Simulating Impacts of Ice Storms on Forest Ecosystems

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Abstract

Ice storms can have profound and lasting effects on the structure and function of forest ecosystems in regions that experience freezing conditions. Current models suggest that the frequency and intensity of ice storms could increase over the coming decades in response to changes in climate, heightening interest in understanding their impacts. Because of the stochastic nature of ice storms and difficulties in predicting when and where they will occur, most past investigations of the ecological effects of ice storms have been based on case studies following major storms. Since intense ice storms are exceedingly rare events it is impractical to study them by waiting for their natural occurrence. Here we present a novel alternative experimental approach, involving the simulation of glaze ice events on forest plots under field conditions. With this method, water is pumped from a stream or lake and sprayed above the forest canopy when air temperatures are below freezing. The water rains down and freezes upon contact with cold surfaces. As the ice accumulates on trees, the boles and branches bend and break; damage that can be quantified through comparisons with untreated reference stands. The experimental approach described is advantageous because it enables control over the timing and amount of ice applied. Creating ice storms of different frequency and intensity makes it possible to identify critical ecological thresholds necessary for predicting and preparing for ice storm impacts.

Introduction

Ice storms are an important natural disturbance that can have both short- and long-term impacts on the environment and society. Intense ice storms are problematic because they damage trees and crops, disrupt utilities, and impair roads and other infrastructure[1,2]. The hazardous conditions that ice storms create can cause accidents resulting in injuries and fatalities[2]. Ice storms are costly; financial losses average $313 million per year in the United States (US)[3], with some individual storms exceeding $1 billion[4]. In forest ecosystems, ice storms can have negative consequences including reduced growth and tree mortality[5,6,7], increased risk of fire, and proliferation of pests and pathogens[8,9,10]. They can also have positive effects on forests, such as enhanced growth of surviving trees[5] and increased biodiversity[11]. Improving our ability to predict impacts from ice storms will enable us to better prepare for and respond to these events.

Ice storms occur when a layer of moist air, that is above freezing, overrides a layer of subfreezing air closer to the ground. Rain falling from the warmer layer of air supercools as it passes through the cold layer, forming glaze ice when deposited on sub-freezing surfaces. In the US, this thermal stratification can result from synoptic weather patterns that are characteristic of specific regions[12,13]. Freezing rain is most commonly caused by Arctic fronts that move southeastward across the US ahead of strong anticyclones[13]. In some regions, topography contributes to the atmospheric conditions necessary for ice storms through cold air damming, a meteorological phenomenon that occurs when warm air from an incoming storm overrides cold air that becomes entrenched alongside a mountain range[14,15].

In the US, ice storms are most common in the "ice belt" that extends from Maine to western Texas[16,17]. Ice storms also occur in a relatively small region of the Pacific Northwest, especially around the Columbia River Basin of Washington and Oregon. Much of the US experiences at least some freezing rain, with the greatest amounts in the Northeast where the most ice prone areas have a median of seven or more freezing rain days (days during which at least one hourly observation of freezing rain occurred) annually[16]. Many of these storms are relatively minor, although more intense ice storms do occur, albeit with much longer recurrence intervals. For example, in New England, the range in radial ice thickness is 19 to 32 mm for storms with a 50-year recurrence interval[18]. Empirical evidence indicates that ice storms are becoming more frequent at northern latitudes and less frequent to the south[19,20,21]. This trend is expected to continue based on computer simulations using future climate change projections[22,23]. However, the lack of data and physical understanding make it more difficult to detect and project trends in ice storms than other types of extreme events[24].

Since major ice storms are relatively rare, they are challenging to study. It is difficult to predict when and where they will occur, and it is generally impractical to "chase" storms for research purposes. Consequently, most ice storm studies have been unplanned post hoc assessments occurring in the wake of major storms. This research approach is not ideal because of the inability to collect baseline data before a storm. Additionally, it can be difficult to find unaffected areas for comparison with damaged areas when ice storms cover a large geographic extent. Rather than waiting for natural storms to occur, experimental approaches may offer advantages because they enable close control over the timing and intensity of icing events and allow for appropriate reference conditions to clearly evaluate effects.

Experimental approaches also pose challenges, especially in forested ecosystems. The height and width of trees and the canopy makes them difficult to experimentally manipulate, as compared to lower-stature grasslands or shrublands. Additionally, disturbance from ice storms is diffuse, both vertically through the forest canopy and across the landscape, which is difficult to simulate. We know of only one other study that attempted to simulate ice storm impacts in a forest ecosystem[25]. In this case, a rifle was used to remove up to 52% of the crown in a loblolly pine stand in Oklahoma. Although this method produced results that are characteristic of ice storms, it is not effective at removing larger branches and does not cause the trees to bend over, which is common with natural ice storms. While no other experimental methods have been used to study ice storms specifically, there are some parallels between our approach and other types of forest disturbance manipulations. For example, gap dynamics have been studied by felling individual trees[26], forest pest invasions by girdling trees[27], and hurricanes by pruning[28] or pulling down whole trees with a winch and cable[29]. Of these approaches, pruning most closely imitates ice storm impacts but is labor intensive and costly. The other approaches cause mortality of whole trees, rather than the partial breakage of limbs and branches that is typical of natural ice storms.

The protocol described in this paper is useful for closely mimicking natural ice storms and involves spraying water over the forest canopy during sub-freezing conditions to simulate glaze ice events. The method offers advantages over other means because the damage can be distributed relatively evenly throughout forests over a large area with less effort than pruning or downing whole trees. Additionally, the amount of ice accretion can be regulated through the volume of water applied and by selecting a time to spray when weather conditions are conducive for optimal ice formation. This novel and relatively inexpensive experimental approach enables control over the intensity and frequency of icing, which is essential for identifying critical ecological thresholds in forest ecosystems.

Protocol

1. Develop the experimental design

1. Determine the intensity and frequency of icing based on realistic values.
2. Determine the size and shape of the plots.
    1. If the goal is to evaluate tree responses, select a plot size that is large enough to include multiple trees and most of their root systems, which varies depending on factors such as tree species and age.
    2. For safety purposes, design the plots so that the entire plot area can be sprayed from outside the boundary.
    3. Space plots far enough apart (e.g., 10 m) so that a treatment in one plot does not affect another.
    4. Establish a buffer zone (e.g., 5 m) around plots to reduce edge effects and ensure a more even distribution of the ice coverage.
    5. Establish subplots within the larger plots for specific sampling needs.
3. Decide on the number of replicate plots.

2. Select and establish a study location

1. Select a homogeneous forest stand with similar features, such as tree species composition, soils, lithology, and hydrology.
2. Select a location for the application in an area where there is access to a water source during winter.
3. Ensure that the supply of water is adequate for the ice application based on the pump rate and other factors such as the diameter of the hose, length of hose, nozzle used, and water pressure.

4. Mark the boundary of the plots, buffer zone, and subplots.
5. Conduct a complete forest inventory with descriptions of tree health conditions including assessments of dead, dying and damaged trees. Additionally, record any potential stressors (e.g., evidence of insect damage or disease) to help interpret the response to the ice treatment.
6. If using UTVs to spray water, create passable trails along the sides of the plots while being careful to minimize disturbance.
7. Once the plots are established, randomly assign a treatment to each plot and type of sampling that will be conducted in each subplot (e.g., coarse woody debris, fine litter, soil samples).

3. Timing of the application

1. Select an appropriate window of time to perform the spraying.
2. Perform the experiment when the weather conditions are conducive (e.g., when air temperature is less than -4 °C and wind speed is less than 5 m/s).
3. If spraying at night, deploy high powered lights around the edge of plots and run them on generators if electricity is not available.

4. Set up the water supply

1. Set up a supply pump at the water source and connect a suction hose.
2. Connect a strainer to the end of the suction hose to keep debris out of the lines.
3. Break through any surface ice and fully submerge the strainer. The minimum depth of the water supply should be about 20 cm.
4. Place a booster pump in the bed of a UTV to improve water pressure. In some cases, a booster pump may not be necessary, especially for low-stature vegetation.
5. Run a firefighting hose from the supply pump to the booster pump.
6. Use a fire-fighting monitor to enable safe, manual control over the high-pressure hose. The monitor can be free standing or mounted on the back of a UTV.
7. Avoid situations that may interrupt the flow of water such as kinks in the hose, water drawdown at the supply source, and running out of gasoline for the pumps.

5. Creating the ice

1. Create ice by spraying water vertically through gaps in the canopy. Make sure the water extends above the height of the canopy so that it is deposited vertically and freezes on contact with sub-freezing surfaces. Avoid stripping branches and bark from trees as water is sprayed upwards.
2. Evenly distribute spray over the forest canopy by slowly driving the UTV back-and-forth along the edge of the application area. If free-standing monitors are used, move these manually to ensure that the coverage is even.
3. Keep track of the timing of the application to help determine factors such as the weather conditions during application and the volume of water sprayed.

6. Measure ice accretion

1. Make ground-based caliper measurements of radial ice thickness on lower-level branches or twigs near the edge of the application area to monitor ice accretion during application and determine when the target thickness has been attained.
2. Obtain more accurate estimates of ice accretion with passive ice collectors after the application (**Figure 1**).
    1. Before the application, construct passive ice collectors with two dowels oriented on three cardinal axes[30] to create collectors with six component arms.
    2. Cut 2.54 cm dowels at a length of 30 cm.
    3. Join the dowels with a 6-way steel connector.
    4. Use an arborist throw weight to string parachute cord over sturdy branches that can withstand the ice load.
    5. Attach the passive ice collectors to the cord and raise them up into the canopy.
    6. Once the application is completed, lower the collectors to the ground, being careful not to lose any ice from the collector.
    7. Make vertical and horizontal measurements of ice thickness with calipers at multiple locations on the collector (e.g., three vertical and three horizontal measurements at three locations along each arm) before and immediately after ice application.
    8. Calculate ice thickness on each collector as the difference between the measurements before and after the application.
    9. To determine ice thickness with the water volume method, use a reciprocating saw to cut each dowel.
    10. Bring the dowels to a heated building, place them in buckets, and let the ice melt off at room temperature.
    11. Measure the volume of meltwater with a graduated cylinder.
    12. Calculate ice thickness based on the water volume and density of ice[31] .

7. Safety considerations

1. Stay well outside of the ice treatment area during spraying because ice loads can cause branches and limbs to break and fall.
2. Wear hard hats or helmets to provide protection while the ice is being applied and during any sampling that occurs in the treated area after the application.
3. Use a monitor to stabilize the hose during spraying.
4. Dress appropriately for hazardous conditions and sub-freezing weather. Wear bright, visible clothing. Be prepared to spend long periods in wet, cold conditions by wearing rain gear and layers of warm clothes. Bring multiple changes of clothes, especially for personnel who are designated to spray.
5. If working in a remote location, set up a temporary warming tent equipped with a portable heater.
6. Allow personnel to have adequate time for breaks, changing out of wet clothes, and addressing problems that arise with equipment, etc.
7. Use radios to communicate among personnel during the experiment. Maintain contact with personnel at a base station.
8. Develop a safety plan in case of medical emergencies. Have medical personnel (e.g., Emergency Medical

Technicians) and emergency equipment and supplies on site during the experiment.

Representative Results

An ice storm simulation was performed in a 70–100 year-old northern hardwood forest at the Hubbard Brook Experimental Forest in central New Hampshire (43° 56′ N, 71° 45′ W). The stand height is approximately 20 m and the dominant tree species in the area of the ice application are American beech (*Fagus grandifolia*), sugar maple (*Acer saccharum*), red maple (*Acer rubrum*) and yellow birch (*Betula alleghaniensis*). Ten 20 m x 30 m plots were established and randomly assigned a treatment. Most of the sampling occurred within a 10 m x 20 m inner plot to allow for a 5 m buffer. The inner plot was divided into eight 5 m x 5 m subplots designated for different types of sampling. There were two replicate plots for each of five treatments, which consisted of a control (no ice) and three target levels of radial ice accretion: low (6.4 mm), mid (12.7 mm), and high (19.0 mm). Two of the mid-level treatment plots (midx2) were iced in back-to-back years to evaluate impacts of consecutive storms. The spraying occurred during the winters of 2016 (January 18, 27–28 and February 11) and 2017 (January 14). Water was pumped from the main branch of Hubbard Brook, which was covered in ice and had stream temperatures near freezing. Surface air temperatures at the time of the applications ranged from -13 to -4 °C and wind speed was less than 2 m/s.

Ice accretion was measured on passive ice collectors (four per plot) using both the caliper and water volume methods as described above (protocol section 6; **Figure 1**). Average ice thickness was less than the target values in the mid and high ice treatments (4.3 mm and 5.8 mm less, respectively). Ice thickness in the low, midx2 y1, and midx2 y2 treatments was within 2 mm of the target values (**Table 1**). Despite some differences from target values, the treatments provided a range of radial ice thickness (0–16.4 mm) for assessing ecosystem effects. This range was comparable to the 0–14.4 mm of radial ice recorded at the Hubbard Brook Experimental Forest after the ice storm of 1998[32]. Average ice accretion on individual collectors indicated a strong positive relationship between caliper and water volume measurement methods ($R^2 = 0.95$; $p < 0.01$; **Figure 2**). Measurements using the water volume method exceeded measurements with the caliper method when there was more than about 8 mm of ice (**Figure 2**). This difference is due to the presence of icicles, which form as ice accumulates, and is captured more effectively with the water volume method. When ice accretion was less than 8 mm, measurements from the water volume method were slightly less than measurements from the caliper method, which is attributed to the density of ice. We calculated ice thickness with the water volume method using the density of glaze ice (0.92 g/cm^3); however, the ice in the treatment had air bubbles and likely had a density less than this theoretical value.

Total spray times (hours/hose) averaged 2 h 20 min for the low, 4 h 50 min for the mid, and 8 h for the high ice treatments. The actual time spent spraying in the field was approximately half of these total times, since two hoses were used simultaneously for spraying each plot. There was a significant positive relationship between spray time and ice accretion measured with the water volume method ($R^2 = 0.46$; $p = 0.03$; **Figure 3a**) and the caliper method ($R^2 = 0.56$; $p = 0.01$). The average rate of ice accretion ranged from 1.4 to 4.2 mm/h across plots. There was a marginally significant inverse relationship between air temperature and ice accretion measured with the water volume method (R^2 =

0.40; p = 0.05; **Figure 3b**) and no significant relationship with the caliper method (R^2 = 0.15; p = 0.27).

Rapid assessments of canopy cover were made during the summers before (2015) and after ice was applied (2016). Data were not collected in the second year after treatment (2017); therefore, the midx2 treatment was only assessed after it had been initially sprayed. An ocular tube was used to record the presence or absence of canopy cover directly overhead along transects in the plots[33]. While this method is effective at estimating canopy cover, it requires intensive sampling, which can be time consuming and costly. Ground based measurements with a larger area of view, such as canopy densiometers[34], provide a measure of canopy closure and require less sampling and have lower stand-level variability[35,36]. However, care must be taken to ensure the view angle does not capture vegetation outside of the treated plot.

Canopy cover data were analyzed using a generalized linear mixed model with a binomial distribution. Ice treatment was included as a fixed effect and plot as a random effect. Results showed no significant differences among the 10 plots in pre-treatment surveys (**Figure 4A**), whereas post-treatment surveys indicate significant decreases in canopy cover in the mid, midx2, and high ice treatments relative to the control (**Figure 4B**). These general declines in canopy cover with increasing ice accretion support results from a more rigorous analysis by Fahey et al.[37] that showed significant structural changes in the forest canopy that were commensurate with the amount of ice applied.

The effects of the simulated ice storms on surface soil temperatures was evaluated during sampling in August 2017 (i.e., two growing seasons after all the plots had been iced once, and the growing season after the midx2 plots had been iced twice). The measurements were made in the afternoon between 12:30 pm and 2:00 pm. Soil temperatures were measured manually with Oakton soil temperature probes (0.5 °C accuracy) that were inserted in the ground at 2 cm and 5 cm depths. Measurements were made on a 2.5 m grid simultaneously in a treatment plot and paired control plot. No measurements were made in the low treatment plots since they showed minimal impacts of ice on vegetation. Soil temperature results showed that the soils in the treated plots were significantly warmer than the control plots at both depths (2 cm and 5 cm) for all three levels evaluated (mid, midx2, high; **Figure 5A,B**). The temperatures were slightly warmer in the shallower soil compared to deeper soil, and the effects of the treatment were greater. The treated plots were 0.4–1.5 °C warmer than the controls for the 2 cm depth and 0.2 to 0.5 °C warmer for the 5 cm depth. The treatments clearly opened the forest canopy, which caused more light to reach the forest floor, resulting in higher soil temperatures.

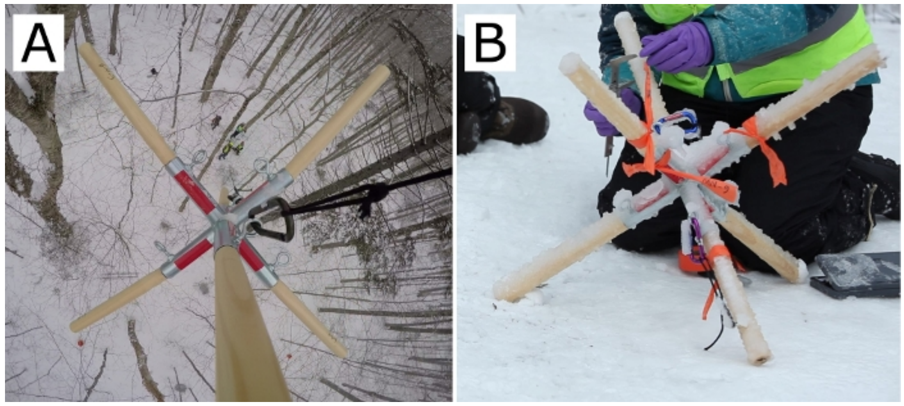

Figure 1: Passive ice collector for measuring radial ice accretion. (**A**) View of the ice collector in the forest canopy before the ice application. (**B**) Making caliper measurements of ice accretion on the collectors after lowering them down from the canopy. Please click here to view a larger version of this figure.

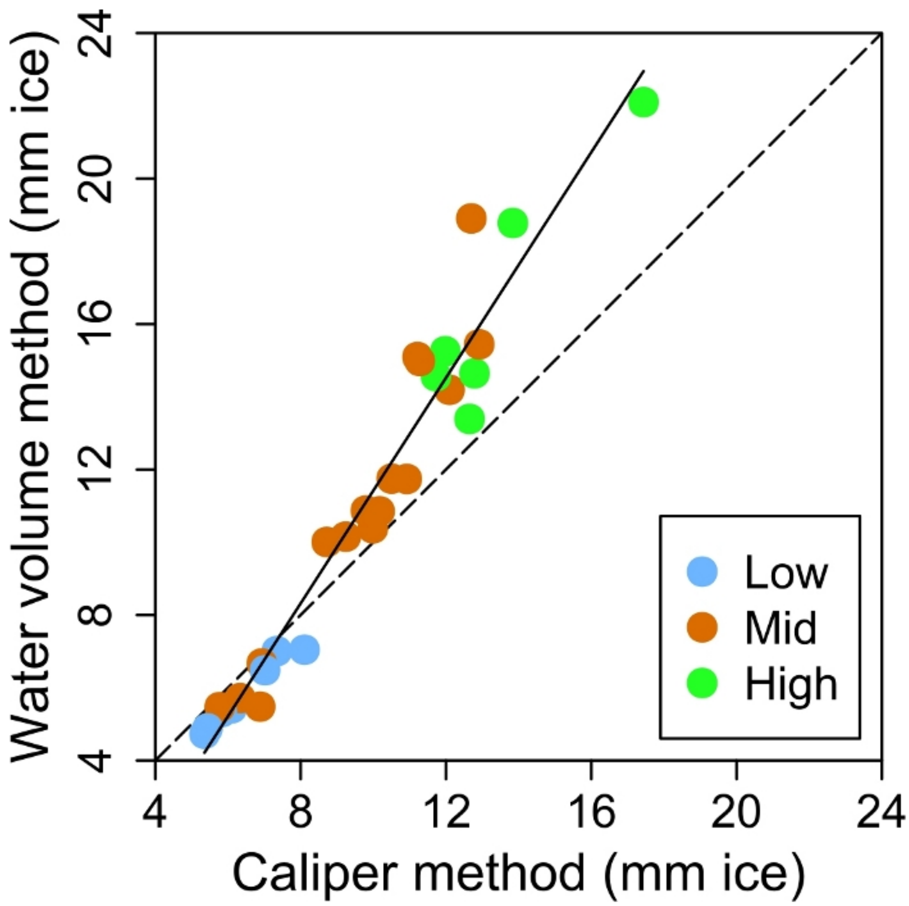

Figure 2: Comparison of two methods for measuring radial ice accretion. The caliper method involves measurements of ice on dowels. The water volume method involves measuring the volume of meltwater from the dowels and calculating radial ice thickness using an assumed ice density. Three target ice accretion levels are shown (low = 6.4 mm, mid = 12.7 mm, high = 19 mm) and the dashed line is the 1:1 line. Each point represents one passive ice collector and is the mean of six measurements on each of six component arms (i.e., 36 measurements per collector). Please click here to view a larger version of this figure.

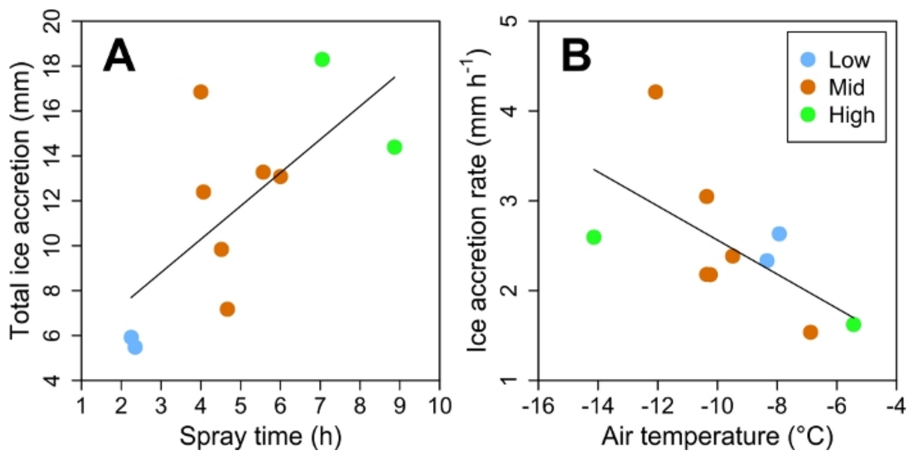

Figure 3: Rates of ice accretion. (**A**) The relationship between spray time and total ice accretion. (**B**) The relationship between mean air temperature during the application and the rate of ice accretion. Three target ice accretion levels are shown (low = 6.4 mm, mid = 12.7 mm, high = 19 mm). Ice accretion values shown were determined with the water volume method. Each point represents one plot, with different points for each year of the midx2 treatment. Please click here to view a larger version of this figure.

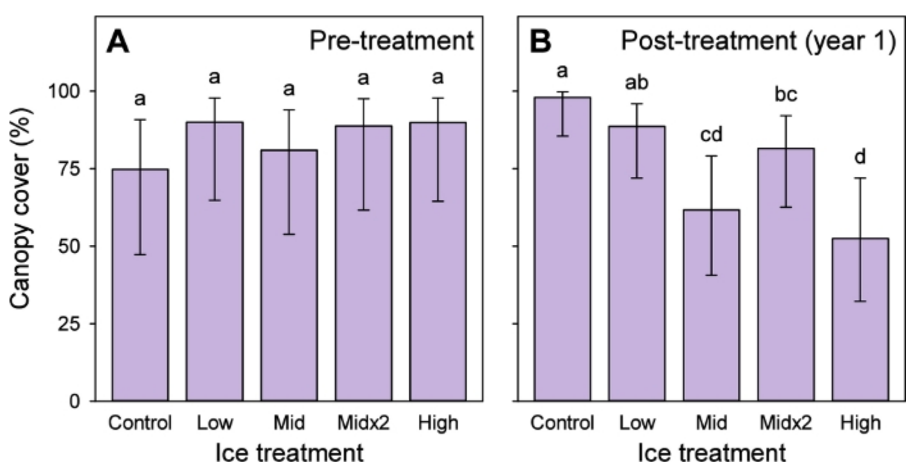

Figure 4: Canopy cover estimated with ocular tubes. (**A**) Pre-treatment canopy cover for the various ice treatments. (**B**) Canopy cover values obtained during the first growing season after ice was applied. Data were analyzed using a generalized linear mixed model with a binomial distribution. The error bars indicate the 95% confidence interval and lowercase letters represent significant differences at α = 0.05. Please click here to view a larger version of this figure.

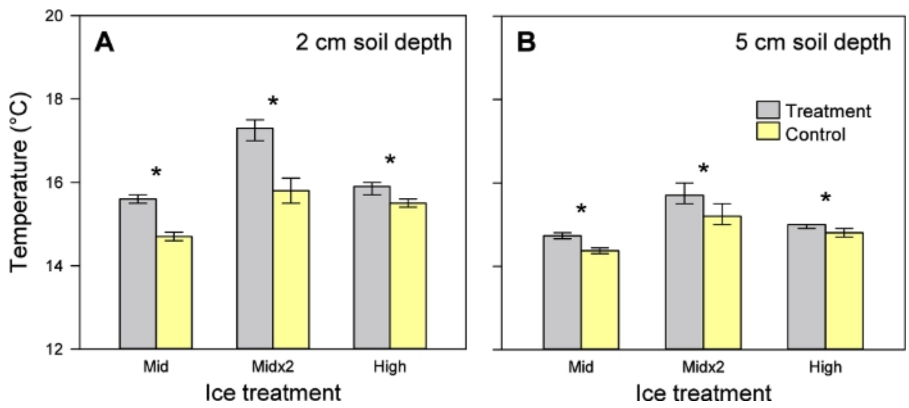

Figure 5: Ice treatment effects on soil temperature. (**A**) Soil temperature measured at 2 cm depth. (**B**) Soil temperature measured at 5 cm depth. Data were analyzed using a general linear model. The error bars indicate the 95% confidence interval and the asterisks indicate significant differences between the control and treatment at α = 0.05. Please click here to view a larger version of this figure.

Method	Low	Mid	Mid x 2 y1	Mid x 2 y2	High
Target	6.4	12.7	12.7	12.7	19.1
Water volume	5.7 (0.2)^{c}	8.5 (1.3)^{bc}	14.6 (2.2)^{a}	13.2 (0.1)^{ab}	16.4 (1.1)^{a}
Caliper	6.3 (0.3)^{c}	8.4 (1.1)^{bc}	11.0 (1.6)^{ab}	11.3 (0.2)^{ab}	13.3 (1.2)^{a}

Table 1: Target ice accretion values compared to actual values measured on passive collectors using both the water volume and caliper methods. The units are millimeter and the standard error is indicated in parentheses. Superscript letters indicate significant differences among treatments as determined with a generalized linear mixed model.

Discussion

It is critical to perform experimental simulations of ice storms under appropriate weather conditions to ensure their success. In a previous study[30], we found that the optimal conditions for spraying are when air temperatures are below -4 °C and wind speeds are less than 5 m/s. Natural ice storms most commonly occur when air temperatures are slightly less than freezing (-1 to 0 °C), and although the ideal temperatures for ice storm simulations are colder, they are still within the temperature range of observed freezing rain events -15 to 0 °C[16]. Because sustained below-freezing temperatures are required, this experimental approach is restricted to more northerly locations, and can be challenging to perform even at relatively cold locations like the Hubbard Brook Experimental Forest, where the average monthly low air temperature is -9 °C in January, but regularly fluctuates above freezing. Spraying at night can be advantageous since it is when air temperatures are typically coldest, and effects of solar radiation are negligible.

There are several challenges with ice storm simulation experiments. In forests with tall canopies, it can be difficult to spray the tops of trees. Many factors affect the height of the spray, including the pump rate and the distance between the water source and application area. Since spray height calculations are complex and specific to the site and equipment used, it is helpful to conduct spraying tests before the experiment so that appropriate adjustments can be made. Another challenge is determining when to stop spraying because measurements of ice thickness are difficult to obtain during the simulation. Passive ice collectors can be used for this purpose but require sturdy branches within the plots for support. Several of the collectors we installed were damaged or fell during the experiment. For safety, we placed the collectors close to the edge of the plots to avoid having to enter the experimental area, which may have contributed to the underestimation of ice accretion in some plots (**Table 1**). It can be time consuming and difficult to lower collectors and make measurements during the application. Ground-based measurements can aid in this regard but may not best represent ice accretion in the upper canopy. The density of ice in the ice storm simulation was somewhat less than ice that forms during a natural ice storm. This difference was supported by ice measurements on collectors and was visually apparent, in that the ice was more opaque than the glaze ice that forms in natural storms. Despite these differences in ice density, the simulated ice storm resulted in a disturbance that was diffuse and caused trees and limbs to bend and break, much like a natural ice storm. Thus, this method more closely mirrors ice storm impacts compared to other potential methods, such as shooting, girdling, pruning or pulling down trees.

Although the plots were relatively large for a manipulative experiment (20 m x 30 m), increasing the size of the plots would reduce the influence of unaffected trees outside the plots. Even with a buffer, tall trees surrounding the plots could potentially impact responses such as litterfall, light availability and soil temperature. Additionally, the plots undoubtedly contained roots from outside the boundary that could have altered belowground processes. Microbial biomass and activity, soil nitrogen, nitrogen mineralization and nitrification, and losses of solutes in soil water all showed no significant effects from ice applications[38] despite major aboveground disturbance[37]. The lack of belowground response was unexpected, especially for nitrate leaching, which was shown to be sensitive to ice storm disturbance following the natural ice storm impacting Hubbard Brook in 1998. Large losses of nitrate in soil solution were observed following that storm and attributed to reduced uptake due to damaged tree crowns[39]. The lack of nitrogen response in the ice storm simulation could be the result of root uptake from healthy trees outside the plots; however, the damage and gaps in the canopy were large enough that some response would be expected. A more likely explanation for the lack of belowground response is the long-term declines in available nitrogen that have been observed at the site, resulting in an overall tightening of the nitrogen cycle, with minimal nitrate leaching[38,40].

The ice storm simulation method has proved successful in the northern hardwood forest at the Hubbard Brook Experimental Forest and has helped to quantify ecosystem responses and identify critical thresholds[37,38]. In future studies, it would be useful to apply this approach in other forest types and under different conditions. For example, the impact of wind on ice-laden trees could intensify effects and has not yet been evaluated in a controlled experiment. Additionally, this method affords an ideal opportunity to quantify impacts from compound stressors that are common in forest ecosystems (e.g., insect outbreaks, pathogens, drought, pollutants, soil freezing). Applying this method in a multi-factorial design would enable a statistically rigorous approach to evaluate interactive effects that would not emerge by assessing ice storm impacts alone, and more closely resemble naturally occurring conditions. Although we have only assessed responses in the first few years after applications, it will be useful to track forest decline or recovery over the long-term. While the focus of our ice storm simulations has been primarily on forest ecosystems, the method could be applied in other ways, such as to evaluate impacts of ice loads on utility lines and other infrastructure. Despite some limitations, the approach is highly effective at simulating natural ice storms and is an improvement over alternative methods.

Disclosures

The authors have nothing to disclose. Reference herein to any specific commercial products, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government, and shall not be used for advertising or product endorsement purposes.

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