Species, stand, and regional response to forest damage in southwestern Quebec following the 1998 ice storm

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ABSTRACT

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The response of four tree species, *Acer saccharum* Marsh., *Acer rubrum* L., *Populus tremuloides* Michx., and *Betula populifolia* Marsh. to ice storm damage was studied in the Northern Hardwood Forest of southwestern Quebec, Canada. The focus of the study was the analysis of tree damage resulting from ice accumulation ranging from 2 to 88 millimeters radial thickness at the species, stand, and regional levels, and to assess the role of the combined effect of ice and wind stress. The study showed that ice accumulation was the primary determinant of tree damage (measured as the mean percent of canopy removed) and that individual species respond differently to ice-loading stress. Stand position (edge versus interior) did not influence susceptibility to damage. The study also showed that smaller stems are more inclined to suffer bending injury, and larger stems are more prone to snapping and crown loss damage. Finally, the research demonstrated that wind was not a significant factor influencing forest periphery damage, but tree damage in forest interiors *is* influenced by the combined effect of ice accretion and wind-loading. The results of the study offer a unique perspective on tree response to a single ice storm in which stem damage is linked to specific ice accretion measurements over a widespread area.

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This thesis is dedicated to the memory of my son, Michael.
September 28, 1970 – August 12, 1995

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INTRODUCTION

Ice storms, also referred to as glaze storms, are a recurring natural disturbance in the deciduous forests of North America (Abell 1934, Whitney and Johnson 1984). Ice storms are large-scale occurrences (Lemon 1961) that can cause major damage to forest communities and urban trees (McKay and Thompson 1969, Hauer *et al.* 1994). The January 1998 ice storm that hit southeastern Ontario, southwestern Quebec, and the northern regions of adjacent New York and New England is an example. This destructive freezing precipitation event caused extensive tree damage over a very large area. In Quebec alone, more than 1.7 million hectares of forestland were damaged by the ice storm (Ministère des Ressources Naturelles 1998 unpublished report).

Numerous researchers have investigated the impact of freezing precipitation on forest systems. The focus and method of the studies have varied, but the common general conclusion of the authors is that the extent of forest damage resulting from an individual icing event is due to the interaction of such factors as ice thickness, wind velocity, topography, and species' intrinsic resistance to injury. Understanding the short-term and the long-term ecological consequences of destructive icing events is important for developing effective forest management strategies.

The current understanding of ice storm meteorology and the impact of ice accretion on trees are briefly summarized in the following literature review. First, I outline the meteorology of ice storms, their spatial occurrence, and return times. Next, I survey the early anecdotal literature, and the more recent scientific research, discussing the effects of ice-loading on individual species and on forest stands. The combined impact of ice and wind is considered. Finally, I summarize what is understood of the ecological consequences of ice storm disturbances.

Ice storms

Meteorology

Freezing precipitation can occur with stationary fronts, occluded fronts or, rarely, cold fronts. Typically, however, freezing precipitation occurs in advance of a winter warm front associated with a sub-tropical low-pressure system (Lemon 1961, Low *et al.* 1986, Yip 1995). A rising warm air mass, with temperatures greater than 0 degrees Celsius, flows over the top of a colder ground-level layer of sub-zero temperature air. Water droplets form aloft in the warm air mass and when the droplets fall through the layer of cold air they become super-cooled liquid water drops (Yip 1995). When the drops come in contact with any surface or structure, ice is formed almost instantaneously in response to the specific heat and thermal conductivity of the impacted surface (Lemon 1961).

There are two types of icing that have the potential for causing significant damage; glaze ice and rime ice. Glaze is usually clear, smooth, hard, and highly adhesive with a specific gravity of approximately 0.9. Rime is opaque, filled with air bubbles, moderately adhesive, and has a specific gravity of approximately 0.3 to 0.8 (McKay and Thompson 1969). The type of ice that forms is largely dependent on the relationship between the time required for a droplet to freeze and the rate of accretion. If the accretion rate is less than the length of time needed for a water drop to freeze, glaze ice accumulates, whereas if the rate of accretion is greater than the time required for a droplet to freeze, rime ice is more likely to form (McKay and Thompson 1969). For the purpose of this paper, no distinction is made between glaze ice and rime ice. The common general term ‘ice’ is used instead.

The combined effect of ice and wind increases the risk and intensity of ice storm damage to trees. Similar damaging effects are likely to occur with conditions of heavy icing and light winds as with moderate ice accretion accompanied by stronger winds (Lemon 1961). Typically, wind speeds during ice storms are relatively low, but the chance of strong winds increases with the length of time the ice accumulation persists (Elfashny *et al.* 1996). Normally, ice accretion is followed by warm temperatures as the warm front passes, but occasionally ice remains long after an icing event in which case wind speeds are a factor as they intensify the stress on branches (Schaub 1996). Research has shown that the ice deposit residency period of most icing events in Quebec is limited to one day, but maximum residency varies enormously; the longest was 37 days, and the average was 3.3 days (Elfashny *et al.* 1996).

Ice forms mainly on the windward side of exposed objects and, depending on the angle of exposure to the wind ice accretion on a surface or structure may exceed the precipitation rate. Small droplets in particular, tend to be readily deflected by the flow of air, while larger drops are far more likely to collide with obstructions (McKay and Thompson 1969).

Icing intensity is highly variable between, and within, individual freezing precipitation events (Laflamme 1995). In summary, ice storm hazard, that is ice and wind load potential, is the result of a complex set of interrelated meteorological factors unique to individual icing events.

Regional occurrence

Freezing precipitation events are confined to areas of the world having the potential for the above-stated meteorological conditions to develop. Regions most commonly subjected to the prerequisite atmospheric conditions are located in the middle to extreme latitudes. In North America, ice storms are a recurring disturbance in most deciduous forests north of the Gulf of Mexico (Abell 1934, Whitney and Johnson 1984, Bruederle and Stearns 1985). Destructive freezing precipitation is a recurrent hazard in southern Ontario and Quebec and in the adjacent northeastern American states (Yip 1995). Although the recurrence of freezing precipitation in this area suggests there is a link between icing events and proximity to large bodies of water (the Great Lakes and St. Lawrence River in this case), there is no agreement in the literature about such a relationship. For instance, Yip (1995) maintains that more icing generally occurs near large bodies of water. However, McKay and Thompson (1969) state that there is no general rule and note that sometimes proximity to open water is seen as a factor that *reduces* the risk of freezing precipitation.

In southern Quebec, freezing precipitation is a possibility from mid-October to mid-April. For the Montreal region the freezing precipitation 'season' is approximately 5½ months. In the St. Lawrence valley the frequency of icing events is 6 events per icing season except in areas where increased elevation can significantly increase the frequency of freezing precipitation (Laflamme and Périard 1996).

Return times

For any geographic location, icing events vary considerably in their frequency and intensity (Lemon 1961, Hauer *et al.* 1994). Various return times for different icing intensities and locations are discussed in the literature. For example, Whitney and Johnson (1984) estimate that destructive ice storms, with greater that 1 centimeter radial ice accumulation, occur approximately once every 20 years in the Appalachians. Rebertus *et al.* (1997) state that the return time for severe ice storms in the American midwest is probably 20 to 25 years. A 1991 storm in New York that deposited approximately 2 to 2.5 centimeters of ice is termed a rare extreme occurrence event - a 50 to 100 year icing event (Seischab *et al.* 1994, Sisinni *et al.*1995). In the St. Lawrence valley, 'major' ice storms have a return time of 20 to100 years (Melancon and Lechowicz 1987). But, the problem with these return times is that they are anecdotal in nature as they deal with regional return times rather than point measurement return times.

Laflamme and Périard (1996) offer the most comprehensive analysis of icing event return times applicable to the eastern deciduous forest region of the St. Lawrence valley. Working with 20 years of freezing precipitation data, extreme values distributions show that in the St. Lawrence valley there is more than one ice-load zone. For instance, according to the Laflamme and Périard (1996) analysis, the 'major' ice storms with 20 to100-year return times that Melancon and Lechowicz (1987) refer to, would infer approximately 45 to 65 millimeters of ice accumulation at Montreal and 35 to 45 millimeters of ice accumulation at Quebec City. It is generally understood that in the St. Lawrence valley, damage-causing freezing precipitation events have a return time of about 20 years. The return time for an ice storm of the intensity of the January 1998 storm is greater than 200 years (Laflamme and Périard 1996).

Ice accretion and tree damage

Methods

Literature dating back to the beginning of the century shows that there has been a long-standing curiosity about the effect ice storms have on trees. Early ice storm studies are primarily descriptive in nature (Von Schrenk 1900, Harshberger 1904, Illick 1916, Rhoades 1918, Rogers 1922, 1923, 1924). Two of these studies involved collecting ice-covered branches and twigs and weighing each one twice; once with the ice on, and again after the ice had melted (Von Schrenk 1900, Harshberger 1904). Harshberger (1904) reports ice-loading increased the weight of branches up to 100 times, and branch loss reduced many crowns by 90 percent. In another study, trees at stand edges were found to be more susceptible to ice storm damage because of asymmetrical crown development; and larger diameter trees tended to suffer greater damage (Illick 1916). By contrast, Rhoades' (1918) research found that young trees with flexible branches were just as damaged by ice accretion as older, larger diameter trees. With respect to 'the most unusual weather phenomenon within the recorded history of the region' Rogers (1924) states that the northern New England ice storm of 1922 caused some birches to snap but generally the birch stems tended to bend to the ground. Maples were the first trees to break under the weight of the accumulating ice followed by the stronger species giving way under the weight of the ice-load. These early studies although anecdotal in nature, clearly illustrate that destructive ice storms can have significant consequences for forest communities.

The more recent ice storm literature and the current research adopt a more analytical approach to freezing precipitation events and forest damage. Specific research interests and methodologies vary, however. For instance, Whitney and Johnson (1984) investigated the impact of icing on regeneration dynamics and tree mortality by assessing tree response in ice-damaged areas and comparing the observations to similar but unscathed forest stands. Bruederle and Stearns (1985) investigated post-ice storm biomass decrease using a modified forest fuel sampling technique to quantify forest floor macro-litter accumulation. Hauer *et al.* (1993) conducted a 'before and after' comparison of previously inventoried urban trees to uncover patterns of icing injury. Typically findings are presented in terms of a species' degree of susceptibility described as low, moderate, and high, or some similar ordinal system (Lemon 1961, Whitney and Johnson 1984, Bruederle and Stearns 1985, Boerner *et al.* 1988, Hauer *et al.* 1993).

Immediate impacts of icing

Species differ in their resistance to the hazards of ice storms (Bruederle and Stearns 1985, Boerner *et al.* 1988, Hauer *et al.* 1994). Early successional species such as elms, birches, and several poplar species are highly susceptible to damage, whereas deciduous forest equilibrium species incur similar moderate damage (Lemon 1961, Whitney and Johnson

1984). An individual's susceptibility to damage is influenced by several factors including branching architecture, branch length/diameter ratio, crown size and shape, tree health and age, wood properties, and the position of the tree in the canopy (Lemon 1961, Bruederle and Stearns 1985, Cannell and Morgan 1989, Seischab *et al.* 1993, Rebertus *et al.* 1997).

Strong horizontal branching and the large surface area associated with many fine branches, increases exposed surface area and increases susceptibility to icing injury (Lemon 1961, Cannell and Morgan 1988). Owing to their large surface area in the winter some authors have argued that gymnosperms tend to suffer more ice-related injury than angiosperms (Illick 1916, Lemon 1961, Bruederle and Stearns 1985, Boerner *et al.* 1988). By contrast, Hauer *et al.* (1993) reporting damage inflicted by approximately 15 millimeters of ice, stated that the largely decurrent branching habit of angiosperms generally predisposes them to greater risk than conifer species for icing injury. Likewise, Rogers (1924) found pines and spruces were relatively resistant to damage because, he hypothesized, their even branches bore the extra weight uniformly.

Stand-level and species-level damage is linked to crown form. Forest edges are thought to receive more damage because of unbalanced ice-loading of asymmetrical crowns. More developed branching and the longer length of the branches on the forest edge influence the extent of crown damage and susceptibility to stem failure at forest perimeters (Seischab *et al.* 1993). Several studies found tree breakage more pronounced at the edges of stands owing to the fact the edge trees have fuller crowns on the open side and thus the uneven ice-loading causes greater structural stress on the larger more horizontal branches (Hauer *et* *al.* 1994, Sampson and Wurtz 1994). The smaller, narrower crowns of interior forest trees are less likely to be damaged than the crowns of more open-grown edge trees (Hauer *et al.* 1993). Crown asymmetry of trees located on slopes predisposes them to greater damage because of unbalanced ice-loading (Bruederle and Stearns 1985, Seischab *et al.* 1994).

Tree health is often a function of age (Bruederle and Stearns 1985) and structural failure is thus closely linked to tree and stand characteristics that commonly develop as part of normal aging. Seischab *et al.* (1993) found that limbs having rotten cores or weak crotches suffered greater damage. Similarly, Bruederle and Stearns (1985) reported that decay and insect damage weakens trees and thus increased susceptibility to ice storm damage. An ice build-up of 6 to 12 millimeters breaks smaller tree and shrub branches, effectively pruning weakened limbs, while an accumulation of 12 to 25 millimeters of ice promotes breakage of healthy branches and causes bole failure of young well-formed individuals (Croxton 1939, Lemon 1961, Hauer *et al.* 1994). The resultant wounds significantly weaken the individual and greatly increase risk of insect and fungal attacks (Campbell 1937, Melancon and Lechowicz 1987, Rebertus *et al.* 1997).

Species-specific wood characteristics are influenced by an individual's age, health, and growing conditions (Lemon 1961). Wood strength is an important factor in a species' ability to withstand the stress of ice accumulation but, by itself, cannot explain variation in damage (Bruederle and Stearns 1985). Contrary to common perception, wood strength is not the primary determinant influencing a tree's ability to resist damage. Tree characteristics such as fine branching, wide crowns, and weak crotches can result in species ordinarily viewed as having superior wood strength, being susceptible to ice-loading damage (Hauer *et al.* 1994). There is no obvious relationship between specific gravity, modulus of rupture, or modulus of elasticity of a tree species and its predisposition to icing damage (Lemon 1961, Hauer *et al.* 1993).

An individual's position in the canopy influences its susceptibility to icing injury (Bruederle and Stearns 1985). Forest understory stems were found to be less susceptible to damage (Downs 1938, Boerner *et al.* 1988, Seischab *et al.* 1993, Hauer *et al.* 1994). In stand interiors most of the ice is deposited on the top of the canopy thus affording a degree of protection for the understory trees. But, on the other hand, understory trees are very prone to injury resulting from overstory branch and stem failure. As a rule, understory individuals are spared direct damage but they are at heightened risk for indirect damage. Indirect injury occurs when trees or limbs fall on other individuals, most often the shorter sub-canopy stems. Direct damage is related to tree characteristics such as crown size, symmetry, growth form, position in canopy, stem diameter, weak crotches, age, and degree of decay (Whitney and Johnson 1984, Bruederle and Stearns 1985, Hauer *et al.* 1993, Seischab *et al.* 1993, Rebertus *et al.* 1997). Boerner *et al.* (1988) reported that sub-canopy damage exhibited great variation from one species to another.

There is a significant correlation between damage to individuals and stem diameter (Boerner *et al.* 1988, Hauer *et al.* 1993, Seischab *et al.* 1993). Specimens with a larger stem diameter are more prone to serious injury (Hauer *et al.* 1993, Sisinni *et al.* 1995).

Smaller diameter individuals are more likely to be understory trees and, therefore, they are less likely to sustain damage irrespective of the species. Smaller diameter specimens tended to bend under the weight of the ice or to be injured by ice-loaded branches and crowns of larger trees falling onto them (Downs 1938, Sisinni *et al.* 1995).

The literature offers little consensus of opinion on species' susceptibility to icing damage. To provide one example, three different studies resulted in three different conclusions for red maple. Whitney and Johnson (1984) found it to be one of the most resistant species, Seischab *et al.* (1993) stated red maple was moderately damaged, and Siccama *et al.* (1976) reported red maple to be (relatively) greatly damaged. These observations, however, do support the widely held consensus that species' susceptibility to ice storm damage is linked to a complex set of biotic and abiotic factors.

Subsequent mortality

Ice storms may be an important cause of mortality in forest stands (Nicholas and Zadaker 1989), but there are few studies investigating the longer-term impacts of ice storm damage on trees and forest communities.

Spaulding and Bratton (1946) assessed forest conditions two full growing seasons after an ice storm deposited a radial thickness of 6 to 57 millimeters of ice. The response to heavy crown loss suffered by sugar maple, beech, white ash, and basswood was significant. Sugar maple failed to sprout adequately to maintain reasonable vigor and mortality was judged likely in the near future. As well, small trees with less than fifty percent of live crown were considered unlikely to resume vigorous growth. The mortality estimates, however, represent projections.

Another study found that by the end of the second growing season approximately 38 percent of ice-damaged trees had died and species-specific mortality ranged from 6 to 76 percent (Whitney and Johnson 1984). Boerner *et al.* (1988) found that individuals suffering extensive damage such as snapped stems or uprooting were unlikely to survive. In more general terms, increased mortality was found to follow greater injury (Rogers 1923, Abell 1934, Lemon 1961, Whitney and Johnson 1984).

Combined effect of ice and wind

Icing damage increases with the additional stress of wind loading (Deuber 1940, Bruederle and Stearns 1985, Seischab *et al.* 1993, Hauer *et al.* 1994). As well, high winds after an ice storm and persistent sub-freezing temperatures greatly increases the risk of damage (Downs 1938, Goebel and Deitschman 1967, Sisinni *et al.* 1995). Damage from the combined effect of ice and wind is closely related to tree characteristics such as crown size and branching form (Seischab *et al.* 1993). Larger crowns have a greater surface area exposed to wind-loading stress and therefore wind-associated damage risk increases with increased crown size (Peltola and Kellomäki 1993, Hedden *et al.* 1995, Richter 1996). Large branches are less flexible than smaller ones and thus have a diminished ability to transfer stress to the proximal stem (Richter 1996). Although branches are cantilevers that allow for a degree of bending and twisting in response to ice and wind loading (Redden 1989), tree damage increases with stronger winds (Hauer *et al.* 1994).

From the windward edge of forest stands into the forest the velocity of prevailing winds will decrease 85 to 90 percent by a distance equal to approximately 12 times tree height (Nägeli 1953). Goebel and Deitschman (1967) found that ice-loaded conifers on windward edges suffered the greatest damage. Another study reported stem-bending was most severe on the windward side of ice-accreted stands (Carvell *et al.* 1957).

Generally, wind is more hazardous for taller, dominant trees than it is for shorter individuals (Carvell *et al.* 1957, Campbell *et al.* 1993, Hedden *et al.* 1995). The taller canopy trees are exposed to the strongest winds (Dyer and Baird 1997). Wind velocity decreases rapidly from the top of the canopy downward (Peltola and Kellomäki 1993). Sub-canopy trees are less exposed to winds and, therefore, their risk of injury is decreased (Bruederle and Stearns 1985, Hedden *et al.* 1995).

Nicholas and Zedaker (1989) studied two icing events where ice accretion of 70 to 100 millimeters had severely damaged forest stands. The authors reported that generally within a stand, tree stems and crowns were all snapped or broken in a similar direction. This observation suggests that wind-loading influenced storm damage.

Ecological consequences of ice storm disturbance

Natural disturbances such as recurrent ice storms shape the structure, development, and composition of forest stands by creating canopy gaps (Spaulding and Bratton 1946, Whitney and Johnson 1984, Boerner *et al.* 1988, Seischab *et al.* 1994). The ecological impact of icing events depends on forest type, stand structure, icing intensity, and local variation in damage severity (DeSteven *et al.* 1991).

Canopy gaps created by destructive ice storms affect the forest community in different ways. Spaulding and Bratton (1946) found that sudden exposure of stems and soil to the heat and drying effect of the sun was the most detrimental short-term consequence of large canopy openings. A long-term consequence is that successional patterns are influenced by destructive freezing precipitation events in regions where they occur frequently (Rebertus *et al.* 1997). Some authors have argued that succession is accelerated when canopy pioneer species suffer greater damage than the more resistant later successional understory individuals (Carvell *et al.* 1957, Lemon 1961, Whitney and Johnson 1984, DeSteven *et al.* 1991). An alternative viewpoint states that extensive canopy removal allows additional light to reach the understory encouraging the growth of shade-intolerant pioneer species and thus tending to invigorate earlier successional populations and retard forest succession (Abell 1934, Siccama *et al.* 1976, Boerner *et al*, 1988, DeSteven *et al.* 1991).

Ice storms appear to influence forest succession by promoting both acceleration and slowing of successional processes because of spatial heterogeneity of landscape features (aspect and elevation) and, hence, disturbance intensity (Boerner *et al.* 1988, Rebertus *et al.* 1997). This heterogeneity of disturbance may contribute to maintaining forest diversity (Siccama *et al.* 1976, Whitney and Johnson 1984, Boerner *et al.* 1988, DeSteven *et al.* 1991).

Summary and objectives

Ice storms are a recurring disturbance in most eastern North American deciduous forests north of the Gulf of Mexico. Many studies have investigated the impact ice storms have on forest communities yet there is little agreement in the literature on species resistance and stand susceptibility to icing injury.

Ice storm forest disturbance is difficult to analyze because susceptibility to icing damage is not influenced by any single readily quantifiable factor. It is difficult to compare study conclusions because of the complex interrelation of the contributing variables such as ice-load and wind-load intensities, tree attributes, and stand characteristics. Nevertheless, continued research directed at understanding the ecological consequences of destructive icing events is important for developing effective forest management strategies. For instance, the issue of whether or not salvage operations are justified following ice storms depends on understanding both the impact storms of varying frequency and intensity have on forest stands, and the concomitant implications of storm damage such as an increased vulnerability to decay and insect attack. Similarly, understanding how trees respond to ice storms has practical applications for maple sugar producers and for limiting the hazard of wire and structure damage associated with stem and branch failure in urban areas.

During the January 1998 ice storm, the mean daily temperature remained below freezing from the 5th to the 9th of the month. As much as 100 millimeters of precipitation fell during this five-day period, 40 millimeters of which fell as rain (Table 1). This ice storm provided a unique opportunity to observe tree damage and to analyze the impact of ice accumulation ranging from 0 to greater than 75 millimeters (radial measurement).

The objectives of this study are:

1. To test the hypothesis that ice-loading stress influences tree damage.
2. To determine whether there are species-specific differences in resistance to damage.
3. To determine whether stand position (edge/interior) influences susceptibility to damage.
4. To determine the relationship between bole size and stem damage.
5. To compare wind and crown asymmetry as contributing causes of stem bending and snapping.

METHODS

Study area

The field observations were carried out in southern Quebec in an area within a radius of approximately 100 kilometers from the island of Montreal (45° 30' N, 73° 40' W) (Figure 1). This region forms part of the Northern Hardwood Forest where the dominant species are sugar maple, *Acer saccharum* Marsh., red maple, *Acer rubrum* L., gray birch, *Betula populifolia* Marsh., paper birch, *Betula papyrifera* Marsh., American basswood, *Tilia americana* L., beech, *Fagus grandifolia* Ehrh., trembling aspen, *Populus tremuloides* Michx., and bigtooth aspen, *Populus grandidentata* Michx. Forest in the study area is fragmented and consists mostly of abandoned agricultural fields of 30 to 90 year-old second growth stands with canopy heights averaging approximately 12 to15 meters.

The study region is the flat terrain of the St. Lawrence River valley except in the most northwest and southeast areas, where the topography is gently rolling. Climate type is humid continental with mild summers. The mean monthly temperature is sub-freezing for four months a year. There is no dry season and the mean annual precipitation is 104 centimeters.

Fieldwork

The fieldwork was completed, after leaf-out, in June and July of 1998. Using a map (Laflamme and Périard 1998) showing radial ice accretion in millimeters for the January

1998 ice storm as a guide, 29 forest stands were sampled along a gradient of mapped ice thickness from 0 millimeters to greater than 75 millimeters (Table 2). To avoid topographical effects, all the stands were on flat terrain. Each forest area selected was larger than 300 meters by 300 meters so that wind speeds in the deep interior of the stand would be about 10 percent of the free wind velocity (Nägeli 1953). Since the prevailing winds were NNE and NE during the ice storm (Table 1), several stands having an edge facing this direction were specifically included among those sampled (Table 2).

The location of each stand was noted on a map (Figure 1) and the compass direction perpendicular to the edge was recorded. Trees were sampled along the stand edge and in the stand interior. The edge area was defined as a width equal to the average height of the trees. The interior was defined as the area greater than 150 meters from any edge into the forest.

Each stem was identified by species and circumference at breast height (CBH) was noted. Damage was recorded using three categories: percent of crown loss, stem bending, and stem snapping. For each individual the percentage of crown loss was estimated visually by assessing damage in the crown (missing limbs and/or limbs broken yet still attached by bark), in combination with an evaluation of the macro litter on the forest floor directly below. Care was taken to ensure that the recorded damage was of recent origin by disregarding any injuries that did not have the characteristic pale-coloured wound associated with fresh injury. For each stem that was damaged by arching, bending assessments were made by estimating crown position in terms of the number of meters its top was from the forest floor. Boles recorded as snapped were those that had been completely severed or those that were snapped but still attached by a small amount of bark.

The analysis focused on the four species that were common in the majority of the stands. These target species were sugar maple (*Acer saccharum* Marsh.), red maple (*Acer rubrum* L.), trembling aspen (*Populus tremuloides* Michx.), and gray birch (*Betula populifolia* Marsh).

In order to analyze the effect of crown asymmetry versus wind as a determinant of direction of bending and snapping I ascended the SSE facing slope (downhill direction 150°), and descended the WNW slope (downhill direction 280°), of Lake Hill at the Mont-Saint-Hilaire Biosphere Reserve (45° 33' N, 73° 10' W) recording the compass direction toward which bent or snapped stems were oriented. Only the direction of stem bending and snapping was relevant, therefore the injured stems were not identified by species. Similarly, for three stands located in areas of greater than 50 millimeters ice accretion, the compass direction toward which arched or snapped interior boles were oriented was recorded as was the orientation of stems injured by bending and snapping at one stand edge.

Analysis I: Ice accretion and mean canopy removed

Stand-specific ice accretion, in millimeters, was determined by interpolating radial ice accretion values from isolines shown on a Hydro-Québec map (Laflamme and Périard 1998) and from additional ice accumulation information provided by Gilles Périard, (Services Conseils en Climatologie, Ste-Foy, Québec). According to Périard, unofficial ice accumulation measurements and immediate post-storm inspection of tree damage strongly support the probability that the radial ice accretion thickness reached 90 or more millimeters in the western proximity of Highway 15 just north of the US border. Stands were grouped, by 10 millimeter intervals, using nine ice-accretion classes for radial ice accumulation from 0 to 90 millimeters.

For stand edges and stand interiors separately, the data were summarized to obtain the mean percent of canopy removed for each species, in each ice accretion class. In the stem bending and stem snapping damage categories, the percent of canopy removed was derived by assigning a crown loss value of 100 percent to stems bent to ≤ 4 meters above the ground, and to stems that were snapped. Small stems less than 30 cm CBH were excluded from the analysis.

(a) I arcsine-transformed (arcsin $\sqrt{p}$) the percent data (dependent variable) and used regression analysis to determine the significance of the statistical relationship of the percent of mean canopy removed (y) versus ice accretion (x). The median values of ice accretion classes were used for the regression analyses. Sugar maple, red maple, and trembling aspen at the edge, and sugar maple, red maple and gray birch in the interior were analyzed. Sample size was inappropriate for gray birch (edge), and trembling aspen (interior).

(b) I next used ANOVA to compare the slopes of the regressions for the species where I had an adequate sample size:

a) slopes of sugar maple, trembling aspen, and red maple (edge)

b) slopes of sugar maple, red maple, and gray birch (interior)

c) edge and interior (for sugar maple)

d) edge and interior (for red maple)

Analysis II: Damage type by species and size for the most damaged stands

For edge and interior separately, the data were lumped, by species, for the fifteen stands with ice accretion greater than 50 millimeters. Stems less than 10 cm CBH were eliminated and the remaining stems were grouped by CBH classes: ≤ 30 cm and > 30 cm. The data were then summarized in three categories:

1. proportion of stems bent to ≤ 4 meters off the ground
2. proportion of stems snapped
3. proportion of stems with ≥ 20 percent crown loss

A two-sample Z-test for difference of proportions was used to analyze the relationship of bole size and tree damage by species.

Analysis III: The roles of crown asymmetry and wind

To analyze the effect of crown asymmetry versus wind as a determinant of direction of bending and snapping the preferred orientation of the arched and snapped boles was determined for the two Mont-Saint-Hilaire slopes, the three stand interiors, and the one stand edge. The significance of the results was assessed using the Rayleigh test for preferred orientation (Hammond and McCullagh 1982).

Statistical methods

The preferred orientation analysis was completed as shown in Hammond and McCullagh (1982). The statistical package PHStat for Excel was used for all the other statistical analyses.

RESULTS

Ice accretion and mean canopy removed

Part I

To determine the statistical relationship of ice accumulation and the mean percent of canopy removed, simple linear regression analyses were completed for the edge and interior samples. Stems less than 30 cm CBH were excluded from the analyses.

Edge

For sugar maple, red maple, and trembling aspen the regression analyses (Figure 2) demonstrated significant ($\alpha = 0.05$) positive relationships for millimeters of ice accretion and the mean percent of canopy removed (see Table 3a for mean values). Ice accumulation accounted for 82.2% ($p = < 0.001$; $n = 9$) of the variation in sugar maple damage, 85.9% ($p = < 0.001$, $n = 9$) of the variation in red maple damage, and 73.8% ($p = 0.003$; $n = 9$) of the variation in trembling aspen damage (Table 4a). There were insufficient data for an analysis of gray birch.

Interior

For sugar maple, red maple, and gray birch the regression analyses (Figure 3) showed significant ($\alpha = 0.05$) positive relationships for millimeters of ice accretion and the percent of mean canopy removed (see Table 3b for mean values). Ice accretion explained 79.1% ($p = 0.001$; $n = 9$) of the variation in sugar maple damage, 57.5% ($p = 0.018$; $n = 9$) of the variance in red maple, and 47.7% ($p = 0.039$; $n = 9$) of the variance in gray birch (Table 4b). The trembling aspen data were insufficient for analysis.

Summary

For both edge and interior samples, the linear regression analyses showed that there was a statistically significant positive relationship between ice accumulation and the percent of mean canopy removed.

Part II

One-way repeated measures ANOVAs ($\alpha = 0.05$) were used to compare the slopes of the regressions. For stand edges, sugar maple, red maple, and trembling aspen were compared. As previously noted, gray birch was excluded due to insufficient data. Similarly, trembling aspen was omitted from the interior analysis that compared the slopes of sugar maple, red maple, and gray birch (see Table 5 for analysis summary).

Only two species, sugar maple and red maple, had both edge and interior sample sizes suitable to complete an analysis of variance comparing species-specific damage at stand edges versus stand interiors (see Table 6 for analysis summary).

a) The analysis demonstrated that at the edge of stands the mean percent of canopy removed for the three species, sugar maple, red maple, and trembling aspen, (see Table 3a for mean values), was significantly influenced by ice accumulation ($p < 0.001$; $n = 9$). As well, damage varied significantly between species ($p = 0.015$; $n = 3$).

b) For stand interiors, the percent of mean canopy removed for sugar maple, red maple, and gray birch, (see Table 3b for mean values) was also significantly influenced by ice accretion ($p = 0.015$; $n = 9$), but there was no statistically significant difference between species ($p = 0.120$; $n = 3$).

c) For sugar maple at edge and interior, the percent of mean canopy removed was significantly influenced by ice accretion ($p = 0.007$; $n = 9$). However, there was no significant effect of edge versus interior ($p = 0.431$; $n = 2$).

d) For edge and interior red maple, ice accretion significantly ($p = 0.003$; $n = 9$) influenced the percent of mean canopy removed, yet, as with sugar maple, there was no statistically significant difference in tree response between the edge stems and the interior stems ($p = 0.130$; $n = 2$).

Summary

Tree damage at both stand edges and stand interiors was significantly influenced by ice accumulation. The edge analysis showed that the species, sugar maple, red maple, and trembling aspen responded differently to ice-loading. In contrast, the analysis of the interior species, sugar maple, red maple, and gray birch, demonstrated that there was no significant difference among the species.

For sugar maple and red maple, comparisons of tree damage at stand edge to tree damage at stand interior showed that, for both species, the mean percent of canopy removed was significantly influenced by ice accretion. Stand position (edge versus interior) did not influence susceptibility to damage, however.

Damage type by species and size for the most damaged stands

A two-sample Z-test for difference of proportions was used to analyze damage type by species and bole size for the fifteen stands where the minimum ice accretion was greater than 50 millimeters radial thickness. Stems ≥ 10 cm CBH were grouped arbitrarily by the CBH classes: ≤ 30 cm and > 30 cm.

__Edge__

For stem classes ≤ 30 cm CBH and > 30 cm CBH (see Table 7a and Figure 4 for data summaries), two-tailed Z-tests (Table 8) demonstrated that the difference in proportion of damaged stems in the *bending* category was statistically significant for red maple ($p = 0.032$; $n = 89$) and trembling aspen ($p < 0.001$; $n = 249$). In both instances, the proportion of stems damaged by bending was greater for the ≤ 30 cm CBH class. The difference in proportion of bent stems was insignificant for sugar maple and gray birch. In the *snapping* category, of the four species only red maple ($p = 0.032$; $n = 89$) showed a statistically significant difference in damage between the two stem-size classes. The proportion of snapped boles was larger for the > 30 cm CBH stem class. For sugar maple, trembling aspen, and gray birch, difference in stem CBH did not significantly influence the proportion of snapped stems.

In the *crown loss* category, the null hypothesis of no difference was rejected for sugar maple ($p < 0.001$; $n = 242$), red maple ($p < 0.001$; $n = 89$), and trembling aspen ($p < 0.001$; $n = 249$). For all three species, the proportion of crown loss was higher for the > 30 cm CBH stems. Only gray birch demonstrated no significant difference in proportion of crown loss between the two stem-size classes.

Summary

For each damage category, not all four species demonstrated a statistically significant difference of proportions between the ≤ 30 cm CBH and the > 30 cm CBH stem classes. However, among the statistically significant findings, the smaller stems were more inclined to suffer bending injury, and the larger stems were more prone to snapping and crown loss damage (Figure 4).

Interior

For all four species the proportion of stems *bending* was greater for small than large trees (Figure 5), but two-tailed Z-tests (Table 9) showed that the difference was statistically significant only for red maple ($p < 0.001$; $n = 114$), gray birch ($p = 0.029$; $n = 172$), and trembling aspen ($p = 0.015$; $n = 36$). Stem size did not influence sugar maple damage; no significant difference in the proportion of bent stems was demonstrated.

For the *snapping* category, the null hypothesis of no difference was rejected for sugar maple ($p = 0.015$; $n = 280$), and red maple ($p < 0.001$; $n = 114$). Both species suffered more snapping damage in the > 30 cm CBH class. Z-tests for gray birch and trembling aspen were insignificant.

In the *crown loss* category, the difference in proportions was significant for two of the four species; sugar maple ($p < 0.001$; $n = 280$) and red maple ($p < 0.001$; $n = 114$). Stems > 30 cm CBH suffered greater crown loss for both of these species. For gray birch and trembling aspen the difference in proportion of damage stems was not statistically significant.

Summary

For stand interiors, in each of the three damage categories, not all four species demonstrated a statistically significant difference of proportion of damage between the ≤ 30 cm CBH and the > 30 cm CBH classes. Nonetheless, for the statistically significant findings, in the bending category the smaller stems suffered greater damage. In the snapping and crown loss categories, it was the larger CBH stems that incurred the greater proportion of damage (Figure 5).

The roles of crown asymmetry and wind

In order to assess the effect of crown asymmetry versus wind as a determinant of direction of bending and snapping the preferred orientation of arched and snapped boles was determined for two slopes (Mont-Saint-Hilaire), three stand interiors, and one stand edge (see Table 10 for summary of results).

Mont-Saint-Hilaire

Slope A

A downhill compass direction of approximately 150° represented the fall line of the slope. The total sample size of bent or snapped stems was forty-five. Analysis of the data showed that the preferred orientation (directional mean) of stem bending and snapping was 156.67 degrees. The Rayleigh test for preferred orientation demonstrated that 156.67° was a statistically significant mean angle (L-value = 80.7%; $p < 0.001$).

Slope B

The fall line of this slope corresponded to a downhill compass direction of approximately 280 degrees. The total of bent or snapped stems sampled was forty-six. The preferred orientation of the damaged boles was 262.95 degrees. The Rayleigh test for preferred orientation showed that 262.95° was statistically significant (L-value = 95.3%; $p < 0.001$).

Stand interiors

During the January storm the wind was blowing from the NNE – NE to the SSW- SW, or approximately from 40 degrees to 220 degrees. For *Stand A*, the mean angle for the injured stems was 228.06 degrees and the *L*-value was 95.0% ($p < 0.001$; $n = 20$). The directional mean for *Stand B* was 209.96 degrees with an *L*-value of 90.8% ($p < 0.001$; $n = 32$). Analysis for *Stand C* demonstrated a mean angle for the bent and snapped stems of 200.16 degrees and the *L*-value was 95.2% ($p < 0.001$; $n = 32$).

Stand edge

The edge sampled was perpendicular to 60° (NE) and a definite windward forest periphery during the January 1998 ice storm. Sample size was thirty-six. Analysis demonstrated that the preferred orientation of damaged stems, 57.07 degrees, was statistically significant (L% =99.2; $p < 0.001$).

Summary

For both *Slope A* and *Slope B*, the preferred orientation of arched and snapped stems was highly significant. In each instance, the degree of preferred orientation of damaged stems approximated the compass degree associated with the downhill direction of the incline.

The mean angle of damaged stems was statistically significant for each of the stand interiors. The mean angle approximated the compass direction in which the prevailing winds were blowing, SSW to SW, or about 220 degrees. For the stand edge, the degree of preferred orientation was highly significant and the directional mean closely paralleled the aspect of the forest edge. In short, where we might expect crown asymmetry (slopes and edges), the trees bent or snapped in the direction of the mass center of the crown. Only in stand interiors does the bending or snapping align with the prevailing (early January) wind.

DISCUSSION

Ice accretion and mean canopy removed

Ice accumulation is the primary determinant of tree damage measured as the mean percent of canopy removed. However, the analyses show that individual species respond differently to ice-loading stress. These general findings support the conclusions of numerous other studies (Rogers 1924, Whitney and Johnson 1984, Bruederle and Stearns 1985, Boerner *et al.* 1988, Hauer *et al.* 1994).

In particular, this study found that two maple species, sugar maple and red maple, were especially vulnerable to icing injury. Regression analysis demonstrated that ice accretion statistically explained 82.2% and 85.9% of the variation in the mean percent of canopy removed at stand edges for sugar maple and red maple respectively. These findings suggest that sugar maple and red maple and are highly susceptible to ice-loading injury, thus corroborating similar conclusions found in previous studies (Rogers 1924, Spaulding and Bratton 1946, Siccama *et al.* 1976). There are, however, contradictory studies. For example, Bruederle and Stearns (1985) and Hauer *et al.* (1994) reported sugar maple to be only moderately susceptible to ice storm injury.

Analysis of variance demonstrated that three edge species, sugar maple, red maple, and trembling aspen, responded differently to ice-loading while three interior species, sugar maple, red maple, and gray birch showed no significant difference in species-specific response to ice accretion. I propose that the impact of indirect tree damage likely influenced this finding at least to some extent. Indirect injury is a common fate for trees located in stand interiors, particularly for the understory individuals (Whitney and Johnson 1984, Hauer *et al.* 1993, Seischab *et al.* 1993, Rebertus *et al.* 1997). Indirect injury occurs when trees or limbs fall on other individuals. The indirectly injured individuals, irrespective of species, are *random* victims that were 'in the wrong place at the wrong time.' Accordingly, the fact that the three interior species, sugar maple, red maple, and gray birch showed no significant difference in species-specific response to ice accretion might be influenced more by 'bad luck' than by any species-specific characteristics. Therefore, had the sampling been completed in a manner that differentiated between direct and indirect injury, analyses of only the directly damaged stems might have demonstrated a statistically significant difference in species-specific response to ice accretion for both the edge species *and* the interior species.

For two species, sugar maple and red maple, tree damage at stand edges was compared to tree damage at stand interiors. Both species demonstrated that stand position did not influence susceptibility to icing damage. This finding is curious as it contradicts the conclusion found in previous investigations. These studies reported that forest edges receive more damage because of unbalanced ice-loading of asymmetrical crowns (Illick 1916, Seischab *et al.* 1993, Hauer *et al.* 1994). Although I agree that trees at forest perimeters tend to have asymmetrical crowns that predispose edge stems to ice-loading damage, I suggest that forest interiors have characteristics that predispose interior stems to damage as well, albeit of a different nature.

In stand interiors most of the ice is deposited on the top of the canopy and this might afford a degree of protection for the understory trees. But, as previously stated, indirect injury is a common fate for trees located in stand interiors. Sub-canopy trees are very prone to injury resulting from overstory branch and stem failure (Whitney and Johnson 1984, Hauer *et al.* 1993, Seischab *et al.* 1993, Rebertus *et al.* 1997). This 'heightened' risk of injury for interior trees could conceivably offset the 'heightened' risk of injury imposed on edge trees by unbalanced crowns. This being the case, my finding, of no statistically significant difference in species response between the edge stems and the interior stems, is not unexpected.

Damage type by species and size for the most damaged stands

For the edge analyses, in the *bending* category not all four species demonstrated a statistically significant difference of proportion of damage between the ≤ 30 cm CBH and the > 30 cm CBH bole-size classes (Table 8a). For the statistically significant findings, (red maple and trembling aspen), the smaller circumference stems suffered greater bending injury. This finding is in agreement with the conclusion of previous studies. As noted above, smaller diameter individuals are more likely to bend in response to ice-loading stress (Downs 1938, Spaulding and Bratton 1946, Sisinni *et al.* 1995). However, my results showed that the bending injury incurred by the sugar maple and gray birch stems was not significantly influenced by bole circumference. I do not think that this somewhat unexpected result might be related to a sample size problem (Table 7a).

Instead, I propose that my result might be more influenced by the fact that the smallest stems, those less than 10 centimeters CBH, were excluded from the analyses.

For stand edges, my research showed that it was the larger size stems that were more prone to snapping and crown loss damage. Hauer *et al.* (1993) report that a high proportion of trees (angiosperms) with larger size stems suffered serious injury. The authors fail to clearly determine the boundaries of 'serious' injury, however. Using the reasoning that trees damaged by snapping and crown loss suffer permanent breakage, whereas trees injured by bending do not incur permanent breakage, a point might be made that snapping and crown loss injury represent 'serious' damage as opposed to the damage caused by bending. I would argue, however, that permanent bending injury is no less 'serious' than damage caused by permanent breakage. In fact, unless crown loss is extensive, (greater than 75 percent), ice-damaged trees have a reasonable chance of survival (Shortle and Smith 1999). On the other hand, although bending may be perceived as a less serious type of damage because no breakage occurs, many stems bent to the ground never regain their original form (Rhoades 1918, Carvell *et al.* 1957, Lemon 1961), and therefore, their long-term survival in seriously compromised by their adverse growing conditions, in particular, their ground-level crown position.

In the stand interiors, sugar maple was the only species where bole circumference did not influence damage in the *bending* category (Table 9a). Again, had the smallest stems not been excluded from the analyses, the proportion of bending damage might have been higher for sugar maple in the ≤ 30 cm CBH class. As with stand edges, for the significant findings in stand interiors, it was the larger circumference trees that incurred the greater proportion of snapping and crown loss damage. For gray birch and trembling aspen, snapping and crown loss were not influenced by bole circumference but it should be noted, however, that the small size of the trembling aspen interior sample (Table 7b) imposes limitations on test results. As for the insignificance of the gray birch tests in the snapping and crown loss categories, it is interesting to note that although sample size was adequate (172), relatively few stems incurred *any* damage (Figure 5).

In broad terms, for all four species, bole size influences susceptibility to damage. However, it is not the severity of damage that stem circumference influences so much as the type of injury that any stem is likely to incur. Although species-specific and/or individual stem characteristics such as branching architecture, crown size and shape, tree health and age, wood properties, and the position of the tree in the canopy have considerable bearing on damage susceptibility (Lemon 1961, Bruederle and Stearns 1985, Cannell and Morgan 1989, Seischab *et al.* 1993, Rebertus *et al.* 1997), generally speaking, it is the smaller stems that tend to suffer bending injury, and it is the larger stems that are inclined to suffer snapping and crown loss damage.

Crown asymmetry, wind, and edge/interior damage

It is generally accepted that wind plays a crucial role in the amount of icing damage trees are likely to sustain in any ice storm. However, in the literature this role is stated largely in generalities. A common theme is that icing damage increases with the additional stress of wind-loading (Deuber 1940, Bruederle and Stearns 1985, Seischab *et al.* 1993). I would agree that ice-loaded trees are more susceptible to damage with increasing wind velocity, but I suggest that the role wind plays with respect to forest damage is counterintuitive to common perception, that is, forest peripheries do not suffer excessively from the effects of the additional stress of wind-loading. Indeed, in the absence of wind, edge stems are at high risk for icing injury because of their more developed branching, and the longer length of their branches along the forest edge. As such, I do not fully agree with the findings of two previous studies that report that stem damage was most severe on the windward side of ice-accreted stands (Carvell *et al.* 1957, Goebel and Deitschman 1967). The conclusion of these authors' implies that wind was a significant factor responsible for the tree damage occurring at the forest edges. In contrast, I propose that stand edges are no more susceptible to damage resulting from the combined effect of ice accretion and wind-loading than are stand interiors.

During the January 1998 ice storm the wind was from the NNE and the NE (Table 1). My research demonstrated that during the ice storm, wind was not a significant factor influencing tree damage along forest peripheries. Stem damage at forest edges is primarily linked to unbalanced ice-loading of asymmetrical crowns. In contrast, however, wind was shown to be a factor influencing damage in stand interiors.

On slopes, trees are more 'open grown' on their downhill side and increased light availability favours development of asymmetrical crowns (Bruederle and Stearns 1985). Accordingly, my hypothesis holds that slope trees that are arched or snapped by ice-loading will consistently bend or break toward the downhill direction. As my analysis shows, for both the SSE facing slope (downhill direction 150°) and the WNW slope (downhill direction 280°) the degree of preferred orientation of damaged stems, 156.67° and 262.95° respectively, was highly significant and closely approximated the compass degree associated with the downhill direction of the incline. In spite of prevailing winds during the ice storm (NNE and NE), no windward/leeward difference in bending or falling orientation was demonstrated; stems invariably arched or snapped toward their more open side because of their unbalanced ice-loaded asymmetrical crowns. This 'unbalanced crown' phenomenon was observed repeatedly in the course of my fieldwork.

While gathering data for this study it became clear that the tree damage observed at stand edges was not significantly influenced by winds. For each of the 29 forest stands sampled, irrespective of edge direction, periphery stems arched and snapped toward their open side in a manner that was consistently near-perpendicular to the forest edge. To verify this field observation, the compass direction toward which the bent and fallen stems of one stand edge were oriented was recorded and analyzed. The stand edge was perpendicular to 60° (NE), and plainly a windward edge during the January 1998 ice storm. The directional mean of stem bending and snapping was 57.07 degrees. This degree of preferred orientation is actually *toward* the direction from which the wind was originating. Typically, if wind was an influential factor, bent or snapped stems would arch or fall in more or less the same direction toward which the wind was blowing which was, in the case of the January 1998 storm, approximately SW. Clearly, if wind was a significant factor influencing periphery damage, the directional mean (57.07°) of the bent and fallen stems of the sampled stand edge would not have so closely approximated the compass direction perpendicular to the forest edge (60°).

Nevertheless, one might argue that wind *is* an important factor in that it tends to increase the amount of freezing precipitation that is intercepted by a stem in the windward direction. But it is not just the trees at forest edges that are at risk for heightened ice accumulation under such circumstances. The risk is the same for dominant canopy trees in stand interiors. However, there are differences in the impact the combined effect of ice accretion and wind-loading has on stand edges versus stand interiors.

Wind damage amounts as such are not quantified in this study. Instead, this study addresses the influence of wind on stem damage at forest edges and in forest interiors. As noted above, wind is not a significant factor in edge damage. At forest edges, the stress imposed by 'windward' ice accretion is linked only to the greater ice accumulation and not the actual effects of the wind velocity. As well, stem damage along forest peripheries is dictated by crown asymmetry whether in the presence, or absence, of wind. On the other hand, it appears that tree damage in forest interiors *is* influenced by the combined effect of ice accretion and wind-loading.

In the absence of wind, ice accumulates uniformly on the interior canopy. But when wind is present the windward sides of dominant canopy trees intercept an increased amount of freezing rain and subsequently are at risk for developing a surface area that is less able to resist the force of the wind. Since wind is more hazardous for taller, dominant trees and the tallest canopy trees are exposed to the strongest winds (Carvell *et al.* 1957, Campbell *et al.* 1993, Hedden *et al.* 1995, Dyer and Baird 1997), it then follows that the dominant ice-loaded canopy stems are at heightened risk for bending, snapping, and crown loss injury.

During the course of collecting data for this study it became evident that heavily damaged stand interiors shared a common trait; all bent or snapped stems were oriented in the same direction. This observation is similar to that of Nicholas and Zedaker (1989) who studied two icing events where ice accretion of 70 to 100 millimeters had severely damaged forest stands. The authors reported that generally within a stand, tree stems and crowns were all snapped or broken in a similar direction. To confirm my suspicion that wind likely influenced this type of tree damage, the bearing toward which the interior stems had bent and snapped was analyzed for three stands located in areas where ice accumulation totaled more than 50 millimeters. In all three cases, the directional mean of the arched and snapped boles proved highly significant (Table 10). In each instance the preferred orientation of the damaged stems paralleled the direction in which the prevailing winds were travelling, that is, approximately at 220 degrees or, southwest. These results suggest that wind is an important factor influencing damage in stand interiors.

Contrary to common perception, my results demonstrate that the stem damage that occurs along forest peripheries during an ice storm is not significantly influenced by the combined effect of ice accretion and wind-loading despite the fact that wind speeds are greatest at stand edges (Nägeli 1953). In fact, it is forest interiors that appear to suffer from the added stress of wind-loading even though wind speeds in the deep interior of stands are about 10 percent of the free wind velocity (Nägeli 1953). As the winds flow over the top of the forest canopy there is a heightened wind-related hazard for dominant canopy stem damage. Consequently, the interior subcanopy stems are also at greater risk owing to the increased likelihood of indirect injury caused by the combined effect of ice accretion and wind-loading on the dominant canopy trees.

It is important to note that these conclusions apply only to the January 1998 storm. It is impossible to predict what might have happened had there been stronger winds during the January storm.

GENERAL CONCLUSIONS

In this section I present the broad conclusions of this study in the context of their ecological implications and their relevance for forest and urban tree management.

1. Ice accumulation is the main cause of tree damage measured as the mean percent of canopy removed; however, individual species respond differently to ice-loading stress. Comparing damage at stand edges versus damage at stand interiors for the two species that had an adequate sample size, showed that stand position did not influence susceptibility to icing damage for either sugar maple or red maple. Although precise relationships are unclear, this study does link overall ice-damage susceptibility to a variety of stand-related and species-related factors including branching architecture, crown size and shape, bole size, wood properties, and the position of the tree in the canopy. Nevertheless, it is important to keep in mind that any ice storm damage is superimposed on complex extant ecological processes.

Little or no forest canopy is removed before a minimum radial ice thickness of approximately 20 millimeters has accumulated (Table 3). Consequently, even where ice storms of this intensity occur with relative frequency, their ecological impact is likely minimal. In contrast, considerable canopy is removed with a radial ice accretion of more than 40 millimeters. The significance of canopy removal is that gaps are created in the forest canopy and these gaps influence the forest floor environment. Canopy removal precipitates short-term changes in forest floor light availability, temperature, and moisture that, in turn, prompt long-term changes in successional patterns (Carvell *et al.* 1957, Lemon

1961, Siccama *et al.* 1976, Whitney and Johnson 1984, DeSteven *et al.* 1991, Rebertus *et al.* 1997, Boerner *et al*, 1988).

2. When bole size classes are assigned arbitrarily as 'smaller' and 'larger,' (in this study, ≤ 30 cm CBH and > 30 cm CBH), stem size influences susceptibility to damage although not uniformly for all four species in each of the damage categories. In general terms, my analysis of stem damage in areas with an ice accumulation of greater than 50 millimeters radial ice thickness showed that for both edge stems and interior stems, in the bending category it is the smaller stems that suffer greater damage and in the snapping and crown loss categories it is the larger circumference stems that incur the greater proportion of damage.

A common premise in the literature is that permanently arched stems are unlikely to resume vigorous growth and therefore their risk of mortality is high (Rhoades 1918, Carvell *et al.* 1957, Lemon 1961). Similarly, for snapped boles and excessive crown loss stem survival is unlikely (Spaulding and Bratton 1946, Boerner *et al.* 1988). In consequence, irrespective of the size of the trees in a particular stand, that is, whether they tend to be smaller circumference stems or larger circumference stems or a combination, mortality following destructive ice storms is an important, yet largely uninvestigated, concern.

3. In the literature it is stated that trees at forest perimeters tend to have asymmetrical crowns (Seischab *et al.* 1993, Hauer *et al.* 1994), and that this condition predisposes edge

stems to greater ice storm injury than interior stems. But, contrary to common perception, my research shows that edge stems are no more vulnerable to the combined effects of ice accretion and wind-loading than are interior stems and that the role played by wind during an ice storm does not heighten the risk for edge stem injury in spite of crown asymmetry. Indeed, the opposite appears more likely. This study suggests that it is the interior of forest stands that are at heightened risk of storm damage inflicted by the combination of ice accretion and wind-loading.

If, as my research suggests, forest peripheries are no more vulnerable than stand interiors during ice storms, then at least with respect to ice storm damage, some of the pessimism associated with forest fragmentation might be allayed. Similarly, when destructive ice storms occur, perhaps commercial sugar bush producers need not be overly concerned with the vulnerability of their edge trees.

Tree response to ice storms is of interest to resource managers of both urban trees and forestland. In an urban setting, information on species' susceptibility to icing damage should be a central consideration in management. In regions where destructive storms (greater than 20 millimeters of ice accumulation) occur frequently, planting of resistant species coupled with a maintenance programme which includes pruning to remove structural weakness and to maintain reasonable crown symmetry should substantially lessen the risk of ice storm damage to private and public property and structures.

For forest managers there are several points that should be incorporated into their management strategies. Following destructive ice storms, in spite of more favourable light conditions created by canopy gaps, immediate post-storm seedbed conditions will likely inhibit regeneration at least in the short-term. Unlike windthrow disturbance in which uprooted trees expose large areas of mineral soil, most ice storms occur when the ground is frozen and thus stems will snap as opposed to being uprooted in response to ice accretion and wind-loading. Not one uprooted tree was observed during my study. Depending on the management objectives, the benefit of scarification of litter to encourage new growth under the most favourable conditions needs to be weighed against the costs incurred by such an operation. Similarly, because ice damage significantly weakens individual stems and greatly increases risk of insect and fungal attacks (Campbell 1937, Melancon and Lechowicz 1987, Rebertus *et al.* 1997), immediate post-storm salvage might be a beneficial option to prevent the development and spread of funghi and insects that could rapidly involve undamaged trees in the stand as well.

Again, depending on the management objectives, there are also considerations for damage prevention schemes. By definition high-density stands have many smaller diameter stems and such stems are more prone to bending damage. In addition, the likelihood of indirect damage increases in high-density stands. On the other hand, low-density stands have fewer, larger diameter stems but these stems are more prone to crown loss and snapping injury. In areas where the frequency and intensity of destructive ice storms warrants it, stand thinning might be a cost-effective choice for certain management goals.

In broad terms, the impact that destructive icing events have on trees and forest stands has significant implications for both short-term and long-term management strategies.

SUBSEQUENT RESEARCH

Considerable research effort has been directed at understanding the immediate post-storm impact destructive ice storms have on trees and forest communities, but there are few studies investigating the longer-term impacts of ice storm damage. In general, there is very little known about the relationship between ice storm damage and the short-term and long-term survivorship of storm-injured stems. Ice storms may be an important cause of mortality in forest stands (Nicholas and Zadaker 1989). Accordingly, a post-storm survey of immediate tree and forest damage is only revealing part of a larger picture in which mortality is likely a crucial, and certainly a poorly understood, element.

First, from the point of view of my own research, it is my intention to re-inventory this study's 29 forest stands for two consecutive years following the initial, summer of 1998, assessment of storm damage. I will evaluate the condition of the damaged trees with the purpose of monitoring immediate post-storm mortality as well as short-term and long-term mortality assessed as a function of crown vigour.

Second, with the above information and the initial crown loss assessments, I will be able to correlate crown loss (mortality) and ice accretion (Hydro-Québec radial ice thickness measurements). I will then be able to link species' response to specific ice accretion measurements and to the return times associated with those ice accretion amounts (return times in Laflamme 1996) in order to estimate the return times for unlikely stem survival and mortality following ice storm damage.

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Table 1. Meteorological summary (Dorval-Montreal) for January 5th to January 9th, 1998. Precipitation over the 5-day period totals 99.8 millimeters.

Date	Mean Temp °C	Precipitation (mm)			Winds (km/h)	
		Rainfall	Snowfall	Total	Average speed	Prevailing Direction
Jan. 5	-5.5	9.0	2.8	23.4	16.8	NNE
6	-3.7	15.0	1.0	17.6	13.8	NE
7	-5.1	3.4	2.0	9.4	17.9	NNE
8	-3.8	2.8	9.4	35.8	25.8	NNE
9	-1.5	9.6	1.8	13.6	19.5	NE

SOURCE: Adapted from Environment Canada Atmospheric Environment Branch

Table 2. Stand summary indicating perpendicular compass direction of each sampled edge and ice accretion in millimeters for stand location.

Stand Number	Edge	Ice (mm)
1	NE	86
2	NE	79
3	E	84
4	SW	87
5	NE	88
6	SW	78
7	SW	79
8	NE	23
9	SW	47
10	SW	74
11	NE	57
12	NE	47
13	NE	77
14	SW	61
15	NE	27
16	NE	32
17	NE	24
18	NE	24
19	E	55
20	SE	57
21	NW	61
22	NE	35
23	NE	38
24	NE	23
25	SE	20
26	NE	17
27	ESE	63
28	NE	7
29	SW	2

Table 3. Mean percent of canopy removed by species for edge and interior samples for stems ≥ 30 cm CBH. Ice class measurement is radial ice thickness in millimeters. There were insufficient data to include gray birch (edge) and trembling aspen (interior).

a. EDGE

Ice class (mm)	Mean percent of canopy removed		
	Sugar maple	Red maple	Trembling aspen
0 – 10	0.00	0.00	0.00
11 – 20	5.00	1.30	10.00
21 – 30	0.48	7.37	10.00
31 – 40	3.33	12.86	51.20
41 – 50	1.43	55.00	28.75
51 – 60	19.29	25.00	54.29
61 – 70	27.62	30.00	25.63
71 – 80	24.06	72.50	52.29
81 – 90	42.50	79.44	81.11

b. INTERIOR

Ice class (mm)	Mean percent of canopy removed		
	Sugar maple	Red maple	Gray birch
0 – 10	0.00	0.00	0.00
11 – 20	0.00	0.48	0.00
21 – 30	0.33	3.85	6.84
31 – 40	8.08	18.33	0.00
41 – 50	0.00	49.06	100.00
51 – 60	10.00	5.00	53.43
61 – 70	19.73	21.59	65.50
71 – 80	62.24	16.67	82.61
81 – 90	61.00	75.15	48.00

Table 4. Summary of regression analyses for crown damage vs ice accumulation. Bole size ≥ 30 cm CBH. There were insufficient data for gray birch (edge) and trembling aspen (interior) analyses.

a. EDGE

Regressions	***n***	R^2	**Anova *p*-value**	**95% confidence of slope**	**95% confidence of intercept**
Sugar maple vs ice	9	0.822	< 0.001	0.275 – 0.667	-13.611 – 6.857
Red maple vs ice	9	0.859	< 0.001	0.478 – 1.021	-17.623 – 10.786
Trembling aspen vs ice	9	0.738	0.003	0.284 – 0.934	-10.967 – 23.006

b. INTERIOR

Regressions	***n***	R^2	**Anova *p*-value**	**95% confidence of slope**	**95% confidence of intercept**
Sugar maple vs ice	9	0.791	0.001	0.367 – 0.992	-28.565 – 4.131
Red maple vs ice	9	0.575	0.018	0.123 – 0.944	-22.383 – 20.544
Gray birch vs ice	9	0.477	0.039	0.054 – 1.595	-42.759 – 37.895

Table 5. ANOVA summaries for differences in the percent of mean canopy removed in relation to the amount of ice accumulation ($\alpha = 0.05$). For stand edges sugar maple, red maple, and trembling aspen were compared. For stand interiors sugar maple, red maple, and gray birch were compared. There were insufficient data for gray birch (edge) and trembling aspen (interior) analyses. Stems ≤ 30 cm CBH were excluded from the analyses.

a. EDGE

Source of variation	***SS***	***df***	***F*-value**	***F*-crit**	***p*-value**
Ice accretion	11581.180	8	6.918	2.591	< 0.001
Species	2309.048	2	5.517	3.633	0.015

b. INTERIOR

Source of variation	***SS***	***df***	***F*-value**	***F*-crit**	***p*-value**
Ice accretion	14484.150	8	3.559	2.591	0.015
Species	2462.616	2	2.420	3.633	0.120

Table 6. ANOVA summaries of comparisons of species-specific damage in relation to the amount of ice accumulation ($\alpha = 0.05$). The mean percent of canopy removed for stand edge versus stand interior is analyzed for the two species, sugar maple and red maple, that had adequate edge and interior sample sizes. Stems ≤ 30 cm CBH were excluded from the analyses.

a. SUGAR MAPLE

Source of variation	***SS***	***df***	***F*-value**	***F*-crit**	***p*-value**
Ice accretion	6193.527	8	6.730	3.438	0.007
Stand position	78.935	1	0.685	5.317	0.431

b. RED MAPLE

Source of variation	***SS***	***df***	***F*-value**	***F*-crit**	***p*-value**
Ice accretion	11209.680	8	8.253	3.438	0.003
Stand position	484.019	1	2.851	5.317	0.130

Table 7. Data summary for two-sample Z-tests for difference of proportions for the edge and the interior samples. CBH measurements are in centimeters. Stems < 10 cm CBH were excluded from the analyses. Minimum ice accretion is > 50 millimeters radial thickness.

a. EDGE

Species	CBH class	*n*	mean CBH	# bent to ≤ 4 m. off ground	# snapped	# ≥ 20% crown loss
Sugar maple	≤ 30	112	19.88	3	5	12
	> 30	130	60.12	1	13	59
Red maple	≤ 30	48	21.15	15	8	8
	> 30	41	41.78	5	15	21
Gray birch	≤ 30	76	21.42	13	0	0
	> 30	49	36.88	11	1	2
Trembling aspen	≤ 30	161	19.23	85	25	27
	> 30	88	46.64	21	14	38

b. INTERIOR

Species	CBH class	*n*	mean CBH	# bent to ≤ 4 m. off ground	# snapped	# ≥ 20% crown loss
Sugar maple	≤ 30	78	22.55	16	5	7
	> 30	202	54.88	27	36	79
Red maple	≤ 30	54	20.96	25	4	5
	> 30	60	50.12	7	20	24
Gray birch	≤ 30	69	22.00	52	0	3
	> 30	103	39.72	61	1	1
Trembling aspen	≤ 30	13	21.31	10	2	1
	> 30	23	50.43	8	4	7

Table 8. Summary of results of two-sample Z-tests for difference of proportions for the stand edges. H_o = stem size (CBH) makes no difference; 95% confidence interval is ±1.960. Minimum ice accretion is > 50 millimeters radial thickness.

a. Bending

Species (*N*)	≤ 30 CBH proportion (*n*)	> 30 CBH proportion (*n*)	*p*-value	Z-test statistic
Sugar maple (242)	0.027 (112)	0.008 (130)	0.245	1.162 do not reject
Red maple (89)	0.313 (48)	0.122 (41)	0.032	2.147 reject
Gray birch (125)	0.171 (76)	0.224 (49)	0.459	-0.741 do not reject
Trembling aspen (249)	0.528 (161)	0.239 (88)	< 0.001	4.414 reject

b. Snapping

Species (*N*)	≤ 30 CBH proportion (*n*)	> 30 CBH proportion (*n*)	*p*-value	Z-test statistic
Sugar maple (242)	0.045 (112)	0.100 (130)	0.102	-1.636 do not reject
Red maple (89)	0.167 (48)	0.366 (41)	0.032	-2.140 reject
Gray birch (125)	0.000 (76)	0.020 (49)	0.211	-1.250 do not reject
Trembling aspen (249)	0.155 (161)	0.159 (88)	0.934	-0.079 do not reject

c. Crown loss

Species (*N*)	**≤ 30 CBH proportion (*n*)**	**> 30 CBH proportion (*n*)**	***p*-value**	***Z*-test statistic**
Sugar maple (242)	0.107 (112)	0.454 (130)	< 0.001	-5.906 reject
Red maple (89)	0.167 (48)	0.512 (41)	< 0.001	-3.467 reject
Gray birch (125)	0.000 (76)	0.041 (49)	0.076	-1.776 do not reject
Trembling aspen (249)	0.168 (161)	0.432 (88)	< 0.001	-4.536 reject

Table 9. Summary of results of two-sample Z-tests for difference of proportions for the stand interiors. H_o = stem size (CBH) makes no difference; 95% confidence interval is ±1.960. Minimum ice accretion is > 50 millimeters radial thickness.

a. Bending

Species (*N*)	**≤ 30 CBH proportion (*n*)**	**> 30 CBH proportion (*n*)**	***p*-value**	**Z-test statistic**
Sugar maple (280)	0.205 (78)	0.134 (202)	0.137	1.487 do not reject
Red maple (114)	0.463 (54)	0.117 (60)	< 0.001	4.109 reject
Gray birch (172)	0.754 (69)	0.592 (103)	0.029	2.185 reject
Trembling aspen (36)	0.769 (13)	0.348 (23)	0.015	2.429 reject

b. Snapping

Species (*N*)	**≤ 30 CBH proportion (*n*)**	**> 30 CBH proportion (*n*)**	***p*-value**	**Z-test statistic**
Sugar maple (280)	0.064 (78)	0.172 (202)	0.015	-2.421 reject
Red maple (114)	0.074 (54)	0.334 (60)	< 0.001	-3.390 reject
Gray birch (172)	0.000 (69)	0.010 (103)	0.412	-0.821 do not reject
Trembling aspen (36)	0.154 (13)	0.174 (23)	0.877	-0.155 do not reject

c. Crown loss

Species (*N*)	**≤ 30 CBH proportion (*n*)**	**> 30 CBH proportion (*n*)**	***p*-value**	**Z-test statistic**
Sugar maple (280)	0.090 (78)	0.391 (202)	< 0.001	-4.900 reject
Red maple (114)	0.093 (54)	0.400 (60)	< 0.001	-3.763 reject
Gray birch (172)	0.043 (69)	0.010 (103)	0.150	1.440 do not reject
Trembling aspen (36)	0.154 (13)	0.304 (23)	0.317	-1.00 do not reject

Table 10. Summary of preferred orientation analyses. Significance of results assessed using the Rayleigh test for preferred orientation (Hammond and McCullagh 1982).

Analysis	Sample size	Directional mean (degrees)	*L*-value (%)	*p*-value
Slope A (Saint-Hilaire)	45	156.67	80.7	< 0.001
Slope B (Saint-Hilaire)	46	262.95	95.3	< 0.001
Interior Stand A	20	228.06	95.0	< 0.001
Interior Stand B	32	209.96	90.8	< 0.001
Interior Stand C	32	200.16	95.2	< 0.001
Edge Stand	36	57.07	99.2	< 0.001

Figure 1. Map showing study area, location of forest stands and Mont St-Hilaire. Superimposed isolines are adapted from Laflamme and Périard (1998).

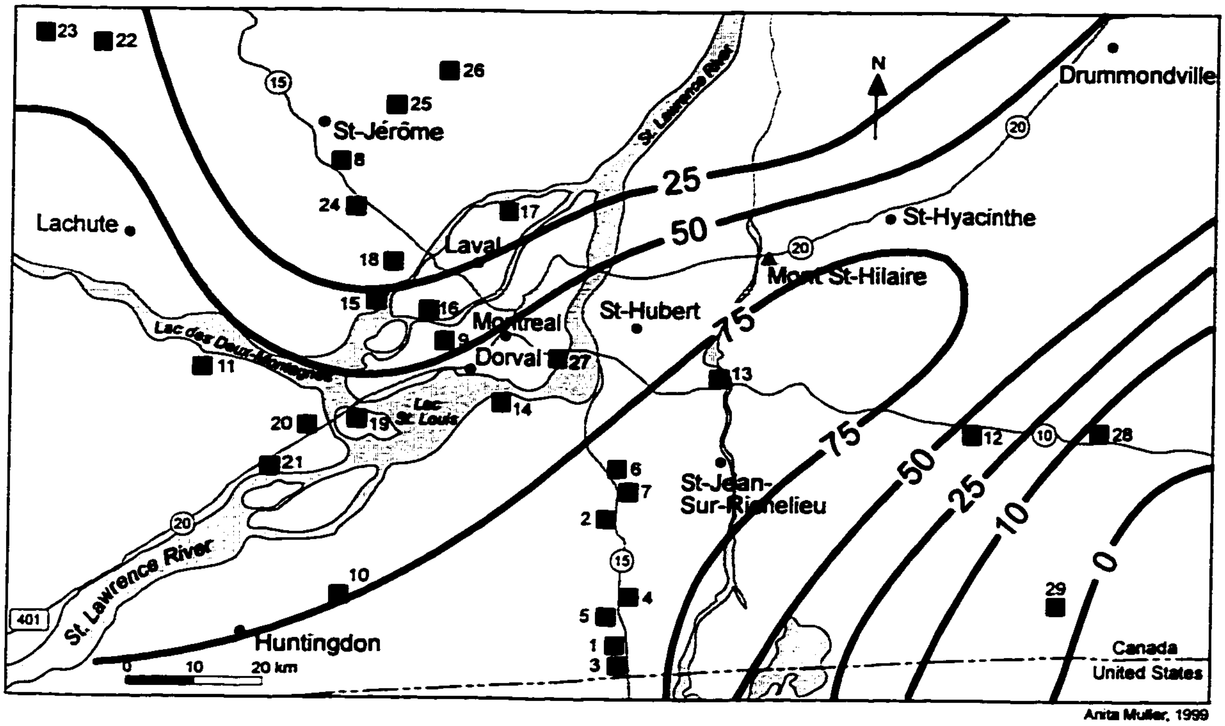
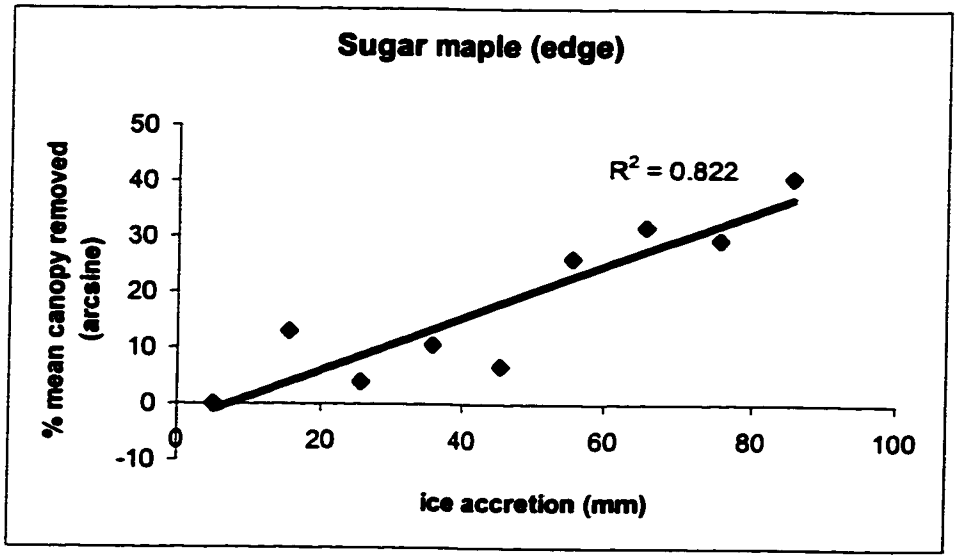
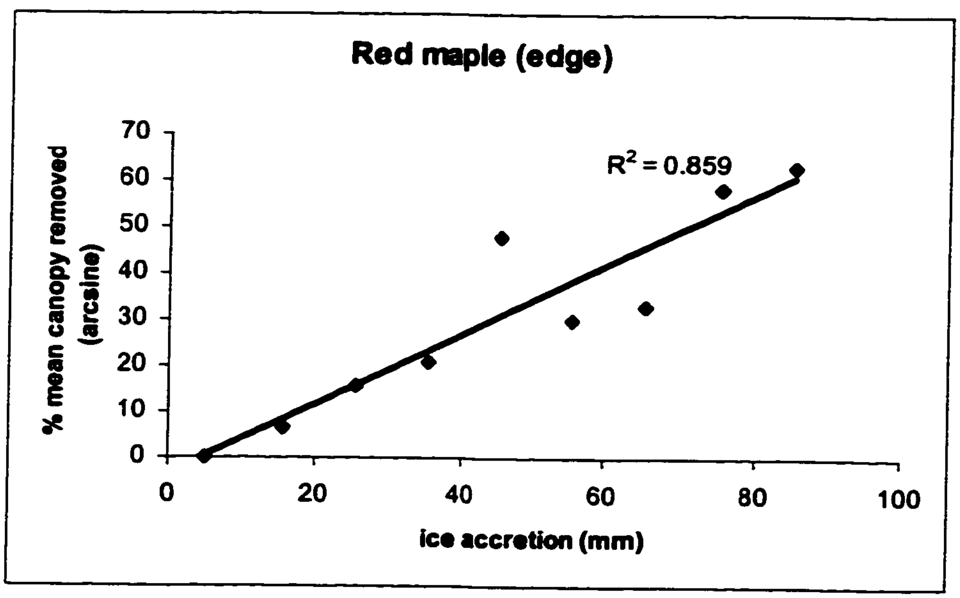


Figure 2. The relationship between ice accretion (radial thickness in millimeters) and the percent of mean canopy removed for stems ≥ 30 cm CBH at stand edges ($\alpha = 0.05$).

a. Sugar maple



b. Red maple



c. Trembling aspen

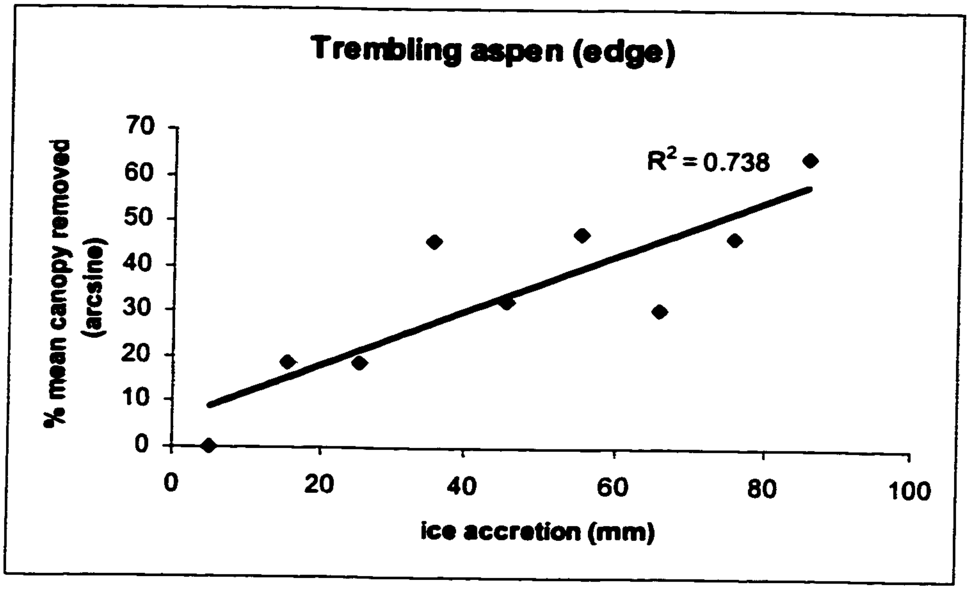
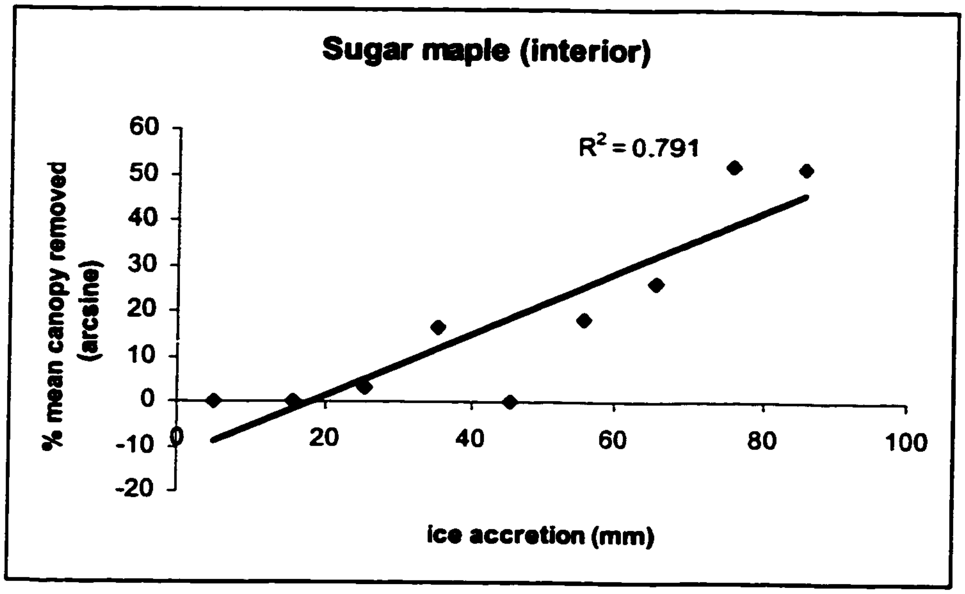
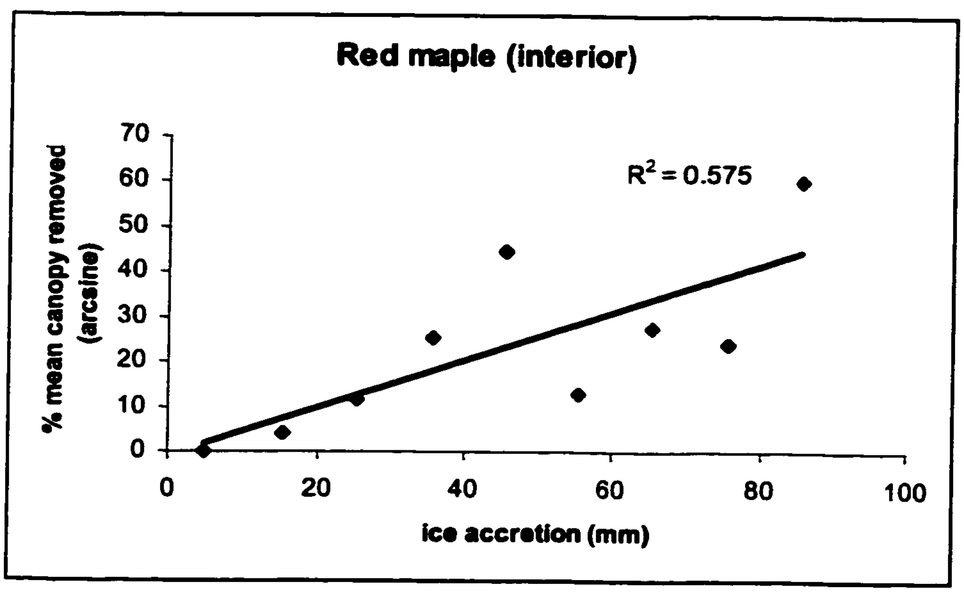


Figure 3. The relationship between ice accretion (radial thickness in millimeters) and the percent of mean canopy removed for stems ≥ 30 cm CBH in stand interiors ($\alpha = 0.05$).

a. Sugar maple



b. Red maple



c. Gray birch

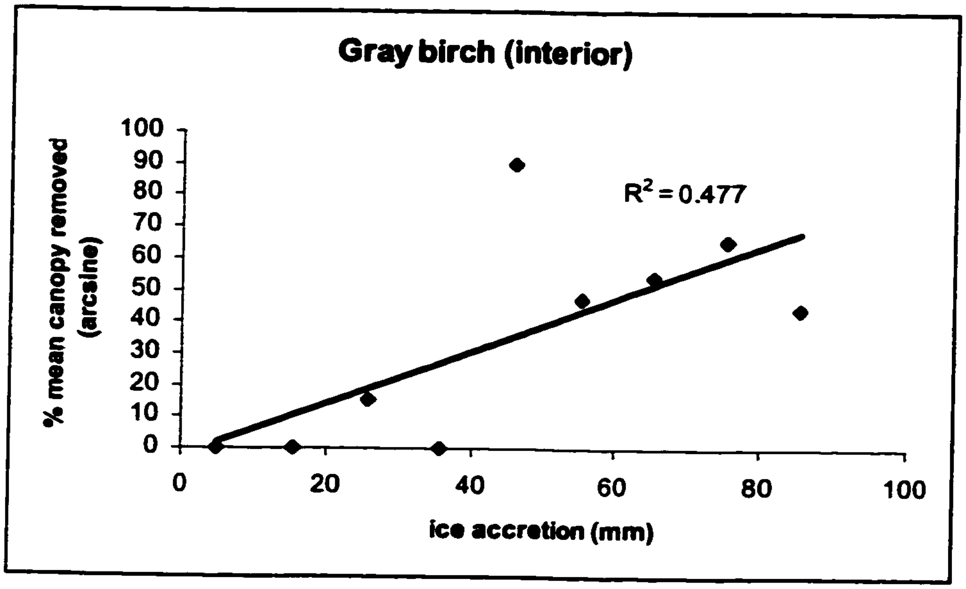
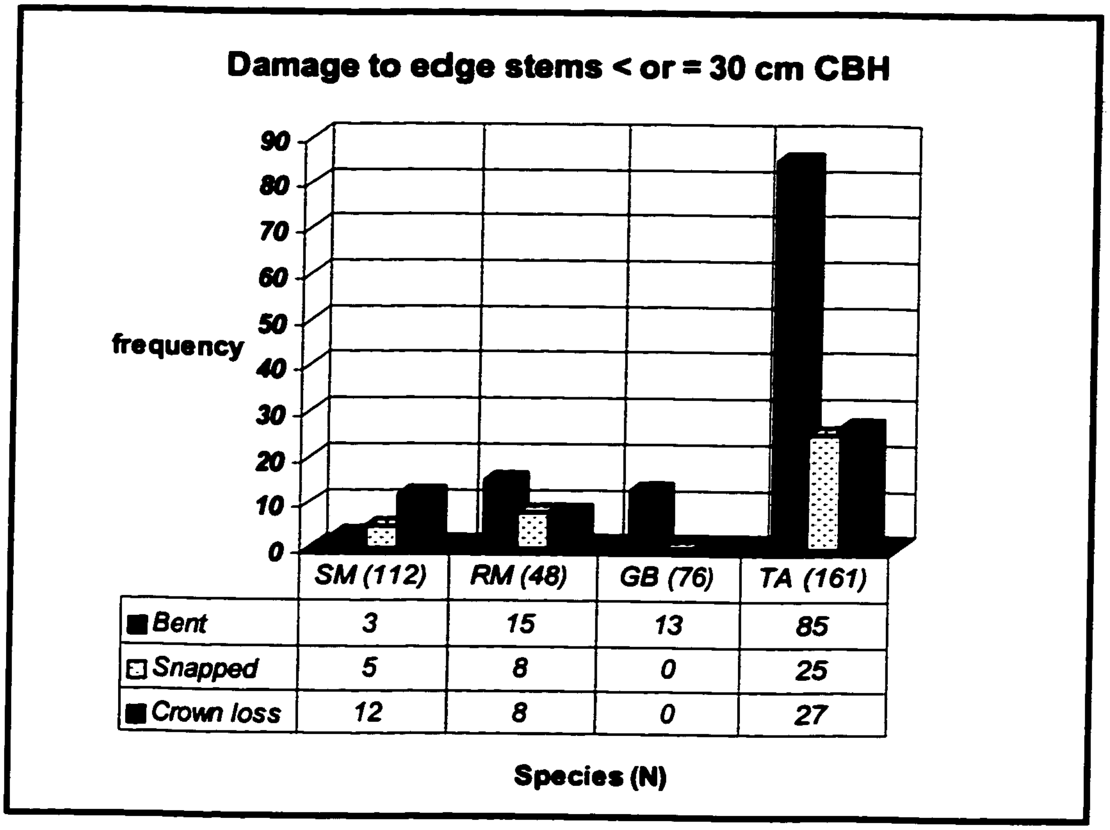

Gray birch (interior)
% mean canopy removed (arcsine)
100
90
80
70
60
50
40
30
20
10
0
0
20
40
60
80
100
ice accretion (mm)
R² = 0.477

Figure 4. Edge stem damage for sugar maple (SM), red maple (RM), gray birch (GB), and trembling aspen (TA) by bole circumference class (≤ 30 cm CBH and > 30 cm CBH) for the categories: bent to ≤ 4 meters off the ground, snapped, stems with ≥ 20 percent crown loss. Ice accretion is > 50 millimeters.

a. Edge stems ≤ 30 cm CBH



	SM (112)	RM (48)	GB (76)	TA (161)
Bent	3	15	13	85
Snapped	5	8	0	25
Crown loss	12	8	0	27

b. Edge stems > 30 cm CBH

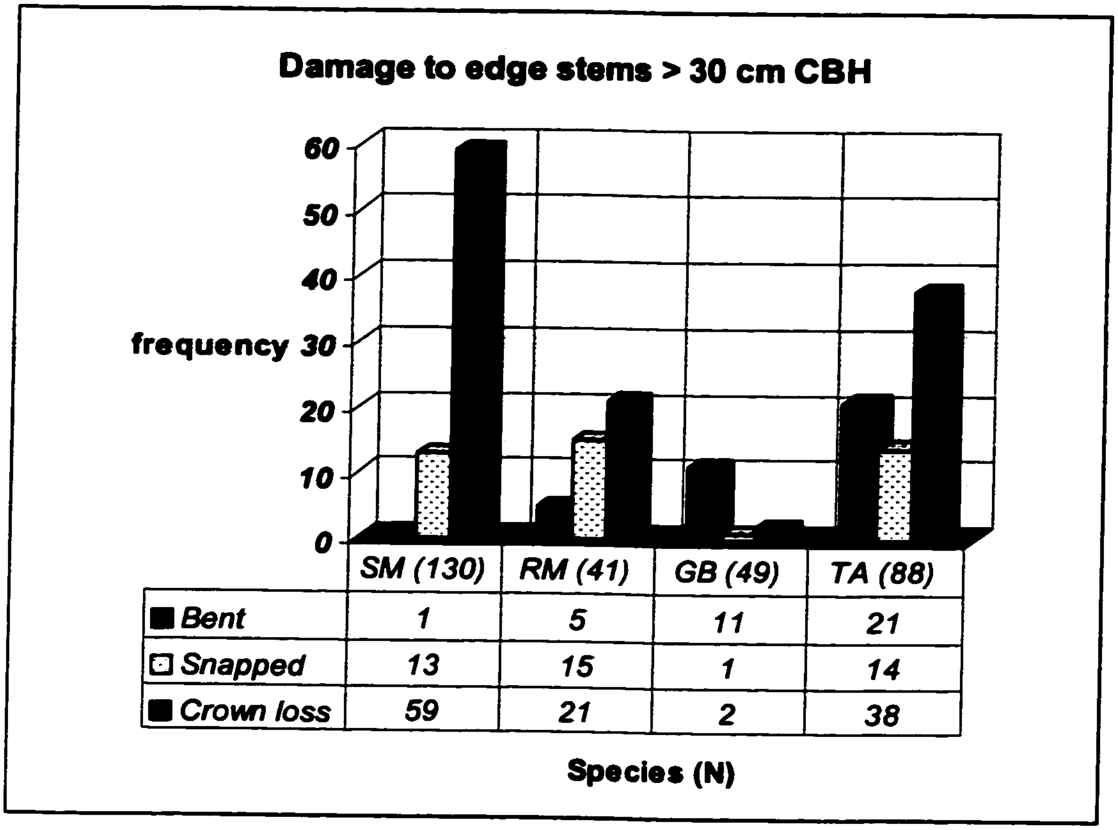
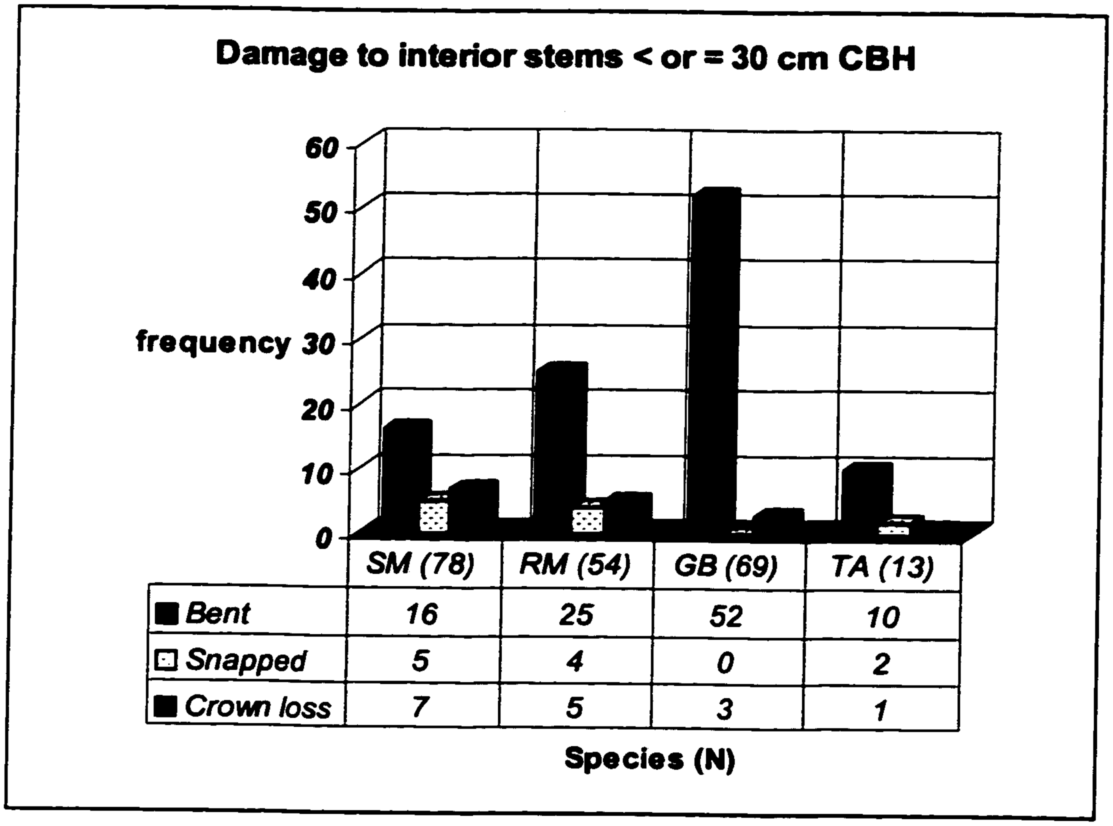


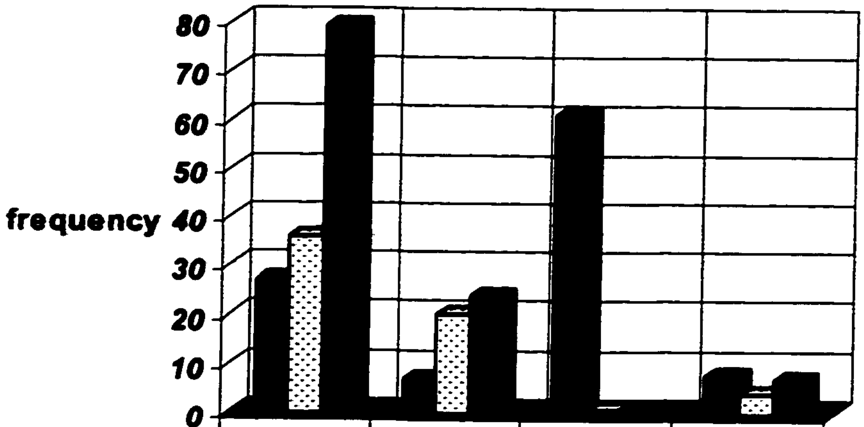
Figure 5. Interior stem damage for sugar maple (SM), red maple (RM), gray birch (GB), and trembling aspen (TA) by bole circumference class (≤ 30 cm CBH and > 30 cm CBH) for the categories: bent to ≤ 4 meters off the ground, snapped, stems with ≥ 20 percent crown loss. Ice accretion is > 50 millimeters.

a. Interior stems ≤ 30 cm CBH



b. Interior stems > 30 cm CBH

Damage to interior stems > 30 cm CBH



	SM (202)	RM (60)	GB (103)	TA (23)
Bent	27	7	61	8
Snapped	36	20	1	4
Crown loss	79	24	1	7

Species (N)