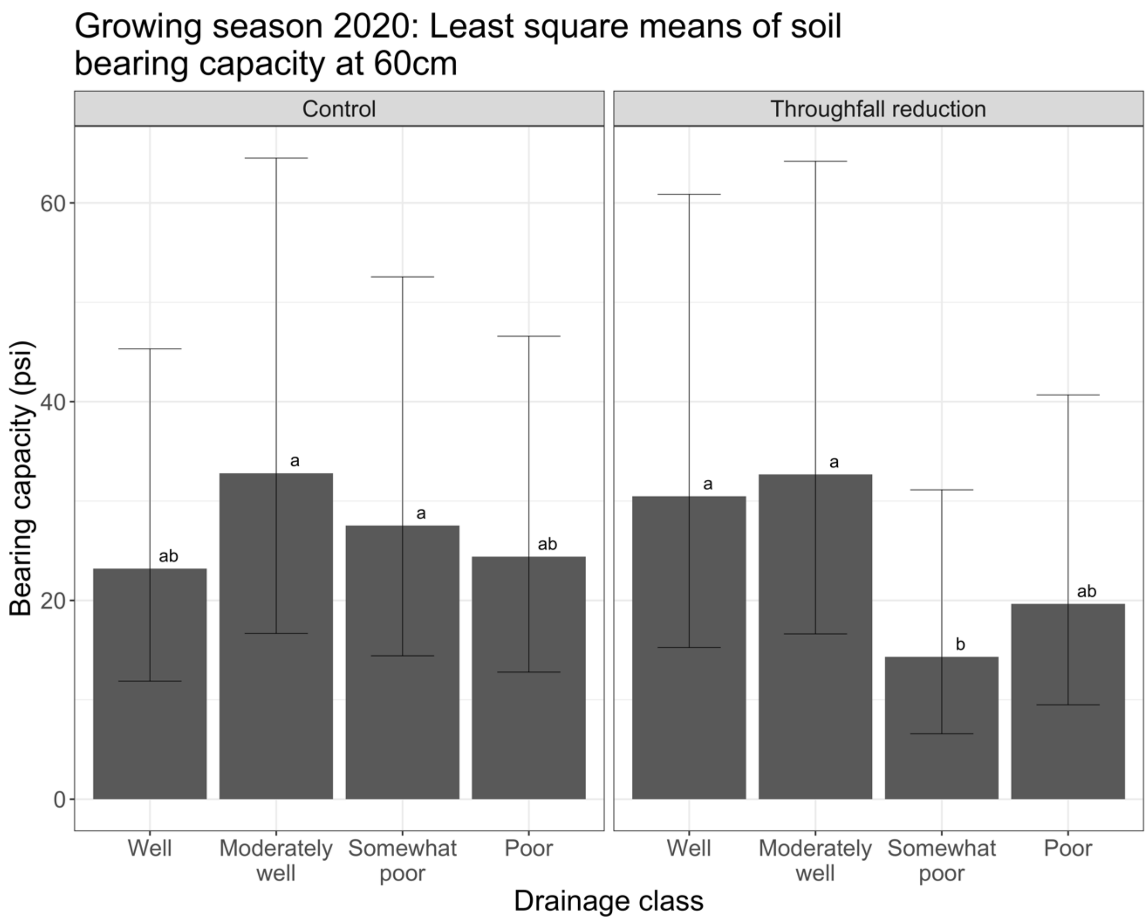


Figure 6: Least square means of soil strength (bearing capacity) across drainage classes and treatments at 60cm. Letters indicate significant differences as a pairwise comparison between drainage class and treatment (p-value < 0.05). Error bars represent 95% confidence intervals.

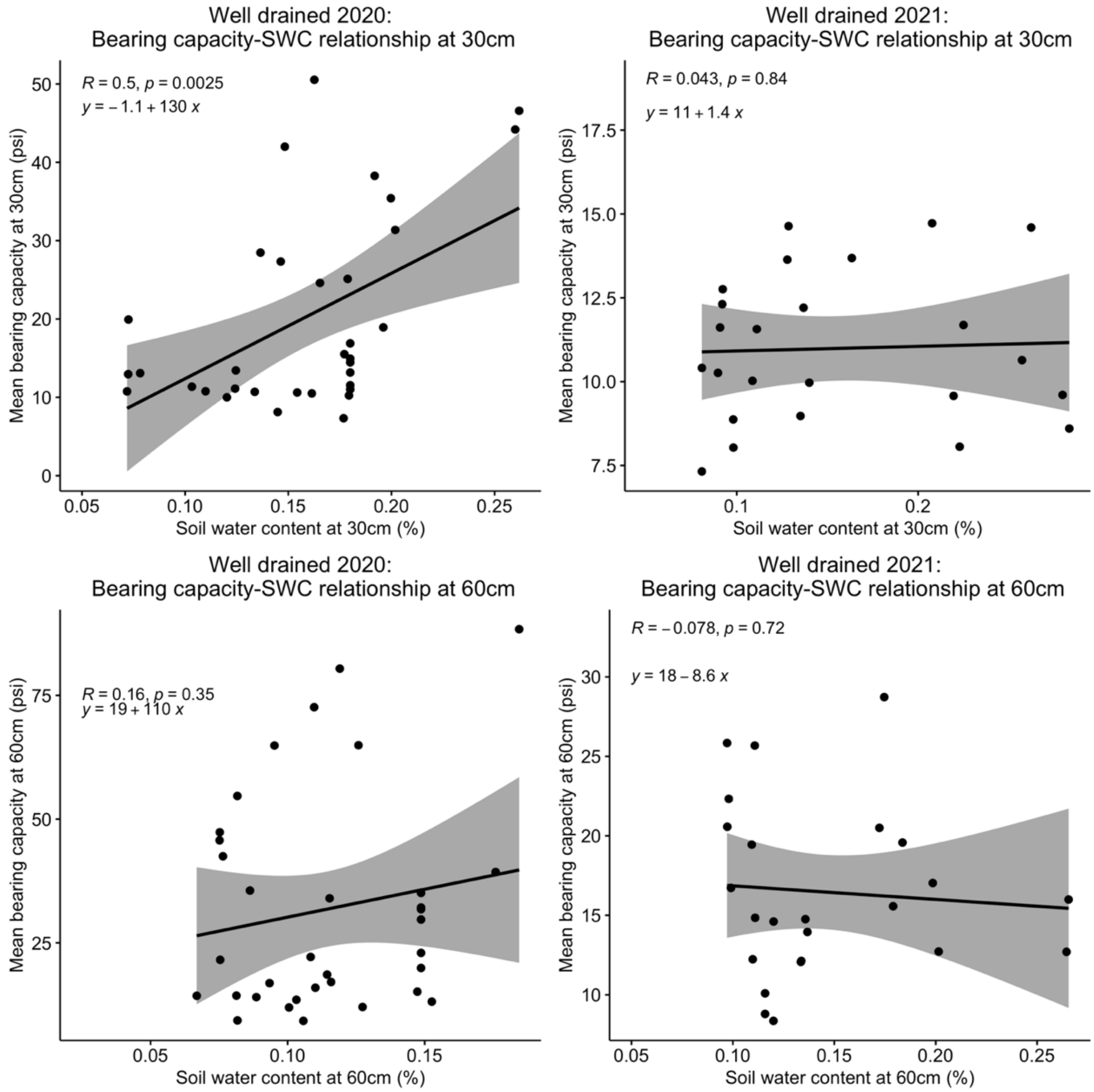


Figure 7. Linear regressions between soil water content and mean bearing capacity for the well-drained class. Confidence intervals are 95% and level of significance is equal to 0.05.

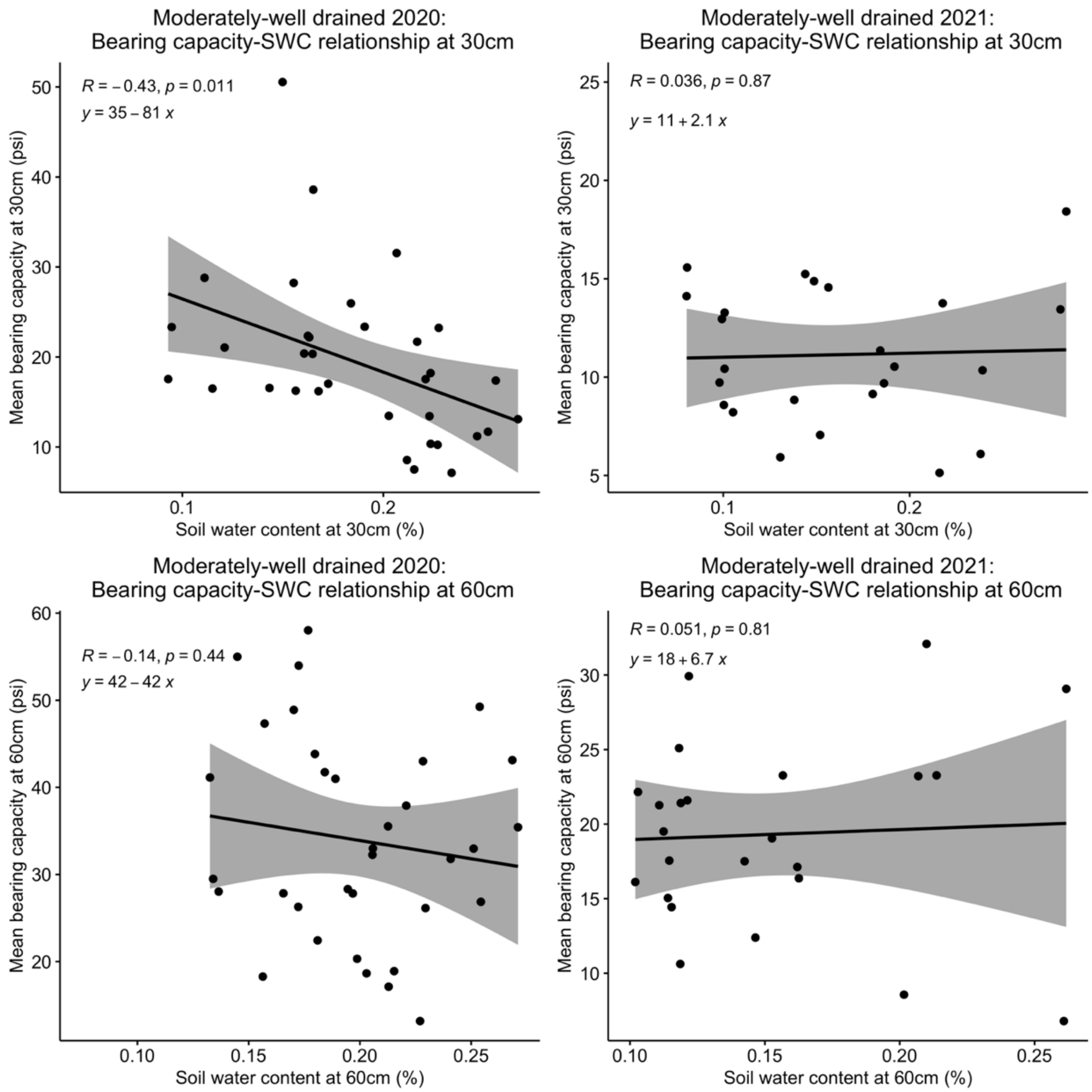


Figure 8: Linear regressions between soil water content and mean bearing capacity for the moderately well-drained class. Confidence intervals are 95% and level of significance is equal to 0.05.

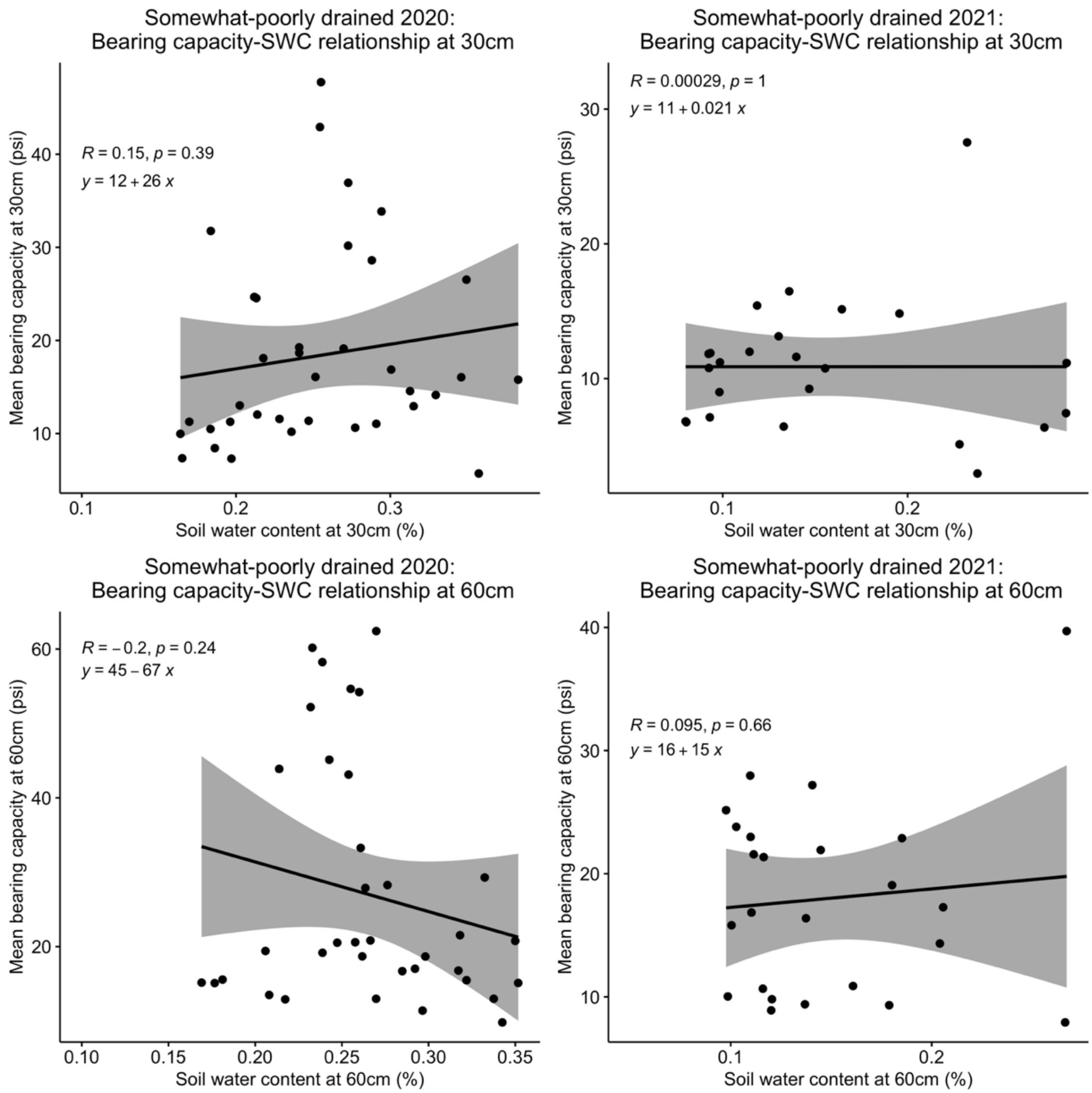


Figure 9: Linear regressions between soil water content and mean bearing capacity for the somewhat poorly-drained class. Confidence intervals are 95% and level of significance is equal to 0.05.

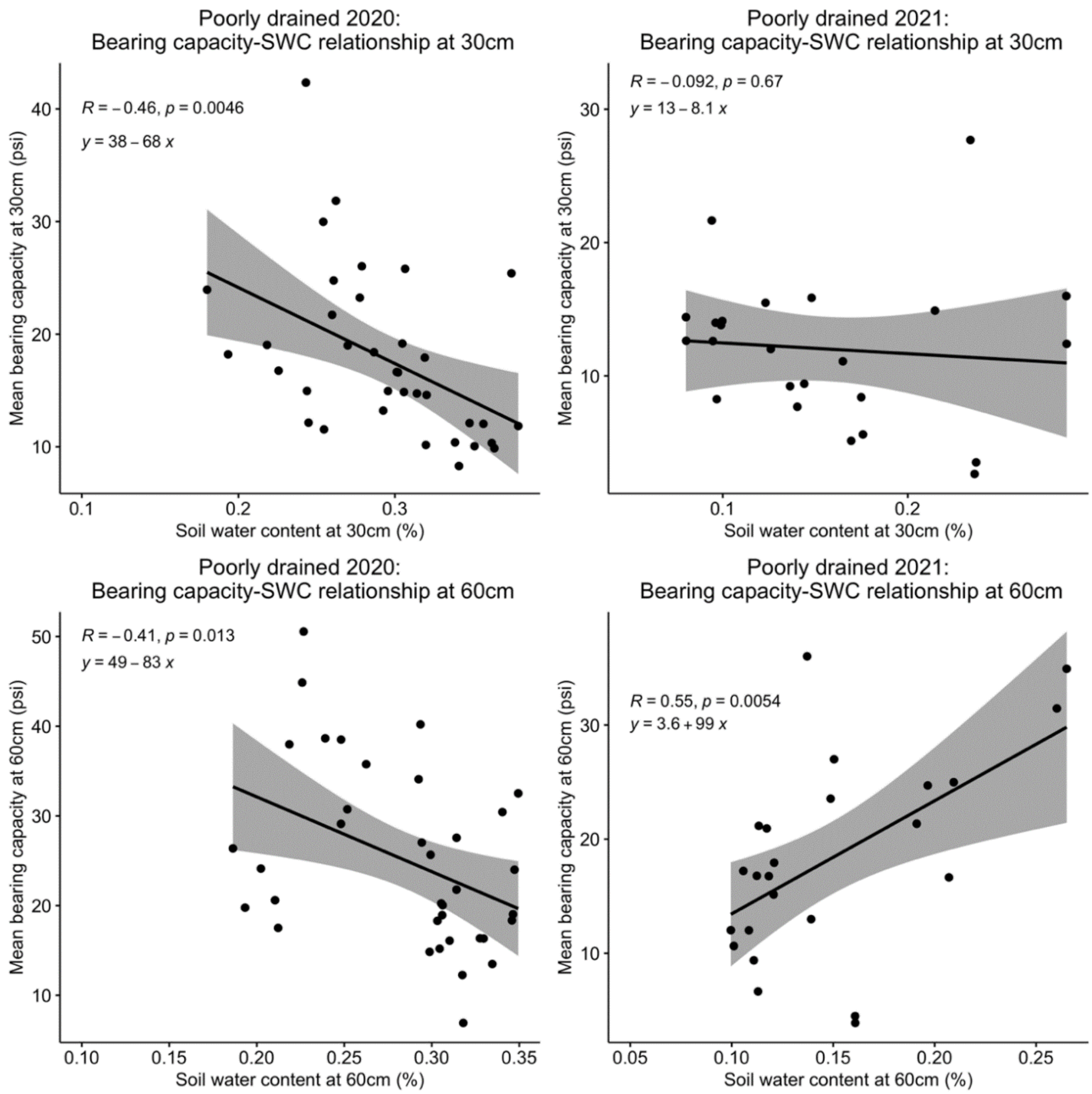


Figure 10: Linear regressions between soil water content and mean bearing capacity for the poorly-drained class. Confidence intervals are 95% and level of significance is equal to 0.05.