2018 Project Abstract
For the Period Ending June 30, 2022

PROJECT TITLE: Develop Strategies for Timber Harvest to Minimize Soil Impacts to Maintain Healthy and Diverse Forests

PROJECT MANAGER: Charlie Blinn
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WEBSITE: https://forestry.umn.edu
FUNDING SOURCE: Environment and Natural Resources Trust Fund
LEGAL CITATION: M.L. 2018, Chp. 214, Art. 4, Sec. 02, Subd. 08f

APPROPRIATION AMOUNT: $200,000
AMOUNT SPENT: $192,459
AMOUNT REMAINING: $7,541

Sound bite of Project Outcomes and Results
Reduced snowfall predicted with climate change is likely to increase the amount of soil frost during winter, increasing the times when forest harvesting can safely occur. We developed tools that will allow managers to predict when and where optimal soil conditions occur to minimize impacts of forest harvesting.

Overall Project Outcome and Results

Soils and forest health can be impacted during forest harvesting depending on how much frost is present during winter and how wet the soils are in summer. Climate change is expected to change these conditions, creating challenges for managers to determine when the optimal harvest time will occur. Our objectives were to determine how 1) snow cover influences the rate of frost development; 2) soil moisture influences soil strength; and 3) each of those relationships vary across areas that span a range of soil drainage (relative wetness). We conducted snow removal and rainfall reduction treatments in three aspen forests and monitored soil temperature and moisture, frost development, and soil strength for a period of three years. Treatments were conducted across a range of drainage classes that were expected to influence the treatment response and which could be readily identified by managers in the field (to improve application of any findings). We determined that snow removal causes significant increases in frost development and that the relationship is dependent on relative soil wetness of the forest: wetter, more poorly drained soils had lower frost development compared to drier, well-drained soils. Rainfall reduction had limited and inconsistent effects on soil moisture, possibly because of the small plot size. The relationships between soil moisture and soil strength were also inconsistent, hindering identification of the optimal soil moisture content where soil strength is optimal to reduce harvest impacts under non-frozen conditions. Based on our findings and previously developed metrics, we developed a map of harvest suitability for all forested areas in Minnesota under two scenarios, which can be used by managers and landowners to identify the season when forest harvesting is likely to have the smallest impact on soil and forest health. The results provide managers with tools that support sustainable forest management and the benefits it provides.

Project Results Use and Dissemination
We summarized the primary project findings into peer-reviewed journal articles that highlight key relationships and considerations that managers can use when determining the optimal time to conduct forest harvests. The information was also shared with resource managers at the annual Research Review conducted annually by UMN's Sustainable Forestry Education Cooperative. The journal articles are still in publication, but a graduate

student thesis is available here that outlines the primary findings. In addition, we created a map of harvest suitability by season for the forested region of Minnesota that can be accessed here. These two references are missing their hyperlink info.

Environment and Natural Resources Trust Fund (ENRTF)
M.L. 2018 ENRTF Work Plan (Main Document) Final Report

Today's Date: 08/12/2022

Date of Next Status Update Report: Final Report

Date of Work Plan Approval: 06/05/2018

Project Completion Date: June 30, 2022

PROJECT TITLE: Develop Strategies for Timber Harvest to Minimize Soil Impacts to Maintain Healthy and Diverse Forests

Project Manager: Charlie Blinn

Organization: University of Minnesota

College/Department/Division: Department of Forest Resources

Mailing Address: 115 Green Hall, 1530 Cleveland Avenue N.

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Email Address: cblinn@umn.edu

Web Address:

Location: All counties in the NE Region of Minnesota in addition to Crow Wing Co., Cass Co., Wadena Co., Mille Lacs Co. Hubbard Co. Clearwater Co., Beltrami Co., Lake of the Woods Co., and Roseau Co.

Total Project Budget: $200,000

Amount Spent: $192,332

Balance: $7,668

Legal Citation: M.L. 2018, Chp. 214, Art. 4, Sec. 02, Subd. 08f

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Appropriation Language: $200,000 the second year is from the trust fund to the Board of Regents of the University of Minnesota to develop strategies and practical tools to minimize soil compaction and other impacts across a range of conditions during timber harvest to maintain timber availability, improve regeneration of diverse forests, and benefit wildlife habitat. This appropriation is available until June 30, 2022, by which time the project must be completed and final products delivered.

I. PROJECT STATEMENT:

Managed forests are essential to maintain clean water, promote wildlife habitat, and regenerate tree species which require disturbance, but only if forest management activities minimize impacts to soils and the critical functions they control. In Minnesota, soil compaction during forest harvesting is a common concern because it can degrade soil and reduce future site productivity. Because of this, logging during winter when soil is frozen is one of the most common approaches to protect soil when harvesting timber. However, compaction can still occur during winter if insufficient frost is present, and there is limited information on what a sufficient level of frost is and under what conditions it will form. In addition, focus on winter harvesting constrains the supply of timber during summer months and may inhibit establishment of certain desirable cover types. Past work and field experience indicates that harvesting can be safely conducted during summer on certain soil types and soil conditions. However, our current ability to predict the soil types and conditions where impacts are minimized during summer harvesting is surprisingly limited.

This project will quantify the factors that control soil operability in summer and winter across a range of soil types, soil conditions, and regional weather patterns. Understanding how these factors control soil operability will allow us to identify soil types and threshold conditions when harvesting can be conducted without degrading the soil and forecast when these situations will exist. We will use the project findings to develop practices and tools that minimize soil impacts and maximize benefits of forest resources including wildlife habitat and the supply of high-quality timber. Specific products that will be developed include a GIS-based soil operability metric and a tool that can be used in the field to directly assess soil operability. The potential impact of this work is large because the products can be easily used by land managers (e.g., the DNR, County land departments, forest industry, and federal agencies) and loggers to identify suitable site operating conditions and reduce uncertainty related to soil impacts. The findings and products will be widely used by the forestry community to increase site access for management and promote a wide range of benefits associated with working forest lands and the communities they support.

II. OVERALL PROJECT STATUS UPDATES:

First January 31, 2019

We have made excellent progress under Activity 1 and are on track with the overall project timeline. Research plots were installed in the fall of 2018 and we continue to monitor soil temperature and moisture at each of them.

Second Update June 30, 2019

Progress continues to be made on Activity 1 and everything is proceeding with the planned project timeline. Rainout shelters were installed at the experimental plots, and soil temperature and moisture continue to be monitored.

Third Update January 31, 2020

Excellent progress continues to be made on Activity 1 with one year of winter and summer measurements completed. Tasks associated with Activity 1 are all on time and we will begin analyzing the first years data later this month**.**

Fourth Update June 30, 2020,

We continue to make good progress on Activity 1, with only minor adjustments associated with the coronavirus outbreak and associated work closures. The first year of data has been fully analyzed and experimental treatments are being maintained. We have also initiated work on Activity 2.

Amendment request June 10, 2020

We are requesting that Robert Slesak be removed as project manager and that Charlie Blinn be named as his replacement. This change is being requested because Slesak has taken a new position which prohibits him from being a PI on UMN affiliated projects. Blinn, who is a UMN faculty member, is on the project team and has been involved in all aspects of work to date. Slesak will continue to be involved in the project going forward, but at a reduced capacity.

Amendment Approved by LCCMR 6/25/2020

Fifth Update January 31, 2021

Work on Activity 1 continues and all data collection is proceeding as planned. We now have two years of data that has been processed and analyzed. Datasets associated with Activity 2 have been acquired and we are currently conducting preliminary analysis. Progress to date is on time.

Amendment request January 31, 2021

We are requesting that funds be shifted from personnel to the travel budget line.

- Personnel budget would be reduced by $3,000 to a revised budget of $158,000
- Travel budget would increase by $3,000 to a revised budget of $18,000

This change is being requested because we underestimated travel costs associated with the project and have identified some savings in personnel costs. The 3 project sites are located north of Duluth, near McGregor, and north of Grand Rapids. We visit the sites at least weekly during the winter and biweekly during the summer, requiring extensive fleet costs. Remaining travel funds are insufficient to cover travel costs associated with Activity 1 throughout the project period.

Sixth Update June 30, 2021

Work proceeds on schedule for both Activity 1 and 2. We do not anticipate any difficulties with completing the project on time.

Seventh Update January 31, 2022

Work proceeds on schedule for Activity 1 and 2. We have identified one issue with Activity 2 which will influence the deliverables outlined in the workplan.

Amendment request January 31, 2022

We are requesting that funds be shifted from personnel to the travel budget line.

- Personnel budget would be reduced by $4,000 to a revised budget of $154,000
- Travel budget would increase by $4,000 to a revised budget of $22,000

This change is being requested because travel costs continue to exceed what we have budgeted given several unplanned field visits which were necessary to maintain the soil monitoring equipment and repair rainout shelters. We have included a cushion in this request to account for more snow removal days associated with Activity 1 that may be necessary this winter. Remaining travel funds are insufficient to cover travel costs associated with Activity 1 throughout the project period.

Overall Project Outcomes and Results

Soils and forest health can be impacted during forest harvesting depending on how much frost is present during winter and how wet the soils are in summer. Climate change is expected to change these conditions, creating challenges for managers to determine when the optimal harvest time will occur. Our objectives were to determine how 1) snow cover influences the rate of frost development, 2) soil moisture influences soil strength, and 3) each of those relationships vary across areas that span a range of soil drainage (relative wetness). We conducted snow removal and rainfall reduction treatments in three aspen forests and monitored soil temperature and moisture, frost development, and soil strength for a period of three years. Treatments were conducted across a range of drainage classes that were expected to influence the treatment response and which could be readily identified by managers in the field (to improve application of any findings). We determined that snow removal causes significant increases in frost development and that the relationship is dependent on relative soil wetness of the forest: wetter, more poorly drained soils had lower frost development compared to drier, well-drained soils. Rainfall reduction had limited and inconsistent effects on soil moisture, possibly because of the small plot size. The relationships between soil moisture and soil strength were also inconsistent, hindering identification of the optimal soil moisture content where soil strength is optimal to reduce harvest impacts under non-frozen conditions. Based on our findings and previously developed metrics, we developed a map of harvest suitability for all forested areas in Minnesota, which can be used by managers and landowners to identify the season when forest harvesting is likely to have the smallest impact on soil and forest health. The results provide managers with tools that support sustainable forest management and the benefits it provides.

III. PROJECT ACTIVITIES AND OUTCOMES:

ACTIVITY 1: Assess the influence of different soils and weather on operability across a range of site conditions
Description: We will develop a network of seven research sites along a temperature gradient and across a range of soil textures in northern Minnesota. Soil texture is a key property that influences soil operability because it controls soil moisture and frost dynamics – the primary factors influencing soil strength and susceptibility to compaction during summer and winter, respectively. For this project we will focus on fine to medium textured soils because these typically are most susceptible to degradation and have the most constraints influencing soil operability. Experimental treatments that manipulate soil moisture during the summer and snow depth during the winter will be replicated at each site. Treatments will be applied throughout the project period to assess the influence of inter-annual variability in weather on soil operability. We will measure and analyze the effect of these treatments on soil temperature and moisture, frost occurrence and depth (during winter), soil strength, and variation in response over a three year time period. Results will be used to identify thresholds of soil strength associated with soil moisture levels and frost depth for a range of soil textural classes.

ENRTF BUDGET: $ 175,500

Outcome	Completion Date
1. Initial site evaluation completed and site selection finalized (7 total)	Sept. 2018
2. Pretreatment field measurements and soil sensors installed	Oct. 2018
3. Assessment of soil conditions (soil strength, water content, frost, etc.) for 3 years	Oct. 2021
4. Data synthesis complete and final report completed	June 2022

First January 31, 2019

Primary work conducted this far includes the hiring of the Research Associate who is leading all efforts related to the field experiment, and the identification of sites and installation of experimental plots and soil sensors. We worked with MN DNR and county land departments to identify sites for inclusion in the study. We were able to install a total of 12 plots (5 more than outlined in the work plan) at three regions that encompass a range of soil texture and drainage classes. Soil moisture sensors and dataloggers were purchased and installed at each of the plots, and data has been collected since early November. We also collected soil samples from each of the sites at time of installation for characterization of soil physical properties. Snow removal treatments are being conducted at each site as needed, and we have completed the first data download across the network. Preliminary design of rainfall exclusion shelters has commenced, and soil samples are currently being processed.

Second Update June 30, 2019

Snow removal treatments were continued throughout the winter period until the end of April. Rainfall exclusion shelters were constructed during May, and installation was completed at each of the plots in mid June (see picture at right). Soil temperature and moisture continues to be measured at high frequency within each of the plots, and data has been downloaded and initially processed up until the April time period. Pretreatment soil samples have been analyzed for total C and N. The protocol for soil strength measures has been finalized, and measurements will commence in the first week of July.

Third Update January 31, 2020

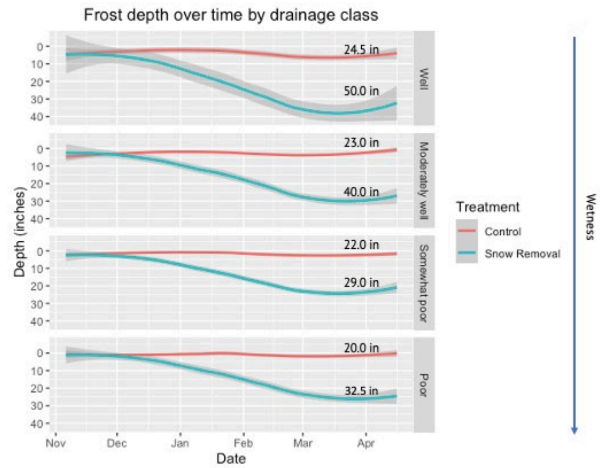
Soil moisture and temperature readings were successfully collected throughout the summer and are currently being analyzed for treatment effects. We also collected soil strength measurements on a biweekly schedule using two different measurement techniques. The rainout shelters were removed in late October and the plots converted in preparation for the winter snow removal which is currently underway fpr the season (see picture at right). Soil frost tubes were purchased and installed this past fall to allow for measurement of soil frost in each of the treatment plots. Lastly, pretreatment soil samples were further analyzed for additional chemical properties (extractable cations and phosphorus) and for soil texture.

Fourth Update June 30, 2020,

Snow removal treatments were maintained throughout the winter field season, and we were able to acquire permission to visit the sites in April to download data and install the rainout shelters. Several faulty sensors were replaced at this time. Soil moisture and temperature data has been processed and analyzed from experiment initiation until November 2019. Early results are promising, with clear effects of snow removal on soil temperature and effects of rainfall exclusion on soil moisture, confirming that treatments are creating the intended soil conditions. In addition, we have analyzed relationships between soil strength and soil moisture measurements by soil drainage class across sites. We will be analyzing frost depth measurements in the coming months and updating the analysis on soil temperature and moisture with new data downloaded in April. Lastly, a new graduate student has been recruited to work on the project starting in June, 2020.

Fifth Update January 31, 2021

Data collection proceeded smoothly throughout the summer despite coronavirus restrictions on travel and personnel activities. We were able to collect soil strength measures on a biweekly schedule across all the sites, and also initiated new measurements on soil chemical properties. Rainout shelters were removed and stored in the fall, and plots were configured for snow removal which began in December. Soil moisture and temperature data has been processed and analyzed to determine effects of soil drainage class and treatment on these variables. We have also completed summation and analysis of soil frost data from winter 2019/20 (see figure to right), and updated regression relationships between soil strength and soil water content for each of the drainage classes.



Sixth Update June 30, 2021

Rainfall exclusion shelters were redeployed in April 2021. One unit was repaired following bear damage to the structure. Data from April 2021 and prior has now all been processed and analyzed for effects of soil drainage and treatment (snow removal and precipitation exclusion) on soil temperature, moisture, and frost depth. We continue to collect soil moisture, temperature, and soil strength data, and have initiated new measurements to quantify the effectiveness of the rainfall exclusion shelters and evaluate biological response to the treatments.

Seventh Update January 31, 2022

There were several issues with faulty dataloggers at the Aitken and Itasca sites in the later summer 2021, which required several field trips to rectify. All loggers and sensors have been repaired and are currently operating as intended. Rainout shelters were removed in October and plots were configured for snow removal treatments. Field measurements and snow removal are being conducted as planned and we do not anticipate any additional issues prior to the end of the project period. We have made substantial progress on data analysis, including summarization treatment effects on soil moisture, temperature, and frost development. We have also evaluated relationships between soil strength and soil moisture, and have concluded that the soil penetrometers were inadequate to quantify soil strength at out sites. Anna Stockstad has measured and quantified treatment effects on soil C and N cycling, and expanded the study to include a lab incubation which was conducted in December 2021. The incubation was conducted to determine how the treatments and drainage class influence production of carbon dioxide, nitrous oxide, and methane under controlled environmental conditions.

Final Report Summary

We were able to increase the number of plots and sites where the experiment was conducted, greatly increasing the inference of findings to northern Minnesota. In particular, this allowed us to stratify the plots across a soil drainage class gradient, which we expected to modify the response to snow removal and rainfall reduction (the treatments we assessed). Plot establishment and treatment implementation went relatively smoothly given the inherent difficulties in reducing rainfall and removing snow in forest locations far from our work locations. Soil moisture, temperature, frost, soil strength, and ancillary variables likely to influence these variables (e.g., snow depth, soil texture, etc) were measured as planned over a three-year period. Key findings from these measurements include:

- Snow removal caused large increases in the rate and total amount of soil frost development as the loss of the insulating effect of snow allowed soils to obtain colder temperatures. The effect was dependent on drainage class (soil wetness), where wetter drainage classes had slower and lower frost development compared to drier drainage classes.

- There was a significant relationship between air freezing index (sum of mean daily temperatures below freezing) and frost development that differed among drainage classes and if snow was present or absent.
- Rainfall exclusion treatments were successful at reducing precipitation by half, but there was no consistent pattern of soil moisture response to this reduction across drainage classes and soil depths.
- Soil strength was measured with two types of soil penetrometers during the growing season of each project year. There was no effect of treatment on soil strength, likely because the rainfall reduction treatment did not consistently affect soil moisture content.
- Relationships between soil moisture and soil strength were variable with no clear patterns; relationships were positive, negative, or most often not significant. Our expectation was that soil strength would increase as soil moisture content decreased, allowing for determination of soil moisture contents where soil strength is greatest. This was not supported by the data.

Our findings have important implications for operational management practices and considerations for similar experiments:

- Increased frost is likely to occur if predicted decreases in snowfall occur in the future. This has important implications for forest management, as it could conceivably increase the times when winter harvesting could occur without impact to soils. A key uncertainty with this conclusion is that we are not accounting for concurrent increases in winter temperature that are expected to also occur. However, future winter temperatures are still predicted to be below freezing, and we observed the deepest frost in our study in winter 2020-21, which had the lowest snow cover and highest air temperatures of the three study years. Because of this, we think it is more likely that future conditions will support more frost development and a longer winter harvest season.
- The models relating air freezing index (AFI) to frost depth may be particularly useful to foresters and loggers, as it will allow them to have some predictive capacity to know when sufficient frost is present at a given site and harvest operations may proceed.
- The incorporation of drainage class into our assessment was very beneficial as it strongly influenced the soil response. This is important because it allowed us to improve the AFI-frost models. On a practical level, inclusion of drainage class will be very useful because it is commonly mapped in spatial datasets and readily identified in the field with minimal training. This should facilitate application of the findings in the field.
- The lack of a consistent effect of rainfall reduction on soil moisture was surprising and may be due to the (relatively) small plot size we used in the study. All field experiments must strike a balance between the ideal and what is achievable; we recommend that future experiments evaluating rainfall reduction utilize plots larger than ours (4 m^2) but within constraints of what is feasible given field conditions and available resources.
- The lack of consistent relationships between soil moisture and soil strength was disappointing, as information to evaluate summer soil operability is desperately needed by the forestry community. The lack of a rainfall reduction effect on soil moisture did not influence this, as we assessed soil strength throughout the growing season and across drainage classes (i.e., across a wide range of soil moisture). Almost assuredly, the lack of relationship was due to the tools we had available to measure soil strength, which are not readily suitable for forest soil applications.

Activity 2: Develop GIS-based soil operability metric and a field measurement tool
Description: Results from Activity 1 will be used to identify key factors and conditions influencing soil operability, and develop guidelines on when operations may occur for a given set of weather scenarios. Specifically, we will develop a GIS-based metric that assigns a given soil type into an operability class (low, medium, high) based on estimated soil conditions (i.e., soil moisture or frost depth). The metric will utilize the soil strength-soil condition relationships identified in Activity 1 in combination with publically-available spatial soil and weather datasets. A field tool, based on relationships between mass and soil strength, will also be developed for direct assessment of real-time conditions by loggers and managers. We will also develop strategies and recommendations to enhance operability under subpar conditions including post-storm rain events and early season snowfall.

ENRTF BUDGET: $ 24,500

Outcome	Completion Date
1. Field tool prototype completed	Apr. 2021
2. Initial development of GIS-based metric completed	Oct. 2021
3. Beta testing of GIS metric completed and updates incorporated into final product	June 2022
4. Specifications for field tool completed	June 2022
5. Strategies and recommendations to improve operability incorporated into final report	June 2022

First January 31, 2019

Work will commence on this task in early 2020

Second Update June 30, 2019

Work will commence on this task in 2020

Third Update January 31, 2020

Work will commence on this task in the coming months.

Fourth Update June 30, 2020,

We have acquired and processed spatial datasets on soil properties and topography for the GIS-based operability metric. Initial work is being conducted to evaluate the suitability of SSURGO database for this effort.

Fifth Update January 31, 2021

Evaluation of the SSURGO database has been completed. There are three counties in MN that do not have updated soil maps available and we are exploring alternative datasets for use in those counties. We have conducted some preliminary analysis to map a metric of soil operability based on drainage class and soil texture.

Sixth Update June 30, 2021

Work has continued processing the spatial datasets and we have preliminary drafts of maps showing estimated soil operability by drainage class for each of the counties in MN that have soil datasets available. We will begin validating and refining the maps over the next project period.

Seventh Update January 31, 2022

The soil operability map has been finalized, and we are now working to incorporate other factors into a GIS that influence operability including season of harvest, equipment type, and time since last precipitation event.

We have attempted to develop a rating curve between soil strength and penetration depth of a rudimentary strength probe, but are unable to identify any relationships between the two variables. This is likely a result of using the portable soil penetrometers to measure soil strength, which are known to be unreliable in forest soil (because of roots, rocks, etc). Because of this, we will not be able to develop the rating curve for the field tool as originally planned.

Final Report Summary

We were able to develop a harvest suitability map using publicly available soils information combined with our findings from Activity 1 and a metric of soil operability previously developed by MN DNR that incorporates information on soil texture, drainage class, depth to restrictive layers, and landscape position (see Supplementary Materials). For the map, we elected to base the suitability on season of harvest since that is the primary aspect considered by foresters when planning a timber sale. In addition, we created two levels of suitability that 1) incorporated the full list of soil properties and their associated constraints in the base metric, and 2) removed the depth to semi-permeable layer constraint and relaxed the classification of a given soil into less restrictive operating seasons based on findings from Activity 1. The map was created by downloading all county-level SSURGO data, developing database queries to extract and define properties used in the metric, and assignment of an operability rating to individual soil map units. When more than one soil component existed in a map unit (e.g., soil associations), the dominant soil type (by area of unit) was used to classify the map unit into an operability class. We then used a statewide landcover map to identify those map units that occur within forested areas of the state. This map can be used by managers and landowners to identify the preferred operating season at a given site, allowing them to plan accordingly to limit impacts to soil (see Supplementary Materials). Note that the metric was originally developed for field application; our conversion for the spatial display of the metric will greatly increase its utility and use, but field application may be more accurate because of inherent constraints of the SSURGO database in estimating soil unit extent and related properties.

One of our objectives for this activity was to develop base information for the development of a tool that could be used be managers to test soil operability conditions in the field. Note that this objective was focused on initially developing a rating curve relating penetration depth of a given mass to soil strength (See approved Research Addendum). The approach we took was to first identify a relationship between soil strength and moisture content, using two types of soil penetrometers that measure soil strength. We conducted these measures over two field seasons and a wide range of soil moisture for each drainage class. However, as noted in Activity 1, we were unable to detect any consistent or meaningful relationships between soil strength and soil moisture content. The primary reason for this is almost certainly related to our use of penetrometers to measure soil strength. These devices are widely used in construction and geotechnical applications, but are known to have limitations in forest soils because of the large amount of woody material (e.g, roots)) and rock fragments present, which cause inaccurate estimates of soil strength. We were aware of this limitation, and originally proposed for funding and development of a customized tool to accurately measure soil strength or compaction in forest soils. In future assessments of forest soil operability or compaction, we recommend that investment be made in such tools to accurately assess the heterogenous conditions typically found in forest soils.

IV. DISSEMINATION:

The products developed from this project are intended to be used by practitioners in a variety of operational settings. A final report will document relationships among soil conditions and soil operability in both winter and summer. Recommendations on optimal soil operability related to these relationships will be included in the report. This report will be made available on the webpages of the Department of Forest Resources and the Minnesota Forest Resources Council. Spatial data products will disseminated directly to primary stakeholders (e.g., DNR, Forest Service, County land departments) and will also be uploaded to the Minnesota Geospatial Commons (https://gisdata.mn.gov/) for general access. In addition, several manuscripts will be written based on this research and submitted for publication in peer-reviewed journals. Results and related recommendations will be also be presented directly to public forest management agencies, forest industry and logging trade organizations, and other forestry professionals in cooperation with the Sustainable Forestry Education Cooperative. All reports and publications from this project will be made available via the Department of Forest Resources web site.

Description:

First January 31, 2019

We have given several presentations on the planned work and project objectives to partners at the DNR and the MN Forest Resources Partnership, and have communicated regularly with members of the MN Forest Resources Council on project status.

Second Update June 30, 2019

Periodic updates have been provided to the MN Forest Resources Council on the project status.

Third Update January 31, 2020

No presentations or external communication related to this project occurred since the last update. We will begin actively disseminating findings to user groups later this year once the first year data has been analyzed and initial findings determined.

Fourth Update June 30, 2020

No presentations or external communication related to this project occurred since the last update.

Fifth Update January 31, 2021

Graduate student Anna Stockstad presented findings from the first two years of the study at the annual Forestry and Wildlife Research Review to forest practitioners and managers on January 14, 2021.

Sixth Update June 30, 2021

No presentations or external communication related to this project occurred since the last update.

Seventh Update January 31, 2022

We developed and delivered a summary document of findings to date to project cooperators and stakeholders in August 2021. We received positive feedback from a number of stakeholders on the document, and plan to send another update in the Spring.

Robert Slesak and Anna Stockstad both gave presentations on project findings at the annual meeting of the Soil Science Society of America meeting, held in Salt Lake City during November 7-10, 2021.

Final Update June 30, 2022

Anna Stockstad gave a final presentation of findings at the annual Forestry and Wildlife Research Review on February 15, 2022. Throughout the project we engaged with key stakeholder groups to share project updates and preliminary findings including MN DNR, MN Association of County Land Commissioners, the MN Forest Resources Council, and UMNs Sustainable Forestry Education Cooperative. Final documents and findings will continue to be shared with our stakeholders at periodic meetings, field tours, and workshops. The presentations by Stockstad and Slesak at the SSSA annual meeting allowed for broader dissemination of findings at the national level. Lastly, two manuscripts have been prepared to disseminate the results more broadly; one manuscript has recently been published in the journal *Forests* and the other manuscript is under review at the journal of *Forest Ecology and Management*. Both of these journals are widely read by forestry professionals, and we expect that findings from this project will be widely disseminated into the natural resource management community.

V. PROJECT BUDGET SUMMARY:

The total recommended budget request is $200,000 over a four year period. Salary (1.0 FTE) and fringe (0.335) is budgeted for a Research Associate for approximately 2 years. The research associate will be responsible for field work associated with Result 1 including site identification, treatment application, and data collection. Salary and fringe (0.15 + 19.32/hr tuition; no summer tuition) is budgeted for one year for 1 graduate student, who will conduct field work, analyses, and interpretation of study data associated with Result 1. The student will begin in the second year of the project so that data is immediately available to them. Work associated with Result 2 will be conducted by the graduate student and members of the project team. The $24,000 budgeted for supplies includes funds for soil temperature and moisture sensors, dataloggers, tipping bucket rain gauges, a soil penetrometer, snow tube and scale, and miscellaneous supplies for treatment application including rainout shelters and shovels. The $15,000 budgeted for travel includes costs associated with mileage (75%) and lodging (25%) within Minnesota for researchers, the research associate, and graduate student to the project sites. A large numbers of visits will be required because sites will be located around the state and require periodic visits following snow and rain events.

A. **Preliminary ENRTF Budget Overview:** See attached budget spreadsheet

Explanation of Capital Expenditures Greater Than $5,000: N/A

Explanation of Use of Classified Staff: N/A

Total Number of Full-time Equivalents (FTE) Directly Funded with this ENRTF Appropriation: 2.5

Total Number of Full-time Equivalents (FTE) Estimated to Be Funded through Contracts with this ENRTF Appropriation: N/A

B. Other Funds:

SOURCE OF AND USE OF OTHER FUNDS	Amount Proposed	Amount Spent	Status and Timeframe
Other Non-State $ To Be Applied To Project During Project Period:			
In-kind salary from R. Slesak (0.1 FTE) , R. Kolka (0.05 FTE) and S. Sebestyen (0.05 FTE)	$ 76,900	$	Secured

VI. PROJECT PARTNERS:

A. Partners receiving ENRTF funding

Name	Title	Affiliation	Role
Charlie Blinn	Professor	UMN	Project Manager, principle investigator (PI)

B. Partners NOT receiving ENRTF funding

Name	Title	Affiliation	Role
Robert Slesak	Research Scientist	USDA Forest Service – PNW Research Station	Co-PI
Randy Kolka	Research Scientist	USDA Forest Service – North. Research Station	Co-PI
Stephen Sebestyen	Research Scientist	USDA Forest Service – North. Research Station	Co-PI
Dan Hanson	ECS Program Coordinator	DNR Forestry	Co-PI

VII. LONG-TERM- IMPLEMENTATION AND FUNDING:

Initial implementation of the GIS metric should go smoothly since members of the forestry community have consistently requested this information and it will be provided in a GIS format that is widely used and accessible. However, future refinements of the metric will likely be needed in response to user feedback and new field data that can be used to improve calibration equations. We will work closely with forestry stakeholders to demonstrate the utility of the metric, and to provide resources needed for its improvement. Further, we expect that the soil operability metric will change with changing weather patterns and climate, so additional work will be needed in the future to maintain overall utility. Funding requests for these efforts will be targeted at state agencies, federal agencies, and forest industry. For the field tool, we will explore working with UMNs Minnesota Innovation Partnerships to identify opportunities for product development. Once the tool becomes available, we will partner with UMN Extension and the MN logger Education Program to train field foresters and loggers in its use.

VIII. REPORTING REQUIREMENTS:

- **The project is for 4 years, will begin on July 1, 2018, and end on June 30, 2022.**
- **Periodic project status update reports will be submitted June 30th of each year.**
- **A final report and associated products will be submitted between June 30 and August 15, 2022.**

IX. SEE ADDITIONAL WORK PLAN COMPONENTS:

A. **Budget Spreadsheet**
B. **Visual component**
C. **Research Addendum**

X. Supplementary Materials

A. Stockstad condensed thesis

B. MN DNR soil operability metric

C. Soil operability map – Scenario 1

D. Soil operability map – Scenario 2

Attachment A:
Environment and Natural Resources Trust Fund
M.L. 2018 M.L. 2018, Chp. 214, Art. 4, Sec. 02, Subd. 08f Project Budget - Final

Project Title: Develop Strategies for Timber Harvest to Minimize Soil Impacts to Maintain Healthy and D
Legal Citation: M.L. 2018, Chp. 214, Art. 4, Sec. 02, Subd. 08f
Project Manager: Charlie Blinn
Organization: University of Minnesota
College/Department/Division: Department of Forest Resources
M.L. 2018 ENRTF Appropriation:
Project Length and Completion Date: 4 years, June 30, 2022
Date of Report: 8.12.2022

ENVIRONMENT AND NATURAL RESOURCES TRUST FUND BUDGET	Budget	Amount Spent	Balance
BUDGET ITEM			
Personnel (Wages and Benefits) - Overall	$149,000	$144,942	$4,058
Research Associate - salary and fringe (0.335) for 2 years who will coordinate treatment application and data collection at the project sites for Activity 1 (Total estimated amount $118,858)			
Graduate student - Salary (0.5 FTE) and fringe (0.15) + 19.32/hr tuitionfor 1 year who will analyze data from Ativity 1 and develop recommendations and tools for Activity 2 (Total estimated amount $42,142)			
Equipment/Tools/Supplies			
Soil temperature and moisture sensors (80 totaling $12,000), dataloggers (16 totaling $8,000), snow tube and scale ($500), shovels, soil penetrometer ($1000), and misc. supplies for treatment application ($2500)	$24,000	$23,512	$488
Travel expenses in Minnesota			
Travel for mileage (75%) and lodging (25%) within Minnesota for researchers, the Research Associate, and Graduate Student to the project sites in Activity 1 and work in Activity 2. A large amount of travel will be requiried because sites will be located across northern Minnesota and require periodic visits following snow events and throughout the growing season	$27,000	$23,878	$3,122
COLUMN TOTAL	$200,000	$192,332	$7,668

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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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A B S T R A C T

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 (r^2 of treatment = 0.8, slope = 0.093, $p < 0.001$; r^2 of control = 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.

1. 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 (National Council for Air and Stream Improvement, 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 a negative influence on forest productivity (Cambi et al. 2015), and recovery can take decades to occur (Curzon et al. 2022). 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. Understanding the type and timing of management activities that limit soil compaction will only increase in importance as precipitation patterns in northern latitudes change in response to climate change.

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). For example, the ideal period of operability during the summer and winter may be reduced which could consequently reduce the total amount of harvested wood, and reductions in summer precipitation may limit forest productivity and yield in the long-term.

The feasibility of harvesting on soils during the summer, and the management practices used to mitigate impacts, will likely be affected

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by the timing and amount of precipitation (Puhlick & Fernandez, 2020; 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. Due to the influence of SWC on soil strength, 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 non-frozen soils of the same texture (Kok & McCool, 1990; Shoop, 1995; Watanabe et al., 2019). 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. Multiple thawing and freezing events may also occur during a single winter as winter temperatures warm, which would be of major concern to operators. There is a need to understand how 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 decreases 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 effects of combined throughfall reduction and snow removal are unclear, but we aimed to determine if: 1. throughfall reduction increases soil strength during the summer, and 2. if snow removal increases frost depth 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.

2. Methods

2.1. 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 glacially-derived parent material (till, alluvial, lacustrine) 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 hazelnut (*Corylus cornuta*), willow (*Salix* spp.), or speckled alder (*Alnus incana*) in the understory. Mean annual temperature for the region ranged from 3.9 to 6.1°C during 2020 and 2021 (PRISM Climate Group). Mean annual precipitation for this region ranged from 711 mm to 813 mm during 2020, and from 610 mm to 711 mm during 2021 (PRISM Climate Group). Mean summer (May – August) temperature for the region ranged from 17°C to 19°C, and 16°C to 19°C during 2020 and 2021, respectively (PRISM Climate Group). Mean winter (November – April) temperature for the region ranged from −3°C to −5°C for the winters of 2019/20 and 2020/21 (2021/2022 data not yet publicly available; PRISM Climate Group). Average precipitation during the summer in the region ranged from 93 mm to 124 mm, and from 38 mm to 48 mm during 2020 and 2021, respectively (PRISM Climate Group).

2.2. 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 (<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).

2.3. Experimental design and treatment implementation

The study occurred from May 2018 until May 2022 using a paired-plot, factorial (4 × 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.

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	Drainage class	Soil texture	Bulk density (Mg m^{-3})
Site 1	46.361908, −93.236416	Milaca-Millward complex	WD, MWD, SPD, PD	Fine sandy loam	1.03–1.21
Site 2	47.688509, −93.546264	Warba-Menahga complex	WD, MWD	Fine sandy loam	1.24–1.31
		Morph very fine sandy loam	SPD	Very fine sandy loam	1.31–1.32
		Baudette silt loam	PD	Silt loam	1.27–1.36
Site 3	47.182644, −92.104667	Aldenlake-Pequaywan complex	WD, MWD	Sandy loam	1.02–1.22
		Brimson stony fine sandy loam	SPD, PD	Stony fine sandy loam	0.84–0.93

Locations of the plots were identified by digging a series of soils pits across a topographic gradient until the desired drainage classes were identified. Snow was removed from treatment plots during the winter (Figure S1), and throughfall was reduced during the growing season (Figure S2).

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 (0.25 mm diameter; 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 (severe drought) 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 × 4 m plot boundary, and displaced throughfall was directed outside the plot boundaries. 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; 21.5 mm ± 1.8 mm) and was 305.5 mL (±108.41 mL; 10.1 mm ± 3.6 mm) for treatment (reduction) plots. Stemflow was considered negligible because previous studies have found stemflow to be minimal (3–4 % of annual water input on similar soils) in aspen forests of northern Minnesota (Kolka et al., 1999).

2.4. Soil water content, soil temperature, and air temperature measurements

Soil temperature and water content were measured every 15 min 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 by excavating a pit and inserting the sensor horizontally into the pit at the assigned depth. Soil was backfilled into the hole and tamped down to the approximate density prior to excavation. Sensors were installed in a cluster at the center of each plot (Figures S1, S2) and connected to EM50 data loggers; factory calibrations were used in estimating SWC and soil temperature (METER Group). Air temperature was recorded at control plots every 90 min by Thermochron iButton sensors at a height of 1.5 m (±0.5°C; Maxim Integrated Products, Inc., Sunnyvale, California) enclosed in a PVC solar shield.

2.5. 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. Snow depth was measured using a yard stick (0.9 m) in the center of control plots.

2.6. 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). At least two full penetrometer runs to a depth of 45 cm were conducted per plot in two random quadrants.

2.7. 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 (mean of 0 – 30 cm, mean of 30 – 60 cm), 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 relationship between frost depth and the air freezing index (AFI) for control and treatment plots using the coefficient of determination (r^2) (Erlingsson & Saliko, 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 (CBR, Equation (1); Black, 1962) and bearing capacity (BC, Equation (2)) in kilopascals (kPa). Runs for each plot were averaged to create a plot-level soil strength estimate.

$$CBR(\%) = \frac{292}{DPB^{1.12}} \tag{1}$$

$$\begin{aligned} BC(psi) &= 4.5915 \times CBR^{0.6105} \\ BC(kPa) &= 6.89476 \times BC(psi) \end{aligned} \tag{2}$$

3. Results

3.1. 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, but mean air temperatures were not significantly different during the winters of 2019/20 and 2020/21.

There was a significant three-way interaction among drainage, treatment, and week for soil temperature in all three years ($p < 0.001$; Table S1; Fig. 1a). On average, soil temperatures were lowest for WD soils and warmest for PD soils over the course of the winter season, which corresponds to the higher water content of the PD plots (Fig. 1a, Figure S5). Additionally, more rapid changes in soil temperatures occurred in the WD plots compared to the PD plots, which showed slower warming during the spring period (Fig. 1a). Soil temperature was consistently lower in the treatment plots throughout the three winters (Fig. 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℃, −13℃, and −9.2℃ 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 2019/20, 2020/21, and 2021/22 ($p = 0.01$, $p < 0.001$, $p < 0.001$, respectively; Table S1; Fig. 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℃, 2.2℃, 2.0℃, 1.9℃, and 1.7℃ 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 (Fig. 1b; Figure S3). Under ambient conditions, differences in mean soil temperature between 10 cm and 60 cm ranged from 0.7℃ and 1.1℃ depending on year, and between 1.0℃ and 3.5 ℃ with snow removal.

There was a significant interaction between treatment and week ($p < 0.001$) in all three years on soil frost (Table S2). 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 (Fig. 2). 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; Figure S4). 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 (Fig. 3; Figure S4). 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 (Fig. 3, $p < 0.001$).

There was a significant positive relationship between AFI and frost depth for both control (variable intercept model) and treatment (variable slope model) plots across all three winters. However, the relationship was stronger in the treatment plots ($r^2 = 0.80$, $p < 0.001$; Fig. 4b) compared to the control plots ($r^2 = 0.18$, $p < 0.001$; Fig. 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.

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 3). 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/℃ day) and PD (0.031 cm/℃ day; Table 3).

Table 2
Least square mean weekly air temperature and snow depth in control plots during the winters of 2019/20, 2020/21, and 2021/22 between November 1st and April 30th. Standard error is shown in parentheses next to the mean. Values within a column containing different letters are significantly different.

Year	Air temperature (°C)			Snow depth (cm)
	Mean (SE)	Max	Min	Mean (*SE*)
2019–20	−5.4 (0.51)[a]	5.7	−15.3	36.7 (2.87)[a]
2020–21	−4.1(0.50)[a]	8.7	−27.6	13.6 (2.82)[b]
2021–22	−7.5(0.51)[b]	3.8	−10.5	29.2 (2.79)[c]

3.2. Effects of throughfall reduction

There was a significant interaction among drainage class, treatment, and depth on SWC in all three years ($p < 0.001$; Table S3, Fig. 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 (Fig. 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 40 cm during 2019 and 2020 (difference of $-0.05\ m^3m^{-3}$ and $-0.04\ m^3m^{-3}$, 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 cm 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 60 cm during 2019, 20 cm and 60 cm during 2020, and 20 cm during 2021.

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 S4 for p-values, Figure S6). 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 112 kPa, Figure S6) and MWD treatment ($p = 0.005$, difference of 127 kPa, Figure S6). SPD treatment was also significantly lower than MWD control ($p = 0.005$, difference of 128 kPa, Figure S6) and SPD control (0.04, difference of 91.0 kPa; Figure S6).

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 (S7, S8, S9, S10). 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 ($r^2 = 0.19$, $p = 0.011$) and the PD class at 60 cm in 2020 ($r^2 = 0.17$, $p = 0.0013$).

4. 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

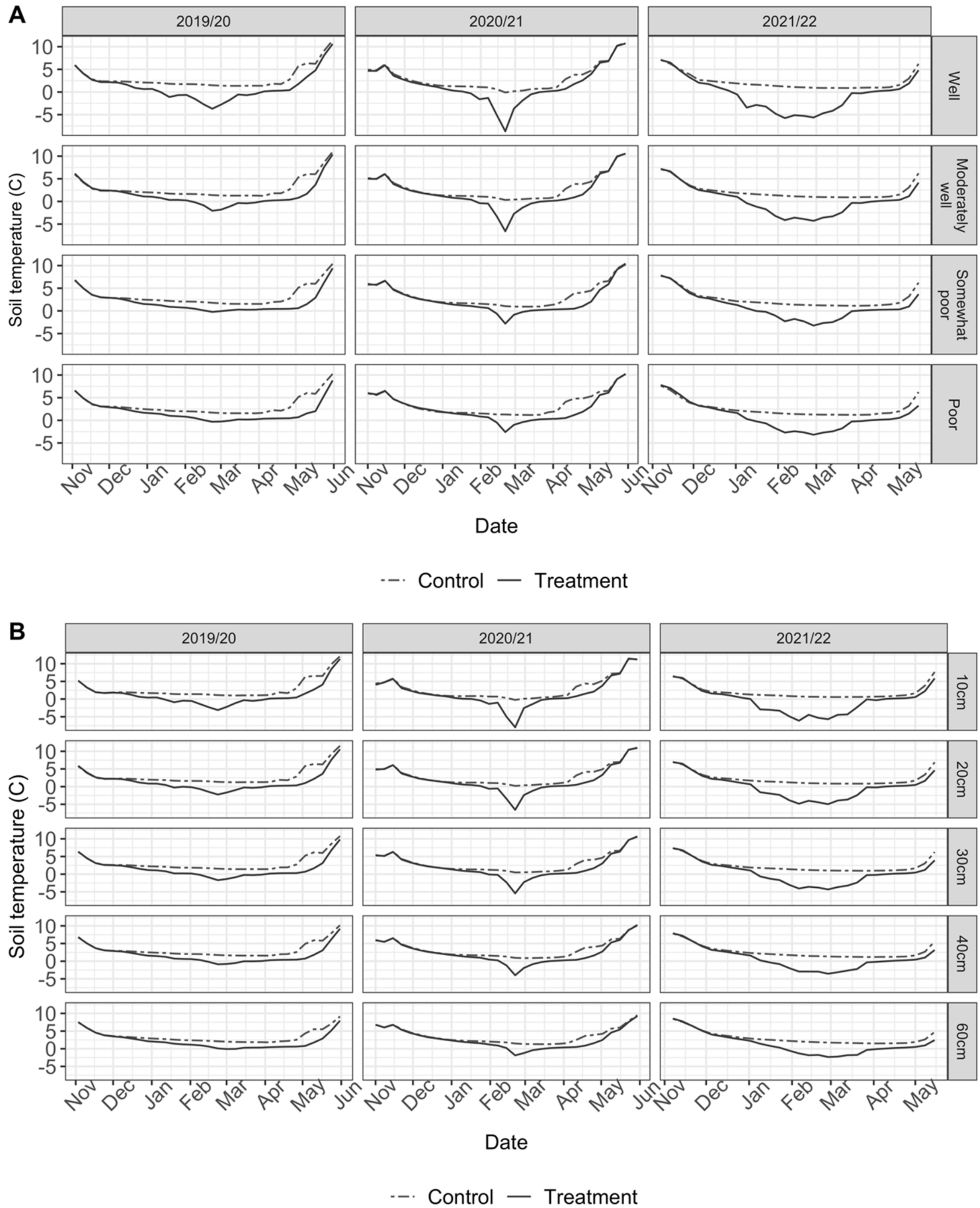

Fig. 1. Mean weekly soil temperature by treatment and drainage class (panel A, averaged across depths) and mean weekly soil temperature by treatment and depth (panel B, averaged across drainage classes) during the three winters of the study.

shown to influence soil strength (Greacen & Sands, 1980; McNabb et al., 2001; Uusitalo et al., 2019). Drainage class was also 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.

4.1. *Effects of snow removal*

Our findings show that snow removal was correlated with decreased soil temperature and increased frost depth. These results are consistent with previous literature that has shown soil temperature is 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, and that temperature variation in soil decreased with depth and when snow was retained. Soil temperature was attenuated as drainage decreased, which mirrors the soil moisture results in that

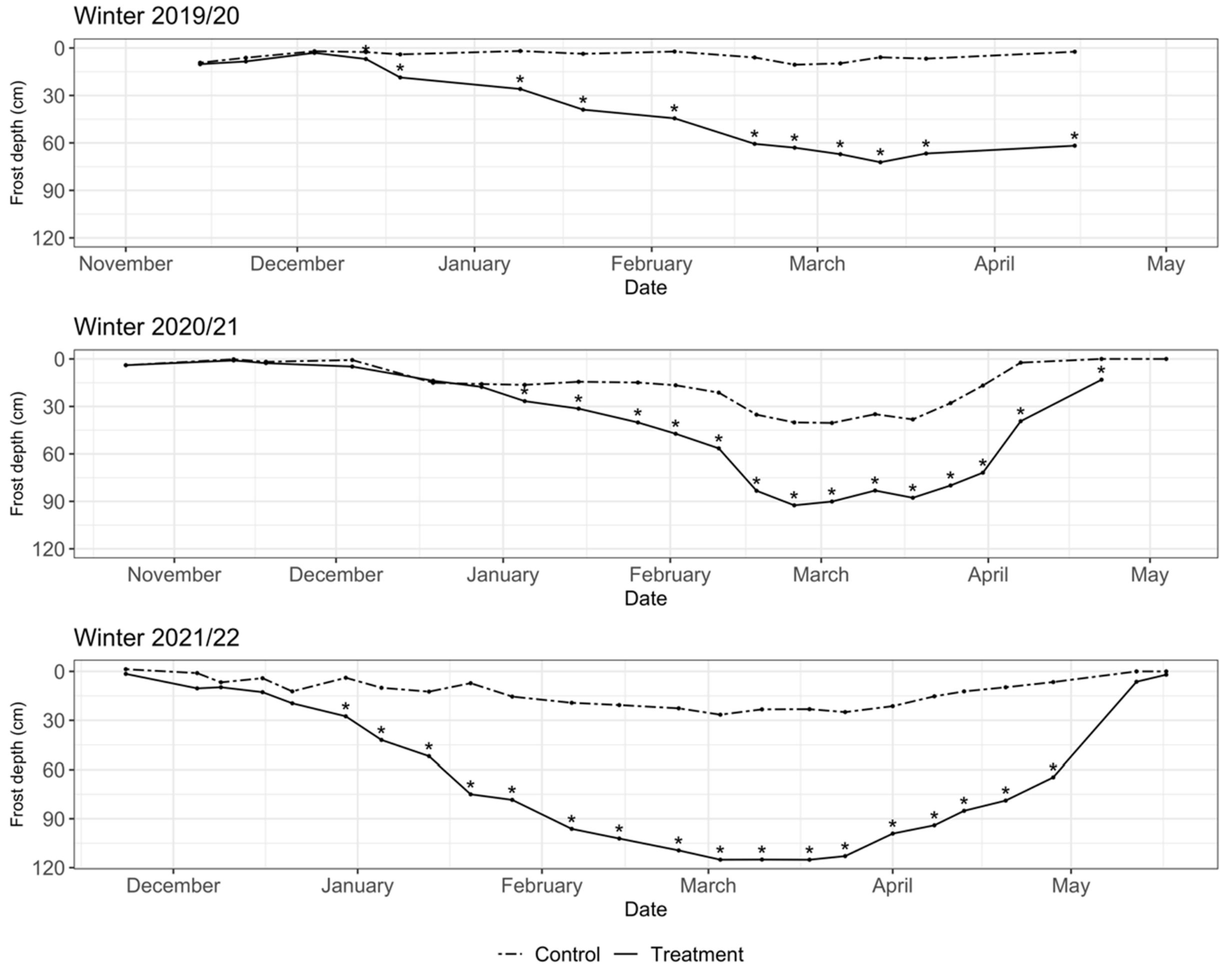

Fig. 2. Least square means of soil frost depth during the winters of 2019/20, 2020/21, and 2021/22 for the significant interaction between treatment and date. Asterisks indicate time periods where there was a significant difference in soil frost depth between treatments.

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 the low thermal diffusivity of wet soils. 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 was correlated with deeper frost development that was further influenced by drainage class. 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 −4.7C (Cleavitt et al., 2008; Hardy et al., 2001). Drainage class partially regulated soil frost depth. For example, frost did not develop to the same depth in wetter drainage classes because soil temperature did not reach sub-freezing temperatures at the same depths as drier drainage classes.

Frost depth increased with increasing 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. 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 across

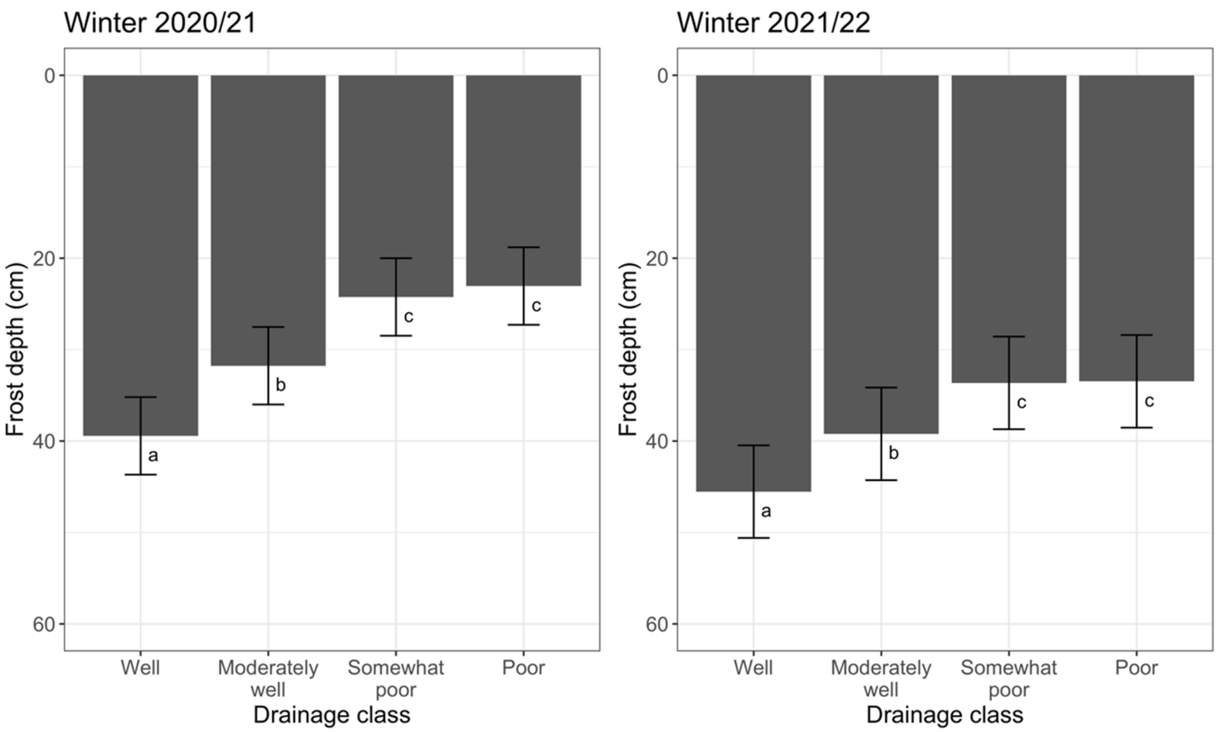

Fig. 3. Least square mean frost depth by drainage class during the winters of 2020/21 and 2021/22. Bars with different letters indicate significant differences between means (p-value < 0.05). Error bars represent standard error.

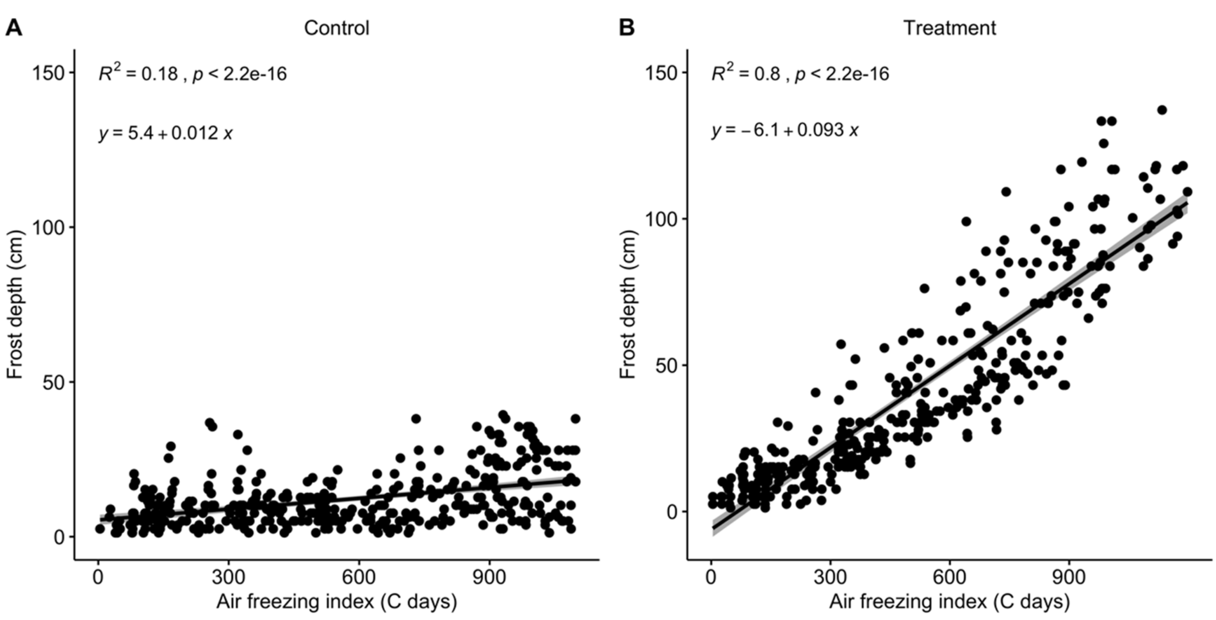

Fig. 4. Linear regressions between Air Freezing Index and frost depth in control (panel A) and treatment (panel B) plots during all three winters of the study. Confidence limits (shading around the line) are 95% confidence intervals.

drainage classes, which makes this relationship a potential tool for forest managers when planning winter harvests.

4.2. *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 (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

Table 3
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

moisture or that another variable was negating the throughfall reduction. Soil water content consistently increased from WD to PD which aligns with the expected relationship between drainage class and soil moisture (Briggs & Lemin, 1994; Henninger et al., 1976; Veneman et al., 1998).

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 (16 m^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, though we found no correlation between soil strength and SWC. We also found no differences in species richness or diversity between sites, drainage classes, or treatments, so differences in vegetation did not contribute to the lack of treatment effect on SWC (Stockstad et al., 2022). 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. There were also inconsistent effects of drainage class on soil strength. 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 × 20 m plots in subtropical planted forests in China and found that throughfall reduction significantly reduced SWC and soil aggregate stability. It is also important to acknowledge that the snow removal treatment may have caused changes in freeze–thaw dynamics, which would have the potential to influence soil strength in addition to throughfall reduction, and snow removal may have impacted SWC early in the growing season.

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.

4.3. Implications for management

The increase in frost development that occurred with snow removal may have implications for future accessibility of forest stands during the

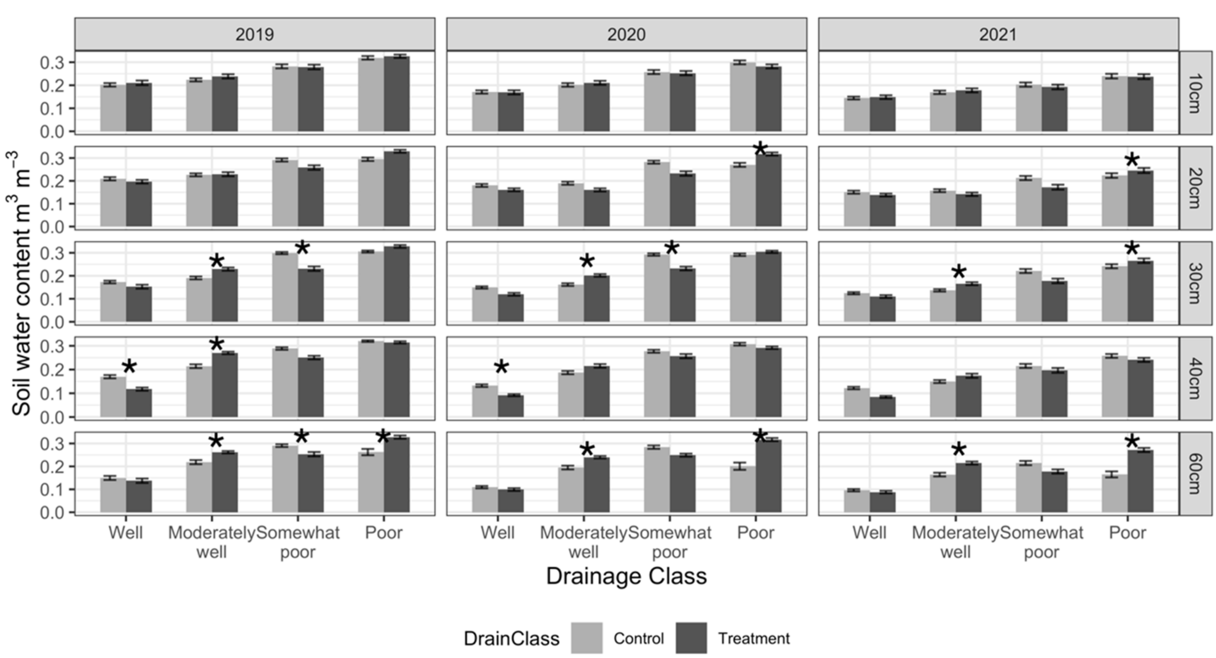

Fig. 5. Least square mean soil water content by treatment, drainage class, and soil depth for the three years of the study. Soil depth in centimeters is shown on the right y-axis. Asterisks indicate significant differences (p-value < 0.05) between control and treatment within a drainage class for a given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

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 dragging 4 to 6 Mg of timber. An example of a modern wheeled grapple skidder from John Deere weighs approximately 19 Mg unloaded. However, freeze–thaw dynamics may be altered under climate change, and there may be additional complications when operating in the winter when more precipitation occurs as rain instead of snow.

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. There may also be effects from the increased frequency of freezing rain events on existing frost in northern latitudes. 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 readily 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 (Erlingsson & Saliko, 2020). 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.

5. 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 also a strong indicator of soil moisture, temperature, strength, and frost development. These results demonstrate the utility of using drainage class as a metric to infer soil moisture and temperature when determining harvesting periods.

CRediT authorship contribution statement

Anna B. Stockstad: Formal analysis, Investigation, Writing – review & editing, Visualization. **Robert A. Slesak:** Conceptualization, Methodology, Writing – review & editing, Supervision, Project administration, Funding acquisition. **Alan J. Toczydlowski:** Formal analysis, Investigation, Visualization, Project administration. **Charles R. Blinn:** Conceptualization, Methodology, Writing – review & editing, Project administration, Funding acquisition. **Randall K. Kolka:** Conceptualization, Methodology, Writing – review & editing, Funding acquisition. **Stephen D. Sebestyen:** Conceptualization, Methodology, Writing – review & editing, Funding acquisition.

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.

Data availability

Data will be made available on request.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.foreco.2022.120538.

References

Arkhangelskaya, T., Lukyashchenko, K., 2018. Estimating soil thermal diffusivity at different water contents from easily available data on soil texture, bulk density, and organic carbon content. Biosyst. Eng. 168, 83–95. https://doi.org/10.1016/j.biosystemseng.2017.06.011.

Beier, C., Beierkuhnlein, C., Wohlgemuth, T., Penuelas, J., Emmett, B., Körner, C., de Boeck, H., Christensen, J.H., Leuzinger, S., Janssens, I.A., Hansen, K., Arnone, J., 2012. Precipitation manipulation experiments – challenges and recommendations for the future. Ecol. Lett. 15 (8), 899–911.

Black, W.P.M., 1962. A method of estimating the California Bearing Ratio of cohesive soils from plasticity data. Géotechnique 12 (4), 271–282. https://doi.org/10.1680/geot.1962.12.4.271.

Blinn, C.R., O'Hara, T.J., Chura, D.T., Russell, M.B., 2015. Minnesota's logging businesses: An assessment of the health and viability of the sector. Forest Science 61 (2), 381–387. https://doi.org/10.5849/forsci.14-013.

Briggs, R.D., Lemin Jr., R.C., 1994. Soil drainage class effects on early response of balsam fir to precommercial thinning. Soil Sci. Soc. Am. J. 58 (4), 1231–1239. https://doi.org/10.2136/sssaj1994.03615995005800040034x.

Cambi, M., Certini, G., Neri, F., Marchi, E., 2015. The impact of heavy traffic on forest soils: A review. For. Ecol. Manage. 338, 124–138. https://doi.org/10.1016/j.foreco.2014.11.022.

Cleavitt, N.L., Fahey, T.J., Groffman, P.M., Hardy, J.P., Henry, K.S., Driscoll, C.T., 2008. Effects of soil freezing on fine roots in a northern hardwood forest. Can. J. For. Res. 38 (1), 82–91. https://doi.org/10.1139/X07-133.

Curzon, M.T., Slesak, R.A., Palik, B.J., Schwager, J.K., 2022. Harvest impacts to stand development and soil properties across soil textures: 25-year response of the aspen Lake States LTSP installations. For. Ecol. Manage. 504, 119809 https://doi.org/10.1016/j.foreco.2021.119809.

Decker, K.L.M., Wang, D., Waite, C., Scherbatskoy, T., 2003. Snow removal and ambient air temperature effects on forest soil temperatures in northern Vermont. Soil Sci. Soc. Am. J. 67 (4), 1234–1242. https://doi.org/10.2136/sssaj2003.1234.

Erlingsson, S., Saliko, D., 2020. In: Correlating Air Freezing Index and Frost Penetration Depth—A Case Study for Sweden. Springer International Publishing, pp. 847–857. https://doi.org/10.1007/978-3-030-48679-2_79.

Fay, P.A., Carlisle, J.D., Knapp, A.K., Blair, J.M., Collins, S.L., 2000. Altering rainfall timing and quantity in a mesic grassland ecosystem: Design and performance of rainfall manipulation shelters. Ecosystems 3 (3), 308–319. https://doi.org/10.1007/s100210000028.

Friesen, H.C., Slesak, R.A., Karwan, D.L., Kolka, R.K., 2021. Effects of snow and climate on soil temperature and frost development in forested peatlands in Minnesota, USA. Geoderma 394, 115015.

Greacen, E., Sands, R., 1980. Compaction of forest soils. A review. Soil Research 18 (2), 163. https://doi.org/10.1071/SR9800163.

Grigal, D.F., 2000. Effects of extensive forest management on soil productivity. For. Ecol. Manage. 138 (1), 167–185. https://doi.org/10.1016/S0378-1127(00)00395-9.

Groffman, P.M., Driscoll, C.T., Fahey, T.J., Hardy, J.P., Fitzhugh, R.D., Tierney, G.L., 2001. Effects of mild winter freezing on soil nitrogen and carbon dynamics in a northern hardwood forest. Biogeochemistry 56 (2), 191–213. https://doi.org/10.1023/A:1013024603959.

Grolemund, G., Wickham, H., 2011. Dates and Times Made Easy with lubridate. J. Stat. Softw. 40 (3), 1–25. https://www.jstatsoft.org/v40/i03/.

Handler, S., Duveneck, M. J., Iverson, L., Peters, E., Scheller, R. M., Wythers, K. R., Brandt, L., Butler, P., Janowiak, M., Shannon, P. D., Swanston, C., Barrett, K., Kolka, R., McQuiston, C., Palik, B., Reich, P. B., Turner, C., White, M., Adams, C., … Ziel, R. (2014). Minnesota forest ecosystem vulnerability assessment and synthesis: A report from the Northwoods Climate Change Response Framework project. Gen. Tech. Rep. NRS-133. Newtown Square, PA; U.S. Department of Agriculture, Forest Service, Northern Research Station. 228 p., 133, 1–228. https://doi.org/10.2737/NRS-GTR-133.

Hardy, J.P., Groffman, P.M., Fitzhugh, R.D., Henry, K.S., Welman, A.T., Demers, J.D., Fahey, T.J., Driscoll, C.T., Tierney, G.L., Nolan, S., 2001. Snow depth manipulation and its influence on soil frost and water dynamics in a northern hardwood forest. Biogeochemistry 56 (2), 151–174. https://doi.org/10.1023/A:1013036803050.

Henninger, D.L., Petersen, G.W., Engman, E.T., 1976. Surface soil moisture within a watershed—Variations, factors influencing, and relationship to surface runoff. Soil Sci. Soc. Am. J. 40 (5), 773–776. https://doi.org/10.2136/sssaj1976.03615995004000050041x.

Herrick, J.E., Jones, T.L., 2002. A dynamic cone penetrometer for measuring soil penetration resistance. Soil Sci. Soc. Am. J. 66 (4), 1320–1324. https://doi.org/10.2136/sssaj2002.1320.

Hoover, D.L., Wilcox, K.R., Young, K.E., 2018. Experimental droughts with rainout shelters: A methodological review. Ecosphere 9 (1), e02088.

Horn, R., Vossbrink, J., Peth, S., Becker, S., 2007. Impact of modern forest vehicles on soil physical properties. For. Ecol. Manage. 248 (1–2), 56–63. https://doi.org/10.1016/j.foreco.2007.02.037.

Kok, H., McCool, D.K., 1990. Quantifying freeze/thaw-induced variability of soil strength. American Society of Agricultural and Biological Engineers 33 (2), 0501–0506. https://doi.org/10.13031/2013.31357.

Kolka, R., Nater, E., Grigal, D., Verry, E., 1999. Atmospheric inputs of mercury and irganic carbon into a forested upland/Bog watershed. Water Air Soil Pollut. 113, 273–294.

Lenth, R.V., 2021. emmeans: Estimated Marginal Means, aka Least-Squares Means. R package version 1 (5), 4. https://CRAN.R-project.org/package=emmeans.

McNabb, D.H., Startsev, A.D., Nguyen, H., 2001. Soil wetness and traffic Level effects on bulk density and air-filled porosity of compacted boreal forest soils. Soil Sci. Soc. Am. J. 65 (4), 1238–1247. https://doi.org/10.2136/sssaj2001.6541238x.

Minnesota Department of Transportation (MNDOT). User guide to the dynamic cone penetrometer. http://www.dot.state.mn.us/materials/researchdocs/User_Guide.pdf. (Accessed January 2020).

National Council for Air, Stream Improvement, Inc. (NCASI), 2004. Effects of heavy equipment on physical properties of soils and on long-term productivity: a review of literature and current research. In: Tech. Bull., 887 National Council for Air and Stream Improvement, Inc, Research Triangle Park, N.C.

PRISM Climate Group, Oregon State University, https://prism.oregonstate.edu, data created 4 Feb 2014, accessed 01 September 2022.

Pinheiro J, Bates D, DebRoy S, Sarkar D, R Core Team (2021). nlme: Linear and Nonlinear Mixed Effects Models. R package version 3.1-153, https://CRAN.R-project.org/package=nlme.

Powers, R.F., Alban, D.H., Miller, R.E., Tiarks, A.E., Wells, C.G., Avers, P.E., Cline, R.G., Fitzgerald, R.O., Loftus Jr., N.S., 1990. Sustaining site productivity in North American forests: problems and prospects. In: Gessel, S.P. (Ed.), Sustained Productivity of Forest Soils. Forestry Publications, University of British Columbia, Vancouver, B.C., pp. 49–80

Puhlick, J.J., Fernandez, I.J., 2020. Influence of mechanized timber harvesting on soil compaction in northern hardwood forests. Soil Sci. Soc. Am. J. 84 (5), 1737–1750. https://doi.org/10.1002/saj2.20127.

Romero-Saltos, H., Sternberg, L.d.S.L., Moreira, M.Z., Nepstad, D.C., 2005. Rainfall exclusion in an eastern Amazonian forest alters soil water movement and depth of water uptake. Am. J. Bot. 92 (3), 443–455.

Shoop, S.A., 1995. Vehicle bearing capacity of frozen ground over a soft substrate. Can. Geotech. J. 32 (3), 552–556.

Soil Science Division Staff, 2017. Soil survey manual. In: Ditzler, C., Scheffe, K., Monger, H.C. (Eds.), USDA Handbook 18. Government Printing Office, Washington, D.C.

Stockstad, A.B., Slesak, R.A., Toczydlowski, A.J., Blinn, C.R., Kolka, R.K., Sebestyen, S.D., 2022. Limited effects of precipitation manipulation on soil respiration and inorganic N concentrations across soil drainage classes in northern Minnesota aspen forests. Forests 13 (8), 1194. https://doi.org/10.3390/f13081194.

Stone, D.M., 2002. Logging options to minimize soil disturbance in the northern Lake States. North. J. Appl. For. 19 (3), 115–121. https://doi.org/10.1093/njaf/19.3.115.

Tan, X., Chang, S.X., Kabzems, R., 2005. Effects of soil compaction and forest floor removal on soil microbial properties and N transformations in a boreal forest long-term soil productivity study. For. Ecol. Manage. 217 (2), 158–170. https://doi.org/10.1016/j.foreco.2005.05.061.

Uusitalo, J., Ala-Ilomäki, J., Lindeman, H., Toivio, J., Siren, M., 2019. Modelling soil moisture – soil strength relationship of fine-grained upland forest soils. Silva Fennica 53 (1). https://doi.org/10.14214/sf.10050.

Veneman, P.L.M., Spokas, L.A., Lindbo, D.L., 1998. Soil moisture and redoximorphic Features: A historical perspective. In Quantifying Soil Hydromorphology. John Wiley & Sons, Ltd, pp. 1–23.

von Wilpert, K., Schäffer, J., 2006. Ecological effects of soil compaction and initial recovery dynamics: A preliminary study. Eur. J. Forest Res. 125 (2), 129–138. https://doi.org/10.1007/s10342-005-0108-0.

Watanabe, T., Tateno, R., Imada, S., Fukuzawa, K., Isobe, K., Urakawa, R., Oda, T., Hosokawa, N., Sasai, T., Inagaki, Y., Hishi, T., Toda, H., Shibata, H., 2019. The effect of a freeze-thaw cycle on dissolved nitrogen dynamics and its relation to dissolved organic matter and soil microbial biomass in the soil of a northern hardwood forest. Biogeochemistry 142 (3), 319–338.

Yahdjian, L., Sala, O.E., 2002. A rainout shelter design for intercepting different amounts of rainfall. Oecologia 133 (2), 95–101. https://doi.org/10.1007/s00442-002-1024-3.

Yang, Y.J., Liu, S.R., Wang, H., Chen, L., Lu, L.H., Cai, D.X., 2019. Reduction in throughfall reduces soil aggregate stability in two subtropical plantations. Eur. J. Soil Sci. 70 (2), 301–310. https://doi.org/10.1111/ejss.12734.

Zhang, T., 2005. Influence of the seasonal snow cover on the ground thermal regime: An overview. Rev. Geophys. 43 (4) https://doi.org/10.1029/2004RG000157.

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Limited Effects of Precipitation Manipulation on Soil Respiration and Inorganic N Concentrations across Soil Drainage Classes in Northern Minnesota Aspen Forests

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Abstract: It is critical to gain insight into the responses of forest soils to the changing climate. We simulated future climate conditions with growing season throughfall reduction (by 50%) and winter snow removal using a paired-plot design across a soil drainage class gradient at three upland, *Populus*-dominated forests in northern Minnesota, USA. In situ bulk soil respiration and concentrations of extractable soil N were measured during the summers of 2020–2021. Soil respiration and N concentrations were not affected by throughfall reduction and snow removal, which was largely attributed to the limited treatment effects on soil moisture content and soil temperature. Drainage class was only a significant factor during the spring thaw period in 2021. During this period, the poorly drained plots had lower respiration rates compared to the well-drained plots, which was associated with the drainage class effects on soil temperature. The results of the companion laboratory incubation with varying levels of soil moisture also indicated no effect of the treatment on soil respiration, but effects of drainage class and moisture content on respiration were observed. Our results indicate that the combined effects of reduced summer and winter precipitation on soil respiration and N dynamics may be limited across the range of conditions that occurred in our study.

Keywords: forest soils; throughfall reduction; snow removal; soil respiration; nitrogen dynamics

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1. Introduction

Forest soils are a major component of carbon (C) and nitrogen (N) cycling, both within upland forest ecosystems and globally [1–3]. Soil respiration is the main pathway for the release of plant-fixed carbon dioxide (CO_2) back to the atmosphere either through root (autotrophic) respiration or the decomposition of soil organic matter by microbes (heterotrophic respiration) [3,4]. N commonly limits growth in upland forest ecosystems as it is an essential macronutrient [1,5]. Microbes and fungi influence the transformation and efflux of C and N in soils, and these factors are largely controlled by climate effects on soil moisture and temperature [1,6–8]. Since forest soils store large amounts of C (as well as N), understanding forest biogeochemical cycling under a changing climate is critical for the development of forest management strategies [1,2].

Changes in summer and winter precipitation as well as changes to winter frost dynamics are likely to alter the cycling and flux of C and N from soil [8–11]. For the Laurentian Mixed Forest Province in northern Minnesota, climate modeling by Handler et al. (2014) projected a slight decrease in total precipitation by 2100, with the largest decline (40 percent) occurring during the summer [12]. Additionally, by the end of the century, winter temperatures are projected to increase by an additional 3–7 °C and more winter precipitation will occur as rain instead of snow [12]. These regional climate change predictions are similar to those for other northern latitudes [12,13].

In northern ecosystems, snowpack serves as an insulative layer over the soil surface, influencing both the soil temperature and frost depth [14]. Decreased snowpack, and thus greater frost depth, have been correlated with decreased net heterotrophic respiration from forest soils [1,8,15]. Increased soil frost reduces soil respiration into the growing season due to extended periods of colder soil temperature and its suppression of biologic activity [16]. With regard to N, Fitzhugh et al. (2001) found that inorganic N concentrations increased following freezing events, and N leaching subsequently increased, similar to the others [17,18]. Increased frost depth may increase N mineralization and nitrification rates due to higher amounts of microbial and root mortality and the disruption of soil aggregates [17].

In the summer, declines in soil moisture associated with reduced rainfall or enhanced evapotranspiration in a warmer climate may cause decreases in microbial activity and root respiration if the soil moisture becomes limiting to biologic activity [9,10]. Past studies have used throughfall reduction, where a percentage of precipitation below the canopy is diverted from experimental plots to approximate the effects of reduced precipitation in the future. In a throughfall reduction study in Massachusetts, USA, Borken et al. (2006) found that complete throughfall exclusion significantly decreased the bulk soil respiration by 10–30% compared to ambient conditions [10]. Additionally, Schindlbacher et al. (2012) found that reductions in the bulk soil respiration due to complete throughfall exclusion offset concurrent increases in the bulk soil respiration due to soil warming [9]. The influence of throughfall reduction on N dynamics, however, is not as clearly understood due to the complexity of N cycling in soils. For example, throughfall reduction has been shown to increase extractable ammonium concentrations but decrease extractable nitrate concentrations, with no discernable effect on the total N supply [19]. It is possible that N supply in soil may not be as sensitive to changes in the soil moisture compared to the soil C fluxes. In a meta-analysis of global N dynamics, Deng et al. (2021) found that drought had no significant effect on the total N concentrations in forest ecosystems [20]. However, as with the above, the extractable ammonium increased under drought conditions, and the extractable N decreased [20].

Drainage class is likely to be an important factor when considering fluctuations in soil moisture and frost associated with climate change and the related effects on C and N dynamics. In the field, soil texture and landscape position create differences in the soil drainage or wetness, which is classified by depth to redoximorphic features (i.e., mottling, gleying) [21]. Soil aeration, relative moisture supply, and potential rooting depth are all influenced by drainage class [22]. As a result of these variations in soil moisture, microbial communities and their activity may also vary with drainage class. For example, the rates of soil respiration versus methanogenesis differ with drainage class due to variations in moisture levels [23]. The effects of reduced rainfall and snowpack may vary by drainage class in forest soils, but we are not aware of any studies to evaluate such an effect.

Paired-plot experiments, with either snow removal or throughfall exclusion treatments compared to an ambient control, have been used to investigate the response of forest soil C and N fluxes to changes in seasonal precipitation [8–11,16,17,24]. However, no studies have combined snow removal and throughfall reduction treatments in one experiment. Applying the two treatments seasonally on the same plot allows for a more representative simulation of future precipitation patterns for the North-Central USA, as projected by climate models. We aim to bridge the gap between existing snow removal and throughfall reduction experiments to better understand the future of aspen forests in Minnesota under a changing climate. Our primary objective was to quantify the influence of combined throughfall exclusion and snow removal on soil respiration and N cycling, and to provide a more comprehensive assessment of the combined seasonal effects of climate change on forest soil biogeochemistry.

2. Materials and Methods

2.1. Study Area

The study included three sites located in Aitkin, Itasca, and St. Louis counties within the Laurentian Mixed Forest Province (LMFP) in northern Minnesota, USA (Table 1). All sites were located in the LMFP and dominated by upland quaking aspen (*Populus tremuloides* Michx.) in the forest canopy with beaked hazel (*Corylus cornuta*), willow (*Salix* spp.), or speckled alder (*Alnus incana*) in the understory. Mean summer (June–August) and winter temperatures for this region are 18 °C and −12 °C, respectively (Handler et al., 2014). The average precipitation in LMFP during the summer is 305 mm, and the average snowfall ranges from 1016 mm to 1778 mm [12].

Table 1. The site locations, map units, and pre-treatment physical and chemical data for the three sites (county) determined from the soil survey information. The soil survey information is from the National Cooperative Soil Survey [25].

Site (County)	Coordinates	Soil Unit	Soil Texture	Bulk Density (g cm^{-3})	% C	% N
Aitkin	46.361908, −93.236416	Milaca-Millward complex	Fine sandy loam	1.03–1.21	1.24–1.94	0.07–0.14
Itasca	47.688509, −93.546264	Warba-Menahga complex	Fine sandy loam	1.24–1.31	0.73–1.07	0.04–0.06
		Morph very fine sandy loam	Very fine sandy loam	1.31–1.32	0.82	0.05
St. Louis	47.182644, −92.104667	Baudette silt loam	Silt loam	1.27–1.36	1.12	0.08
		Aldenlake-Pequaywan complex	Sandy loam	1.02–1.22	1.24–1.90	0.08–0.13
		Brimson stony fine sandy loam	Stony fine sandy loam	0.84–0.93	3.25–5.25	0.22–0.39

2.2. Site Characteristics

Mature quaking aspen (40–60 years) dominated the overstory canopy at all sites. Loamy soils occurred on relatively flat topography (less than 10% slope; Table 1). Plot locations within the target drainage classes (well-drained through poorly drained) were identified based on depth to redoximorphic features (Table 1). 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) [25].

2.3. Experimental Design

The study occurred from May 2018 until May 2022. We used a paired-plot, 4 × 2 factorial design with Factor 1 being drainage class and Factor 2 being treatment (precipitation manipulation or control conditions). Treatments were replicated across the three sites, with each site containing eight 4 × 4-m plots across the four drainage classes for a total of twenty-four plots across all three sites (three replications per drainage class × treatment combination). The paired treatment and control plots (ambient conditions) were located adjacent to each other within each drainage class. Within each plot, treatments included both snow removal during the winter (Supplementary Materials Figure S1) and throughfall reduction during the growing season (Supplementary Materials Figure S2).

2.4. Snow Removal Treatment

Snow was removed from the treatment plots during the winter according to the method developed by Friesen et al. (2021) [24]. To allow for snow removal without impacting the soil surface, gray aluminum window screening (Phifer Incorporated, Tuscaloosa, AL, USA) 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 annually 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 of the experimental control. Snow was cleared after every event of 5 cm or more, or at least weekly.

2.5. Throughfall Reduction Treatment

Throughfall reduction shelters were installed during the growing season to simulate a 50% reduction in throughfall similar to the design implemented by Yahdjian and Sala (2002) [26]. The shelters were guttered with 10.16 cm wide, U-shaped white vinyl gutters that extended 40 cm past the plot boundary. The ridgeline of the A-frame shelter ran along a north–south transect so that the panels were situated on an east–west transect to avoid warming created by a south-facing panel. Control plots were left as an experimental reference and did not receive any precipitation reduction treatment. To assess the 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 the moderately drained plots at each site (n = 4 collectors per plot and site).

2.6. Soil Moisture, Soil Temperature, and Air Temperature Measurements

Soil temperature and moisture were measured every 15 min throughout the study at depths of 10, 20, 30, 40, and 60 cm via Decagon 5 TM sensors (±0.1 °C, ±0.08 m^3 m^{-3} SWC; METER Group, Pullman, WA, USA). Sensors were installed in a cluster at the center of the plots (Supplementary Materials Figures S2 and S3) and connected to EM50 dataloggers (METER Group). Air temperature was recorded in control plots every 90 min with Thermochron iButton sensors (±0.5 °C; Maxim Integrated Products, Inc., Sunnyvale, CA, USA) enclosed in a PVC solar shield.

2.7. In Situ Measurements of Bulk Soil Respiration

Bulk soil respiration (µmol m^{-2} s^{-1}) was measured biweekly during the growing season of 2020 (late June–September 2020) and 2021 (April–September 2021). Fluxes of CO_2 were measured with a LI-COR LI-8100 Automated Soil CO_2 Flux System, which was calibrated three times (LI-COR Biosciences, Lincoln, NE, USA). Collars made of PVC with a diameter of 20 cm were installed at a depth of 1.5–5 cm two weeks prior to the first measurement. Measurements of CO_2 concentrations within the chamber were taken over a two-minute period with a forty-five second post-purge. The soil surface temperature at the time of measurement was measured with a Procheck Handheld soil water content and temperature probe (METER Group, Pullman, WA, USA).

2.8. Extractable Soil N

A sequential core technique was used to assess N availability during the growing seasons of 2020 and 2021, with cores being deployed at the same time as each growing season and then sequentially extracted over consecutive months. Four PVC tubes (25 cm long and 5 cm diameter) were hammered 20 cm into the soil along a transect in each plot. One core was removed from each plot each month. Ten gram samples from each depth (0–5 cm, 5–20 cm) were separated after cutting crosswise and homogenizing, and then stored in a refrigerator overnight prior to extraction. The remaining soil was oven-dried at 105 °C for twenty-four hours to calculate the gravimetric water content in the samples. The 10 g samples were then combined with 40.0 mL of a 2.0 mol/L potassium chloride (KCl) solution, shaken for one hour (via shaker table), and chilled for one hour at 1.7–3.9 °C to limit any additional reactions within the slurry. Soil slurries were then filtered (Whatman 42 filter paper) using gravity filtration into plastic 20 mL sample vials, and frozen until analysis. Samples were analyzed for ammonium (NH_4^+), nitrate + nitrite (NO_3^- + NO_2^--N), and total N (TN) concentrations (ppm) using a Lachat Quickchem 8500 Flow Injection Analysis System (Hach, Loveland, CO, USA) in the USDA Forest

Service Northern Research Station chemistry laboratory in Grand Rapids, Minnesota. Following analysis, the concentrations were corrected for soil mass (adjusted based on oven dried mass) and converted to units of milligrams per kilogram of soil.

2.9. Laboratory Incubation

A laboratory incubation of field soils was used to determine the effect of varying moisture levels on heterotrophic soil respiration under a controlled environment. Four subsamples of soil were collected at the end of the experiment from each plot to a depth of 15 cm and combined to produce a bulk soil sample for each of the twenty-four plots. The bulk soil samples were air-dried for one month and then sieved through a 2 mm mesh. Three 10.0 g subsamples of soil were taken from each bulk soil sample for each combination of site, drainage class, and treatment ($n = 72$). Each subsample received one of three levels of moisture manipulation to establish a moisture gradient during the incubation: 2.5 mL, 5.0 mL, or 7.5 mL of deionized water.

Soils were then incubated for fourteen days in 237 mL glass jars inside a 20 °C growth chamber in the absence of light. The lids remained sealed during the incubation, but the jars were opened every three days for three minutes to maintain an aerobic environment. Two HOBO U23-002 temperature loggers (±0.2 °C; Onset Computer Corporation, Bourne, MA, USA) were placed within the growth chamber and recorded the air temperature every fifteen minutes (one on the top shelf and one on the bottom shelf). The average temperature for the top shelf was 20.4 °C ± 0.05 °C and 19.9 °C ± 0.144 °C for the bottom shelf.

Three days prior to sampling, the vials were evacuated using ultra high purity helium (He). Gas samples (12 mL) were collected on the seventh and fourteenth days of the incubation. To begin, jars were opened and allowed to equilibrate with the atmosphere. After 90 s, a time-zero (T0) gas sample was taken to represent ambient conditions. Gas samples were immediately transferred with a needle from the syringe to 9 mL glass vials sealed with butyl rubber septa. Following the T0 measurement, jars were resealed with a lid and septa and allowed to incubate for 1 h. Gas samples were then taken from each jar after 1 h (T1) through the septa and immediately transferred to the vials. Gas samples were analyzed within 24 h using a gas chromatograph (Model 5890, Agilent/Hewlett-Packard, Santa Clara, CA, USA) in conjunction with an autosampler (Tekmar 7000, Teledyne Tekmar, Mason, OH, USA). The gas chromatograph was equipped with a thermal conductivity detector for CO_2. Fluxes (μg g^{-1} h^{-1}) of CO_2 were calculated from the T0 and T1 measurements.

2.10. Data Analysis

Repeated measures, linear mixed effect models were used to evaluate the influence of drainage class, treatment, and time on the soil water content (SWC), soil temperature, soil respiration, and extractable N concentrations. For the SWC and soil temperature, the analysis was constrained to the growing season (May–September/October 2019–2021) to focus on the effects of the throughfall reduction treatment, which was expected to have the most influence on the soil respiration and extractable N. For the soil incubation, drainage class, treatment, moisture content, and time were used as factors in repeated measures, mixed effect models. Site (block) was included as a random effect in all models. Soil temperature, pre-treatment C (%), and clay content (%) were included as covariates in the model of soil respiration. Pre-treatment N (%) and clay content were also included as covariates in the NH_4^+, NO_3^- + NO_2^--N, and TN models.

The mixed effect model analysis with repeated measures was performed using the R package "nlme" [27]. Autocorrelation matrices (corAR1 function) were included in the models to account for temporal correlation in the data [27]. For all analyses, each year was run separately. The least square means analysis with the Tukey *p*-value adjustment was performed when significant effects were found by using the "lsmeans" package in R [28].

The datasets were checked for outliers using plots of residuals and boxplots. The only dataset with outliers that skewed the distribution were in the extractable N dataset from 2021. Extreme outliers were assumed to be from sample contamination and were removed from the dataset. Plots of standardized residuals and quantile–quantile (Q–Q) plots were used to visually validate the assumptions of normality, linearity, constant variance, and independence. The respiration fluxes were transformed using a natural logarithm to correct for non-normality. The CO_2 values from the incubation were also log-transformed to correct for non-normality. The quantile–quantile plots and plots of the standardized residuals were used to identify the best transformation of the dependent variable. If transformed to meet the assumptions of linear models, the least square means and confidence intervals are presented as back-transformed values in the figures.

All of the statistical analyses and data visualizations were performed using R statistical software in RStudio (RStudio Version 1.1.463, Boston, MA, USA). The level of significance (alpha) was defined as a p-value < 0.05.

3. Results

3.1. Effects of Treatment on Soil Water Content and Temperature

There was a significant interaction between drainage class, treatment, and depth on summer SWC in both years ($p < 0.001$ for both years; Supplementary Materials Table S2). Notably, there were limited effects of throughfall reduction across the drainage classes on SWC in the surface horizons, even though the biweekly average throughfall volume measured in the control plots was 648.6 mL (±54.44 mL) and 305.5 mL (±108.4 mL) for the treatment plots (Figure 1). Significant differences in SWC between the control and treatment within a drainage class at a given depth were mainly present for depths of 30–60 cm for the WD, MWD, SPD, and PD classes during both years. 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 40 cm during 2020 (difference of -0.04 m^3 m^{-3}, and there was no significant difference ($p = 0.15$) during 2021. The treatment plots in the MWD class had significantly higher SWC than the control plots at 30 and 60 cm during 2020 and 2021 with differences ranging from 0.04 to 0.06 m^3 m^{-3}. The PD class showed a similar trend at 20 cm and 60 cm during 2020 and 20 cm during 2021. Differences in SWC at 60 cm in the PD class were likely due to fluctuations in the water table.

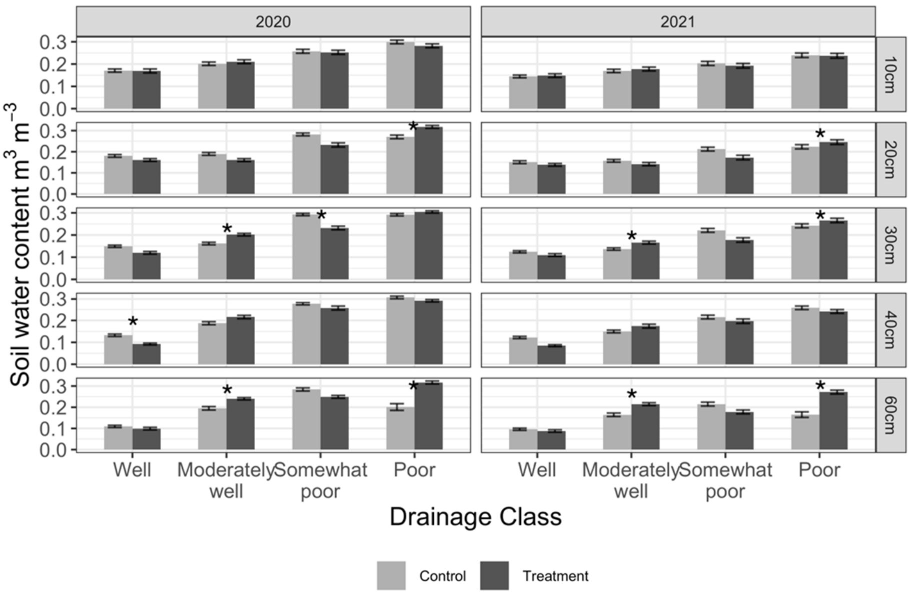

Figure 1. Three-way interaction between treatment, drainage class, and sensor depth for the two years of SWC models. Asterisks indicate a significant difference ($p < 0.05$) between the control and treatment within each drainage and treatment combination. Error bars indicate the standard error. The sensor depth in centimeters in shown on the right y-axis.

There were significant interactions between treatment and time in the growing season soil temperature models for both years (Supplementary Materials Table S3). Soil temperature was significantly lower in the treatment compared to the control during early May in both years due to snow removal and its effect on frost development (2020: difference of 4.4 °C; 2021: difference of 1.6 °C). Soil temperature equilibrated between the ambient and treatment conditions later in the growing season during 2020 (mid-June) compared to 2021 (mid-May) (Figure 2).

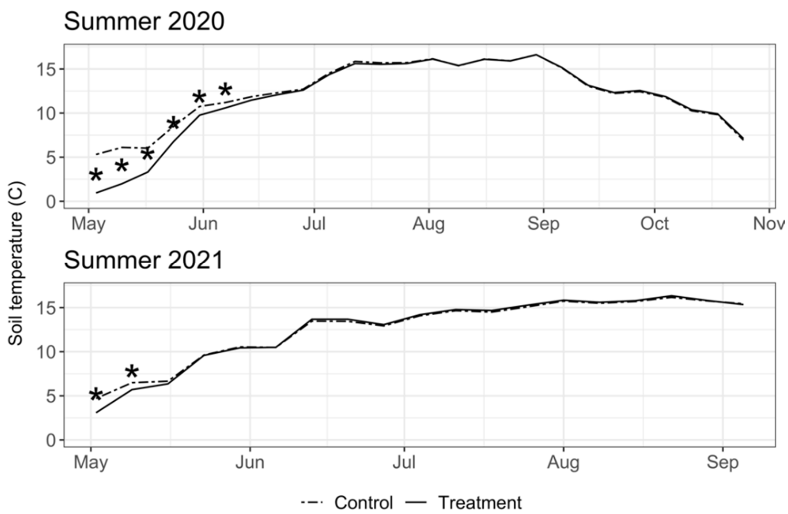

Figure 2. Mean weekly soil temperature during the growing seasons of 2020 and 2021 by treatment. Asterisks indicate weeks with significant difference between the means of the control and treatment.

There was also a significant interaction between drainage class and treatment on the growing season soil temperature in both years; Supplementary Materials Table S3). Mean growing season soil temperature decreased from WD to PD (difference of 0.55–0.75 °C for the control during the summers of 2020 and 2021; Figure 3), with soil temperatures in the treatment plot typically being slightly lower (difference of 0.13–0.83 °C) compared to the control within each drainage class (except WD, MWD in 2021, differences of −0.12, −0.08 °C respectively; Figure 3).

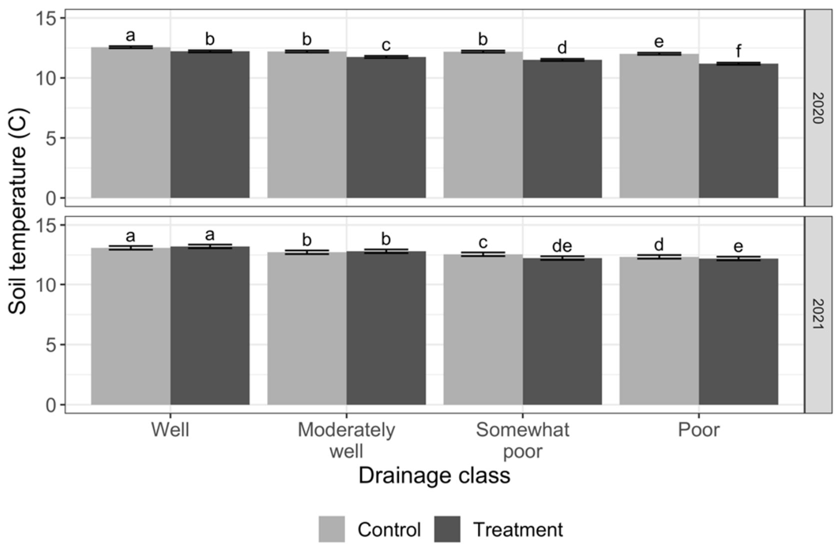

Figure 3. Mean soil temperature by drainage class and treatment for the growing seasons of 2020 and 2021. The letters indicate significant differences (p-value < 0.05) among the drainage classes within each year.

3.2. In Situ Bulk Soil Respiration

There was no effect of treatment on in situ bulk soil respiration in either year ($p = 0.2$ in 2020, $p = 0.9$ in 2021), but there was a significant effect of drainage class in 2021 (Supplementary Materials Table S4). In 2021, the well-drained class had a higher respiration rate compared to the other drainage classes with differences of 0.15–0.31 µmol m^{-2} s^{-1} (WD-MWD $p = 0.04$, WD-SPD $p = 0.02$, WD-PD; Figure 4). Visual examination of the data indicated that there was some evidence of differences in bulk soil respiration during the thaw period among drainage classes in 2021 (Supplementary Materials Figure S5). Bulk soil respiration was suppressed in the wetter drainage classes (SPD and PD) during this period compared to the WD and MWD classes (non-significant difference of 1.38 µmol m^{-2} s^{-1} between WD and PD). The later initiation of sampling in 2020 may have missed any thaw period effect between treatments and among drainage classes.

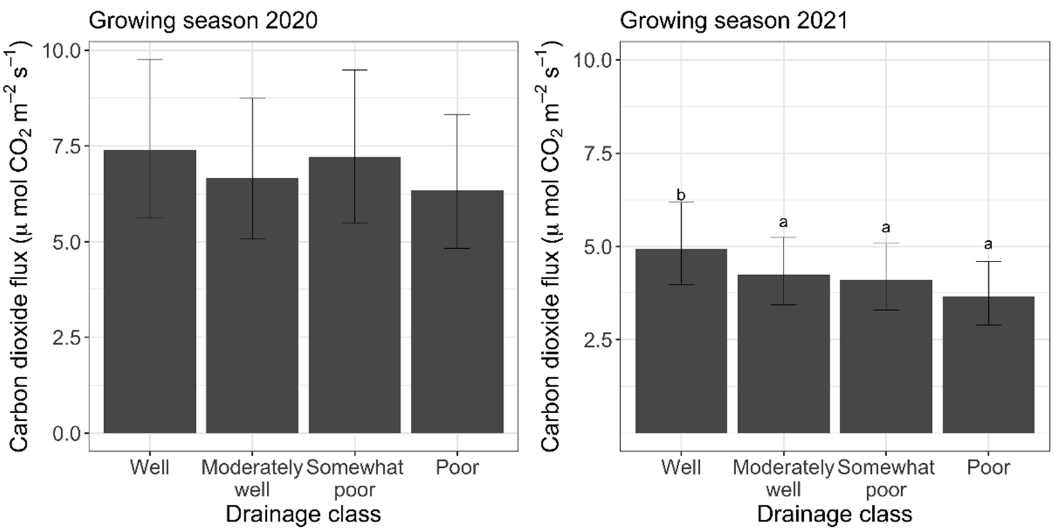

Figure 4. The least square mean values of bulk soil respiration by drainage class for 2020 and 2021. Letters represent significant differences between the drainage classes within a specific year (p-value < 0.05). Error bars represent 95% confidence intervals.

There was a notable decline in soil respiration rates (CO_2 flux) from 2020 to 2021 that was associated with a drought during 2021 in the study region. Across treatments and drainage classes, bulk soil respiration rates decreased by roughly 25% from 2020 to 2021 during the growing season ($p < 0.001$; Supplementary Materials Tables S4 and S5).

3.3. Extractable Soil N

There was no effect of treatment on the extractable N concentrations in either year, and no significant interaction between drainage class and treatment (Supplementary Materials Table S6). The concentrations of extractable N were mainly influenced by drainage class (statistics presented in Supplementary Materials Table S6), and drainage class also significantly affected the TN concentrations during 2020 and 2021 ($p < 0.001$ for both years). The main differences in extractable TN concentrations in 2020 and 2021 were driven by higher values in the SPD class compared to other drainage classes (Table 2). In 2020, TN concentrations in the SPD class were higher than the WD, MWD, and PD classes by 6.5 mg kg^{-1} ($p < 0.001$), 5.6 mg kg^{-1} ($p = 0.002$), and 4.2 mg kg^{-1} ($p = 0.02$), respectively. There was a significant increase in TN concentrations from 2020 to 2021 (Table 2, Supplementary Materials Table S5). The same pattern was maintained across years, with SPD having the highest mean concentration of TN, then PD, MWD, and WD having the lowest mean concentration (Table 2).

Table 2. The least square means of the concentrations of the extractable total N, ammonium, and $NO_3^- + NO_2^-$-N by drainage class during the growing seasons of 2020 and 2021. Groups with different superscript letters indicate significant differences (*p*-value < 0.05) between drainage classes within a given year.

	Total N (mg kg^{-1}) (95% *Confidence Interval*)	
Drainage Class	**2020**	**2021**
WD	5.51 (*3.6–8.4*) ^{a}	10.6 (*5.6–20.2*) ^{a}
MWD	6.45 (*4.2–9.9*) ^{a}	11.5 (*6.1–21.9*) ^{ab}
SPD	12.0 (*7.9–18.2*) ^{b}	17.5 (*9.2–33.3*) ^{c}
PD	7.81 (*5.0–12.3*) ^{a}	15.7 (*8.13–30.2*) ^{bc}
	Ammonium (mg kg^{-1}) (*95% confidence interval*)	
Drainage class	2020	2021
WD	2.51 (*0.72–8.7*) ^{ab}	15.8 (*3.4–73.8*) ^{a}
MWD	3.81 (*1.1–13.1*) ^{ab}	14.2 (*3.03–66.3*) ^{a}
SPD	4.00 (*1.2–13.7*) ^{b}	12.0 (*2.4–59.3*) ^{a}
PD	2.09 (*0.58–7.5*) ^{a}	18.0 (*3.7–86.9*) ^{a}
	Nitrate + nitrite (mg kg^{-1}) (*95% confidence interval*)	
Drainage class	2020	2021
WD	0.43 (*0.17–1.0*) ^{a}	0.09 (*0.01–0.65*) ^{a}
MWD	1.48 (*0.61–3.6*) ^{b}	0.70 (*0.09–5.7*) ^{b}
SPD	1.59 (*0.66–3.8*) ^{b}	3.78 (*0.26–53.9*) ^{c}
PD	1.24 (*0.48–3.2*) ^{b}	2.29 (*0.21–25.1*) ^{bc}

Concentrations of extractable N were mainly influenced by drainage class (statistics presented in Supplementary Materials Table S6), and drainage class also significantly affected the TN concentrations during 2020 and 2021 ($p < 0.001$ for both years). The main differences in extractable TN concentrations in 2020 and 2021 were driven by higher values in the SPD class compared to other drainage classes (Table 2). In 2020, the TN concentrations in the SPD class were higher than the WD, MWD, and PD classes by 6.5 mg kg^{-1} ($p < 0.001$), 5.6 mg kg^{-1} ($p = 0.002$), and 4.2 mg kg^{-1} ($p = 0.02$), respectively. There was a significant increase in TN concentrations from 2020 to 2021 (Table 2, Supplementary Materials Table S5). The same pattern was maintained across years, with SPD having the highest mean concentration of TN, then PD, MWD, and WD having the lowest mean concentration (Table 2).

Drainage class was a significant factor in the NH_4^+ model during 2020 and was not significant in 2021 ($p = 0.014$, $p = 0.372$ respectively). In 2020, the only difference in extractable NH_4^+ concentrations was between the SPD and PD class (−1.91 mg kg^{-1}; Table 2). There was an increase in NH_4^+ concentrations from 2020 to 2021 for both treatments and across drainage classes (*p* values < 0.05; Supplementary Materials Table S5). The increase in NH_4^+ concentrations from 2020 to 2021 parallels the increase in TN concentrations between the two growing seasons.

Extractable $NO_3^- + NO_2^-$-N concentrations were affected by the drainage class in both 2020 and 2021 ($p < 0.001$ for both years; Table 2, Supplementary Materials Table S5). In 2020, only the WD class was different and had the lowest concentration of $NO_3^- + NO_2^-$-N compared to all other drainage classes (Table 2; 1.2–1.6 mg kg^{-1}). Similarly in 2021, the WD class also had a lower concentration of $NO_3^- + NO_2^-$-N (difference 0.7–3.9 mg kg^{-1}) compared to MWD, SPD, and PD (Table 2). Additionally, $NO_3^- + NO_2^-$-N concentrations in the SPD class during 2021 were higher than the MWD class (Table 2; 3.1 mg kg^{-1}), but not different from PD. The pattern in $NO_3^- + NO_2^-$-N concentrations during 2021 mirrors that of TN concentrations (Table 2), with SPD having the highest concentration of $NO_3^- + NO_2^-$-N, then PD, MWD, and WD having the lowest concentration. There was an increase in $NO_3^- + NO_2^-$-N concentrations from 2020 to 2021 across both treatments and drainage classes (all *p*-values < 0.05; Supplementary Materials Table S5).

3.4. Laboratory Incubation

The results of the soil incubation were generally consistent with the field results with respect to soil respiration (CO_2 flux). As with the field results, there was no effect of treatment on CO_2 flux ($p = 0.44$; Supplementary Materials Table S10) while there was an effect ($p = 0.004$) of drainage class on the CO_2 fluxes during the incubation. Only the MWD class had a lower CO_2 flux compared to the other drainage classes (Figure 5; $p = 0.01$ MWD–SPD, $p = 0.01$ MWD–WD, $p = 0.003$ MWD–PD).

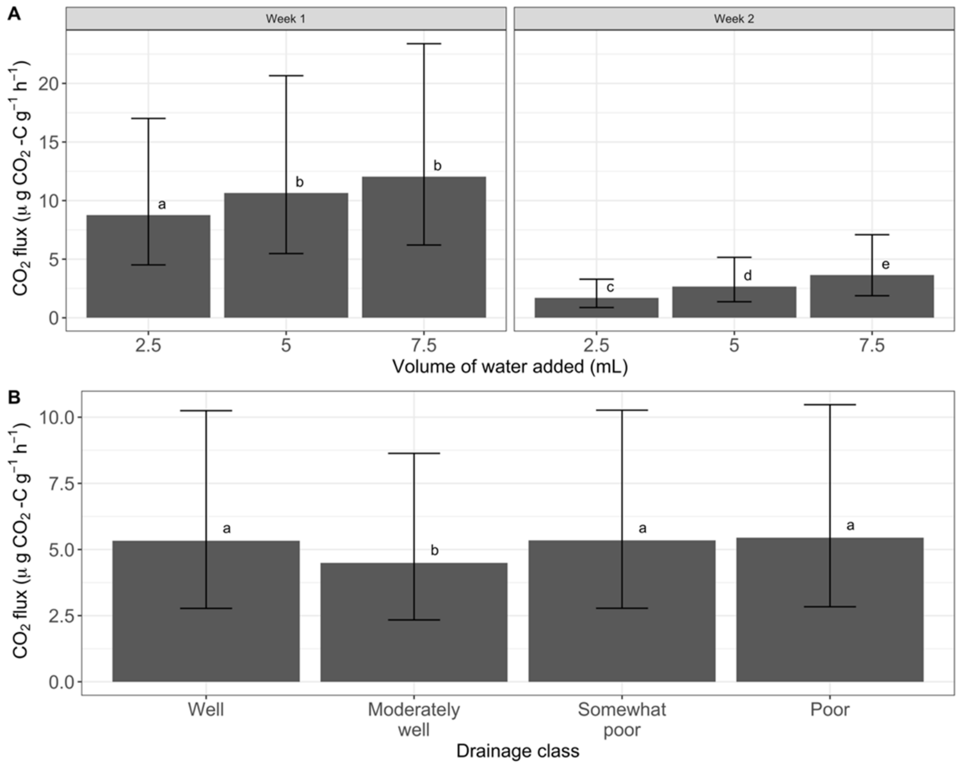

Figure 5. The least square mean values of the CO_2 flux for pairwise comparisons of the volume of water (soil moisture status) added by week are shown in panel (**A**). The least square means of CO_2 flux by drainage class are shown in panel (**B**). Letters represent significant differences (*p*-value < 0.05). Error bars represent 95% confidence intervals.

There was an interaction between the amount of water added (representative of soil moisture status) and sample date ($p < 0.001$). Fluxes of CO_2 increased with the volume of water added, and this pattern was seen during both sampling periods (Figure 5). However, during the second week of the two-week incubation, CO_2 fluxes for each level of water added were different ($p < 0.001$). The 5.0 mL and 7.5 mL levels were not different during week one. Fluxes of CO_2 decreased from the first to second week of the incubation (>50% reduction).

4. Discussion

Evaluating biogeochemical responses to changes in precipitation and temperature is crucial for understanding forest soils under a changing climate. We used a field study to simulate reduced summer and winter precipitation and found minimal effects of throughfall reduction and snow removal on soil respiration and extractable N concentrations. Drainage class was a stronger indicator of soil respiration and extractable N concentrations than treatment, but the effects were limited likely due to the limited efficacy of the throughfall reduction treatment on SWC, and the snow removal effects on soil temperature that did not persist into the period when spring/summer respiration was measured. Results from the laboratory incubation support findings from the field that there were significant effects of SWC on CO_2 fluxes, but no treatment effect under controlled conditions.

4.1. Soil Respiration

The treatment (summer throughfall reduction followed by winter snow removal) did not result in differences in the in situ bulk soil respiration during either year of the study. These results are in contrast with previous studies that have shown a decline in soil respiration with throughfall reduction [9,10]. However, these studies excluded all throughfall from entering the plots (similar in size to plots in the current study) to simulate severe drought, resulting in SWC reductions at the soil surface [9,10]. In contrast, our 50% reduction in throughfall in the current study had inconsistent effects on SWC across drainage classes, with the treatment plots being wetter at times compared to the control plots (Figure 1). The lack of a consistent effect of treatment on SWC is likely why there was no effect of treatment on the soil respiration. Experimental artifact may have contributed to the insignificant treatment effect on SWC. For example, the small size of the plots may have limited any treatment effect on SWC within the plots or created an edge effect from lateral soil water flow [29,30].

Snow removal resulted in a temperature lag, where soil temperature was significantly lower in the treatment plots compared to the control from May–June in both years (Figure 2). However, there were no differences in soil respiration between the ambient and treated conditions during this period, despite the strong influence of soil temperature on soil respiration [3,9,11,23]. The timing of respiration measurements and early spring thaw may have inhibited the detection of any treatment effect. For example, in early May 2021, mean soil temperature was significantly lower in the treatment plots (3.0 °C) compared to the control (4.7 °C), but soil temperature equilibrated between the control and treatment relatively quickly in early June (Figure 2). In addition, in 2020, sampling began in late June (delayed due to COVID-19 pandemic restrictions on field research) after soil temperature had normalized between the control and treatment. The larger differences in soil temperature between treatments that occurred in the spring of that year (Figure 2) likely would have had a larger effect on soil respiration. Thus, the lack of treatment effect may have not been captured during either year due to delayed sampling (2020) or an earlier thaw (2021). If this is the case, then any treatment effect would have been short in duration.

The effect of drainage class on soil respiration in 2021 was minimal as only the WD class had a higher respiration rate compared to the other three drainage classes (Figure 4). Davidson et al. (1998) showed that soil respiration generally decreased with increasing SWC (from WD to PD), but that soil respiration was also suppressed at low values of SWC ($\theta_v < 0.12$) under drought conditions [23]. The lack of more pronounced and consistent effects of drainage class may be due to the offsetting effects of SWC and soil temperature on soil respiration, which may mask any response, or to minimal differences in microbial responses, as suggested by the incubation results (Figure 5). It is also possible that the variation in soil water contents among drainage classes was not large enough to become limiting to soil respiration. The positive effect of increasing moisture content on soil respiration in the lab incubation supports this: the maximum moisture content during the incubation ($\theta_{g\text{-incubation}} = 0.75$, average bulk density of in situ soils = 1.05 g cm^{-3}, $\theta_{v\text{-incubation}} \approx 0.71$) was higher than the maximum moisture content observed in the field across all three years ($\theta_{v\text{-field}} = 0.47$).

The comparison of the laboratory incubation to the field experiment removes the effects of the field microclimate on the response and any contributions of autotrophic respiration, which allows for the direct observation of heterotrophic respiration associated with the microbial community and available C substrate. The lack of a treatment effect under controlled laboratory conditions is consistent with the field observations, indicating that the treatment did not modify the soil microbial community or other factors that influence C efflux (e.g., microbial community composition, litter quality, enzyme activity, etc.). Since microbial transformations of C are strongly affected by soil moisture and temperature, a treatment effect on the microbial community or C substrate should have appeared under controlled incubation conditions without the influence of vegetation [23,31,32].

The observed effect of drainage class and volume of water added indicated that soil C differed by drainage class and responded to changes in SWC (Figure 5). The drainage effect during the incubation was minimal, since only the MWD class had a significantly lower CO_2 flux, which could be due to lower microbial activity or substrate availability compared to the other drainage classes. This pattern suggests that similar soil respiration in the field among the MWD, SPD, and PD classes was due to higher autotrophic respiration in the MWD class. Furthermore, the highest in situ respiration rate in the WD class during 2021 was likely to be caused by higher autotrophic respiration compared to the other drainage classes. The investigation of the differences in autotrophic versus heterotrophic respiration was beyond the scope of this study, but it emphasizes the complexity of soil–microbe–plant interactions across a drainage gradient in forest soils.

4.2. Extractable Soil N

The lack of any treatment effects on the extractable N concentrations is also likely to be a result of the insignificant effect of throughfall reduction on the SWC of the surface horizons, since microbial transformations of N are dependent on soil moisture and temperature [7,19,20]. Previous studies have shown the response of extractable N concentrations to reduced precipitation to be complex and the direction of the change variable. For example, drying may limit the transport of substrates and enzymes via changes in water potential or alter soil structure by disrupting soil aggregate content [33], though this likely did not occur in our study since there was no effect of treatment on the surface SWC. Homyak et al. (2017) found that precipitation reduction decreased the extractable NH_4^+ but NO_3^- was not affected, potentially due to the increase in the microbial mortality and decline in plant uptake of NH_4^+, and decline in the production and consumption of NO_3^- [19]. In contrast, Deng et al. (2021) found that both NH_4^+ and NO_3^- concentrations increased with drought in forest ecosystems, potentially due to the decreased uptake of N by plants and reduced NO_3^- leaching as a result of the reductions in saturation [20]. The increase in the concentrations of extractable nitrogen from 2020 to 2021 may have been due to the mechanisms proposed by Deng et al. (2021) including an increase in the extractable nitrogen due to the decreased plant uptake and decreased leaching.

Our experiment differed from past throughfall reduction studies due to the combination with snow removal and the inclusion of a drainage class gradient. There may have been offsetting the effects of throughfall reduction and snow removal on extractable N, since snow removal increased frost depth, which may have increased the microbial and fine root mortality, as shown in other studies [8,11,17,34]. Still, the lack of treatment effect in this study was most likely due to the insignificant effect of throughfall reduction on the SWC of the surface horizons. However, even if there were offsetting effects of the treatment components, the lack of biogeochemical responses are a valid representation of the future response of C and N dynamics to reduced precipitation in both the winter and summer.

There were some small and inconsistent effects of drainage class on the soil extractable N concentrations. Even though transformations of N via microbes are dependent on soil moisture and the drainage class clearly influenced SWC (Figure 1), the absolute differences in SWC were apparently insufficient to influence the extractable N concentrations. In aerobic mineral soils, concentrations of NH_4^+ typically increase with increasing soil moisture, but mineralization is limited at high moisture levels due to anoxic conditions and at extremely low moisture conditions due to reduced substrate supply and enzyme activity [35]. Under favorable conditions (warm and moderate water content), nitrification may occur quickly and thus shift the mineral N balance toward NO_3^- dominance [35]. In this study, NH_4^+ concentrations were expected to increase from WD to PD since the SWC increased from WD to PD, assuming that a high limiting SWC was not reached in PD. Since soil temperatures and water contents are low and moderate for a large portion of the year, respectively, one could also expect $NO_3^- + NO_2^-$ to be a smaller component of the mineral N balance due to less ideal conditions for rapid nitrification (Table 1) [35]. This pattern was not observed in the field, but NH_4^+ was a larger component of the mineral N balance compared to $NO_3^- + NO_2^-$-N. Typically, the SPD class had the highest concentrations of TN, NH_4^+, and $NO_3^- + NO_2^-$-N, and the lowest concentrations were observed in WD. This pattern may have been due to the optimal moisture content for microbial activity in SPD, but moisture may have been limiting in PD (too wet) and WD (too dry). Although the effect of drainage class was not clear, the use of a drainage class gradient in a throughfall reduction and snow removal study has not been implemented in prior studies, and thus our findings provide insight in the context of the experimental design and C and N dynamics across varying moisture conditions in a forested landscape.

5. Conclusions

Overall, our results indicate that the response of soil respiration and N dynamics under reduced precipitation scenarios is complex, but may not be greatly affected by the combination of reduced snow cover and throughfall over the range of conditions that was observed in our study. The additional effects of climate change such as concurrent warming may alter the response of C and N dynamics as observed here, and merit further study under reduced precipitation scenarios across drainage classes in forest ecosystems as well as in combination with warming. Understanding these processes is crucial when predicting the future of forest biogeochemical cycling and productivity under a changing climate.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/f13081194/s1, Figure S1: 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); Figure S2: 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); Figure S3: Mean weekly soil temperature during the winters of 2018/19, 2019/20, and 2020/21 across drainage class, treatment, depth, and week; Figure S4: Mean weekly soil water content during the growing seasons of 2019, 2020, and 2021 by drainage class, treat-ment, and depth; Figure S5: Soil respiration during 2021 across time and drainage classes. Let-ters indicate significant differences (p-value < 0.05); Figure S6: Least square mean values of ex-tractable ammonium across drainage classes for 2021. Letters indicate significant differences between drainage classes (p-value < 0.05). Error bars represent 95% confidence intervals; Table S1: Mean percentages of pre-treatment carbon and nitrogen by site and drainage class; Table S2: Four-way ANOVA summary for soil water content models for the growing seasons of 2020 and 2021. Model coefficient p-values are shown. Bolded values indicate a significant result (p-value < 0.05); Table S3: Four-way ANOVA summary for soil temperature models for the growing sea-sons of 2020 and 2021. Model coefficient p-values are shown. Bolded values indicate a significant result (p-value < 0.05); Table S4: Three-way ANOVA results summary for the field bulk soil res-piration model. Numerator degrees of freedom and model coefficient p-values are shown. Bolded values indicate a significant result (p-value < 0.05); Table S5: Mean soil respiration, total nitrogen, ammonium, and nitrate/nitrite for summers of 2020 and 2021. Superscript letters indi-cate significant differences between means within a given year. Level of significance (alpha) is 0.05. Confidence intervals are 95% confidence; Table S6: Three-way ANOVA results for total ni-trogen, ammonium, and nitrate/nitrite models. Pre-treatment nitrogen and percent clay were included as covariates in the models. Bolded values indicate a significant result (p-value < 0.05); Table S7: Two-way ANOVA summaries of mixed models of species richness and Shannon's Di-versity Index for 2021 vegetation community surveys. Site was included as a random variable in the models. Numerator degrees of freedom are shown. Bolded values denote significant result (p-value < 0.05); Table S8: Species richness (number of species) for all plots by location; Table S9: Shannon's Diversity Index for all plots by location; Table S10: Four-way ANOVA results for carbon dioxide model. Numerator degrees of freedom and model coefficient p-values are shown. Bolded values indicate a significant result (p-value < 0.05).

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References

1. Bernal, S.; Hedin, L.O.; Likens, G.E.; Gerber, S.; Buso, D.C. Complex Response of the Forest Nitrogen Cycle to Climate Change. *Proc. Natl. Acad. Sci. USA* **2012**, *109*, 3406–3411. [CrossRef] [PubMed]
2. Schlesinger, W.H.; Andrews, J.A. Soil Respiration and the Global Carbon Cycle. *Biogeochemistry* **2000**, *48*, 7–20. [CrossRef]
3. Wei, W.; Weile, C.; Shaopeng, W. Forest Soil Respiration and Its Heterotrophic and Autotrophic Components: Global Patterns and Responses to Temperature and Precipitation. *Soil Biol. Biochem.* **2010**, *42*, 1236–1244. [CrossRef]
4. Högberg, P.; Read, D.J. Towards a More Plant Physiological Perspective on Soil Ecology. *Trends Ecol. Evol.* **2006**, *21*, 548–554. [CrossRef] [PubMed]
5. Rennenberg, H.; Dannenmann, M.; Gessler, A.; Kreuzwieser, J.; Simon, J.; Papen, H. Nitrogen Balance in Forest Soils: Nutritional Limitation of Plants under Climate Change Stresses. *Plant Biol.* **2009**, *11*, 4–23. [CrossRef] [PubMed]
6. Haaf, D.; Six, J.; Doetterl, S. Global Patterns of Geo-Ecological Controls on the Response of Soil Respiration to Warming. *Nat. Clim. Chang.* **2021**, *11*, 623–627. [CrossRef]
7. Knoepp, J.D.; Swank, W.T. Using Soil Temperature and Moisture to Predict Forest Soil Nitrogen Mineralization. *Biol. Fertil. Soils* **2002**, *36*, 177–182. [CrossRef]
8. Monson, R.K.; Lipson, D.L.; Burns, S.P.; Turnipseed, A.A.; Delany, A.C.; Williams, M.W.; Schmidt, S.K. Winter Forest Soil Respiration Controlled by Climate and Microbial Community Composition. *Nature* **2006**, *439*, 711–714. [CrossRef] [PubMed]
9. Schindlbacher, A.; Wunderlich, S.; Borken, W.; Kitzler, B.; Zechmeister-Boltenstern, S.; Jandl, R. Soil Respiration under Climate Change: Prolonged Summer Drought Offsets Soil Warming Effects. *Glob. Chang. Biol.* **2012**, *18*, 2270–2279. [CrossRef]
10. Borken, W.; Savage, K.; Davidson, E.A.; Trumbore, S.E. Effects of Experimental Drought on Soil Respiration and Radiocarbon Efflux from a Temperate Forest Soil. *Glob. Chang. Biol.* **2006**, *12*, 177–193. [CrossRef]
11. Muhr, J.; Borken, W.; Matzner, E. Effects of Soil Frost on Soil Respiration and Its Radiocarbon Signature in a Norway Spruce Forest Soil. *Glob. Chang. Biol.* **2009**, *15*, 782–793. [CrossRef]
12. Handler, S.; Duveneck, M.J.; Iverson, L.; Peters, E.; Scheller, R.M.; Wythers, K.R.; Brandt, L.; Butler, P.; Janowiak, M.; Shannon, P.D.; et al. Minnesota Forest Ecosystem Vulnerability Assessment and Synthesis: A Report from the Northwoods Climate Change Response Framework Project. In *Gen. Tech. Rep. NRS-133. Newtown Square, PA.*; U.S. Department of Agriculture, Forest Service, Northern Research Station: Madison, WI, USA, 2014; 228p. [CrossRef]
13. Collins, M.; Knutti, R.; Arblaster, J.; Dufresne, J.-L.; Fichefet, T.; Gao, X.; Gutowski, W.J., Jr.; Johns, T.; Krinner, G.; Shongwe, M.; et al. Long-Term Climate Change: Projections, Commitments and Irreversibility. In *Climate Change 2013—The*

Physical Science Basis: Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change; Cambridge University Press: Cambridge, UK, 2013; 108p.
14. Campbell, J.L.; Ollinger, S.V.; Flerchinger, G.N.; Wicklein, H.; Hayhoe, K.; Bailey, A.S. Past and Projected Future Changes in Snowpack and Soil Frost at the Hubbard Brook Experimental Forest, New Hampshire, USA. *Hydrol. Process.* **2010**, *24*, 2465–2480. [CrossRef]
15. Hardy, J.P.; Groffman, P.M.; Fitzhugh, R.D.; Henry, K.S.; Welman, A.T.; Demers, J.D.; Fahey, T.J.; Driscoll, C.T.; Tierney, G.L.; Nolan, S. Snow Depth Manipulation and Its Influence on Soil Frost and Water Dynamics in a Northern Hardwood Forest. *Biogeochemistry* **2001**, *56*, 151–174. [CrossRef]
16. Öquist, M.G.; Laudon, H. Winter Soil Frost Conditions in Boreal Forests Control Growing Season Soil CO2 Concentration and Its Atmospheric Exchange. *Glob. Chang. Biol.* **2008**, *14*, 2839–2847. [CrossRef]
17. Fitzhugh, R.D.; Driscoll, C.T.; Groffman, P.M.; Tierney, G.L.; Fahey, T.J.; Hardy, J.P. Effects of Soil Freezing Disturbance on Soil Solution Nitrogen, Phosphorus, and Carbon Chemistry in a Northern Hardwood Ecosystem. *Biogeochemistry* **2001**, *56*, 215–238. [CrossRef]
18. Mitchell, M.J.; Driscoll, C.T.; Kahl, J.S.; Murdoch, P.S.; Pardo, L.H. Climatic Control of Nitrate Loss from Forested Watersheds in the Northeast United States. *Environ. Sci. Technol.* **1996**, *30*, 2609–2612. [CrossRef]
19. Homyak, P.M.; Allison, S.D.; Huxman, T.E.; Goulden, M.L.; Treseder, K.K. Effects of Drought Manipulation on Soil Nitrogen Cycling: A Meta-Analysis. *J. Geophys. Res. Biogeosci.* **2017**, *122*, 3260–3272. [CrossRef]
20. Deng, L.; Peng, C.; Kim, D.-G.; Li, J.; Liu, Y.; Hai, X.; Liu, Q.; Huang, C.; Shangguan, Z.; Kuzyakov, Y. Drought Effects on Soil Carbon and Nitrogen Dynamics in Global Natural Ecosystems. *Earth Sci. Rev.* **2021**, *214*, 103501. [CrossRef]
21. Veneman, P.L.M.; Spokas, L.A.; Lindbo, D.L. Soil Moisture and Redoximorphic Features: A Historical Perspective. In *Quantifying Soil Hydromorphology*; John Wiley & Sons, Ltd.: Hoboken, NJ, USA, 1998; pp. 1–23. [CrossRef]
22. Briggs, R.D.; Lemin, R.C., Jr. Soil Drainage Class Effects on Early Response of Balsam Fir to Precommercial Thinning. *Soil Sci. Soc. Am. J.* **1994**, *58*, 1231–1239. [CrossRef]
23. Davidson, E.A.; Belk, E.; Boone, R.D. Soil Water Content and Temperature as Independent or Confounded Factors Controlling Soil Respiration in a Temperate Mixed Hardwood Forest. *Glob. Chang. Biol.* **1998**, *4*, 217–227. [CrossRef]
24. Friesen, H.C.; Slesak, R.A.; Karwan, D.L.; Kolka, R.K. Effects of Snow and Climate on Soil Temperature and Frost Development in Forested Peatlands in Minnesota, USA. *Geoderma* **2021**, *394*, 115015. [CrossRef]
25. Ditzler, C.; Scheffe, K.; Monger, H.C. (Eds.) Soil Science Division Staff. In *Soil Survey Manual*; USDA Handbook 18; Government Printing Office: Washington, DC, USA, 2017.
26. Yahdjian, L.; Sala, O.E. A Rainout Shelter Design for Intercepting Different Amounts of Rainfall. *Oecologia* **2002**, *133*, 95–101. [CrossRef] [PubMed]
27. Pinheiro, J.; Bates, D.; DebRoy, S.; Sarkar, D.; R Core Team. *nlme: Linear and Nonlinear Mixed Effects Models*; R Package Version 3.1-153; R Foundation for Statistical Computing: Vienna, Austria, 2021; Available online: https://CRAN.R-project.org/package=nlme (accessed on 1 September 2020).
28. Lenth, R.V. *Emmeans: Estimated Marginal Means, AKA Least-Squares Means*; R Package Version 1.5.4; R Foundation for Statistical Computing: Vienna, Austria, 2021; Available online: https://CRAN.R-project.org/package=emmeans (accessed on 1 September 2020).
29. Beier, C.; Beierkuhnlein, C.; Wohlgemuth, T.; Penuelas, J.; Emmett, B.; Körner, C.; de Boeck, H.; Christensen, J.H.; Leuzinger, S.; Janssens, I.A.; et al. Precipitation Manipulation Experiments—Challenges and Recommendations for the Future. *Ecol. Lett.* **2012**, *15*, 899–911. [CrossRef]
30. Fay, P.A.; Carlisle, J.D.; Knapp, A.K.; Blair, J.M.; Collins, S.L. Altering Rainfall Timing and Quantity in a Mesic Grassland Ecosystem: Design and Performance of Rainfall Manipulation Shelters. *Ecosystems* **2000**, *3*, 308–319. [CrossRef]
31. Barba, J.; Curiel Yuste, J.; Poyatos, R.; Janssens, I.A.; Lloret, F. Strong Resilience of Soil Respiration Components to Drought-Induced Die-off Resulting in Forest Secondary Succession. *Oecologia* **2016**, *182*, 27–41. [CrossRef]
32. Schlesinger, W.H.; Dietze, M.C.; Jackson, R.B.; Phillips, R.P.; Rhoades, C.C.; Rustad, L.E.; Vose, J.M. Forest Biogeochemistry in Response to Drought. *Glob. Chang. Biol.* **2016**, *22*, 2318–2328. [CrossRef]
33. Borken, W.; Matzner, E. Reappraisal of Drying and Wetting Effects on C and N Mineralization and Fluxes in Soils. *Glob. Chang. Biol.* **2009**, *15*, 808–824. [CrossRef]
34. Groffman, P.M.; Driscoll, C.T.; Fahey, T.J.; Hardy, J.P.; Fitzhugh, R.D.; Tierney, G.L. Effects of Mild Winter Freezing on Soil Nitrogen and Carbon Dynamics in a Northern Hardwood Forest. *Biogeochemistry* **2001**, *56*, 191–213. [CrossRef]
35. Porporato, A.; D'Odorico, P.; Laio, F.; Rodriguez-Iturbe, I. Hydrologic Controls on Soil Carbon and Nitrogen Cycles. I. Modeling Scheme. *Adv. Water Resour.* **2003**, *26*, 45–58. [CrossRef]

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 non-frozen 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.

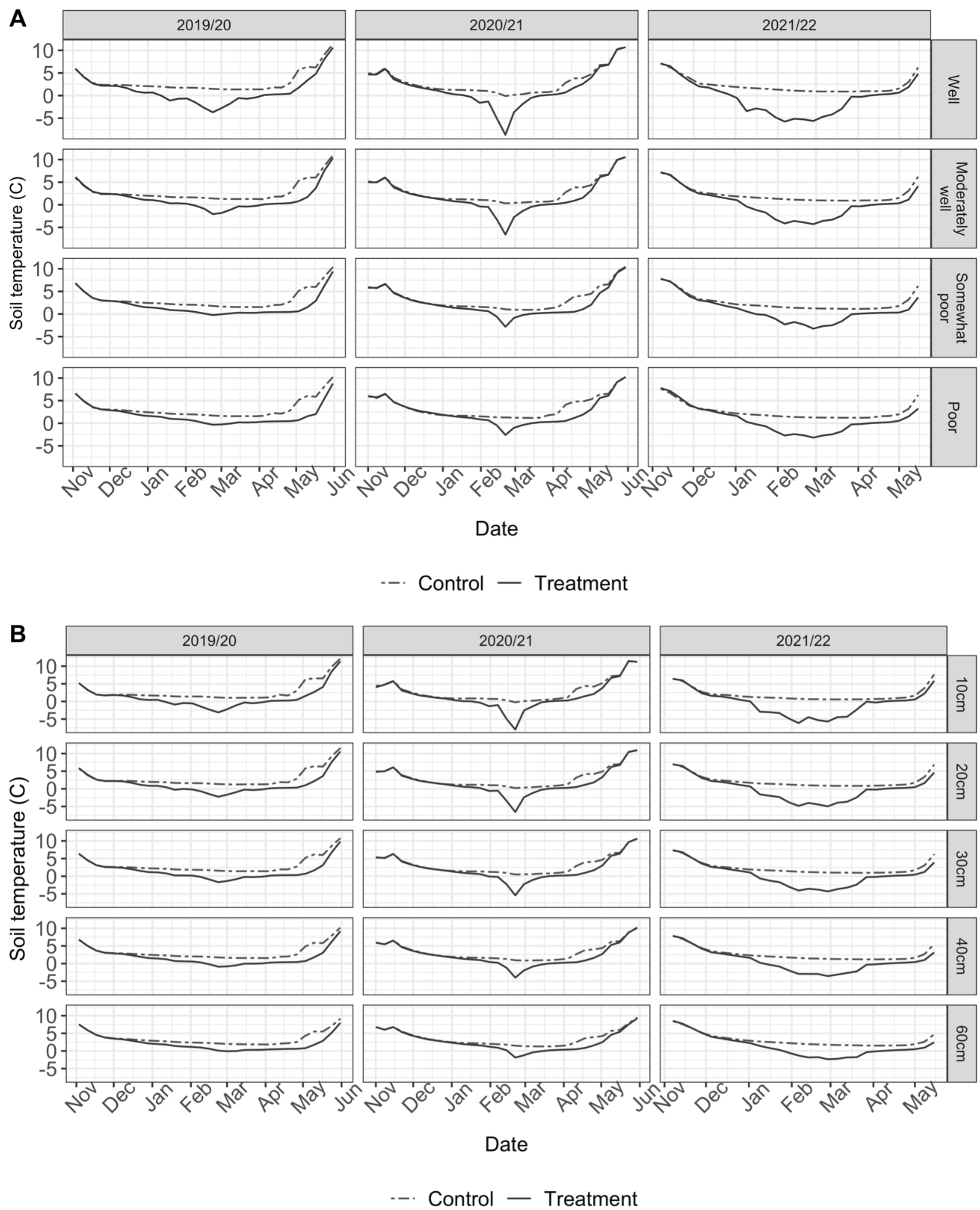

Figure 1: Mean weekly soil temperature by treatment and drainage class (panel A) and mean weekly soil temperature by treatment and depth (panel B) during the three winters of the study.

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, $p < 0.001$).

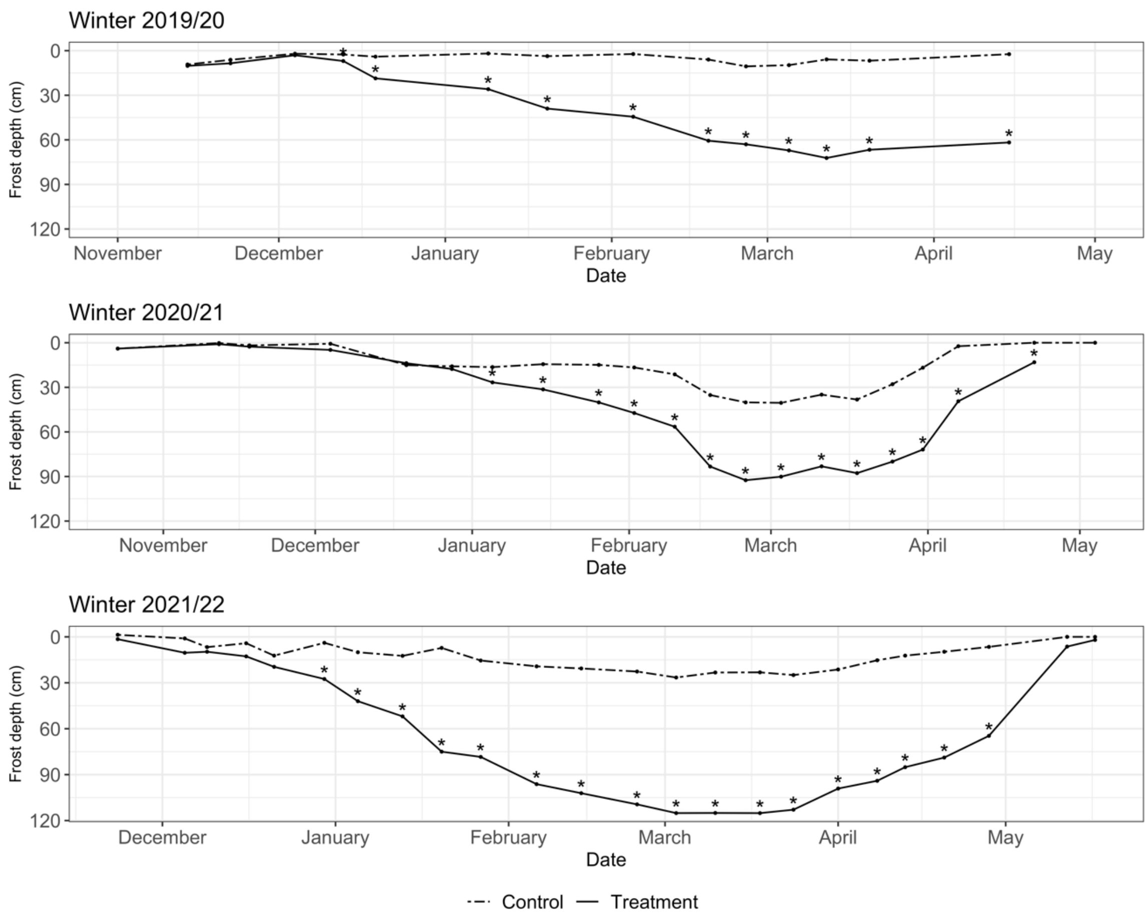

Figure 2: Least square means of soil frost depth during the winters of 2019/20, 2020/21, and 2021/22 for the significant interaction between treatment and date. Asterisks indicate time periods where there was a significant difference in soil frost depth between treatments.

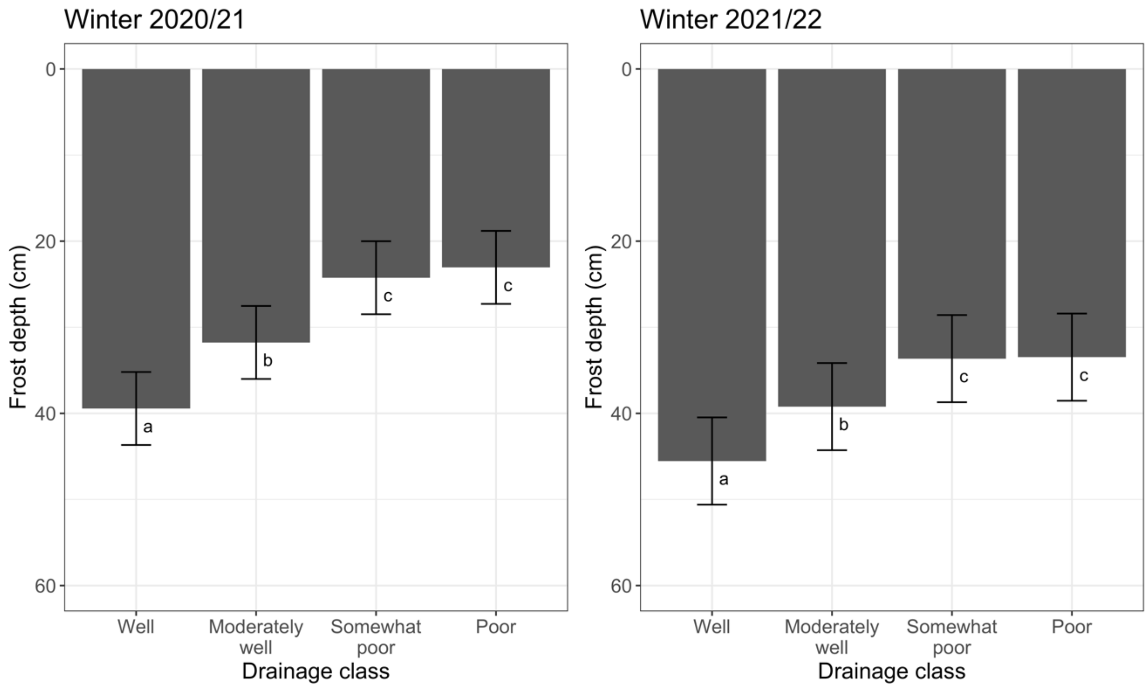

Figure 3: Least square mean frost depth by drainage class during the winters of 2020/21 and 2021/22. Bars with different letters indicate significant differences between means (p-value < 0.05). Error bars represent standard error.

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.

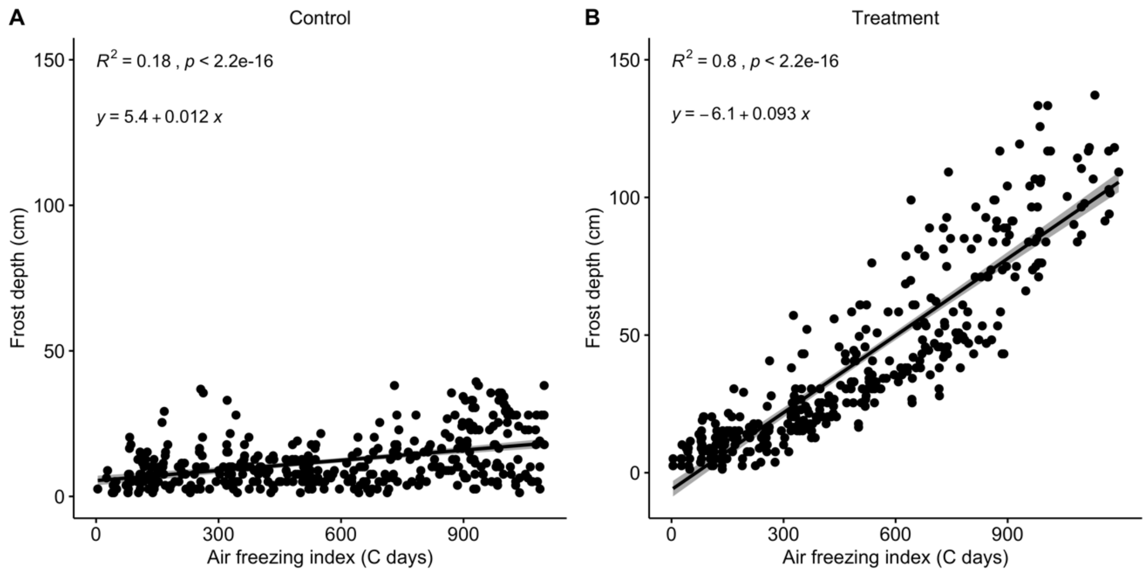

Figure 4: Linear regressions between Air Freezing Index and frost depth in control (panel A) and treatment (panel B) plots during all three winters of the study. Confidence limits (shading around the line) are 95% confidence intervals.

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.

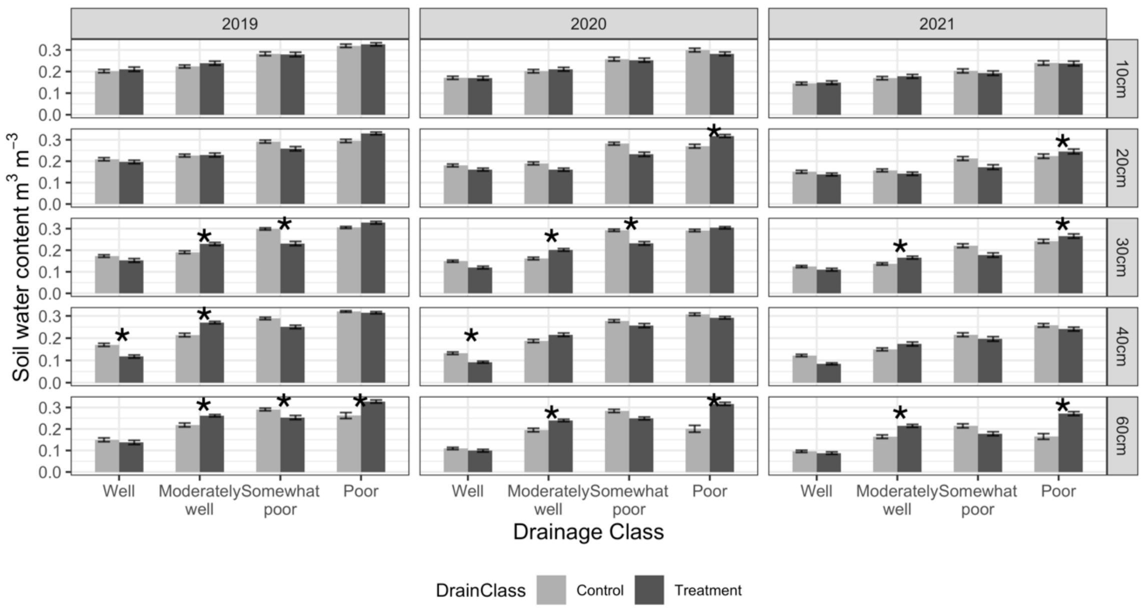

Figure 5: Mean soil water content by treatment, drainage class, and soil depth for the three years of the study. Soil depth in centimeters is shown on the right y-axis. Asterisks indicate significant differences (p-value < 0.05) between control and treatment within a drainage class for a given depth.

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.

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References

Arkhangelskaya, T., & Lukyashchenko, K. (2018). Estimating soil thermal diffusivity at different water contents from easily available data on soil texture, bulk density, and organic carbon content. Biosystems Engineering, 168, 83–95. https://doi.org/10.1016/j.biosystemseng.2017.06.011

Beier, C., Beierkuhnlein, C., Wohlgemuth, T., Penuelas, J., Emmett, B., Körner, C., de Boeck, H., Christensen, J. H., Leuzinger, S., Janssens, I. A., & Hansen, K. (2012). Precipitation manipulation experiments – challenges and recommendations for the future. Ecology Letters, 15(8), 899–911. https://doi.org/10.1111/j.1461-0248.2012.01793.x

Black, W. P. M. (1962). A method of estimating the California Bearing Ratio of cohesive soils from plasticity data. Géotechnique, 12(4), 271–282. https://doi.org/10.1680/geot.1962.12.4.271

Blinn, C. R., O'Hara, T. J., Chura, D. T., & Russell, M. B. (2015). Minnesota's Logging Businesses: An Assessment of the Health and Viability of the Sector. Forest Science, 61(2), 381–387. https://doi.org/10.5849/forsci.14-013

Briggs, R. D., & Lemin, R. C., Jr. (1994). Soil Drainage Class Effects on Early Response of Balsam Fir to Precommercial Thinning. Soil Science Society of America Journal, 58(4), 1231–1239. https://doi.org/10.2136/sssaj1994.03615995005800040034x

Cambi, M., Certini, G., Neri, F., & Marchi, E. (2015). The impact of heavy traffic on forest soils: A review. Forest Ecology and Management, 338, 124–138. https://doi.org/10.1016/j.foreco.2014.11.022

Cleavitt, N. L., Fahey, T. J., Groffman, P. M., Hardy, J. P., Henry, K. S., & Driscoll, C. T. (2008). Effects of soil freezing on fine roots in a northern hardwood forest. Canadian Journal of Forest Research, 38(1), 82–91. https://doi.org/10.1139/X07-133

Curzon, M. T., Slesak, R. A., Palik, B. J., & Schwager, J. K. (2022). Harvest impacts to stand development and soil properties across soil textures: 25-year response of the aspen Lake States LTSP installations. *Forest Ecology and Management*, *504*, 119809. https://doi.org/10.1016/j.foreco.2021.119809

Decker, K. L. M., Wang, D., Waite, C., & Scherbatskoy, T. (2003). Snow Removal and Ambient Air Temperature Effects on Forest Soil Temperatures in Northern Vermont. Soil Science Society of America Journal, 67(4), 1234–1242. https://doi.org/10.2136/sssaj2003.1234

Division of Forestry. (2021). Minnesota's forest resources 2018. St. Paul, MN: Minnesota Department of Natural Resources. Retrieved from https://files.dnr.state.mn.us/forestry/um/forest-resources-report-2018.pdfDomke, G. M., Ek, A. R., Kilgore, M. A., & David, A. J. (2008). Aspen in the Lake States: A research review. Nat Counc Paper Ind Air Stream Impr Inc, Tech Bull 39, 1–46.

Erlingsson, S., & Saliko, D. (2020). Correlating Air Freezing Index and Frost Penetration Depth—A Case Study for Sweden. In C. Raab (Ed.), *Proceedings of the 9th International Conference on Maintenance and Rehabilitation of*

Pavements—Mairepav9 (pp. 847–857). Springer International Publishing. https://doi.org/10.1007/978-3-030-48679-2_79
Fay, P. A., Carlisle, J. D., Knapp, A. K., Blair, J. M., & Collins, S. L. (2000). Altering Rainfall Timing and Quantity in a Mesic Grassland Ecosystem: Design and Performance of Rainfall Manipulation Shelters. Ecosystems, 3(3), 308–319. https://doi.org/10.1007/s100210000028
Friesen, H. C., Slesak, R. A., Karwan, D. L., & Kolka, R. K. (2021). Effects of snow and climate on soil temperature and frost development in forested peatlands in Minnesota, USA. Geoderma, 394. https://doi.org/10.1016/j.geoderma.2021.115015
Greacen, E., & Sands, R. (1980). Compaction of forest soils. A review. Soil Research, 18(2), 163. https://doi.org/10.1071/SR9800163
Grigal, D. F. (2000). Effects of extensive forest management on soil productivity. Forest Ecology and Management, 138(1), 167–185. https://doi.org/10.1016/S0378-1127(00)00395-9
Grolemund, G., Wickham, H (2011). “Dates and Times Made Easy with lubridate.” Journal of Statistical Software, 40(3), 1–25. https://www.jstatsoft.org/v40/i03/.
Handler, S., Duveneck, M. J., Iverson, L., Peters, E., Scheller, R. M., Wythers, K. R., Brandt, L., Butler, P., Janowiak, M., Shannon, P. D., Swanston, C., Barrett, K., Kolka, R., McQuiston, C., Palik, B., Reich, P. B., Turner, C., White, M., Adams, C., … Ziel, R. (2014). Minnesota forest ecosystem vulnerability assessment and synthesis: A report from the Northwoods Climate Change Response Framework project. Gen. Tech. Rep. NRS-133. Newtown Square, PA; U.S. Department of Agriculture, Forest Service, Northern Research Station. 228 p., 133, 1–228. https://doi.org/10.2737/NRS-GTR-133
Hardy, J. P., Groffman, P. M., Fitzhugh, R. D., Henry, K. S., Welman, A. T., Demers, J. D., Fahey, T. J., Driscoll, C. T., Tierney, G. L., & Nolan, S. (2001). Snow depth manipulation and its influence on soil frost and water dynamics in a northern hardwood forest. Biogeochemistry, 56(2), 151–174. https://doi.org/10.1023/A:1013036803050
Henninger, D. L., Petersen, G. W., & Engman, E. T. (1976). Surface Soil Moisture within a Watershed—Variations, Factors Influencing, and Relationship to Surface Runoff. Soil Science Society of America Journal, 40(5), 773–776. https://doi.org/10.2136/sssaj1976.03615995004000050041x
Herrick, J. E., & Jones, T. L. (2002). A dynamic cone penetrometer for measuring soil penetration resistance. Soil Science Society of America Journal, 66(4), 1320–1324. https://doi.org/10.2136/sssaj2002.1320
Hoover, D. L., Wilcox, K. R., & Young, K. E. (2018). Experimental droughts with rainout shelters: A methodological review. Ecosphere, 9(1), e02088. https://doi.org/10.1002/ecs2.2088
Horn, R., Vossbrink, J., Peth, S., & Becker, S. (2007). Impact of modern forest vehicles on soil physical properties. Forest Ecology and Management, 248(1–2), 56–63. https://doi.org/10.1016/j.foreco.2007.02.037

Kok, H, McCool, D.K. (1990). Quantifying freeze/thaw-induced variability of soil strength. American Society of Agricultural and Biological Engineers, 33(2), 0501-0506. https://doi.org/10.13031/2013.31357
Kolka, R., Steber, A., Brooks, K., Perry, C. H., & Powers, M. (2012). Relationships between Soil Compaction and Harvest Season, Soil Texture, and Landscape Position for Aspen Forests. Northern Journal of Applied Forestry, 29(1), 21–25. https://doi.org/10.5849/njaf.10-039
Lenth, R.V. (2021). emmeans: Estimated Marginal Means, aka Least-Squares Means. R package version 1.5.4. https://CRAN.R-project.org/package=emmeans
McNabb, D. H., Startsev, A. D., & Nguyen, H. (2001). Soil Wetness and Traffic Level Effects on Bulk Density and Air-Filled Porosity of Compacted Boreal Forest Soils. Soil Science Society of America Journal, 65(4), 1238–1247. https://doi.org/10.2136/sssaj2001.6541238x
Minnesota Department of Transportation (MNDOT). User Guide to the Dynamic Cone Penetrometer. n.d. http://www.dot.state.mn.us/materials/researchdocs/User_Guide.pdf
National Council for Air and Stream Improvement, Inc. (NCASI). (2004). Effects of heavy equipment on physical properties of soils and on long-term productivity: A review of literature and current research. Technical Bulletin No. 887. Research Triangle Park, N.C.: National Council for Air and Stream Improvement, Inc.
Pavelka, M., Acosta, M., Marek, M. V., Kutsch, W., & Janous, D. (2007). Dependence of the Q10 values on the depth of the soil temperature measuring point. Plant and Soil, 292(1), 171–179. https://doi.org/10.1007/s11104-007-9213-9
Pinheiro J, Bates D, DebRoy S, Sarkar D, R Core Team (2021). nlme: Linear and Nonlinear Mixed Effects Models. R package version 3.1-153, https://CRAN.R-project.org/package=nlme.
Powers, R.F., Alban, D.H., Miller, R.E., Tiarks, A.E., Wells, C.G., Avers, P.E., Cline, R.G.,Fitzgerald, R.O., Loftus Jr., N.S. (1990). Sustaining site productivity in North American forests: problems and prospects. In: Gessel, S.P. et al. (Eds.), Sustained Productivity of Forest Soils. Forestry Publications, University of British Columbia, Vancouver, B.C., pp. 49–80
Romero-Saltos, H., Sternberg, L. da S. L., Moreira, M. Z., & Nepstad, D. C. (2005). Rainfall exclusion in an eastern Amazonian forest alters soil water movement and depth of water uptake. American Journal of Botany, 92(3), 443–455. https://doi.org/10.3732/ajb.92.3.443
Selker, J., & Or, D. (2019). Soil Hydrology and Biophysics. Oregon State University. Retrieved March 7, 2022, from https://open.oregonstate.education/soilhydrologyandbiophysics/
Shoop, S. A. (1995). Vehicle bearing capacity of frozen ground over a soft substrate. Canadian Geotechnical Journal. https://doi.org/10.1139/t95-057
Singh, R. K., & Sharma, R. V. (2017). Numerical analysis for ground temperature variation. Geothermal Energy, 5(1), 22. https://doi.org/10.1186/s40517-017-0082-z

Soil Science Division Staff. (2017). Soil survey manual. C. Ditzler, K. Scheffe, and H.C. Monger (eds.). USDA Handbook 18. Government Printing Office, Washington, D.C.

Stone, D. M. (2002). Logging Options to Minimize Soil Disturbance in the Northern Lake States. Northern Journal of Applied Forestry, 19(3), 115–121. https://doi.org/10.1093/njaf/19.3.115

Tan, X., Chang, S. X., & Kabzems, R. (2005). Effects of soil compaction and forest floor removal on soil microbial properties and N transformations in a boreal forest long-term soil productivity study. *Forest Ecology and Management*, *217*(2), 158–170. https://doi.org/10.1016/j.foreco.2005.05.061

Uusitalo, J., Ala-Ilomäki, J., Lindeman, H., Toivio, J., & Siren, M. (2019). Modelling soil moisture – soil strength relationship of fine-grained upland forest soils. Silva Fennica, 53(1). https://doi.org/10.14214/sf.10050

Veneman, P. L. M., Spokas, L. A., & Lindbo, D. L. (1998). Soil Moisture and Redoximorphic Features: A Historical Perspective. In Quantifying Soil Hydromorphology (pp. 1–23). John Wiley & Sons, Ltd. https://doi.org/10.2136/sssaspecpub54.c1

von Wilpert, K., & Schäffer, J. (2006). Ecological effects of soil compaction and initial recovery dynamics: A preliminary study. European Journal of Forest Research, 125(2), 129–138. https://doi.org/10.1007/s10342-005-0108-0

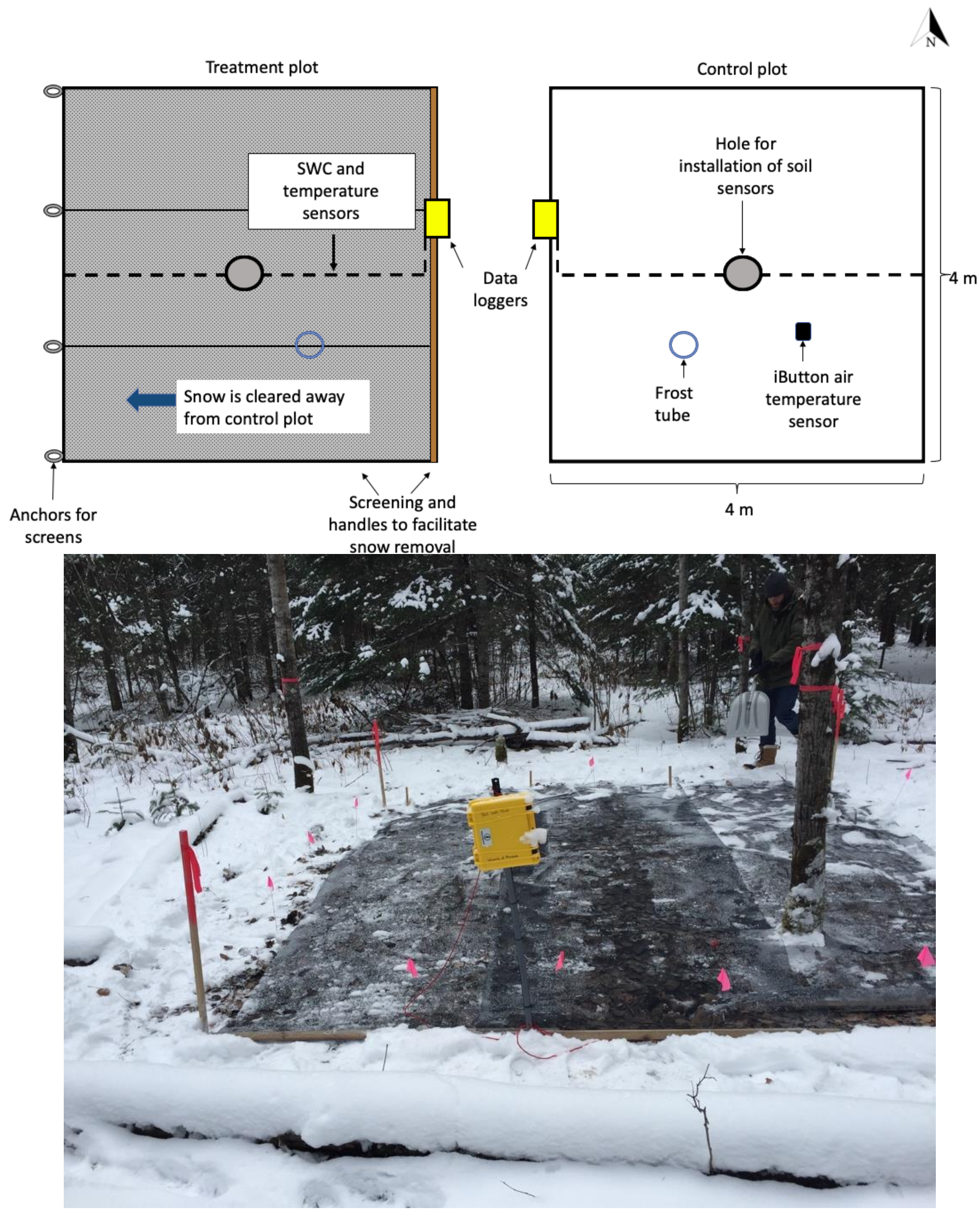
Yahdjian, L., & Sala, O. E. (2002). A rainout shelter design for intercepting different amounts of rainfall. *Oecologia*, *133*(2), 95–101. https://doi.org/10.1007/s00442-002-1024-3

Yang, Y. J., Liu, S. R., Wang, H., Chen, L., Lu, L. H., & Cai, D. X. (2019). Reduction in throughfall reduces soil aggregate stability in two subtropical plantations. European Journal of Soil Science, 70(2), 301–310. https://doi.org/10.1111/ejss.12734

Zhang, T. (2005). Influence of the seasonal snow cover on the ground thermal regime: An overview. Reviews of Geophysics, 43(4). https://doi.org/10.1029/2004RG000157

SUPPLEMENTAL MATERIALS

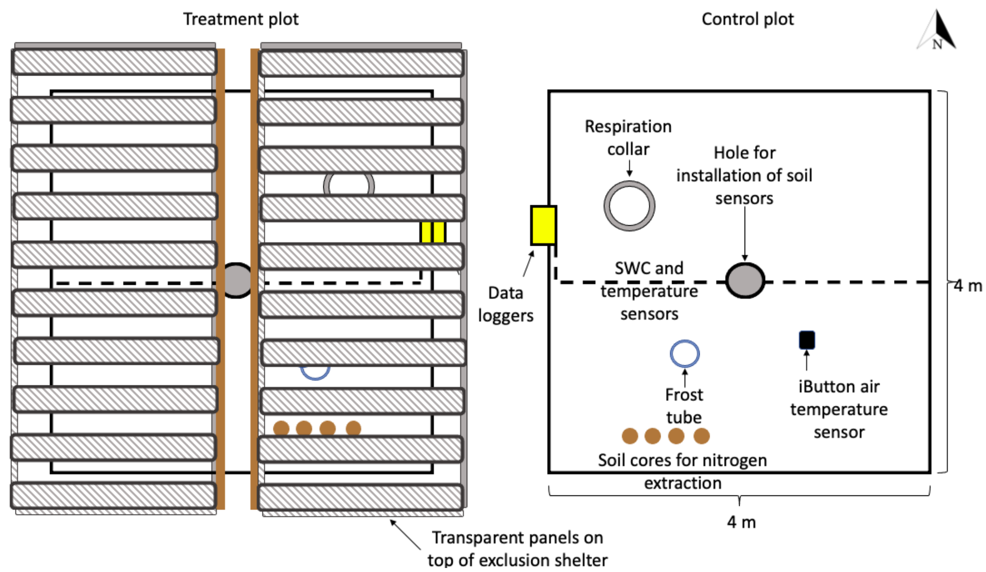
A



B

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		**2019/2020**		**2020/2021**		**2021/2022**	
	2018/11/04 - 2019/05/26		2019/11/03- 2020/05/31		2020/11/01 - 2021/05/31		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

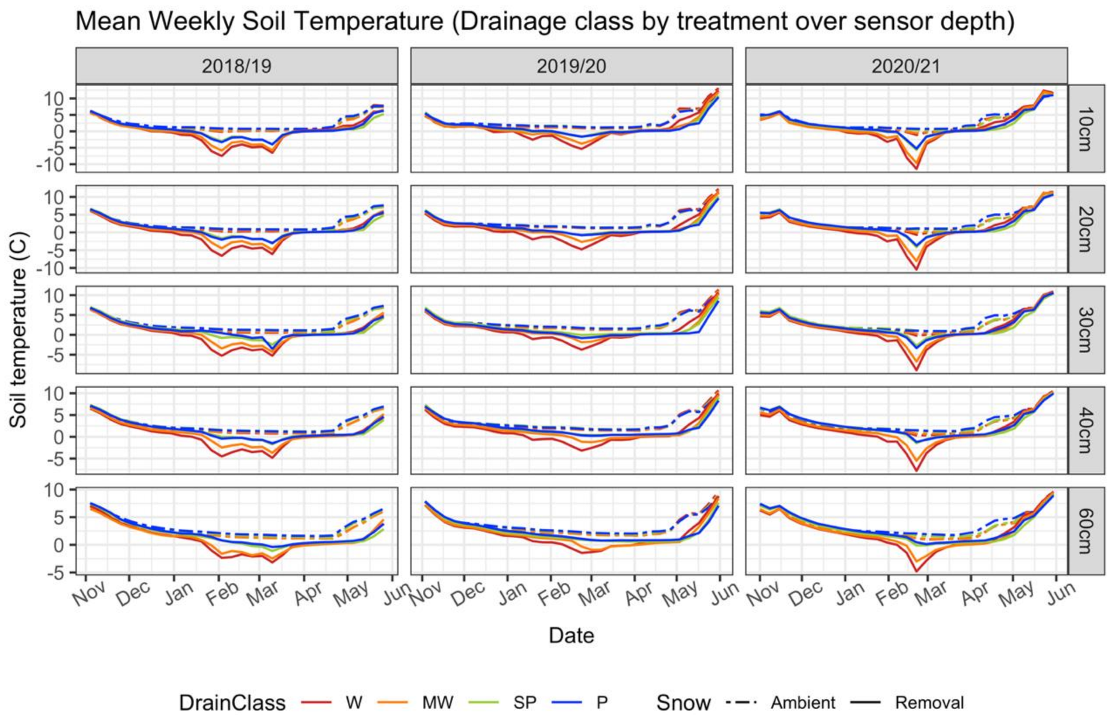


Figure 3: Mean weekly soil temperature during the winters of 2018/19, 2019/20, and 2020/21 across drainage class, treatment, depth, and week.

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

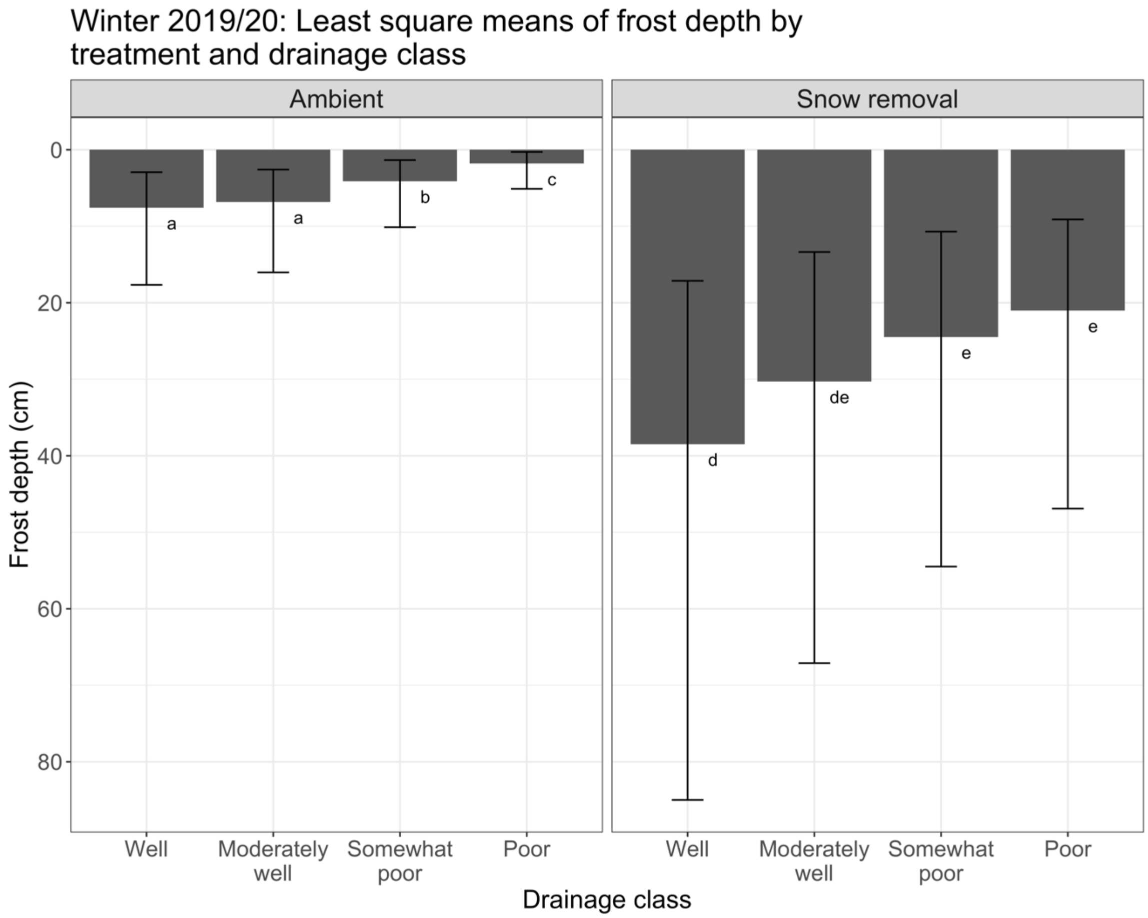


Figure 4: Least square means of frost depth by treatment and drainage class during the winter of 2019/20. Bars with different letters indicate significant differences between the means (p-value < 0.05). Error bars represent 95% confidence intervals.

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

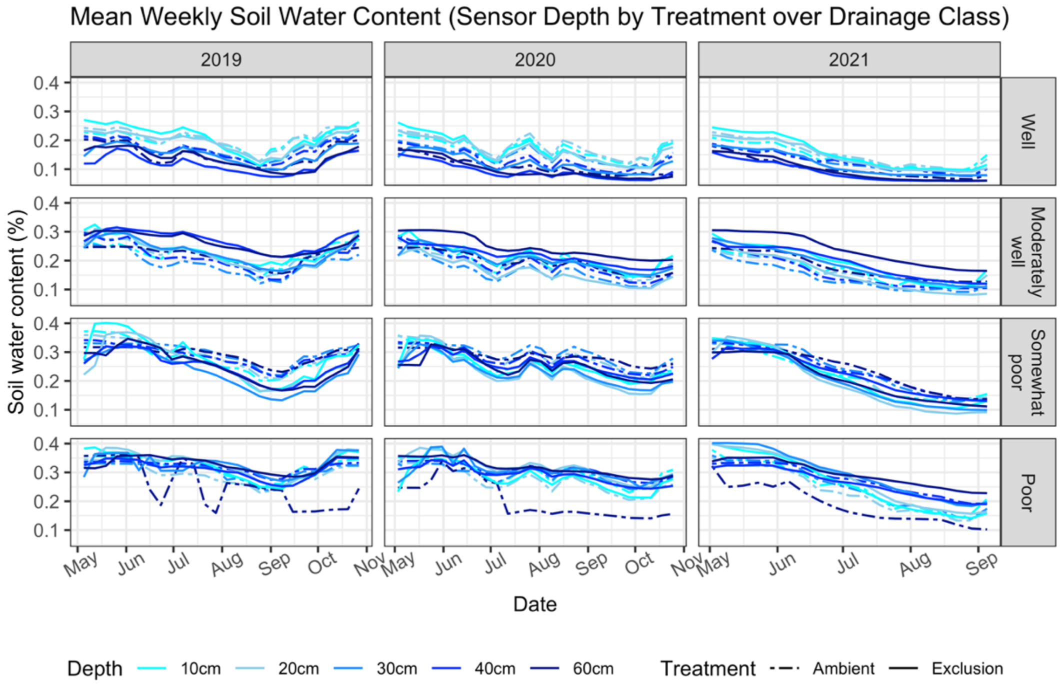


Figure 5: Mean weekly soil water content during the growing seasons of 2019, 2020, and 2021 by drainage class, treatment, and depth.

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

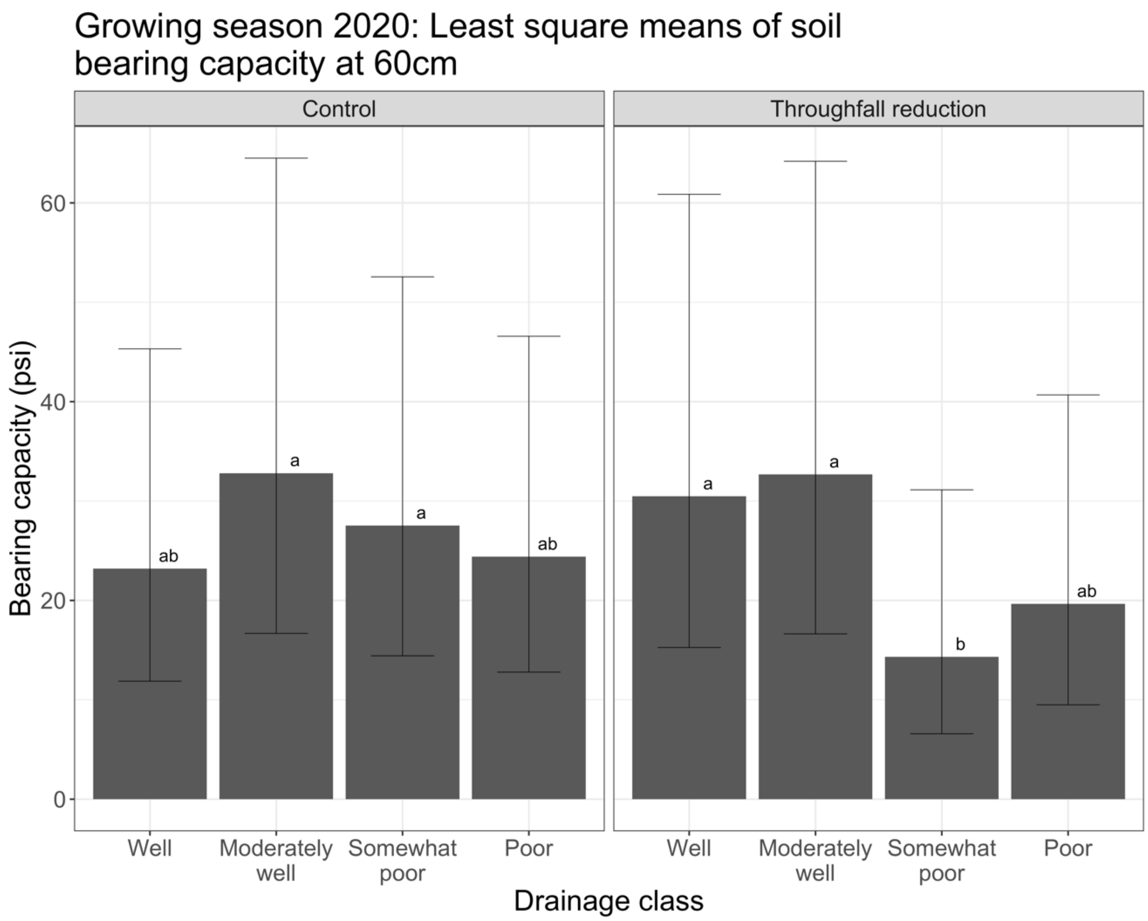


Figure 6: Least square means of soil strength (bearing capacity) across drainage classes and treatments at 60cm. Letters indicate significant differences as a pairwise comparison between drainage class and treatment (p-value < 0.05). Error bars represent 95% confidence intervals.

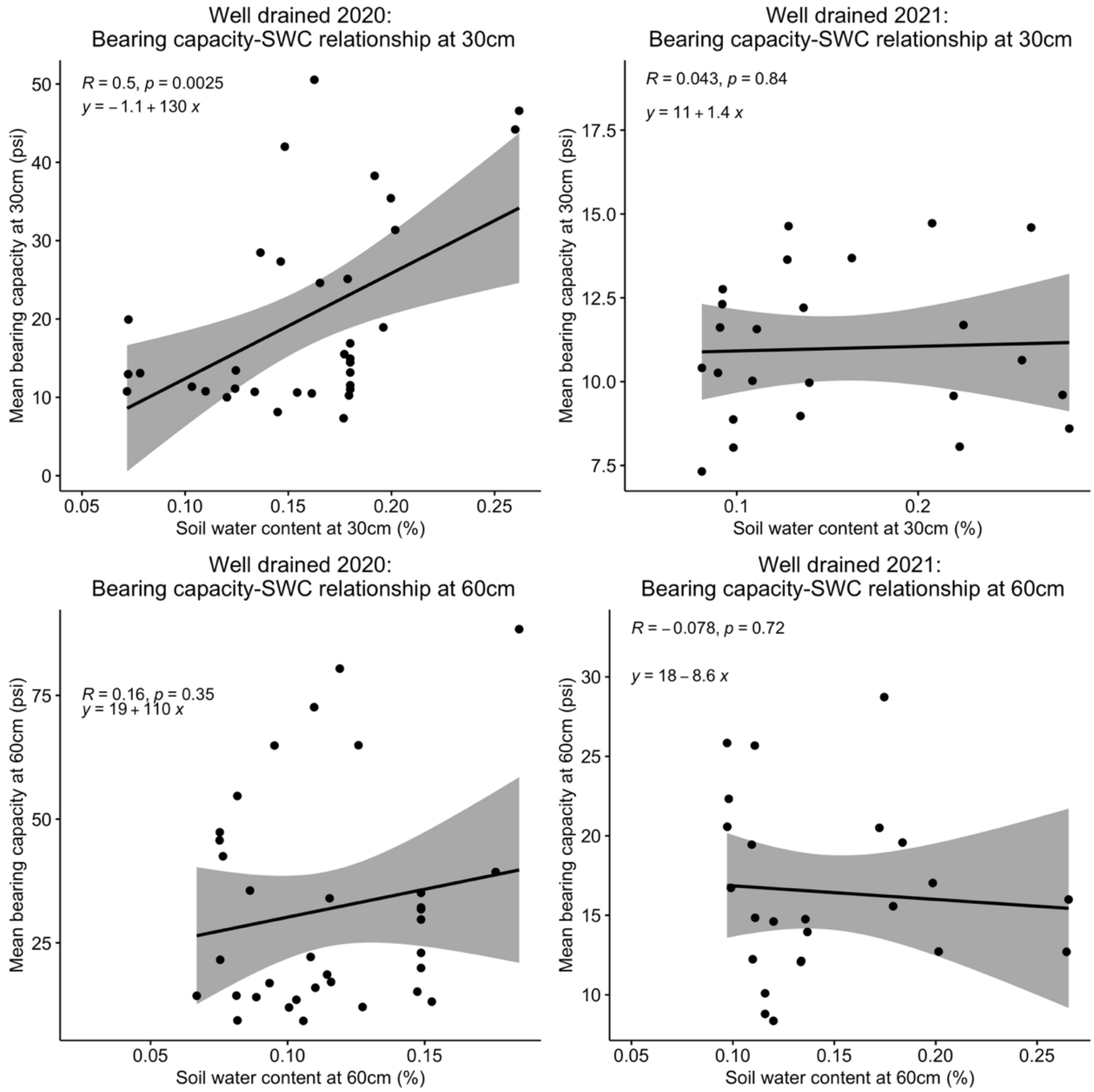


Figure 7. Linear regressions between soil water content and mean bearing capacity for the well-drained class. Confidence intervals are 95% and level of significance is equal to 0.05.

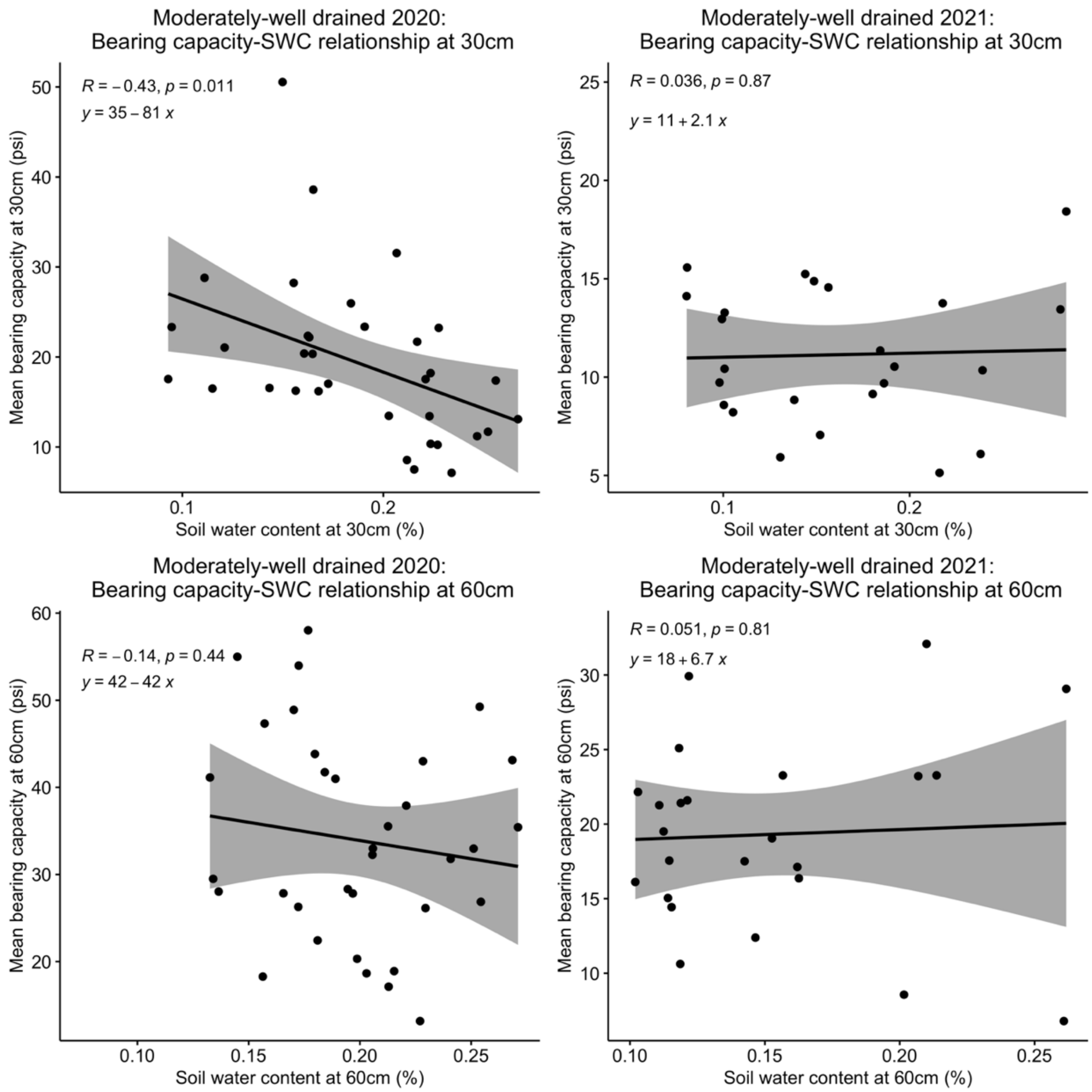


Figure 8: Linear regressions between soil water content and mean bearing capacity for the moderately well-drained class. Confidence intervals are 95% and level of significance is equal to 0.05.

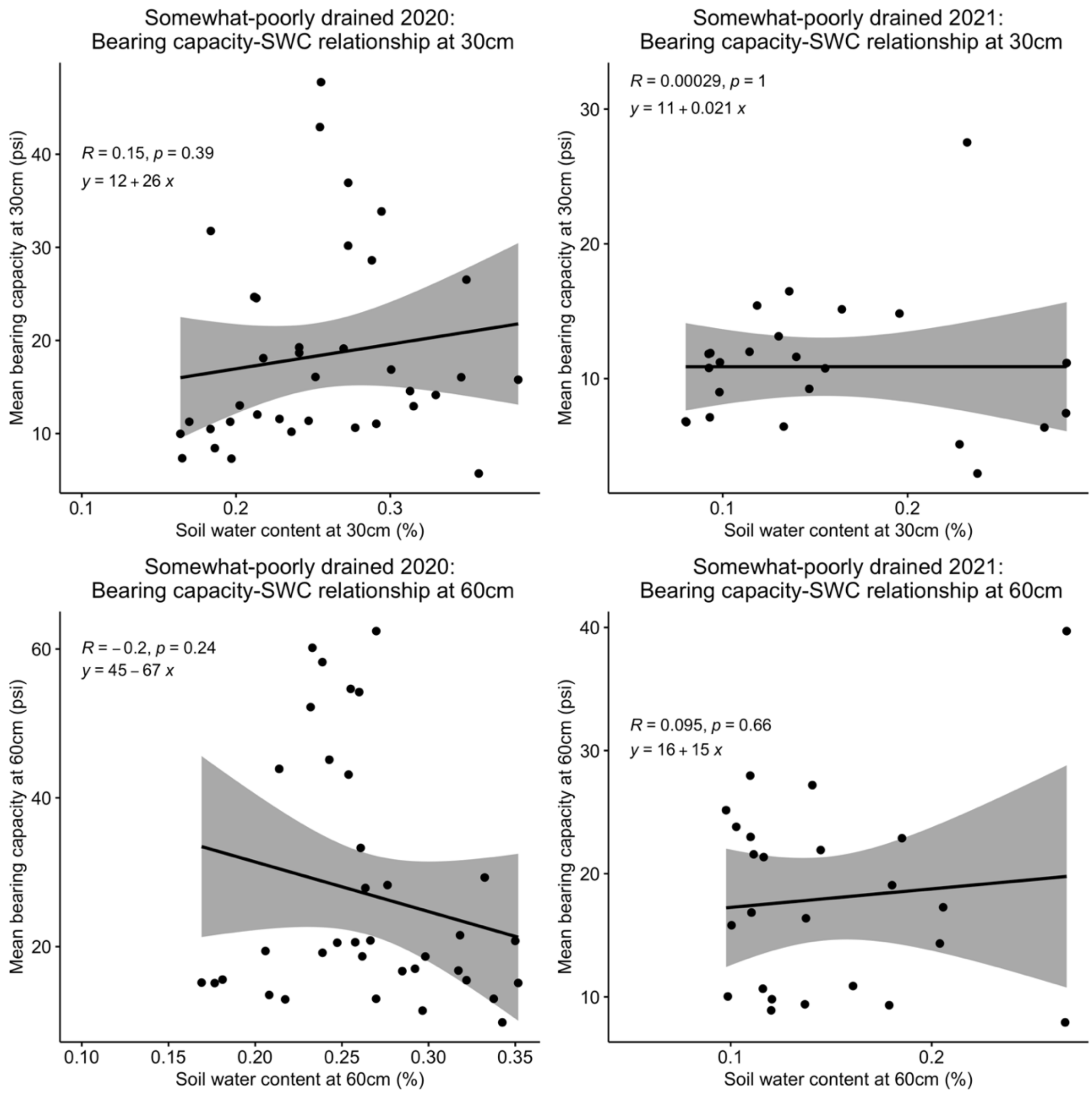


Figure 9: Linear regressions between soil water content and mean bearing capacity for the somewhat poorly-drained class. Confidence intervals are 95% and level of significance is equal to 0.05.

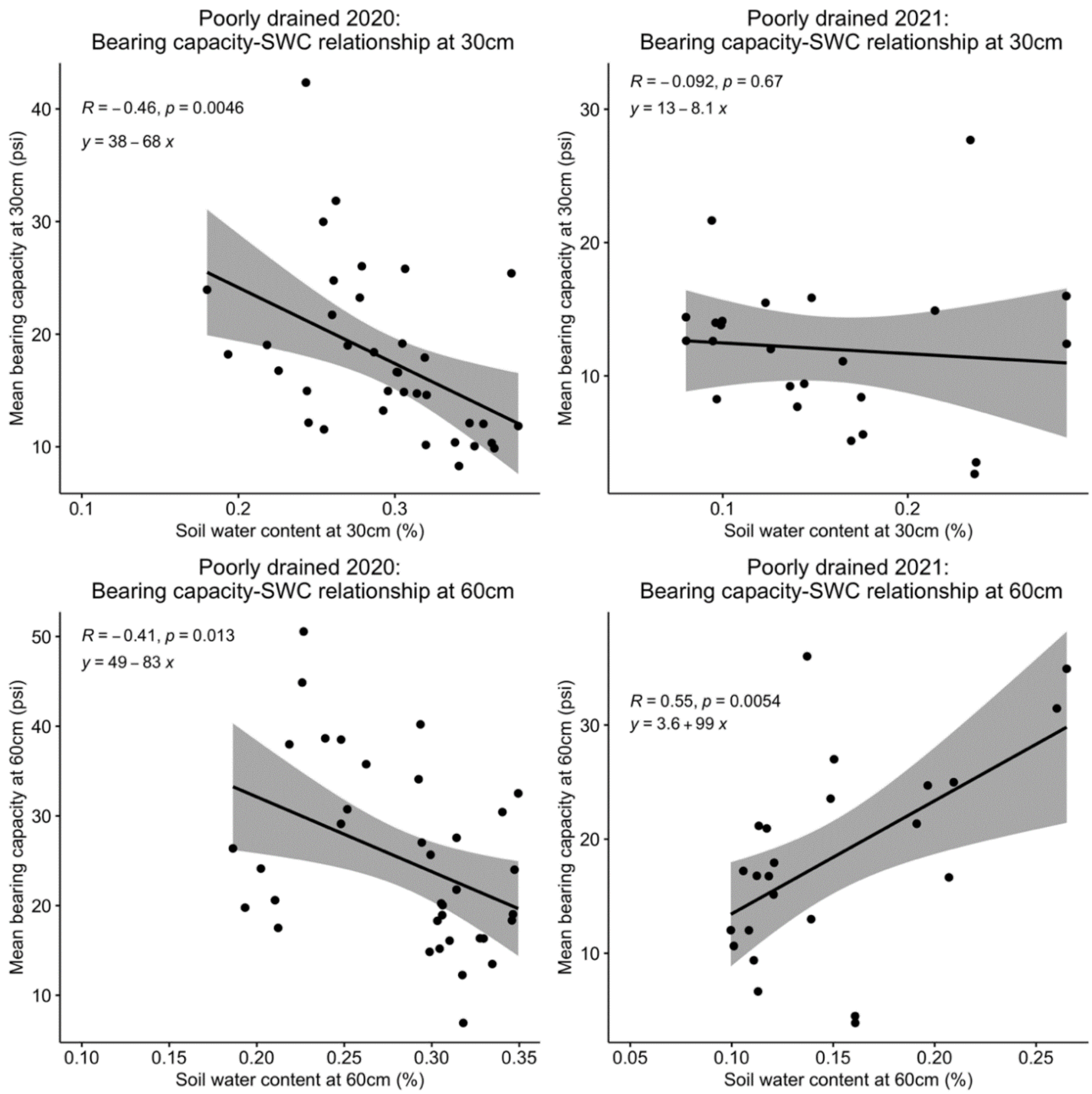


Figure 10: Linear regressions between soil water content and mean bearing capacity for the poorly-drained class. Confidence intervals are 95% and level of significance is equal to 0.05.