A novel ice storm manipulation experiment in a northern hardwood forest

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Abstract: Ice storms are an important natural disturbance within forest ecosystems of the northeastern United States. Current models suggest that the frequency and severity of ice storms may increase in the coming decades in response to changes in climate. Because of the stochastic nature of ice storms and difficulties in predicting their occurrence, most past investigations of the ecological effects of ice storms across this region have been based on case studies following major storms. Here we report on a novel alternative approach where a glaze ice event was created experimentally under controlled conditions at the Hubbard Brook Experimental Forest, New Hampshire, USA. Water was sprayed over a northern hardwood forest canopy during February 2011, resulting in 7–12 mm radial ice thickness. Although this is below the minimum cutoff for ice storm warnings (13 mm of ice) issued by the US National Weather Service for the northeastern United States, this glaze ice treatment resulted in significant canopy damage, with 142 and 218 g C·m^{-2} of fine and coarse woody debris (respectively) deposited on the forest floor, a significant increase in leaf-on canopy openness, and increases in qualitative damage assessments following the treatment. This study demonstrates the feasibility of a relatively simple approach to simulating an ice storm and underscores the potency of this type of extreme event in shaping the future structure and function of northern hardwood forest ecosystems.

Résumé : Les tempêtes de verglas sont la cause d'une perturbation naturelle importante dans les écosystèmes forestiers du nord-est des États-Unis. Les modèles actuels indiquent que la fréquence et la sévérité des tempêtes de verglas pourraient augmenter au cours de la prochaine décennie en réaction aux changements climatiques. Parce que les tempêtes de verglas sont par nature aléatoire et que leur occurrence est difficile à prédire, la plupart des travaux de recherche passés portant sur les effets écologiques des tempêtes de verglas dans cette région ont été basés sur des études de cas à la suite de tempêtes majeures. Cette étude porte sur une approche alternative originale qui consiste à produire expérimentalement dans des conditions contrôlées un épisode de verglas à la forêt expérimentale de Hubbard Brook, au New Hampshire, É.-U. La canopée d'une forêt de feuillus nordiques a été arrosée avec de l'eau en février 2011 provoquant la formation de glace dont l'épaisseur radiale a atteint 7 à 12 mm. Bien que cela soit sous le seuil minimal (13 mm de glace) pour que le Service météorologique nationale des États-Unis lance un avis de tempête de verglas pour le nord-est des États-Unis, ce traitement a provoqué des dommages importants entraînant le dépôt sur la couverture morte de respectivement 142 et 218 g C·m^{-2} de débris ligneux fins et grossiers, une augmentation significative de l'ouverture de la canopée feuillue et des augmentations dans les évaluations des dommages qualitatifs à la suite du traitement. Cette étude démontre la faisabilité d'une approche relativement simple pour simuler une tempête de verglas et fait ressortir la capacité de ce type d'événement extrême d'influencer de façon déterminante la structure et la fonction à venir des écosystèmes forestiers de feuillus nordiques.

[Traduit par la Rédaction]

Introduction

Extreme events

Human-induced climate change has the potential to alter the prevalence and severity of extreme climate events such as heat waves, cold waves, wind storms, floods, and droughts (IPCC 2007). A growing recognition and concern exists within the global change community that these types of events can have equal — or greater — impact on natural and managed systems than the more gradual change in means that are typically associated with climate change (Katz and Brown 1992; Dale et al. 2001; Arnone et al. 2011). Although considerable advances have been made in the past few decades on understanding and modeling the impacts of gradual or small step increases in single and multiple drivers of global change on terrestrial and aquatic ecosystems (Rustad 2006, 2008; Luo and Hui 2008; Leuzinger et al. 2011), less is known about short- and longer term consequences of extreme events. These events pose a unique challenge to the research and modeling community due to their heterogeneous nature in time and space. By definition, they have relatively long return intervals (e.g., "the 100 year flood") and although we can identify broad regions susceptible to different natural disturbance regimes (e.g., areas popularly known as "hurricane alley" in the mid-Atlantic ocean, or "the ice belt" of North America), the actual occurrence is often local and regionally patchy. Long-term research and monitoring programs at a single site, such as those that have been effective at docu-

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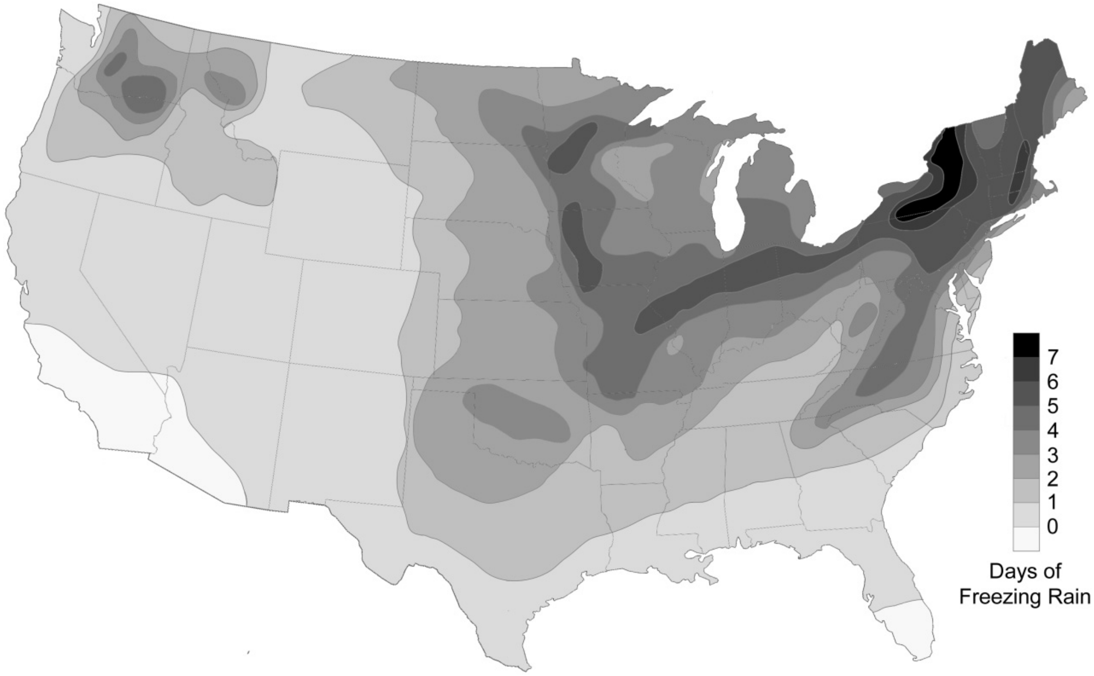
Fig. 1. Average annual number of days of freezing rain in the United States (modified from Changnon 2003).



menting long-term changes in climate and its impacts (e.g., Hughes 2000; Kullman 2007), are not necessarily suitable for studying impacts of extreme events. New experimental approaches are needed to provide in-depth understanding of cause-and-effect relationships between the severity and frequency of extreme events and key metrics of ecosystem structure and function. These results need to be further incorporated into ecosystem, regional, and earth system models.

Ice storms

Ice storms are one type of extreme event common to temperate and boreal forest regions worldwide (Changnon 2003; Ding et al. 2008). These storms form under unique climatological conditions when moisture-rich warmer air overrides a layer of subfreezing air at ground level. Precipitation falling from the warmer upper air layer reaches the cold layer as rain. The raindrops then supercool as they fall through the cold air and subsequently form a freezing layer of ice when they land on cold objects such as tree branches or power lines. Local and regional heterogeneity of ice storm damage can be attributed to differences in elevation, proximity to large bodies of water (e.g., Atlantic Ocean, Great Lakes), inclination and aspect of slope, microvariations in ground surface temperature, variations in the type (rain, freezing rain, ice pellets, snow) and intensity of precipitation, and direction and velocity of the wind. In forested ecosystems, ice storm damage is primarily characterized by branch and crown loss, with consequent reductions in the photosynthetic area of trees and decreased carbohydrate production needed for growth, wound closure, and the production of plant protection compounds necessary to control the spread of pathogens. Secondary impacts related to creation of canopy gaps include alterations in light regimes, soil microclimate, and seedling establishment.

In the United States, ice storms are particularly prevalent in the broad “ice belt” that extends from east Texas to New England (Irland 2000; Changnon 2003) (Fig. 1), with the greatest risk for damage (based on event frequency, ice thickness, storm size and shape, and financial loss) occurring in the northeastern states (Changnon 2003). Although these glazing events (defined by the US National Weather Service for the northeastern United States as 13 mm or more of ice) are often perceived as rare occurrences, return intervals are as short as 2–5 years in the most ice storm prone northeastern United States (Irland 2000; Changnon 2003). Data for this region from the National Climatic Data Center's Storm Data archives and historical records document 17 major ice storms since the late 1800s (Table 1).

One of the most devastating of these ice storms occurred in 1998, depositing 80+ mm of freezing rain in some locations and resulting in ice accretions (measured as radial thickness) of up to 50 mm (Irland 1998; DeGaetano 2000). This storm affected nearly 10 million hectares of forest from northwestern New York and southern Quebec to south-central New England, caused considerable damage to forest canopies, paralyzed power grids, left millions of people without power, and cost over 4.4 billion dollars in economic damage (Gyakum and Roebber 2001).

At the Hubbard Brook Experimental Forest (HBEF) in New Hampshire, the 1998 ice storm had a major impact on ecological processes, even though ice accretions were moderate compared with other regions affected by this storm. At the HBEF, 83 mm (water equivalent) of freezing precipitation was recorded over a 42 h period. Ice accretion was highly variable and increased with elevation, with radial ice thickness measured on tree branches ranging from 5.9 mm ($\pm$0.06 SE) at low elevation (<625 m) to 12.3 mm ($\pm$0.68 SE) at midelevation (625–709 m) to 14.4 mm ($\pm$0.75 SE) at high elevation (709–791 m) (Rhoads et al. 2002). During the growing season after the storm, canopy leaf area had declined by as much as a third in some areas but recovered to pre-storm levels after 3 years (Rhoads et al.

Table 1. Major storms of the northeastern United States and Canada (updated through 2011).

Year(s)	Dates	Areas most affected*	Representative Reference
1886	28–29 Jan.	NH, ME	Zielinski and Keim 2005
1921	25–29 Nov.	RI, MA	Burnham 1922
1929	17–20 Dec.	NY, NH, ME	Spencer 1929
1936	17–19 Mar.	NY, PA	Downs 1938
1942	29–30 Dec.	CT, MA, VT, NH, NY	Christie and Chartier 1943
1948–1949	31 Dec. – 5 Jan.	NY	Lemon 1961
1953	8–11 Jan.	PA, NY, CT	Changnon 2003
1964	4–11 Dec.	NY, MA	Jones and Mulherin 1998
1969	26–27 Dec.	MA, NH, VT	Ackley and Itagaki 1970
1973	16–17 Dec.	CT	Siccama et al. 1976
1976	2–5 Mar.	NY	Jones and Mulherin 1998
1979	8–25 Jan.	ME, NH	Jones and Mulherin 1998
1983	13–14 Dec.	NY, QC	Melancon and Lechowicz 1987
1986	14–15 Feb.	NH	Jones and Mulherin 1998
1991	3–6 Mar.	NY, VT, NH, ME, QC	Seischab et al. 1993
1998	4–10 Jan.	NY, NH, VT, CT, QC, ON	DeGaetano 2000
2008	11–12 Dec.	NY, NH, MA, ME, VT, CT	None as of yet

*CT, Connecticut; MA, Massachusetts; ME, Maine; NH, New Hampshire; NY, New York; ON, Ontario, Canada; PA, Pennsylvania; QC, Quebec, Canada; RI, Rhode Island; VT, Vermont.

2002). Vegetation assessments 8 years after the storm indicated that while leaf areas of damaged and undamaged zones were similar, the storm had significantly altered canopy structure, regeneration, and species composition (Weeks et al. 2009). Openings in the canopy immediately after the storm caused a short-term increase in soil temperature, but soil microclimate recovered within 3 years as a result of shading by regeneration in gaps (Likens et al. 2004). Despite the increase in soil temperature and litter inputs, there was no detectable ice storm effect on soil moisture, nitrogen mineralization, and nitrification, as indicated by measurements taken during 1998 (after the storm) and 1999 (Houlton et al. 2003). The most notable biogeochemical response was a marked increase in soil solution and streamwater nitrate (NO_3^-) during the growing season after the storm. Since a microbial nitrogen mineralization and nitrification responses were undetectable, the increase in NO_3^- was attributed to a reduction in plant uptake of this important nutrient due to damaged vegetation (Houlton et al. 2003). The amount of NO_3^- exported from watersheds may have been even greater were it not for in-stream nitrogen processing, which was thought to be enhanced by the ice storm (Bernhardt et al. 2003).

Future projections for the northeastern United States and eastern Canada suggest that there will be greater frequency and severity of extreme events, such as ice storms, during the coming decades, although the ability to predict the timing of these events remains a challenge (Cheng et al. 2007, 2011; Hayhoe et al. 2007). For example, Cheng et al. (2007) used future climate scenarios and statistical downscaling procedures to predict a 40%–85% increase in freezing rain events by the 2050s as compared with the average occurrence over the past 40 years in south-central Canada, with a greater increase in more northern regions compared with southern regions. These patterns suggest that the North American "ice belt" will move northward with warming temperatures and more frequent winter freezing rain events.

Given the potential for an increase in the frequency and severity of ice storms in the coming decades coupled with the power of these storms to disrupt forest ecosystems, it is critical to gain a better understanding of the consequences of ice storms for forested regions of northeastern North America. Because of the stochastic nature of ice storms and difficulties in predicting their occurrence, most past investigations of freezing rain and ice across this region have been done for (1) case studies of major storms (e.g., Bruederle and Stearns 1985; Rebertus et al. 1997; Rhoads et al. 2002), (2) assessment of the risk of icing to specific facilities such as buildings, wires, or aircraft (e.g., Hoffmann 1984; Jones 1996, 1998; Kudzys 2006), and (or) (3) research relating to the forecasting of freezing-rain conditions (e.g., Changnon 2003; Cheng et al. 2004, 2011). Few studies have had the opportunity to focus on a robust suite of ecological effects in natural ecosystems.

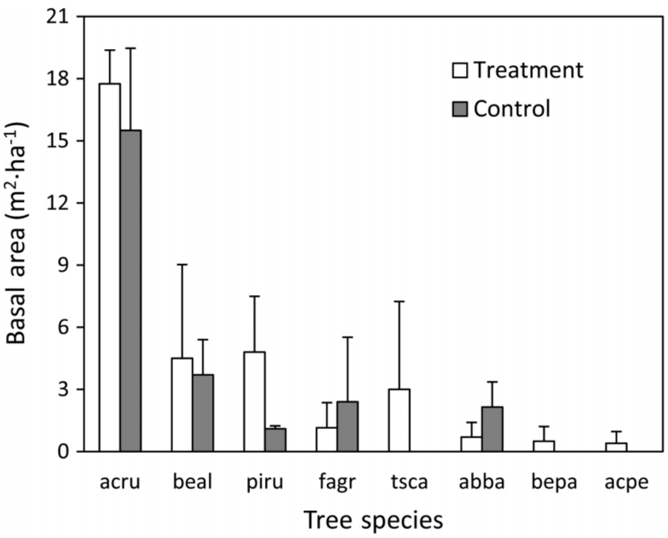
An alternative to attempting to opportunistically study ice storm effects when and where they occur is to experimentally create glaze ice events under controlled conditions. The ability to manipulate the severity (e.g., radial diameter of ice accretion) and frequency (multiple icing events within or between years) for different ecosystem types or age classes will dramatically improve our ability to elucidate cause-and-effect relationships and provide for a mechanistic understanding of the response of forested ecosystems to these important natural disturbances. This paper describes the design of what appears to be the first ever controlled, experimental ice storm manipulation in a forest ecosystem, the evaluation of the ice accretion obtained, and the impacts on several key response variables.

Methods

Site description

The HBEF is 3160 ha, bowl-shaped valley in the White Mountain National Forest in central New Hampshire, USA (43°56′46″N, 71°47′19″W). The climate is humid continental with mean monthly air temperatures ranging from –9 °C in

Fig. 2. Basal area of trees greater than 3 cm diameter at breast height in the simulated ice storm treatment and control plots (abba, *Abies balsamea* (balsam fir); acpe, *Acer pensylvanicum* (striped maple); acru, *Acer rubrum* (red maple); beal, *Betula alleghaniensis* (yellow birch); bepa, *Betula papyrifera* (paper birch); fagr, *Fagus grandifolia* (American beech); piru, *Picea rubens* (red spruce); tsca, *Tsuga canadensis* (eastern hemlock)).



January to 18 °C in July. Precipitation is distributed fairly evenly throughout the year amounting to a total annual average of 1400 mm, approximately 30% of which is snow. The winter snowpack typically persists from late December to mid-April and has a mean annual maximum depth of 90 cm (24 cm snow water equivalent). Vegetation within the HBEF is composed primarily of northern hardwoods (sugar maple (*Acer saccharum* Marsh.), American beech (*Fagus grandifolia* Ehrh.), and yellow birch (*Betula alleghaniensis* Britton)) on the lower and middle slopes and red spruce (*Picea rubens* Sarg.), balsam fir (*Abies balsamea* (L.) Mill.), and white birch (*Betula papyrifera* var. *cordifolia* (Regel) Fernald) at higher elevations and on rock outcrops.

The ice storm manipulation experiment occurred in an area next to the main branch of Hubbard Brook in the far western portion of the Experimental Forest (560 m altitude). The experimental design consisted of four 15 m × 15 m plots (two treatment, two control), each of which was divided into nine 5 m × 5 m subplots. Trees species composition on the plots comprised eight species: *F. grandifolia*, *A. balsamea*, eastern hemlock (*Tsuga canadensis* (L.) Carrière), *B. papyrifera*, red maple (*Acer rubrum* L.), *P. rubens*, striped maple (*Acer pensylvanicum* L.), and *B. alleghaniensis*. The plots were dominated by deciduous hardwoods, which comprised 74% of the basal area in the treatment plots and 87% in the control plots (Fig. 2). More than half of the basal area comprised *A. rubrum* (54% in treatment and 62% in control plots), whereas each of the other species comprised less than 15%. Canopy height was ~15–20 m and stand age was estimated at ~73 years, with the stand likely originating from the 1938 hurricane.

Ice storm simulation

An ice storm was simulated on the treatment plots by spraying water over the forest canopy during subfreezing conditions (Fig. 3). Stream water was pumped from the main branch of Hubbard Brook using a fabric-covered hose (3.8 cm diameter) with a straight bore nozzle (1.0 cm diameter orifice) connected to two Mark 3 centrifugal pumps running in tandem, portable equipment that is typically used for wildland fire suppression. Water was sprayed into the air from ground level through natural gaps in the canopy at a rate of 175 L·min^{-1}, taking care that the water column did not damage vegetation. The spray height exceeded the tallest trees (15–20 m) and the falling water froze on contact. The ice storm simulation began at 7 a.m. on 9 February 2011 and lasted 3.5 h (100 min on Plot 1 and 110 min on Plot 2). The air temperature was –14 °C at the beginning of the experiment and increased to –9 °C by the end, with relative humidity at 75%. Approximately 75 cm of snow (10 cm snow water equivalent) was on the ground at the time of treatment.

Fig. 3. Simulated ice storm on 9 February 2011 at the Hubbard Brook Experimental Forest, New Hampshire.

Ice and water measurements

Ice that accumulated on branches is reported as equivalent radial ice thickness (R_{eq}), which is the thickness of ice that would be measured if the actual ice accretion on a branch was of uniform thickness. Measurements of R_{eq} were made with a passive device constructed of six dowels coupled together with a six-way PVC connecter. Each of the dowels was 30 cm long and 2.86 cm diameter and they were oriented on the three cardinal axes (X,Y,Z). The day before the experiment, four of these devices were raised up into the forest canopy with parachute string in each of the treated plots and were lowered back down immediately after spraying ceased. On each dowel, ice thickness was measured with calipers in six places (36 measurements per device). Measurements were made in the middle of the dowel and 5 cm from each end. The dowel was then rotated 90° and three more measurements were made. If the devices were damaged or if ice on the dowel did not remain completely intact while the devices were being lowered, measurements were not taken.

Radial ice thickness was also calculated with the equation below using ice water equivalent measurements (Jones and Mulherin 1998). After ice thickness was measured with calipers, the dowels were placed in plastic bags and transported to the laboratory where the ice melted off at room temperature. The volume of meltwater from each dowel was measured and applied to the following equation:

$$R_{\mathrm{eq}} = -\frac{D}{2} + \sqrt{\left(\frac{D^2}{4} + \frac{V}{\pi \rho_i L}\right)}$$

where D is the diameter of the dowel (centimetres), L is the length of the dowel (centimetres), V is the volume of melted ice (millilitres), and ρ_i is the density of glaze ice (grams per cubic centimetre).

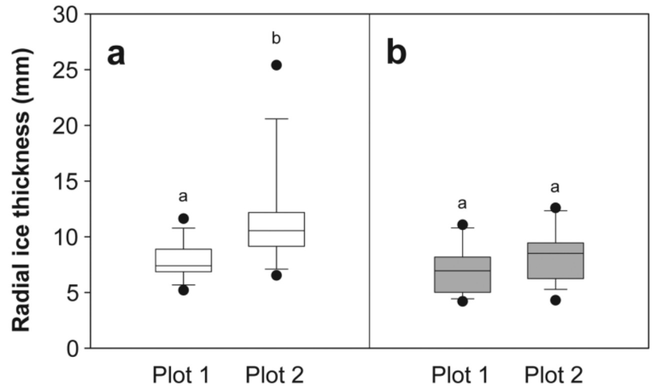
Canopy throughfall volume was measured with 20 L buckets (28.7 cm diameter) placed on the ground in the center of each treated subplot (nine buckets per plot). After the experiment, tared buckets were weighed in the field to obtain throughfall volume. Additionally, the buckets were transported to the laboratory and field values were confirmed by melting the ice in the buckets and recording the volume.

Litter measurements

Fine litter was collected with baskets (52 cm length × 37 cm width × 27 cm height) that were placed in the center of each subplot in both treatment and control plots (nine baskets per plot). Baskets were left in the field for 9 days and all fine litter less than 2 cm diameter that accumulated in the baskets was collected. In instances where fallen branches lay on the litter baskets, twigs less than 2 cm were clipped around the perimeter of the basket and were included as part of the sample. After the experiment, baskets in the treated plots were placed in plastic bags and transported to the laboratory where they were stored at room temperature until the ice and snow that accumulated in the baskets melted. The remaining fine litter in the basket was then oven-dried at 60 °C for 24 h and weighed. In keeping with Fahey et al. (2005), the amount of carbon in fine litter was assumed to be 50% of the oven dry mass.

Coarse litter greater than 2 cm diameter was measured on three randomly selected subplots in both the treatment and control plots. Prior to the experiment, all coarse litter was cleared from the subplots by hand in December 2010, before the snowpack began to develop. Post-treatment coarse litter was collected in June 2011. Downed branches that crossed subplot boundaries were cut on the border with a hand saw. The mass of all coarse litter collected on the subplots was measured in the field (wet mass). A subsample comprising approximately 20% of the total wet mass of coarse litter was brought back to the laboratory and oven-dried at 60 °C to a constant mass to obtain dry mass. The dry mass of coarse litter for each subplot was calculated using the field measurement corrected for water content. As with fine litter, half of the coarse litter oven-dried mass was assumed to be carbon.

Fig. 4. Boxplots of radial ice thickness in the two treated plots determined using (*a*) caliper measurements and (*b*) the volume of ice melted off the dowels.



Canopy measurements

Canopy openness was estimated with digital hemispherical photography in both treatment and control plots. All images were taken vertically from beneath the forest canopy just before sunrise to ensure adequately uniform sky conditions. A high-resolution camera equipped with a 180° fisheye lens was mounted on a self-leveling monopod 1 m above the ground. Pre-treatment photographs were taken at the center of each subplot (nine per plot) with leaves on and off the canopy, respectively, in September and December 2010. However, no pre-treatment images were taken in the control plots during leaf-off. Post-treatment photographs were taken in the same locations with leaves on and off the canopy, respectively, in April and July 2011. Digital images were processed using Gap Light Analyzer software to produce canopy openness percent.

A qualitative post-treatment tree damage assessment was made with leaves off in March 2011 on treated and untreated plots. All trees greater than 3.0 cm diameter at breast height were identified and assigned an injury class value based on a visual inspection of the branches. The following crown injury classes were used, following Smith and Shortle (2003): 1, no visible damage; 2, 1%–49%; 3, 50%–75%; 4, >75%; 5, dead.

Results

Water input, throughfall, and canopy ice retention

Water was sprayed for 100 min in Plot 1 and 110 min in Plot 2 at a rate of 175 $L \cdot min^{-1}$, amounting for a total of 78 mm depth in Plot 1 and 86 mm in Plot 2, assuming that all of the water sprayed on top of the canopy landed within the plot boundary. Average depth of throughfall (measured as melted ice) was 42 mm (±6 SE) in Plot 1 and 40 mm (±8 SE) in Plot 2, with no significant difference between plots. These results suggest that, in this experiment, roughly half of the water sprayed onto the plot was retained in the canopy as ice.

Ice accretion

Radial ice thickness as measured with calipers indicated that the two treatment plots had significantly different amounts of ice accretion (t test, p = 0.01). Average radial ice thickness was 7.8 mm (±0.4 SE) (n = 19) in Plot 1 and 11.6 mm (±1.3 SE) (n = 14) in Plot 2 (Fig. 4*a*). In contrast,

Fig. 5. Change in canopy openness as determined by hemispherical photography. Images were taken before and after the ice manipulation in treatment and control plots. Letters indicate statistical differences at the 0.05 level.

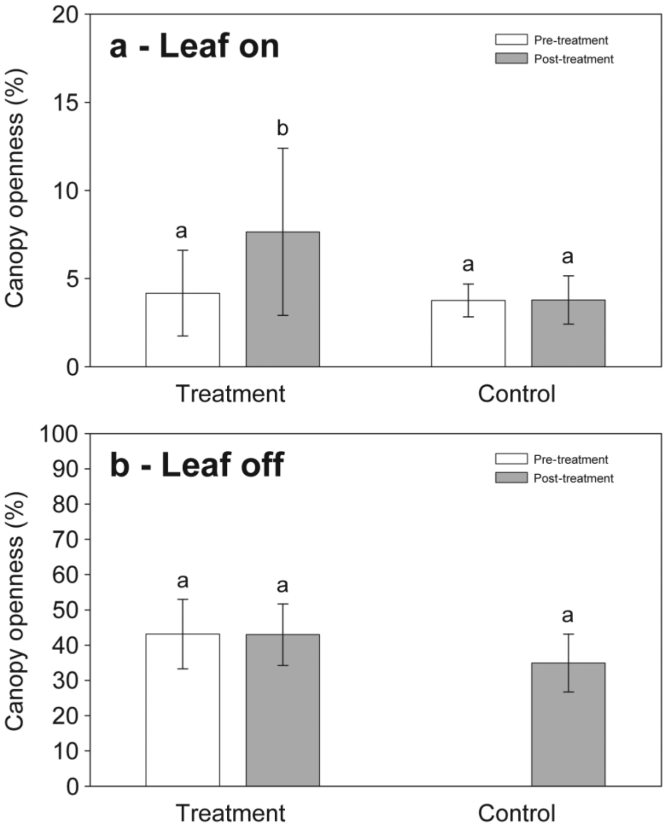
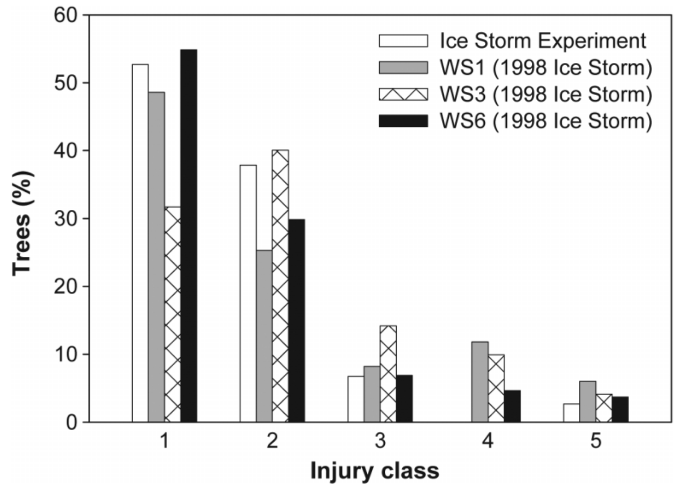


Fig. 6. Percentage of trees in each damage class after the ice storm experiment as compared with three watersheds (WS1, WS3, and WS6) that were assessed with the same method following the ice storm of 1998.



there was no significant difference (t test, $p = 0.16$) in ice accretion between plots when radial ice thickness was measured by melting the accumulated ice and calculating values with the aforementioned equation (Fig. 4*b*). Using this method, average radial ice thickness was 7.1 mm (±0.5 SE) in Plot 1 and 8.2 (±0.6 SE) in Plot 2. The accumulated ice lasted on trees a total of 9 days before entirely melting on 18 February 2011.

Vegetation response

Fine litter falling on the plots during the 9 day period when ice remained on the trees amounted to 171 (±33 SE) and 113 (±23 SE) g C·m^{-2} in Plots 1 and 2, respectively. The litter baskets in the control plots had negligible amounts of fine litter after the 9 day collection period, amounting to less than 0.04 g C·m^{-2}.

Coarse litter was collected on 21 June 2011, 132 days after the ice manipulation. Despite the different length of collection periods, coarse litterfall amounts were somewhat similar to fine litterfall, although more variable, with 325 (±138 SE) and 110 (±67 SE) g C·m^{-2} falling in Plots 1 and 2, respectively. As with fine litter, coarse litter collected on the control plots was negligible (<2 g C·m^{-2}).

Results from hemispherical photography indicated that when leaves were on the trees, percent canopy openness increased significantly after the treatment (Fig. 5). No significant difference was observed between pre- and post-treatment canopy openness in the control plots. During the leaf-off period, there was no significant difference in canopy openness between the pre- and post-treatment periods.

The qualitative damage assessment indicated that a little more than half of the trees had no visible damage and 38% had only minor damage (i.e., <50% crown injury) (Fig. 6). Approximately 10% of the trees had crowns that were severely injured or snapped off.

Discussion

Overall, results showed that, under appropriate climatic conditions, it is possible to experimentally simulate a glaze ice event in a mature northern hardwood forest canopy with reasonably consistent and uniform ice coverage. Here, winter canopy spray treatments resulted in 7–12 mm of ice accretion. This is below the minimum cutoff for ice storm warnings (13 mm of ice) issued by the US National Weather Service for the northeastern United States. It is notable that the ice storm of 1998 coated a large area of the northeastern United States and eastern Canada with up to five times the amount measured in this experiment.

The simulated ice storm, even though it would not have triggered an official weather service warning, had a significant impact on the forest canopy. The average amount of fine litter collected over the 9 day period following the ice manipulation (142 (±29 SE) g C·m^{-2}) was similar to the long-term annual mean of 171 g C·m^{-2} collected at the HBEF (Fahey et al. 2005) (Table 2), indicating that as much fine litter was deposited to the soil surface in 9 days as is typically deposited in a year. The quality of this litter would be different, as it was primarily comprised of carbon-rich twigs and small branches, as compared with annual litterfall collections, which are dominated by more nitrogen- and nutrient-rich leaves that drop during fall senescence. The average amount of coarse litter (218 g C·m^{-2}) was considerably higher than the long-term mean (20 g C·m^{-2}) (Table 2). Results from the hemispherical photographs demonstrate that these increases in fine and coarse downed woody debris translated into increased canopy openness for at least the first growing season following the simulated ice storm, which log-

Table 2. Fine and coarse litterfall (g C·m^{-2} ± SE) for the ice storm experiment compared with the 1998 ice storm and longer term annual averages (1996–2000 for fine litter and 1995–2002 for coarse litter; Fahey et al. 2005).

	Ice storm experiment			
	Treatment	Reference	1998 ice storm	Annual mean
Fine litter	142±29	0±0	—	171
Coarse litter	217±107	1±1	434*	20

Note: For the ice storm experiment, fine and coarse litter were collected for 9 and 200 days, respectively, whereas the other values are expressed on an annual basis.

*Measured in the most heavily damaged zone.

ically would result in declines in photosynthetic capacity and hence annual net primary production.

Compared with the 1998 ice storm, we applied a comparable amount of water to the plots: 78–86 mm in this simulation compared with 83 mm recorded during the 1998 storm event, resulting in similar ice accretions: 7.1–11.6 mm in this simulation compared with 5.9–14.4 mm during the 1998 storm event. Mean simulation-derived coarse litter input was similar to that reported for the less impacted, lower elevation band at the HBEF and about half of what was measured in the most heavily damaged zone (Table 2). No fine litter estimates are available from the 1998 ice storm at the HBEF. Qualitative damage estimates resulting from this experiment were similar to those measured in three undisturbed watersheds at the HBEF after the natural ice storm event of 1998 (Fig. 6).

Conclusions

This study demonstrates the feasibility of simulating an extreme winter weather event — an ice storm — in a mature northern hardwood forest. Total amount of water added, ice accretion, and basic metrics of response (coarse woody debris, canopy damage assessments) were remarkably similar in the simulation compared with a natural event occurring in 1998 for which extensive site specific information was available. The experimental technique described here has the advantage that it could allow for future icing event simulations of different intensity and frequency in different forest types. In this experiment, a large volume of water (roughly 5 kL·plot^{-1}·h^{-1}) was applied to the forest canopy under very cold conditions in a short time span. To more closely simulate natural icing events, we recommend that water be applied as a fine spray over a longer time period and under warmer conditions that are more typical of natural ice storms. We also note that the three-dimensional structures constructed of wooden dowels that were raised up into the canopy prior to the icing event served as useful surfaces on which to measure ice accretion. Volumetric measurements of radial ice thickness on these devices were less variable than measurements made with calipers and are likely better because they are unaffected by uneven freezing and icicle formation that was observed.

Although our understanding and ability to predict the occurrence of extreme events such as ice storms is still limited, the scientific consensus remains that the frequency and intensity of these types of events are likely to increase (IPCC 2007; Smith et al. 2009; Yohe 2010; Cheng et al. 2011). As such, it is imperative to improve our understanding of the direct and indirect and short- and longer-term impacts of extreme events on natural and managed ecosystems. This study demonstrates the feasibility of a relatively simple approach to simulating an ice storm in a northern hardwood forest in New Hampshire.

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