Spatial Analysis of Forest Damage in Central Massachusetts Resulting from the December 2008 Ice Storm

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Abstract - Ice storms are severe meteorological events that often result in damage to forested areas in the mid-latitudes. On 11 December 2008, an ice storm affected northern New York and New England and caused extensive damage to forested areas. We examined topographical and biological factors influencing the spatial distribution of forest damage due to the 2008 ice storm. We assessed 57 forest plots in 7 locations. Forest impacts from the storm were highly variable across the study area. Analysis of genera indicated that *Prunus* (cherry)*, Fraxinus* (ash)*, Fagus* (beech), and *Acer* (maple) were particularly susceptible to damage, while *Tsuga* (hemlock), *Pinus* (pine), and *Carya* (hickory) were more resistant. Elevation, latitude, and topographic exposure to post-storm winds after ice-loading were the dominant factors influencing damage levels.

Introduction

Large-scale forest disturbances play a key role in determining the structure, diversity, and function of the ecosystem. They represent a continuous yet punctuated process that exerts both destructive and creative forces on the landscape (Carreiro and Zipperer 2011). Severe meteorological events such as ice storms, hurricanes, microbursts, tornados, and flooding are primary causes of tree mortality in North American forests (Gandhi et al. 2007). Ice storms result from a stratified mixing of warm, moist air and cold, dry air producing liquid precipitation that freezes upon contact with solid features at or near the earth's surface (Glickman 2000). Typically, the effects of these storms are spatially heterogeneous, particularly in complex terrain, where exposure to damage varies among landforms (Stueve et al. 2007). Topographic factors such as slope (Lafon 2004) and aspect (Issacs et al. 2007, Stueve et al. 2007) have been shown to impact the level of damage. Biological factors including stand size (Foster 1988), tree species (Rhoades and Stipes 2007), and tree species diversity (Lafon 2004) also influence the degree of resulting damage, as does the spatial scale over which the analysis is conducted (Issacs et al. 2014).

Ice-storm impacts include downed trees and broken limbs and branches that create gaps in the canopy that can have a significant impact on forest ecology. These events can trigger changes in species distribution and animal-population dynamics (Beaudet et al. 2007, Faccio 2003). Plant species diversity may change as regeneration occurs (Rhodes et al. 2002, Takahashi et al. 2007). The damage also influences animal-population dynamics as a result of changes in the abundance of debris, availability of forage, and any hydrologic alterations that occur (Warren and Kraft

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2006). Ice storm damage increases the risk of insect infestation, and the resulting fallen debris adds to the risk of potential forest fire (Rhodes et al. 2002).

Research on ice-storm disturbance heterogeneity, spatial distribution, and causes can be differentiated into site-specific studies or regional approaches that employ remote sensing to examine effects on a regional scale. Site-specific studies utilize field assessment of a limited number of sites or plots over an affected area or a random selection of trees over the entire study area (Rhoades and Stipes 2007). Sample-plot configurations have included transects (Lafon 2004) as well as square (Rhoades et al. 2002, Weeks et al. 2009) or circular (Hooper et al. 2001, Rebertus and Shifley1997) plots.

Stueve et al. (2007) determined that topography exerts an important control on the spatial variability of ice-storm damage. Post-storm changes in atmospheric conditions such as temperature, and wind direction and speed also affect damage levels (Carvell et al. 1957, Hauer et al. 1994, Jones 2009). In addition, ice loading is an important factor in branch breakage, and total loading varies with tree structure and surface area (Jones 2009, Lemon 1961, Melancon and Lechowicz 1987, Milton and Bourque 1999, Siccama et al. 1976). Rebertus and Shifley (1997) found *Tilia americana* L. (American Basswood) to be the most susceptible species, followed by *Ulmus americana* L. (American Elm), *Acer saccharum* Marshall (Sugar Maple), and *Quercus rubra* L. (Red Oak), whereas *Carya ovata* (Mill.) K. Koch (Shagbark Hickory) and *Quercus alba* L. (White Oak) were the least vulnerable. Irland (2000) identified *Acer rubrum* L. (Red Maple), *Betula populifolia* Marshall (Grey Birch), and Sugar Maple as having low-to-average resistance to ice damage; *Fraxinus americana* L. (White Ash), Red Oak, and *Pinus strobus* L. (Eastern White Pine) as showing average to strong resistance; and *Tsuga canadensis* (L.) Carrière (Eastern Hemlock), White Oak, and *Picea* sp. (spruce) as exhibiting strong resistance.

The 11–12 December 2008 ice storm that caused the damage we studied developed from the interaction of a cold front and a cyclonic system. A cyclonic system developed in the southeastern US and tracked northeast, passing over the mid-Atlantic region late on 11 December and southern New England the following morning (Grumm and LaCorte 2010). The initial event was characterized by heavy precipitation—hourly precipitation rates were 1–2 cm per h for several hours (Abel and Ellement 2008). Freezing rain was the dominant type of precipitation in an area extending from northeastern Pennsylvania through the Hudson Valley and into western and central Massachusetts and southern Vermont and New Hampshire (Grumm and LaCorte 2010).

The Worcester, MA, airport weather station recorded that precipitation started on 11 December at 1210 EST in the form of freezing rain. Winds were from the northeast (wind direction: 40–60°) at 9–26 km per h (6–17 mph) (Fig. 1). Precipitation continued in the form of freezing rain until the next morning, 12 December, stopping at ~1033 EST. Precipitation totals for the duration of the storm were 3.18 cm. After the front passed, winds shifted to the northwest (wind direction: 300–330º) with speeds of 17–27 km per h (11–17 mph) and gusts up to 35 km per h (22 mph) (Fig. 2). We obtained data on storm duration, wind, and precipitation from

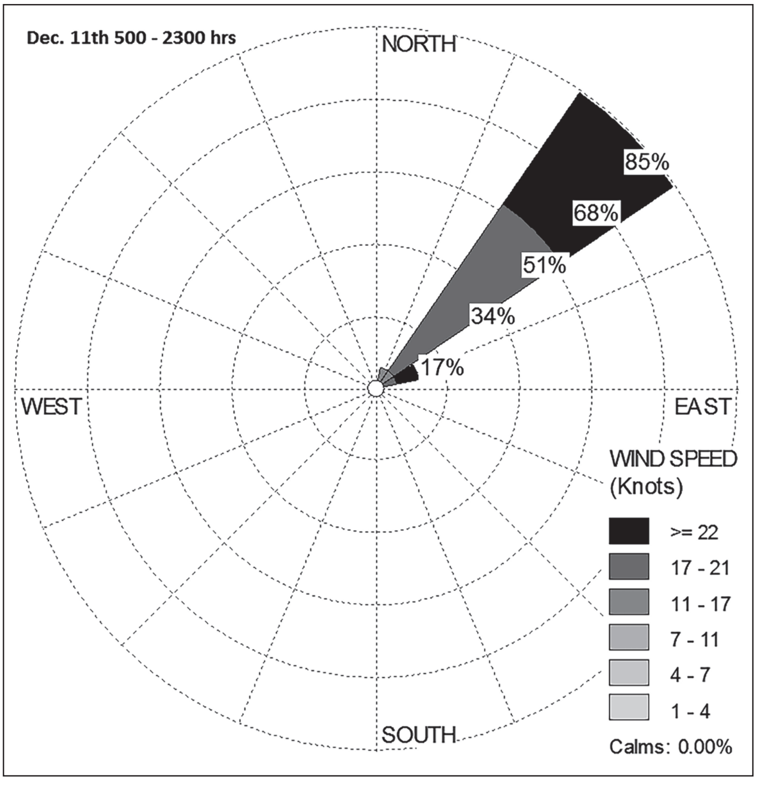

Figure 1. Ice-storm duration wind-rose diagram, based on data from Worcester Airport quality controlled local climatological data retrieved from http://cdo.ncdc.noaa.gov/qclcd.

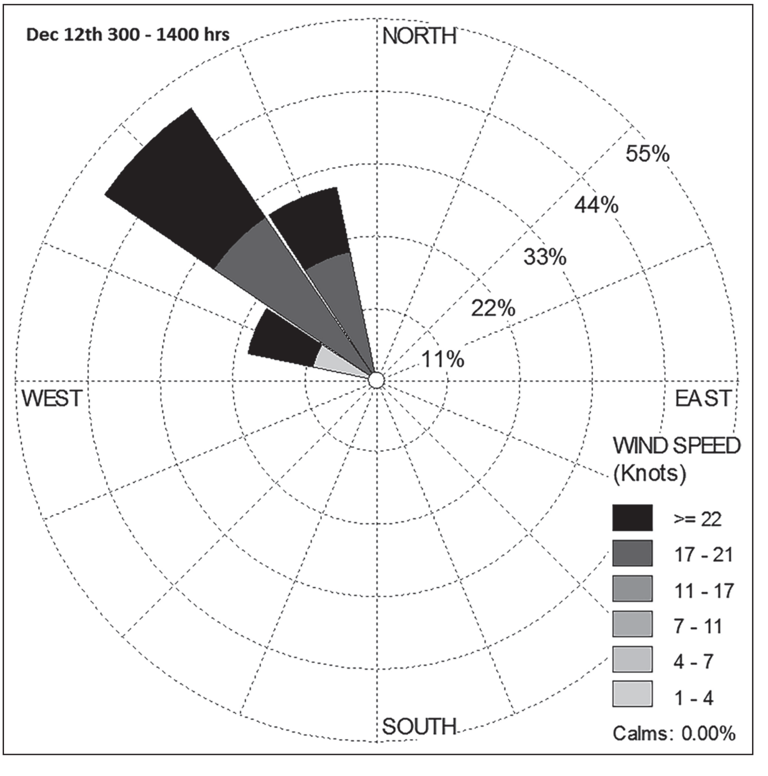

Figure 2. Post-storm wind-rose diagram, based on data from Worcester Airport quality controlled local climatological data retrieved from http://cdo.ncdc.noaa.gov/qclcd.

the National Oceanographic and Atmospheric Administration (NOAA) quality-controlled local climatological data (QCLCD) online-access site (NOAA 2013). The QCLCD does not track ice thickness, a primary factor in damage variation (Proulx and Greene 2001). The US Army Corps of Engineers' Cold Regions Research and Experiments Lab (CRREL) modeled equivalent radial ice-thickness based on the precipitation type and duration for stations, such as Worcester Airport, with detailed hourly data and freezing-rain sensors (Jones 2009). The CREEL simple model estimated 17.0 mm radial ice-thickness, and the sensor model estimated 12.2 mm; both are low-end estimates because the sensor was not functioning for 4 h during the storm (Jones 2009).

The variation in tree damage following ice storms is caused by a combination of physical and biological factors. We hypothesized that tree damage resulting from the 2008 ice storm was more dependent on post-storm wind exposure than exposure during the storm event because the winds following passage of the storm front were stronger and acted on ice-loaded trees. The objectives of this study were to: (1) quantify the variation in ice-storm damage across the study region; (2) document the impact of the ice damage by species and vegetation association using vegetation classification and ordination; and (3) examine the role of topographic and physical setting including latitude, elevation, slope, and aspect in the spatial variation in damage across an extensive study area. We applied the concept of topographic exposure to combine the impacts of the topographic setting with specific storm-event wind speed and direction, and introduced an evaluation of pre- and post-storm wind exposure in our damage assessment.

Field-site Description

We analyzed 57 forest plots in 7 locations in central Massachusetts that were impacted by the 11–12 December 2008 ice storm. We assessed the sites between June and September 2009. Our sites are located in an area bounded by the City of Worcester in the east, State Route 9 in the south, the Quabbin Reservoir in the west, and State Route 2 in the north (Fig. 3). We chose this area for analysis because it is topographically diverse and ice-storm effects there were significant and varied. We established our damage assessment and long-term study plots in large sections of forest held in conservation ownership; all plot locations were designated open space, state-owned, land trust properties, or privately owned land that is part of the Massachusetts Chapter 61 program, a program where property owners declare their land holdings as conservation land in return for a lower property-tax rate. We obtained the boundaries of the sites from the MassGIS open-space data layer (MassGIS 2005b).

The elevation in the study area varies from 612 m at Mount Wachusett, in the northeast section of the study area, to 150 m near the Quabog River, in the southeastern section of the study area. Mean elevation across the study area is 267 m. We derived elevation data from the MassGIS digital terrain model (DTM, MassGIS 2005c), a gridded dataset developed from photogrammetric processing of 2005 digital imagery (MassGISa 2005). We applied a 3 x 3 low-pass filter to the

DTM to remove inherent sinks and spikes and provide a more useful surface for landscape-scale analysis and derivation of slope and aspect. We classified land-use/land-cover based on the 2005 MassGIS land-use dataset (MassGIS 2009) and the multi-resource land-cover (MRLC) dataset (Homer et al. 2012).

Forest is the dominant land-cover type in the region, accounting for 68,900 ha or 71% of the area. Massachusetts' forests are comprised of 4 major forest types: northern hardwoods (*Fagus* [beech] *Betula* [birch] *Acer* [maple]), central hardwoods (*Quercus* [oak] and *Carya* [hickory]), northern conifer (*Picea* [spruce], *Abies* [fir], *Juniperus* [cedar], and *Larix* [tamarack]), and temperate conifers (White Pine, *Pinus resinosa* Sol. Ex Aiton [Red Pine], and Eastern Hemlock) (Cogbill et al. 2002). For this study area, the dominant forest types are northern hardwoods in the north and at higher altitudes grading into temperate conifers and central hardwoods in the southern part of the study area.

Methods

We used a geodatabase created in ArcGIS version 9.1 in the Worcester State University (WSU; Worcester, MA) GIS lab to designate 10-m-radius sample plots

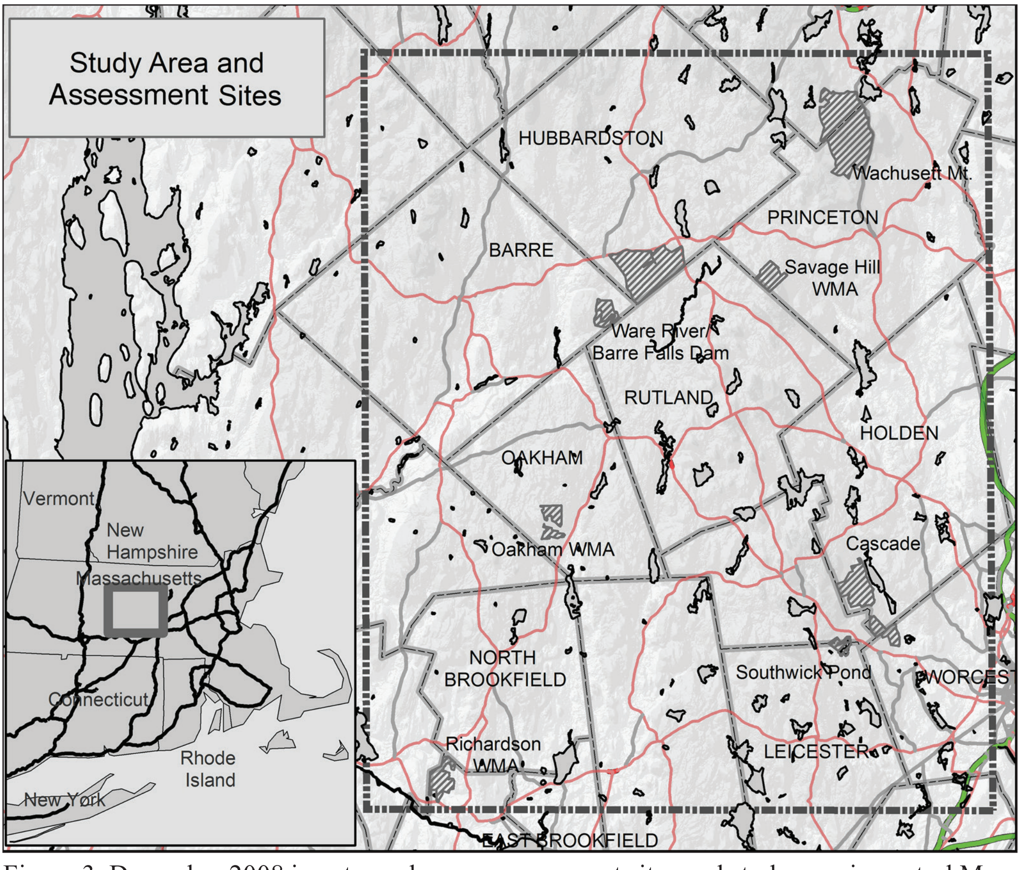

Figure 3. December 2008 ice-storm damage-assessment sites and study area in central Massachusetts with town boundaries data from MassGIS.

at a number of sites in a variety of physical settings based on factors that could influence the level of damage, such as slope (Lafon 2004) and aspect (Issacs et al. 2007, Stueve et al. 2007). Given the documented influence of tree species (Rhoades and Stipes 2007) and tree species diversity (Lafon 2004) on ice-damage severity, we used forest type as the third criterion. The screening-criteria datasets were slope and aspect derived from the DTM and a land-cover dataset created from the multi-resolution land characteristic (MRLC) dataset. MRLC is a landcover and associated-raster dataset derived from nationwide, multi-temporal Landsat imagery developed to provide consistent nationwide landcover-classification information. We classified slope as low (<5%), medium (5–10%) and high (>10%), and aspect as north, south, east, or west. We employed the landcover classes used in the MRLC dataset: deciduous, evergreen, and mixed forest. We combined the landcover, slope, and aspect layers to produce unique physical-settings categories.

We used the DTM and weather data from 2 regional weather stations to calculate the topographic exposure (TopEx) and wind speed in the study area for the duration of the storm. Topographic exposure is a measurement of the level of protection in a geographic area provided by the surrounding topography (Mikita and Kilmanek 2010). This variable has been widely used to assess the potential forest damage due to wind exposure (Ruel et al. 2000) and model the resulting damage from storms (Boose et al. 1994, Merry et al. 2011). TopEx is commonly quantified by measuring the elevation angle to the highest topographic feature in each of the 8 cardinal directions, and summing the angles (Chapman 2000). Boose et al. (1994) implemented the EXPOS topographic exposure model for hurricane Hugo in Puerto Rico and for the New England hurricane of 1938. Mikita and Klimanek (2010) applied the same concept to examine vegetation-zone variations by using the hillshade function in ArcGIS to create a TopEx dataset by summing re-classed hillshade images for the 8 cardinal directions into a summed-exposure dataset.

We used the hillshade method in ArcGIS (Mikita and Klimanek 2010) for our analysis. The 5-m DTM was our input dataset, and extracted datasets included slope and aspect of 5-m-grid cells. We used wind data from the Worcester and Westfield airports to determine the input azimuth-values for the time period of the storm; an inflection angle of 5 was used. To examine the sequence and timing of the storm, we made a modified TopEx calculation based on the predominant wind direction during the storm and after the change in wind direction as the front passed because wind direction and speed were available in hourly increments for the duration of the storm. We normalized the wind-exposure factors to the wind speed and summed them to determine the storm and post-storm wind azimuths. This approach was based on the computational methodology of Vigiak et al. (2003) in their examination of wind speed around windbreaks in an agricultural area in East Anglia, UK, where detailed wind-speed and direction measurements were available. The calculation for wind vector wr_j for direction j is defined in the following equation:

$$wr_j = \sum_{i=1}^{n} V_{ij},$$

where *V* is the wind velocity in m s^{-1}, *n* is the total number of hours *i* in direction *j*. We calculated a total wind-vector as a sum for all directions *j* in the wind rose weighted by the percentage of the time the wind was moving from direction *j*.

We selected the individual plot locations a priori to represent the diversity of physical characteristics present in the sites, including slope, aspect, and forest type; each characteristic type was represented by a minimum of 5 plots. We established 10-m-radius circular plots at each sampling site and assigned a plot ID and physical-setting category to each one. We identified to species, measured for diameter, and assessed for ice-damage level all trees with a diameter at breast height (DBH) > 5 cm. Based on the approach of Rhoades and Stipes (2007), we set damage-level classes as: <10%, 10–25%, 25–50%, or >50% limb loss; full crown-loss, and entire tree uprooted. We considered ≥25% damage to be major damage when 1 or more main, large limbs were broken off at the trunk, or in the case of conifers over 25% of branches.

We used an ArcPad 9.1 running on a Trimble Juno GPS unit to gather data in the field; the unit has been demonstrated to have an acceptable accuracy of 2.7–5.1-m root mean-square error (Klimanek 2010), which is well within the plot size. We selected the tree closest to the plot centroid based on the GPS reading, and used it to mark the center of the 10-m–radius plot. This methodology ensured that the positional accuracy of the GPS would not impact the determination of which trees were within the plot.

Prior to analysis, we normalized raw species-counts to percent abundance by plot and totaled the number of trees in each damage category for the plots. We converted individual DBH values to m^2 of basal area and summed them across plots. We determined the physical characteristics of the plots by mapping them in GIS and recording the slope, aspect, latitude, and summary wind-speed vectors for the storm duration and post-storm period from our GIS-data layers. Mean values for each factor within each 10-m-radius circular plot were calculated for all grid cells (5-m-cell size) intersecting the plot. For aspect, we used a majority value. We examined the physical characteristics of the plots, the vegetation clusters, and the ordination for linear correlations with heavy damage by calculating the Pearson product-moment correlation coefficient using SPSS statistical software from IBM Corp. (2012); ice damage across aspects was examined using a one-way ANOVA on 8 directions.

We classified and conducted an ordination of the tree species and plot results to reduce the dimensionality of the data and examine the vegetation structure and its variation by plot across the study area. We classified plot results by species abundance using a 2-step analysis. We employed hierarchical cluster-analysis to examine the hierarchical relationship of species abundance between plots using between-group linkage via Euclidean distance. We applied the approach of Cogbill et al. (2002) to produce final clustering categories by k-means clustering using dendrogram-hierarchy cluster analysis to determine linkage distance (LD).

We used canonical correspondence analysis (CCA) in SPSS (IBM 2012) to ordinate vegetation-abundance values for dominant species and physical factors. Canonical correspondence analysis is a multivariate-analysis technique that relates the composition of the ecological community to variations in environmental or habitat measures (ter Braak 1986). This tool provides a visual representation of relationships and patterns within and among variable groupings, and provides a means of examining the impact of environmental factors on community composition.

Results

We examined a total of 57 plots at 7 sites across the study area. Plot elevation ranged from 193 m in the Richardson Wildlife Management Area (WMA) to 607 m at Wachusett Mountain. There was an average of 1050 trees per ha across all plots; the maximum was 3726 trees/ha at the peak of Wachusett Mountain, where we also recorded the smallest average DBH. Ice damage resulting from the 2008 ice storm varied greatly across the study area (Table 1, Fig. 4), though overall, 17.3%

Table 1. Ice damage severity (%) across 7 sites in central Massachusetts and the number of trees assessed. WMA = wildlife management area.

Site name	Number of trees	>50% damage	10–50% damage	<10% damage
Cascades	202	16.8	17.3	65.9
Gods Acre/ Southwick Pond	50	18.0	4.0	78.0
Oakham WMA	280	5.0	5.0	90.0
Richardson WMA	271	1.8	0.7	97.5
Savage Hill WMA	284	38.1	33.1	33.8
Wachusett Mountain State Forest	501	17.4	19.2	63.5
Ware River Watershed/ Barre Falls Dam	421	5.7	11.9	82.4

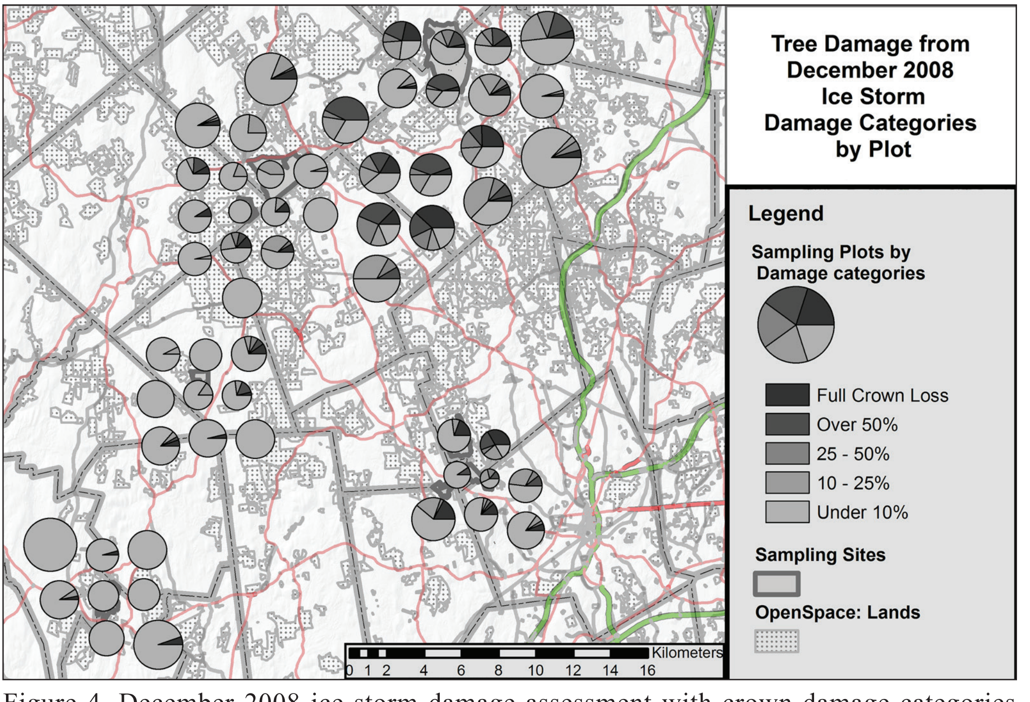

Figure 4. December 2008 ice-storm damage-assessment with crown-damage categories by plot.

of the trees sustained major damage. The most heavily damaged plot was in the Savage Hill WMA, where 57% of the trees had over 50% damage: 38% were either uprooted or had full crown-loss, and 19% had >50% damage but not full crown-loss. Only 20% of the trees at this site experienced low levels of ice damage. The Wachusett Mountain and Cascades sites showed similar significant impact, with 17.4% and 16.8% of the trees heavily damaged and 63.5% and 65.9% minimally damaged, respectively. Both sites are on the eastern edge of the study area (Fig. 3). The lowest level of damage occurred at the Richardson WMA, where over 97% of the trees sustained only minimal damage. This site is in the southwest corner of the study area at the lowest elevation of any of the sites.

Examination of the hierarchy cluster-analysis dendrogram showed separation into 4 groupings at an initial LD of 17, including a large group comprising 57% of the plots (Fig. 5). At an LD of 15, the distribution resolved to 6 clusters, with a maximum cluster of 42% of plots. We carried out an additional classification using k-means clustering with 6 clusters. An ANOVA comparison on species abundance between the cluster methods (k-means and hierarchical) using the species present at over 5 plots indicated better discrimination using k-means, with 6 of the 13 species showing a significant difference between groups at $P \leq 0.01$.

The eigenvalues for the first 2 CCA ordination axes of species scores were 0.91 for axis 1 and 0.79 for axis 2 (Fig. 6). These axes represented 41.0% and 35.6% of the variance, respectively. Correlations of canonical variables with species indicated that Red Maple ($r = 0.82$, $P \leq 0.01$) and White Pine ($r = -0.55$, $P \leq 0.01$) were significantly correlated with axis 1, and Red Oak ($r = -0.72$, $P \leq 0.01$) and *Prunus serotina* Ehrh. (Black Cherry) ($r = -0.39$, P≤ 0.05) were significantly correlated with axis 2. For environmental variables, post-storm TopEx was correlated with axis 1 ($r = 0.38$, $P \leq 0.05$) and both elevation ($r = -0.80$, $P \leq 0.01$) and latitude ($r = -0.62$, $P \leq 0.01$) were significantly correlated with axis 2.

The CCA diagram suggests a strong separation of heavy damage into 2 groupings (Fig. 6). One is in the upper left of the plot and is associated with latitude and the post-storm TopEx. A second grouping of heavily damaged plots is associated with the elevation gradient extending along the second axis into the lower left quadrant of the diagram. The environmental gradients for slope and storm-duration TopEx are associated with the upper right quadrant of the CCA diagram, with low levels of damage (Fig. 6). Species scores demonstrated less distinction in CCA space with some grouping of mature beech and hemlock stands and of oak and cherry southern hardwoods.

There was no significant relationship among topographic aspect and ice damage (data not shown). The results of the Pearson correlation are shown in Table 2. Slope and basal area were not significantly correlated with major ice-damage, although both plot latitude ($r = 0.372$) and elevation ($r = 0.432$) were (Table 2). The TopEx and wind factor based on the wind direction and speed for the storm duration were not correlated with heavy damage. However, the post-storm TopEx was correlated with damage ($r = 0.239$, $P \leq 0.05$). Hierarchical-cluster membership was also significantly correlated with major ice-damage (one-way ANOVA; $F = 3.079$, $P \leq 0.05$).

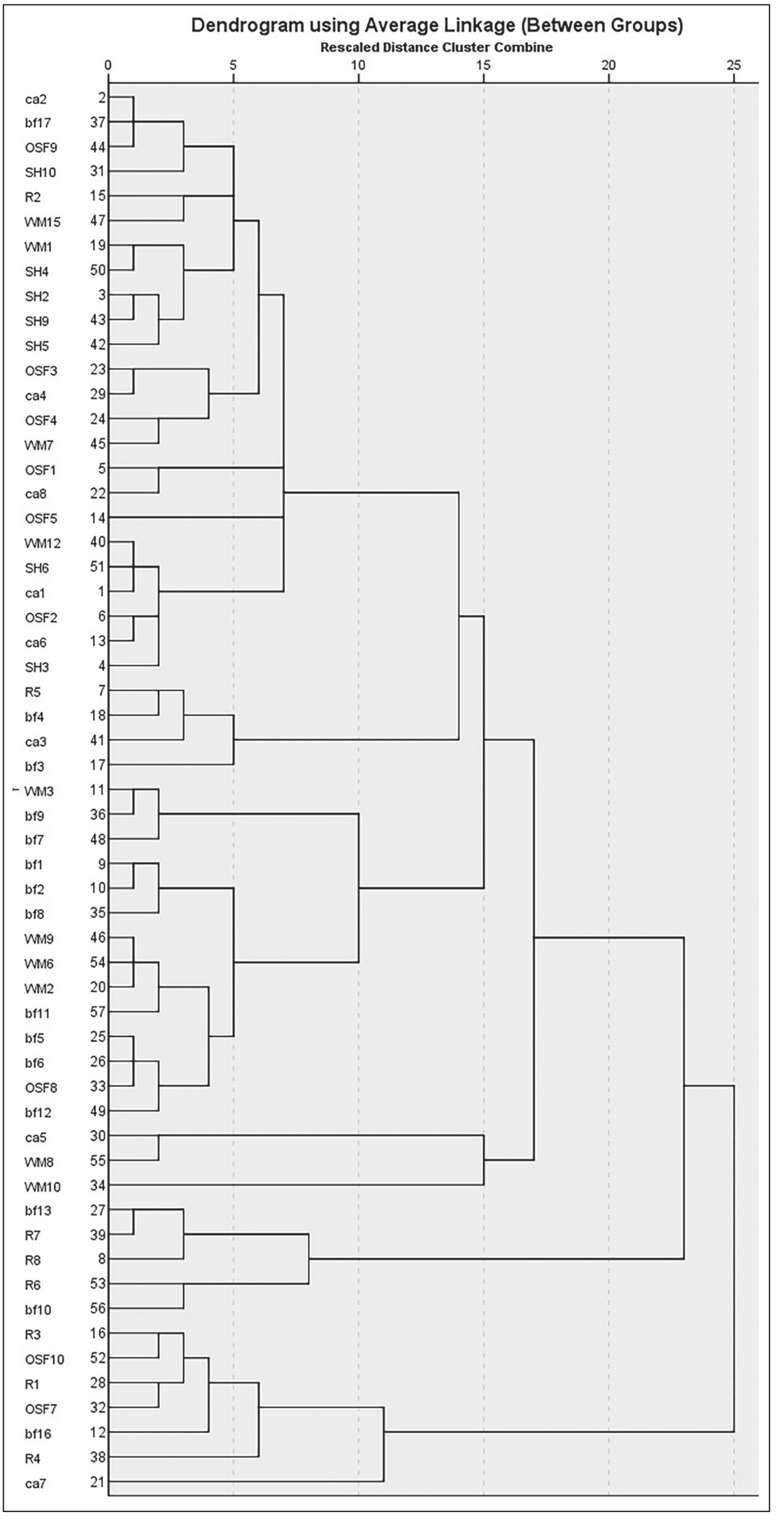

Figure 5. Hierarchical cluster of species composition across 57 plot locations in central Massachusetts.

The damage results for the most common species ($n > 10$), are shown in Table 3. The species most susceptible to ice damage was Black Cherry, with 61% of trees sustaining major damage. Over 25% of ash, *Fagus grandifolia* Ehrh. (American Beech), and American Basswood trees sustained heavy damage. Less than 10% of Eastern Hemlock, White Pine and Shagbark Hickory individuals sustained heavy damage. Across the 5 most-abundant genera, the conifers sustained significantly less damage than the 3 most-abundant deciduous genera—maple, oak, and birch (Fig. 7). Maple showed the heaviest damage, with 24% of the trees assessed

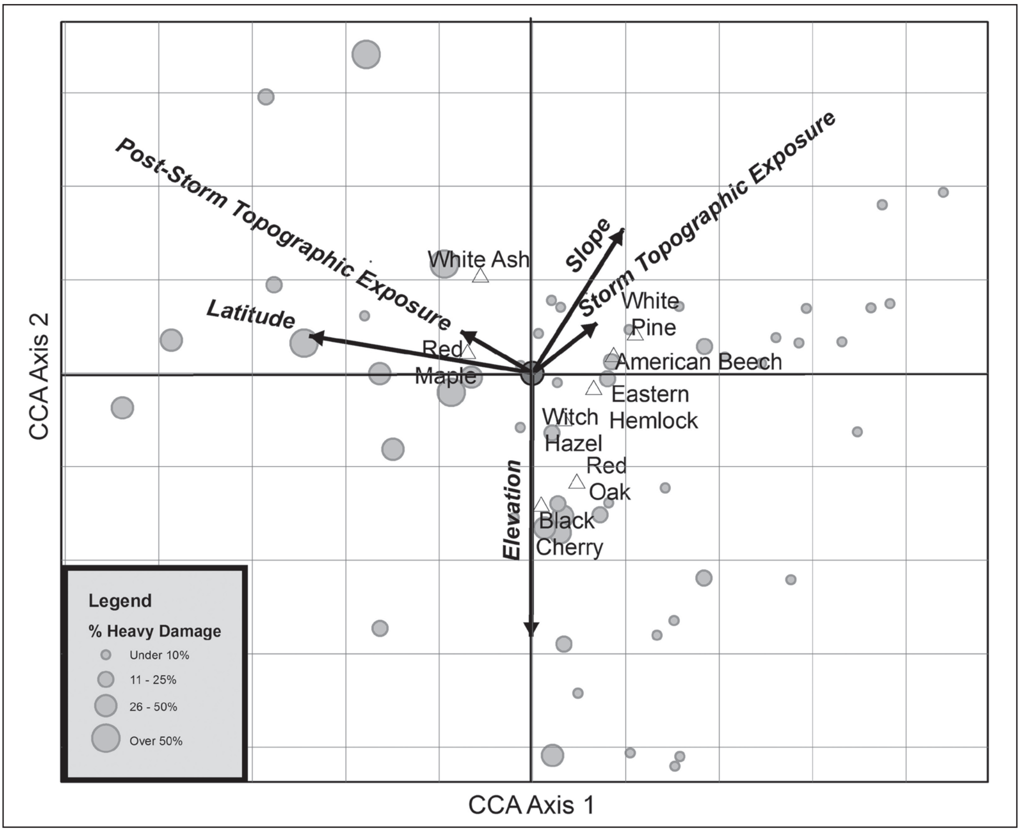

Figure 6. Canonical correspondence analysis axis 1 and axis 2 with species scores, environmental-variable vectors, and plots symbolized by ice-damage severity.

Table 2. Correlation of percent of plot trees with >25% damage with stand and physical factors. * indicates $P \leq 0.05$, ** indicates $P \leq 0.01$.

	>25% damage	Basal area	Latitude	Elevation	Storm TopEx	Post-storm TopEx	Slope
>25% damage	-	0.145	0.372**	0.432**	-0.084	0.239*	-0.107
Basal area		-	0.032	-0.025	0.005	0.005	-0.277*
Latitude			-	0.768**	-0.016	0.162	-0.012
Elevation				-	0.133	0.133	-0.021
Storm TopEx					-	0.129	0.054
Post-storm TopEx						-	-0.332*

Table 3. Ice damage by tree species in decreasing order of severity with number of individuals (*n*) and average diameter at breast height (DBH).

Species	*n*	>25% damage	Average DBH (cm)
Prunus serotina (Black Cherry)	18	61.1	23.7
Fraxinus americana (White Ash)	13	46.2	29.0
Fagus grandifolia (American Beech)	50	36.0	13.7
Tilia americana (American Linden)	20	30.0	20.2
Fraxinus pennsylvanica Marsh. (Green Ash)	14	28.6	35.0
Ulmus rubra Muhl. (Slippery Elm)	11	27.3	24.0
Betula papyrifera Marshall (Paper Birch)	20	25.0	30.2
Acer rubrum (Red Maple)	480	24.6	21.7
Acer saccharum (Sugar Maple)	59	22.0	33.2
Betula populifolia (Grey Birch)	25	20.0	9.2
Betula lenta L. (Sweet Birch)	91	18.7	28.6
Quercus rubra (Red Oak)	330	17.6	26.3
Populus grandidentata Michx. (Bigtooth Aspen)	21	14.3	32.3
Quercus alba (White Oak)	76	13.2	27.8
Tsuga canadensis (Eastern Hemlock)	196	7.1	15.6
Pinus strobus (Eastern White Pine)	225	7.1	23.9
Carya ovata (Shagbark Hickory)	34	5.9	18.5

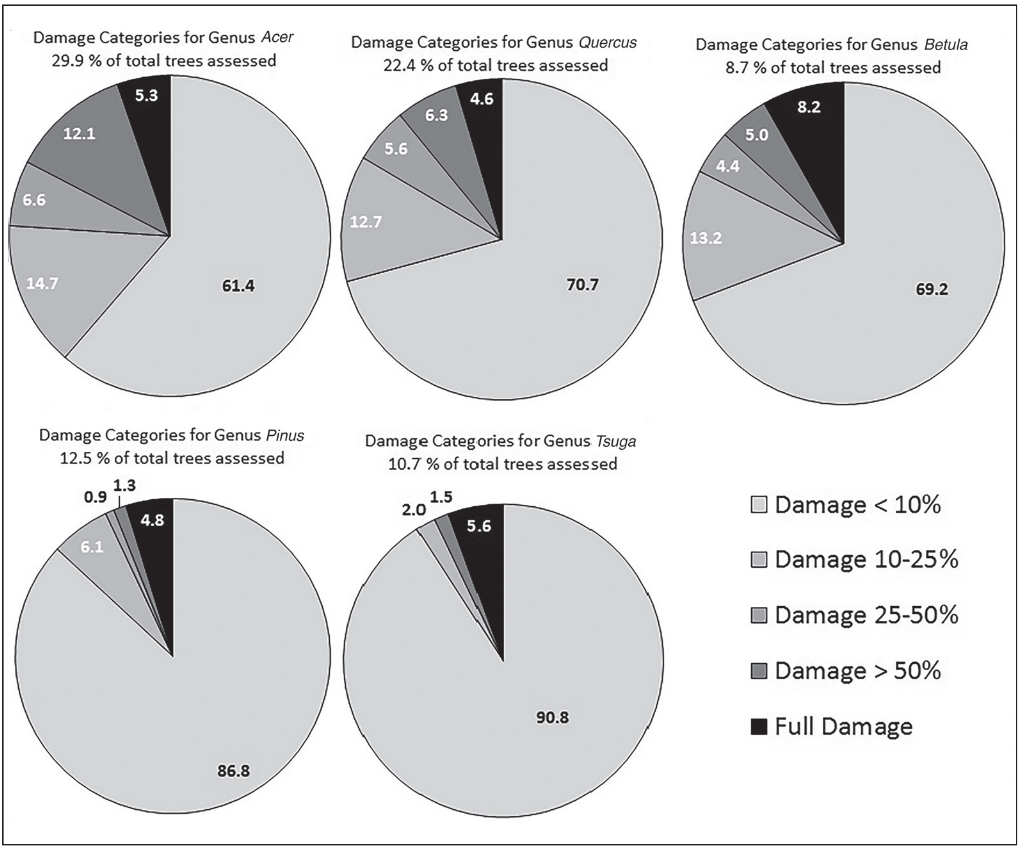

Figure 7. Ice-damage severity of major tree genera across all plots in central Massachusetts.

experiencing >25% limb damage. Oak (16.5%) and birch (17.6%) had similar levels of significant (>25%) damage, but almost half of that for birch was full crown-loss. Degree of damage in pine and hemlock was similar, with only 7.0–7.1% of trees exhibiting >25% damage.

Discussion

Forest impacts from the December 2008 ice storm in central Massachusetts resulted in highly variable damage across the study area. Elevation was the most significant factor influencing ice damage due to the effects of atmospheric lifting (Stueve et al. 2007). The severity of damage was higher in the northern portion of the study area due to the storm location, frontal configuration, and the relationship between elevation and latitude within the study area. Although the site is in an exposed, high-elevation northern location where mean tree-size was smaller and tree density was greater, damage levels at Wachusett Mountain were lower than expected, though still relatively high compared to most of the other sites. Slope did not have a strong effect on the distribution of damage, likely due to the direction of storm movement mirroring the south-southwest to north-northeast trend of topographic features in the landscape and the gradual increase in elevation along the storm track. Aspect also often controls the amount of ice-storm damage (Isaacs et al. 2007) but did not prove significant in our study. The complex interplay between shifting winds including the abrupt change in wind direction from the northeast during the storm to the northwest after the storm, combined with the east to west movement of this particular storm along a south-southwest to north-northeast trending terrain system minimized the influence of aspect in this particular storm. These results are consistent with previous studies that identified elevation as the most important factor in damage variability, with aspect having variable impact across studies, and slope as having little effect (Irland 2000, Perry 2006).

Vulnerability results showed cherry, ash, birch, and maple to be highly vulnerable to damage, which is consistent with results reported by Hauer et al. (1994) and Irland (2000). Eastern Hemlock and White Pine, conifers abundant in the region, were resistant to damage. This finding reflects the structural differences between coniferous and deciduous trees, including lack of major limbs and the shielding impact and resiliency of needles and smaller branches. Hauer et al. (1994) and Irland (2000) identified Eastern Hemlock as having strong resistance to ice damage and pines exhibiting average resistance. We found the hardwoods oak and hickory to be resistant to damage. In a study of hardwoods in Missouri, Rebertus and Shifley (1997) found Shagbark Hickory to have the lowest susceptibility index.

When we examined the impact of TopEx and compared the direction and intensity of winds during and after the ice storm, we found that damage was correlated with post-storm winds rather than the wind direction during the storm. The wind rose (Fig. 3) indicates that post-storm winds were stronger on average; these stronger winds were acting on trees that were then coated with ice. Ice storms are unique with respect to other severe meteorological events in that wind magnitude is not the primary factor in the likelihood of damage to individual trees. In a study where ice-thickness gradient was determined from a detailed Hydro Quebec measurement network, Proulx and Greene (2001) showed that the thickness of ice-loading and tree size were the primary controls of damage, with wind playing a minor role.

Both our results and those of Proulx and Greene (2001) suggest that under certain conditions, most damage likely occurs after the actual storm event. The extent of this phenomenon would vary given pre- and post-storm wind intensity, direction, temperature, and other meteorological conditions such as cloud cover. Further analysis would be needed to support this conclusion; previous studies of variation in ice-storm damage have not specifically examined topographic exposure as a physical factor. Previous studies combining directional wind-speed data, topographic exposure, and forest damage examined tropical storms (Boose et al. 1994) or were regional studies modeling potential forest damage (Mikita and Klimanek 2010, Perry 2006). We found no other studies of ice-storm damage and meteorological data based on TopEx when we searched the published literature.

Our analysis of the impact of post-storm versus storm-duration winds during the December 2008 ice storm support the hypothesis that significant damage to forests occurs after the storm event when trees are most-heavily ice loaded. Our results, while preliminary, are an interesting finding that warrants further examination. In most severe weather events, the maximum wind-speed acting on the forested area occurs at the height of the storm and is the major cause of damage. Tree vulnerability is based on species, structure, and exposure. Ice storms are unique among severe weather events in that accretion of ice progressively alters the vulnerability of a tree during the duration of the storm. More-detailed examination of the variation in ice accretion and wind direction and intensity would facilitate assessing these findings. In our study, elevation and latitude were strongly correlated, which magnified the influence of each factor on damage. Examining an event where these factors demonstrate a greater degree of independence would allow better comparison between individual physical factors with the influence of TopEx. Topographic exposure as a factor in forest damage has not been previously applied to ice storms, yet it seems to offer researchers an additional tool for examining variation due to individual storm events acting on a particular terrain as opposed to independent factors of the physical landscape and ice loading.

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