United States
Department of
Agriculture

Forest Service

**Northern
Research Station**

General Technical
Report NRS-60

Hardwood Crown Injuries and Rebuilding Following Ice Storms: A Literature Review

Martin J. Kraemer
Ralph D. Nyland

Abstract

Ice storms occur frequently in northeastern North America. They damage and kill trees, change the structural characteristics of a forest, and may importantly alter the goods and services that owners realize from their land. This literature review summarizes 90 years of relevant information, mainly from fairly short term studies published between 1904 and 2006. It documents ice storm severity and the effects on hardwood branch loss, primarily among upper canopy trees; methods for estimating and classifying hardwood crown damage; and factors influencing epicormic branch formation on hardwood trees. It also summarizes management recommendations for dealing with crown loss and for managing stands after damage by ice storms.

The Authors

MARTIN J. KRAEMER, 11205 Deborah Drive, Potomac, MD 20854; lowrider39@aol.com

RALPH D. NYLAND, corresponding author: Department of Forest and Natural Resources Management, State University of New York, College of Environmental Science and Forestry, 1 Forestry Drive, Syracuse, NY 13210; rnyland@syr.edu

Cover Photo

Used with permission by Ralph D. Nyland, SUNY ESF.

Manuscript received for publication 7 July 2009

Published by:

U.S. FOREST SERVICE
11 CAMPUS BLVD SUITE 200
NEWTOWN SQUARE PA 19073-3294

April 2010

Available online only

U.S. Forest Service
Publications Distribution
359 Main Road
Delaware, OH 43015-8640
Fax: (740)368-0152

Visit our homepage at: **http://www.nrs.fs.fed.us/**

Photo used with permission by Ralph D. Nyland

Figure 1.—The severity of ice storms is gauged by return time, thickness of ice, duration, amount of damage to trees, and/or resultant costs and other economic losses.

BACKGROUND OF ICE STORMS

Weather events depositing a glaze of ice on forests have occurred at least once per decade, from east Texas through New England (Ashe 1918, Abell 1934) and across southeastern Canada. Major ice storms happen once or twice per century (Irland 2000). Their severity varies, gauged by the return time, thickness of ice, duration, amount of damage to trees, and resultant costs and other economic losses (Fig. 1). Generally, ice storms in the United States increase in intensity from the southwest to the northeast (Lemon 1961).

Damage caused by these storms concerns landowners for several reasons. First, timber production objectives might be compromised by discoloration and decay of valuable saw logs due to breaking of major branches or loss of tree tops. Second, because the ice loading reduces the leaf mass on a tree by braking or stripping off branches, at least short-term diameter growth will decrease. Third, broken tops result in crooks on the main stem, given that the tree lives and a new crown forms through time. Fourth, severe breakage on a high proportion of trees may amount to a stand-replacing event and the loss of values associated with closed forests. In addition, breakage due to ice loading could alter the general character of a forest appreciably, changing its functionality and reducing many ecosystem services and values important to an owner.

In New York State, serious ice storms occurred in 1884, 1909, 1914, 1922-23, 1925, 1929-30, 1936, 1942-43, 1948-49, 1956-57, 1959, 1991, and 1998. (Spencer 1929, Lemon 1961, Seischab et al. 1993, Miller-Weeks and Eagar 1999). Severe storms struck North and South Carolina in 1915 (Rhoads 1918); Michigan in 1922 (Seeley 1922); Wisconsin in 1922 (Rogers 1922, 1923, 1924); Illinois in 1924 (Root 1924); North Carolina in 1932 (Abell 1934); Texas in 1938 (Reed 1939); an area from Pennsylvania to Boston in 1940 (Deuber 1940); West Virginia in 1956 (Carvell et al. 1957); Ohio in 1986 (Boerner et al. 1988); Missouri, Kansas, and Iowa in 1994 (Rebertus et al. 1997); Arkansas in 1974, 1979, and 1994 (Guo 1999); Virginia in 1994 (Lafon et al. 1999, Rhoads 1999, Warrillow and Mou 1999, and Mou and Warrillow 2000); and New York, Vermont, New Hampshire, Maine, and southeastern Canada in 1998 (Miller-Weeks and Eagar 1999, Coons 1999, Boulet et al. 2000). Missouri probably has a return rate of 20 to 25 yr, similar to that of southern Appalachia (Rebertus et al. 1997). Quebec had freezing rain or drizzle lasting at least 3 hr on 180 occasions between 1953 and 1997, and for 7 hr during 66 storm events. But in 1998 the glazing occurred over 70 hr during a 5-d period (Milton and Bouroque 1999).

The January 1998 ice storm that covered the northeastern United States and eastern Canada was characterized as a 100-yr event (Miller-Weeks and Eagar 1999), affecting nearly 17.3 million acres (Miller-Weeks and Linnane 2001, Faccio 2003). It reduced the standing biomass of a southwestern Quebec forest by 7 to 10 percent, similar to the largest recorded hurricanes such as Hugo and Gilbert (Hooper et al. (2001). This is 10 to 20 times greater than normal annual woody debris production for

Photo used with permission by Ralph D. Nyland

Figure 2.—Heavy ice loading often breaks large branches from trees, covering the forest floor with a heavy layer of woody debris.

Photo used with permission by Ralph D. Nyland

Figure 3.—Tornados and hurricanes often topple trees across in a large area, compared to ice loading that breaks branches from big trees and bends over small ones.

North American temperate deciduous forests and greater than effects from any other reported non-fire disturbance. And, while icing events of 1921, 1956, 1969, and 1973 were of comparable magnitude in New York and Maine, only the 1921 event covered as large a geographic area in Quebec (DeGaetano 2000). A more recent ice storm during December 2008 had similar effects across eastern New York and through parts of New England (Fig. 2). Others with varying degrees of severity will certainly follow in the future.

Despite the frequency of these storms, little has been documented about the long-term survival and crown rebuilding of hardwoods affected by them (Proulx and Greene 2001). Unlike ice events, hurricanes and tornadoes tend to uproot trees and snap the stems (Foster 1988, Peterson and Pickett 1991). In fact, approximately 70 percent of standing trees blew down during a 1938 hurricane in Massachusetts, with 87 to 100 percent of the damage from uprooting (Foster 1988). Peterson and Pickett (1991) report that a northwestern Pennsylvania tornado toppled essentially all trees regardless of age, size, or species (Fig. 3). One-third of the trees had snapped stems, and two-thirds were uprooted. By contrast, <1 percent of 3,510 trees on North American Maple Project plots affected by the 1998 ice storm were uprooted. Common effects included broken tops, broken branches within the crown, loss of major branches, damage to the bole, and breaking off below the crown (DesRochers and Allen 2001). Ice loading bent other trees, and the trunks of some split (Irland 2000).

Effects from an ice storm may differ from one stand to another. First, ice loading will vary across landscapes with differences in topography, topographic position, and forest community composition (Bennett 1959, Bruederle and Stearns 1985, Lafon et al. 1999, Miller-Weeks and Eagar 1999, Mou and Warrillow 2000). Also, meteorological conditions affecting the intensity of freezing precipitation, its type, the air temperature, and any existing snow cover will amplify or modulate the effects. Wind speed may also affect the degree of damage by increasing ice accumulation on surfaces or from the degree of physical stress on the trees (Milton and Bourque 1999). In fact, storms often leave a mosaic of damage across large areas (Rhoads et al. 2002, Millward and Kraft 2004). To illustrate, the widespread ice storm across New York, New England, and southeastern Canada in December 1942 left an ice cover about 0.5 to 1.0 in. thick at 500 to 1,000 ft elevation and 1.25 to 2.5 in. thick at sites over 1,000 ft. Little ice accumulated at sites below 500 ft (Spaulding and Bratton 1946). The Virginia storm in 1994 caused heaviest losses on south- and east-facing mountain slopes (the windward aspects), reducing stand basal areas by 30 to 60 percent, and creating large canopy openings (Lafon et al. 1999).

Based on early aerial photo reconnaissance, glazing associated with the 1998 ice storm in New York caused heavy damage to approximately 733,500 acres, moderate damage to 1.12 million acres, and light damage across 1.13 million acres (Beil 2001). Later on-the-ground sampling at 200 random locations revealed no branch

U.S. Forest Service

Figure 4.—Ice storms often cause damage to forests in elevational zones and have heterogeneous effects related to topography and aspect.

breakage across 26 percent of the total area covered by the icing, < 10 percent breakage across 70 percent of the area, and >30 percent on <10 percent of the area (Manion and Griffin 2001). Among Adirondack stands, ice loading caused a heterogeneous pattern of damage, with the most severe effects generally clustered around landscape features and east-northeast exposures (Allen et al. 1998, Millward and Kraft 2004). In general, severe glazing occurred at elevations below 1,200 ft and at higher elevations along waterways and on northeasterly slopes (Staats 2001).

A post-storm inventory in Vermont found 62 percent of sample plots with moderate to high damage, mostly at high elevations and on east-facing slopes (Fig. 4). Other plots had little or no visible effect (Faccio 2003). Glazing in New Hampshire affected about 1.06 million acres, either above 1,500 ft elevation across the southern part of the state or above 2,000 ft in the White Mountains (Bofinger 2001). Damage was patchy, but severe at 1,970 to 2,460 ft elevation and on south-facing slopes (Rhoads et al. 2002). Effects varied with stand age. Among older stands, damage depended on tree diameter and species. Also, trees infected with beech bark disease showed more damage. In younger stands, damage appeared more heterogeneous, varying with elevation, topography, stand age, and species composition.

Assessments following other storms revealed a similar elevational demarcation between damaged and undamaged areas (Abell 1934, Carvell et al. 1957). Ashe (1918) observed that ice storms in the Appalachian Mountains south of Pennsylvania generally occur in an elevation belt or zone covering only a few hundred feet, but stretching across many miles. Illick (1916) found the greatest and most frequent damage on the top of hills compared to valley bottoms. In like fashion, the January 1998 storm left appreciable glazing in an elevational zone, with some variation in the upper and lower bounds across the affected region (Miller-Weeks and Eagar 1999).

U.S. Forest Service

Figure 5.—Loss of large branches leads to discoloration of wood near the injury and opens potential infection courts for decay fungi.

HARDWOOD CROWN INJURIES

W.H. Smith (in Irland 1998) suggested three general scenarios for tree damage based on tree size. Saplings bent over by ice loading will partly or completely return to an upright position, or not at all. Much depends on species and tree age, plus other factors. Poles commonly fail below the crown, with subsequent mortality or sprouting depending on species. Larger trees with broken branches will resprout within the crown from dormant buds. Among these trees, the chance of subsequent decay is greatest with large broken branches and depends on successful infection by a wood-rotting organism (Fig. 5). Any spread of decay and stain depends on wound size and position, and on tree vigor and vitality. Yet discoloration from breaks in the crown may never reach the butt log (Shortle et al. 2003).

Generally, ice loading causes branch breakage and main stem snap among upper canopy hardwood trees, resembling that from windstorms (Bruederle and Stearns 1985) or due to logging. In 1998, areas receiving at least 3 in. of freezing rain had the highest probability of crown damage and broken tops (DesRochers and Allen 2001). Total accumulated ice load depends on the total length of branches and twigs (Jones 2001), but trees with fine branches are more susceptible than those with coarse ones (Hauer et al. 1994, Jones 2001). Damage is greater when heavy winds accompany the ice loading (Hauer et al. 1994).

Jones et al. (2001b) found more damage among main-canopy trees than mid-story ones, but with differences in susceptibility between species. Among mid-story trees, American hornbeam (*Carpinus caroliniana* Walt.) and American beech (*Fagus grandifolia* Ehrh.) were affected more than sugar maple (*Acer saccharum* Marsh.) and oak (*Quercus*). In the main canopy, oak and American beech were the most susceptible, and ironwood (*Ostrya virginiana* (Mill.) K. Koch) and ash (*Fraxinus*) the least. In northern New York, dominant and codominant black cherry (*Prunus serotina* Ehrh.) and white ash (*Fraxinus americana* L.) ≥8 in. d.b.h. had more damage than sugar and red maple (*Acer rubrum* L.) (Kraemer 2003). Branch breakage increased with branch basal diameter up to 3 in. with red and sugar maples and among decapitated black cherry. Conversely, breakage decreased with branch size up to 4 in. on white ash. In central Vermont, about 78 percent of damage was branch and stem breakage. Half of those trees lost >50 percent of the crown, and 34 percent lost >75 percent (Fig. 6). Uprooting and flattening destroyed the remainder, but mostly among smaller trees (Faccio 2003).

Duguay et al. (2001) noted that within an old-growth northern hardwood forest in Quebec, 97 percent of trees with a d.b.h. >4 in. had broken branches, and 35 percent lost more than half the crown. Collectively, the breakage reduced canopy closure by 11 percent. Ice loading or falling debris also broke off or flattened 78 percent of trees between 1.5 and 10 in. d.b.h. In Ontario, Jones et al. (2001a) measured a significant reduction of foliage in the upper canopy layers, and Chapeskie (2001) observed >76 percent crown loss in 1 percent of 278 sugarbushes surveyed, 51 to 75 percent loss in 50 percent, and 25 to 50 percent loss in 40 percent. Also, Hopkin et al. (2003) observed less damage on smaller than larger trees. About one-third of those ≥10 in. d.b.h. and 53 percent of those 5 to 10 in. had no damage. Neither did 72 percent of trees <5 in. d.b.h. Of those 10 to 16 in. d.b.h., 24 percent had at least 50 percent crown damage, while only 14 percent of larger trees showed as much crown loss. In one survey within New York, Manion and Griffin (2001) observed ≥75 percent crown loss on ~10 percent of the 5- to 15-in. trees, and some breakage on 30 percent of the trees 10 to 30 in. d.b.h.. From another assessment they reported that proportionally more trees ≥18 in. d.b.h. sustained at least 25 percent branch loss during the same 1998 ice storm (Manion et al. 2001).

Photo used with permission by Ralph D. Nyland

Figure 6.—Effects of ice loading vary with species and the size of a tree, often resulting in different degrees of branch loss within a single forest.

In New Hampshire, damage among 60- to 120-yr-old forests was greatest among trees >12 in. d.b.h.. Little damage was found in a 14-yr-old stand, but intense damage was found among 24- to 28-yr-old stands (Rhoads et al. 2002). For North American Maple Project plots across the entire area affected by the 1998 ice storm, risk of damage was generally higher among smaller trees (DesRochers and Allen 2001).

Within a 19-yr-old sweetgum (*Liquidambar styyraciflua* L.) plantation in Arkansas, Guo (1999) observed that trees with crown damage had larger diameters and wider crowns than undamaged trees. Also, leaning trees had smaller diameters than the undamaged ones. Contrary to this, Illick (1916) reported that 3- to 12-in. diameter hardwood trees suffered the most in a 1914 storm, usually from broken boles. The main stem of species such as oak and hickory (*Carya*) often broke within the crown (Ashe 1918). A logistics regression based on bole damage to trees in the north of New York's Adirondack Mountains identified tree diameter and slope steepness as predictors of the probability of damage. Chances of bole damage were higher for larger trees, probably due to reduced flexibility of their branches. Damage was greater on steeper slopes, possibly due to the tendency of trees leaning downhill, having asymmetrical crowns, and falling over neighboring trees (Lafon 2004). Large trees may have lost branches and had the main stem broken within the crown, while many poles broke below the crown (Abell 1934).

The degree of damage normally varies with thickness of the glaze and the characteristics of a storm (Fig. 7). Smaller branches break when ice thickness reaches 0.25 to 0.5 in. One-half to 1 in. of clear ice will cause conspicuous breakage. In general, medium branches have a higher strength to surface area ratio than large or very small ones, and there is a rough proportion between the amount of ice accumulated and the winter surface area of the tree (Lemon 1961). Ice accumulation of 3 in. or more has occurred during several storms (Buttrick 1922, Bruederle and Stearns 1985, Proulx and Greene 2001). In fact, McEvoy (2002) reported that during the 1998 storm the coating of clear ice on some twigs reached between 16 and 159 times their normal weight.

U.S. Forest Service

Figure 7.—Crown loss depends on the thickness of ice loading relative to branch diameter, as well of exposure to winds before the ice melts.

In New Hampshire northern hardwoods, effects of ice loading differed with stand age (Rhoads et al. 2002). For 60- to 120-yr-old stands, damage was greatest at elevations above about 1,970 ft, and among trees at least 12 in. d.b.h. Degree of damage was American beech > yellow birch (*Betula alleghaniensis* Britton) > sugar maple. The 24- to 28-yr-old stands received intense damage, but a 14-yr-old stand had little. The most severe effects on young stands occurred between 1,970 and 2,460 ft elevation, on steep slopes, and with pin cherry. In thinned even-aged hardwood stands of Quebec, ice loading severely damaged 39 percent of yellow birch, 14 percent of white ash, and 10 percent of sugar maple (Zarnovican 2001).

In Ontario, the effect did not differ between appropriately managed (never removing more than one-third of the basal area) and unmanaged hardwood stands receiving light and moderate damage (Fig. 8). Managed ones had re-grown for at least 6 yr after the silvicultural treatment. Instead, damage varied among stands based on species composition, basal area, and component tree size (Nielsen et al. 2003). Similarly in Maine, Wisher and Ostrofsky (2001) observed no significant difference in degree of damage between thinned and unthinned stands, but a tendency for greater damage after heavy thinning. Consistent with that finding, heavily thinned Appalachian hardwoods were more susceptible than ones where thinning removed <30 percent of the volume. Differences seemed a consequence of the more open

Photo used with permission by Ralph D. Nyland

Figure 8.—Trees in stands previously thinned to an appropriate level of residual stocking withstood ice loading better than those in heavily thinned areas.

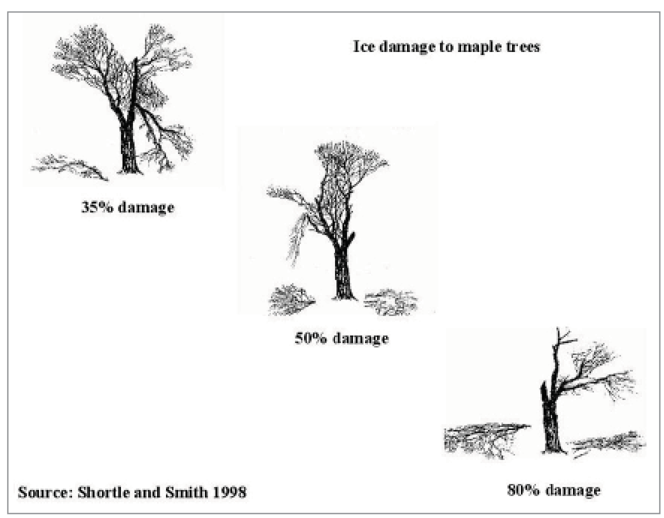
canopy and less mutual support among residual trees (Carvell et al. 1957). Similarly, yellow birch had greater damage in plots thinned heavily from below (59 percent of basal area removed) 13 yr earlier, compared to lightly (11 percent basal area removed) and moderately (26 percent of basal area removed) thinned ones. Untreated plots showed the least damage. Proportions of trees with severe damage were 8 percent unthinned, 16 percent lightly thinned, 34 percent moderately thinned, and 44 percent heavily thinned (Zarnovican 2001).

CROWN LOSS ESTIMATION AND DAMAGE CLASSES

The effect on damaged trees, including their potential for survival depends on the extent of crown loss (Whitney and Johnson 1984, Shortle and Smith 1998). Yet crown loss is difficult to quantify and interpret (Bruederle and Stearns 1985, Kraemer 2003). Aerial surveys have value in assessing the extent and general severity of storm effects over large areas (Barry et al. 1993, Lautenschlager and Nielsen 1999, Miller-Weeks and Eagar 1999). Also, analysis of new downed woody debris after a storm will reveal the degree of branch and top loss at a stand level (Bruederle and Stearns 1985, Melancon and Lechowicz 1987, De Steven et al. 1991, Seischab et al. 1993, Rebertus et al. 1997, Hooper et al. 2001). Volume is calculated from measurements of fallen branch diameters and mass.

Accessible literature describes several methods to evaluate individual trees and categorize the damage by severity classes. Commonly, observers estimate the percent of crown lost and assign each tree to a damage class (Kidon et al. 1998, Miller-Weeks and Eagar 1999, Boulet et al. 2000), generally based on 25 percent or 50 percent increments (Rogers 1923, Lamson and Leak 1998, Shortle and Smith 1998, Lautenschlager and Nielsen 1999, Warrillow and Mou 1999). Other approaches combine smaller classes (e.g., 10 percent) into fewer composite ones (Miller-Weeks and Eagar 1999, DesRochers and Allen 2001). Still others use descriptive characteristics such as large broken limbs, main stem snap, tree bending, or uprooting (Downs 1938, Whitney and Johnson 1984, Boerner et al. 1988, Rebertus et al. 1997, Winship and Smallidge 1998, Rhoads 1999, Proulx and Greene 2001). Shortle and Smith (1998) and Boulet et al. (2000) provide illustrations of typical trees for different damage classes (Fig. 9). However, users can effectively apply these methods only in the dormant season when observers have an unobstructed view of all branches.

Many researchers have used branch counts to assess damage, sometimes in conjunction with percent crown loss estimates (Lautenschlager and Winters 2001, Manion et al. 2001, Rubin and Manion 2001). In conjunction with this, Ter-Mikaelian and Lautenschlager



U.S. Forest Service

Figure 9.—Diagrams illustrating different degrees of crown loss help observers to evaluate effects of ice damage on individual trees.

Photo used with permission by Ralph D. Nyland

Figure 10.—The amount of crown lost to decapitation during an ice storm provides a general guide to the degree of reduced radial increment after the trees refoliate.

(2001) found that tree d.b.h. (with or without height to base of the live crown) can be used to predict pre-storm leaf biomass. Then the total number of branches on a tree (between 1- and 2-in. basal diameter) serves as an excellent predictor of post-storm leaf biomass, accounting for >96 percent of the tree-to-tree variation. Forest managers can use the difference between these measures as an estimate of crown loss, in preference to destructive sampling techniques and other ocular estimates. Yet no one has demonstrated an easy method to accurately estimate branch basal diameter from the ground or even to make reliable branch counts. In fact, Lautenschlager and Winters (2001) compared the ground counts of all productive third-order (or higher) branches ≥2 in. diameter to that made by a climber 7 mo later. The climber counted all 1- and 2-in. diameter branches, recording approximately 3.4 branches for every one of those >2 in. observed earlier from the ground. Kraemer (2003) suggested that main stem breakage (decapitation) may serve as a useful indicator of crown loss and reduced mean radial growth (Fig. 10). It is easier to determine from the ground and less subjective than counting branches of different sizes.

The Tracing Radiation and Architecture of Canopies (TRAC) instrument has been used to document Leaf Area Index (LAI) among ice damaged stands. It measures canopy gap size distribution and LAI in forests with non-random or clumped leaf elements such as found on damaged trees having epicormic branches. The instrument has a wand with a visible light sensor (400-700 nm) and a data storage unit that records 32 measurements per second when activated. Observers take readings along transects while walking at a steady pace (3.4 ft per 3 s), holding the wand about 4.5 ft above the ground. They must take the measurements on clear days, at the same time of day, and between 11 a.m. and 3 p.m. Tests showed that LAI decreased significantly and clumping increased with higher degrees of storm damage. Such instrument-based measurements can complement visual estimates of crown damage and allow more reliable monitoring of canopy changes through time (Olthof et al. 2001).

PATTERNS OF INJURY

Many interrelated factors determine the extent of ice damage to any given tree (growth form; crown architecture, size, and class; tree health; tree diameter and crown position; and brittleness of wood), or forest community (species composition, previous thinning treatments, age, ice load, topography, aspect, slope, wind, and overall health) (Lemon 1961, Seischab et al. 1993, Hauer et al. 1994, Jones et al. 2001b). Warrillow and Mou (1999) found that wood strength by itself was not a good predictor of the susceptibility of a species to ice loading. Rather, branch breakage occurs when ice weight exceeds wood resistance or further stresses a weakened branch (Fig. 11). Susceptibility varies by species and increases among trees with broad or imbalanced crowns, a high degree of lateral branch surface area, decaying or dead branches, and in-grown bark at branch junctures.

Photo used with permission by Ralph D. Nyland

Figure 11.—Factors other than wood strength alone determine whether branches bend and break, including the amount of ice that accumulates on the surface.

Photo used with permission by Ralph D. Nyland

Figure 12.—Under moderate ice loading, large trees mainly lost branches and tops, while smaller ones broke off below the crown or became bent over.

These factors seem to influence breakage more than wood strength alone (Illick 1916, Hauer et al. 1994). In some species there is a significant positive relationship between the thickness of accumulated ice and mean percent of crown lost to the loading. Degree of ice accumulation and tree size will better indicate the degree of damage than factors such as crown architecture, wood density, or modulus of rupture values (Proulx and Greene 2001).

Codominant and dominant trees generally sustain more damage than intermediate and overtopped ones (Downs 1938, Carvell et al. 1957, Rhoads 1999). Consistent with this, taller trees sustain greater damage than shorter trees (Boerner et al. 1988, Sisinni et al. 1995, Miller-Weeks and Eagar 1999). In fact, Rhoads (1999) found only one-third as much damage among understory trees as those of the upper canopy. Upper canopy trees typically have more exposure to stronger winds (Carvell et al. 1957). Yet one assessment showed that damage varied between dominant vs. codominant and intermediate trees, but not significantly (Warrillow and Mou 1999). Abell (1934) found that large trees lost branches and had main stems broken within the crown, while many poles broke off below the crown (Fig. 12).

Severity of damage generally increases with tree size (Boerner et al. 1988). In fact, one assessment showed that sugar maple and American beech stands with an average tree d.b.h. between 10 and 16 in. suffered heavy damage due to ice loading (Spaulding and Bratton 1946). Similarly, approximately 60 percent of the trees over 10 in. d.b.h. were injured in the 1998 storm, and the extent of damage increased up to 14 in. d.b.h. (Miller-Weeks and Eagar 1999). One other estimate after the

1998 ice storm suggests that a higher percentage of trees >17.7 in. d.b.h. sustained at least 25 percent branch loss (Manion et al. 2001). And, while one evaluation indicated that damage correlated with tree diameter for American basswood (*Tilia americana* L.), hophornbeam, and northern red oak (*Quercus rubra* L.), it did not correlate with tree diameter for white oak (*Quercus alba* L.) (Rebertus et al. 1997). In another case, more than 20 percent branch loss occurred mostly on trees >5 in. d.b.h., and damage was not species specific (Proulx and Greene 2001).

Broad crowns (decurrent branching) have a higher susceptibility to ice damage than slender conical (excurrent branching) crowns (Buttrick 1922, Boerner et al. 1988, Hauer et al. 1993, Hauer et al. 1994). Also, branches attached with acute angles bear more weight than ones attached at 90° (Lemon 1961, Horn 1971), and they better resist damage from ice loading (Rogers 1923). In 1922, young trees proved more resistant than older ones during a Wisconsin glaze storm. Red and silver maples were most severely damaged. Willow (*Salix*) branches bent over to the ground, but did not break. Lindens (*Tilia*) accumulated the most ice, but with little apparent effect. Lombardy poplar (*Populus nigra* L. cv. *Italica*) and cottonwood (*Populus*) were stripped of branches. Elms (*Ulmus*) and hickories had shattered trunks and limbs that hung downward, but effects on hawthorns depended on crown shape. Mulberry (*Morus*), hornbeams (*Ostrya*), and birches (*Betula*) bent over, and many of the latter snapped under the added weight. Oaks, catalpa (*Catalpa speciosa* Warder), and butternut (*Juglans cinerea* L.) showed little effects of the ice loading. Buttrick (1922) found that sugar maple trees in Michigan often lost upper limbs growing from the trunk at a sharp angle. Trees with unbalanced crowns (such as those with previous branch loss) appeared more susceptible to ice damage than those with symmetric crowns (Illick 1916, Lemon 1961, Hauer et al. 1994).

One early assessment following the 1998 ice storm indicated that aspen (*Populus*), birches, black cherry, maples, white ash, and oaks were all affected in heavily damaged areas (Fig. 13). Paper birch (*Betula papyrifera* Marsh.), yellow birch, and American beech were most susceptible to bending, particularly in young stands having 10- to 15-ft-tall saplings (Miller-Weeks and Linnane 2001). Other assessments indicated that species with a straight, stout main stem and small flexible branches sustain the least damage (Rogers 1923, Lemon 1961, Bruederle and Stearns 1985). The flexible twigs accumulate ice, bend, and concentrate the weight onto the larger, less flexible branches. Those, in turn, may break under sufficient stress (Lemon 1961, Bruederle and Stearns 1985). Large branches generally break off away from the main stem. And, while hardwoods with brittle, soft wood (e.g., aspen) are damaged more than strong-wood species such as oak (Buttrick 1922, Rogers 1923, Miller-Weeks and Eagar 1999), some storms deposit sufficient ice to damage all species and age classes (Rhoads 1918). Damage is more severe in crowns infested with grapevines (*Vitis*) than among trees free of them (Siccama et al. 1976).

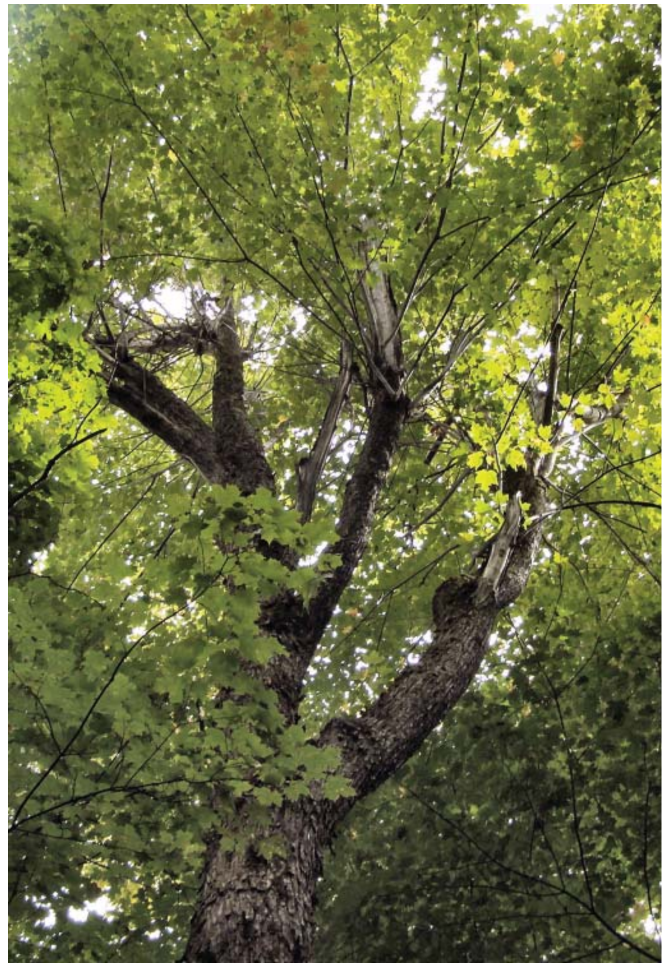


Photo used with permission by Ralph D. Nyland

Figure 13.—Aspen, birches, black cherry, maples, white ash, and oaks all had broken tops and branches in heavily damaged stands.

Irland (1998) reported more severe damage among edge than interior trees during the 1998 ice storm in Ontario. Yet Proulx and Greene (2001) found no difference related to position within a stand. Generally, trees along forest edges bend or snap toward a clearing, while interior trees break or bend with the prevailing wind (Proulx and Greene 2001). Black cherry may not recover its original form if severely bent (Lemon 1961). Also, isolated trees and those in open woods have often been more heavily damaged than ones in dense woods. This probably reflects the lack of mutual support between neighboring crowns (Buttrick 1922, Lemon 1961).

EPICORMIC BRANCHES AND THEIR DEVELOPMENT

Many factors influence epicormic branch formation, numbers, and persistence on hardwoods (Fig. 14). They often develop after damage to a tree including branch loss, breakage, and main-stem snap. Epicormics also develop when a tree is stressed due to low energy reserves, an injury to the main stem, or top removal (Shigo 1986). These stresses can result from ice loading. Each species has a general propensity for epicormic branching, but this varies among trees within species (Wahlenberg 1950, Shigo 1986, Miller 1996). In fact, the number of shoots that emerge, their development, and their persistence depend on the interaction of many factors such as crown class, tree height, extent of damage, and intensity of release. And, while most epicormics are firmly attached, if two or more epicormic branches originate from the same point, their bases may fuse and kill the cambial zones. That weakens the attachment. Epicormics that emerge near a cut in the bark and wood along the main stem frequently curl inward at the base, also weakening the point of attachment (Shigo 1991).

Experience with epicormic branching independent of natural disturbances suggests likely responses on trees after stand and tree damage by ice loading. Observations indicate that release by thinning, patch cutting, and clearcutting has triggered more epicormic branching on intermediate and overtopped trees than on codominant and dominant ones (Brinkman 1955; Smith 1965, 1966), and more epicormics have formed on trees bordering clearcut openings than on interior ones

Photo used with permission by Ralph D. Nyland

Figure 14.—Crowns rebuild from epicormic branches along the main stem and off branch stubs following damage due to ice loading.

(Blum 1963, Smith 1965, Trimble and Seegrist 1973). Around edges of clearcuts (Fig. 15), degree of epicormic branching has increased with height above the ground and with increased diameter of an opening (Smith 1965, Trimble and Seegrist 1973). Similarly, 1 yr after patch cutting, Blum (1963) found about three times as many epicormic branches on the border trees than on ones 1 chain inside uncut parts of the stand.

After thinning, epicormic branching can prove beneficial, as long as the new shoots develop within the crown. These increase the foliage density and crown volume. To illustrate, white and black (*Quercus velutina* Lam.) oak released by thinning developed more effective crowns due to the formation of epicormic branches and the growth of existing ones, and the trees grew better than ones in unthinned stands (Brinkman 1955). Nitrogen fertilizer has also increased the growth and vigor of epicormic branches above the second log of northern red

Photo used with permission by Ralph D. Nyland

Figure 15.—Trees of some species develop epicormic branches along sides of the main stem exposed along large openings.

oak and yellow-poplar (*Liriodendron tulipifera* L.) trees (Auchmoody 1972). In other thinning studies, more epicormics developed on the second and higher logs than on lower ones (Jemison and Schumacher 1948; Smith 1966, 1977), and sprouting differed among hardwood species (Ward 1966, Smith 1977, Miller 1996). In one study, sprouting increased among uninjured yellow-poplar trees that already had many epicormics. Further, compared to lightly sprouting trees, the others developed three times as many epicormic shoots along the top portion of the boles during the 10-yr post-thinning period. Epicormics on the butt sections (under 33 ft) of all trees decreased significantly over the same period (Wahlenberg 1950).

Consistent with these findings, open stands have more and larger epicormic shoots per tree than stands at high densities (Brinkman 1955). Also, the numbers of epicormics on dominant and codominant hardwoods increase with a greater intensity of thinning (Ward 1966, Smith 1977, Miller 1996), and they may become excessive in even-aged stands with a relative density below 60 to 65 percent (Marquis 1986, Lamson and Leak 1998) or 80 ft^2/acre of residual basal area (Huppuch 1961). Black cherry and northern red oak trees produced new epicormic shoots in the second log section during a 10-yr period after cutting to a residual stand density of 20 ft^2/acre (Miller 1996). Sprouting incidence was similar between a partial cut that removed about one-fourth the original stocking and a seed-tree method cut of low residual density, although the effect varied by species (Stubbs 1986). Other studies showed no significant relationship between the numbers of epicormic branches and thinning intensity after 7 yr (Jemison and Schumacher 1948) or after 2, 5, and 8 yr (Smith 1977). Likewise, Books and Tubbs (1970) found that thinning to a radius of 20 ft around sample trees did not have a significant effect on epicormic sprout numbers during the next growing season.

Artificial pruning also may stimulate epicormic growth (Godman and Mattson 1970, Grisez 1978), and decapitation (Fig. 16) will release buds from dormancy (Books and Tubbs 1970, Godman and Mattson 1970, Kraemer 2003). In fact, sprout numbers increased significantly below the crown after removing all main-stem branches and leaves or after severing the bole at the base of the live crown (Godman and Mattson 1970). Further, 83 percent of dormant buds within 5 ft below the base of the live crown of sugar maple broke dormancy on decapitated trees (Books and Tubbs 1970). Similarly, four growing seasons after a tornado on the Tionesta Scenic Area in northwestern Pennsylvania snapped off one-third of the trees and uprooted two-thirds, 25 percent of the snapped trees had sprouted new crowns. However, only 68 percent of those remaining survived (Peterson and Pickett 1991).

In pruning trials, Grisez (1978) found that an average of 12 epicormics persisted for 10 yr on butt logs of open-grown black cherry pruned to 75 percent of their total height. Trees pruned to 50 percent had an average of two

Photo used with permission by Martin Kramer

Figure 16.—Decapitation releases dormant buds below the break, and the epicormic shoots contribute to crown rebuilding and tree survival.

Photo used with permission by Ralph D. Nyland

Figure 17.—These heavily damaged white ash and black cherry of upper canopy positions redeveloped crowns, ensuring their survival and returning diameter growth toward the pre-injury level.

epicormics. The number of surviving epicormics varied greatly within each treatment, suggesting an influence of genetic factors. Other evidence gathered 19 yr after pruning 11-yr-old dominant sugar maple trees suggests that significantly fewer (3 percent) had an epicormic shoot growing near at least one of the pruning wounds, compared to 87 percent of the overtopped trees (Skilling 1957). Conover and Ralston (1959) found that, while most epicormics die within 8 yr after pruning, they persist longer on understory than overstory trees.

CROWN REBUILDING

Few studies have addressed crown rebuilding of ice-damaged trees. Rhoads et al. (2002) noted that among New Hampshire forests affected by the 1998 ice storm, leaf area index had increased significantly by 2000. Root growth also increased during the period, but with rates varying from moderately damaged > intermediately damaged > undamaged plots. Other information suggests that species most prone to injury from ice loading also rebuild their crowns the best (Boulet et al 2000). Thus, severely damaged white ash and black cherry will likely survive better than equally affected sugar maple (Fig. 17). Parker (2003) observed that areas with the greatest initial crown loss and resultant lowest leaf area index had higher understory and air temperature and lower understory humidity. Other assessments in southeastern Ontario indicated that effects of ice loading on crown canopy coverage had little immediate effect on understory plant species composition. Yet the cover of deciduous trees, herbs, and total near-ground vegetation increased in proportion to the degree of canopy opening

(Lautenschlager et al. 2003a). In both cases, post-storm crown rebuilding diminished these effects by increasing overstory crown coverage back toward pre-storm levels.

Among trees in an old-growth northern hardwood stand, 53 percent of damaged trees had some new shoots during the first growing season. Substantial numbers of sugar and red maple, hophornbeam, white ash, basswood, and red oak sprouted from the base. But most trees had epicormics developing off broken branches. Among upper-canopy trees, American beech showed the least sprouting, and sugar maple and red oak showed the most (Duguay et al. 2001). Two years after the 1998 ice storm, Kraemer (2003) found no significant relationship between estimated crown loss and the number of epicormic branches on black cherry, red maple, sugar maple, and white ash trees.

Certain readily observed branching characteristics bear witness to past ice storms (Fig. 18). Tulip-poplar, basswood, cucumbertree (*Magnolia acuminata* L.), American chestnut (*Castanea dentata* (Marsh.) Borkh.), and other species with comparatively brittle wood will form epicormic shoots on the stubs of large broken branches. This creates a distinctive branching pattern within the crown. The main stem of stronger wood species such as oak and hickory often breaks off within the crown, and the tree develops a broad, flat mushroom-shaped crown afterward. A new leader often forms from a shoot growing off the side of a horizontal branch. A normally shaped crown can develop from this new leader, but the main stem will have an offset at the point where the break occurred (Ashe 1918). Over a period of five growing seasons after an ice storm, height growth of damaged dominant and codominant trees within a fertilized (nitrogen and phosphorus) 25-yr-old sweetgum plantation in Arkansas exceeded that on undamaged ones (5.5 vs. 4.4 ft per yr, respectively). By contrast, the damaged trees grew significantly slower in diameter (0.23 vs. 0.14 in. per yr) (Guo and Vanderschaaf 2002).

Photo used with permission by Ralph D. Nyland

Figure 18.—Different species develop distinctive crown shapes following ice storm damage, but evidence of the injuries remains visible in the branching patterns of the new crown.

To determine the patterns of crown rebuilding, Remphrey and Davidson (1992) studied randomly selected parent shoots within 11- to 14-yr-old branch complexes taken from mid-crown positions of widely spaced green ash (*Fraxinus pennsylvanica* Marsh.) street trees (average age 25 yr) in Winnipeg, Manitoba, Canada. Each complex contained four to five orders of branches. Epicormic numbers varied greatly (3-34) within the complexes and did not correlate well with tree age, height, or main-stem diameter. Most of the 87 sample shoots originated close to the distal end of the parent shoot. The proportion of epicormics to non-epicormic laterals decreased with increasing branch order. Thirty-one percent of the epicormic shoots arose 2 yr after parent shoot expansion, and 39 percent after 5 yr. Epicormic and non-epicormic branches had similar lengths, but the former varied more. In contrast, epicormics had much shorter terminal daughter shoots. Further, the epicormic branches had a 9° greater angle of branch divergence from the parent shoot. This leads to a more perpendicular development from the main branch axis and increased filling of the inner crown (Remphrey and Davidson 1992).

OTHER EFFECTS OF CROWN INJURIES

Loss of appreciable numbers of branches will reduce the photosynthetic surface in a crown, and that should result in reduced radial increment (Fig. 19). Yet Lafon and Speer (2002) observed two kinds of growth changes. Radial increment decreased among trees with appreciable branch loss, and the effect persisted for several years. Diameter growth of others increased, apparently due to reduced competition resulting from injury to or loss of adjacent trees. In some trees the growth rate did not change appreciably. Degree of crown loss, rate of re-foliation, and degree of crown release seem to temper the response. In southeastern Ontario, the highly variable pre-storm diameter growth of sugar maple trees decreased to an all-time low level for 2 yr following crown injury. It decreased the most in severely affected trees and little among slightly affected ones. Canopy loss of 80 percent resulted in a 50-percent reduction of growth. A supplementary combination of understory mistblowing and fertilization (phosphorus, potassium, and lime) did not significantly increase the short-term responses (Lautenschlager et al. 2003b). After another fertilization experiment, ice-damaged sugar maple trees given P and K had a 22-percent and 15-percent increase in basal area increment, respectively, during the second and third growing season (Timmer et al. 2003).

Photo used with permission by Ralph D. Nyland

Figure 19.—Loss of appreciable parts of a tree crown to ice loading results in reduced radial increment, at least until the leaf area increases due to epicormic branch formation and growth.

Redevelopment of a crown should once more restore radial growth. In fact, Noland et al. (2006) found that crown loss initially reduced diameter growth, but the rates had increased and did not differ by damage level after three growing seasons. Smith and Shortle (2003) measured increment cores from sugar and red maple, yellow birch, and white ash. They observed no reduction of mean radial increment after 3 yr among trees where ice loading reduced the crown by less than one-half. By contrast, growth was significantly less for sugar and red maple and yellow birch that lost more than one-half of the crown, but not so for white ash. Sugar and red maple grew the least of all species and had the greatest growth reduction following crown loss of more than three-fourths. Kraemer (2003) found a significant reduction in mean radial growth for decapitated black cherry, sugar maple, and white ash after the 1998 ice storm. Conversely, decapitated red maple, red maple with intact main stems, and intact sugar maples did not show significant reductions in mean radial growth. Overall, effects on radial increment depended on the species and rate of crown rebuilding, as well as the severity of crown loss.

Northern hardwood species vary in resistance to decay (Smith et al. 2001). Injuries that break or shatter large branches make some trees (but not all) susceptible to the establishment of decay organisms (Campbell 1937, Deuber 1940, Shortle and Smith 1998, Miller-Weeks and Eagar 1999, Shortle et al. 2003). For all species, large wounds caused by broken forks low on the trunk increase the susceptibility, particularly in black cherry and sugar maple. Yet moderate-size top or trunk wounds in black cherry and sugar maple ≤40 yr old have low decay potential. In fact, dissection of 45-yr-old sugar maple trees 10 yr after an earlier ice storm showed that most wounds had healed without apparent decay. Those associated with large branches often led to wood discoloration. Similar injuries to red maple over 20 yr old would likely develop into discoloration and extensive decay (Campbell 1937). Because of the rot resistance of white ash trees, decay may not extend down from large branch wounds for 10 yr (Spaulding and Bratton 1946). In general, several years may pass before discoloration and decay develop and the value decreases (Smith et al. 2001).

Compartmentalization is most effective around wounds located adjacent to a vigorous, healthy branch (Smith et al. 2001). For large trees with crown injury, growth goes into developing buds and new epicormic shoots. Possibly a concurrent reduction in root development, diameter growth, and defensive compound synthesis may weaken the trees and make them more susceptible to insect damage, diseases, or soil moisture stress (Irland 1998). Generally, broken boles or branches >3 in. in diameter will likely trigger discoloration (Fig. 20), and it will progress at the rate of 6 to 18 in. annually. Decay fungi may follow within 8 to 10 mo later. Wood borers and ambrosia beetles may invade the year after injury. Hardwood trunk wounds that penetrate <2 in. and have surface area <144 in.^{2} will have only localized stain and little decay (Barry et al. 1993).

These guidelines appear consistent with observations after an ice storm in March of 1936 that caused severe damage to forests in northern Pennsylvania and southern New York. Examination of 191 top wounds on 40- to 50-yr-old black cherry trees and 94 top wounds on sugar maples revealed that decay had developed within 3 to 4 yr after the storm. Decay in black cherry was concentrated in what had been sapwood at the time of injury. For top breaks and broken limbs, the average extent of decay (23.5 in.) was related to the diameter of the break, but varied considerably. Decay extended about 30 in. for breaks >4 in. in diameter. The rate of spread slowed between 19 and 40 mo after injury. Sugar maple with top wounds <5 in. in diameter had decay for no more than 6 in. below the break. Greenish discoloration extended a few inches past the decay. For both species, upper stem wounds ≥3 in. in diameter did not affect the potential for sawtimber production if the crown regenerated vigorously. Trees with badly splintered tops seemed likely to develop heart rot and should be harvested within 10 to 15 yr after a storm (Campbell and Davidson 1940).

U.S. Forest Service

Figure 20.—Discoloration will develop up and down from broken branch stubs, and decay may enter through the wound, but both progress rather slowly and to a limited extent in damaged trees.

Forty-six years after an ice storm injured trees in Pennsylvania, Rexrode and Auchmoody (1982) felled and dissected 38 dominant or codominant black cherry trees to determine the extent of decay. These trees averaged 70 yr old, 13 in. diameter, and 90 ft tall. Twenty of them showed signs of injury from the storm, mainly as forked boles or crooks at about 42 ft from the ground. In many cases the injury caused a small stem swell or left dead branches. Forty-five percent of the affected trees had measurable decay in the main stem, while the others had no rot or rot only in the broken branches. The decay always extended downward from a point of injury and averaged only <1 percent of the total volume. Previous studies of black cherry damaged during this same storm showed that decay advanced about 6 in. per yr for the first 4 yr after injury (Sleeth 1938, Campbell and Davidson 1940). During the next 42 yr, the decay spread at an average of 2 in. per yr. These findings support earlier ones by Downs (1938).

MORTALITY AND DEGRADATION AFTER ICE DAMAGE

Few studies have tracked the long-term impacts of ice storm damage to trees and forests (Van Dyke 1999, Proulx and Greene 2001). Professional judgment suggests that most injured hardwoods will sustain minimal damage or value loss from secondary insects (D.C. Allen in Irland 1998). Also, most early reports following the 1998 ice storm forecast that hardwoods sustaining <50 percent crown loss would have a good chance for recovery (Lamson and Leak 1998; McEvoy and Lamson 1998; Miller-Weeks and Eagar 1999; Shortle and Smith, in Irland 1998), with only a slight short-term reduction in growth and minimal risk of wood degradation (Shortle and Smith, in Irland 1998). On the other hand, Spaulding and Bratton (1946) suggested that sugar maple with >50 percent crown loss will not likely rebuild their crowns and some may die. More recent assessments suggest that most trees with 50 to 75 percent crown loss will likely survive (Shortle and Smith, in Irland 1998; Miller-Weeks and Eagar 1999) with a variable degree of growth reduction and wood degradation, except among those with split forks and bark injuries (Shortle and Smith, in Irland 1998). Most trees with >75 percent crown loss will probably not survive (Shortle and Smith, in Irland 1998; Miller-Weeks and Eagar 1999), or survivors will show severe and long-term growth reduction and heavy wood degradation (Shortle and Smith, in Irland 1998). Yet Barry et al. (1993) suggest that many hardwood trees with even 100 percent crown loss seldom die and will sprout and recover (Fig. 21). However, damaged trees may take at least 25 yr to recover (Buttrick 1922).

Among Ontario forests, early assessments showed that relatively few trees (<4 percent overall, and <1 to 2 percent for most species) died due to damage from the ice storm, and losses were primarily among ones that lost ≥75 percent of the crown. For black cherry, 22 percent succumbed within 3 yr. Other data from Quebec indicate that among sugarbushes at well-situated sites, mortality would run 45 to 57 percent by 2 to 5 yr after a 61 to 80 percent canopy loss, and 77 to 94 percent for trees with ≥80 percent stand canopy loss (Boulet et al 2000). During 4 yr following the 1998 ice storm, Noland

Photo used with permission by Ralph D. Nyland

Figure 21.—While trees that lost >75 percent of the crown may recover slowly, most survive and remain part of the aftermath forest.

(2003) and Noland et al. (2005, 2006) found reduced autumn root starch among trees that lost >50 percent of the crown, particularly in years with drought. Yet, after 5 yr, root starch did not differ among surviving trees with initially different levels of crown loss.

American beech and eastern hophornbeam tree densities greatly declined over the 16-yr period after an earlier glaze storm in Wisconsin. The numbers of sugar maple (the dominant species by far), basswood, white ash, and shagbark hickory (*Carya ovata* (Mill.) K. Koch) remained about the same (De Steven et al. 1991). In another study, about 38 percent of the trees in damaged stands died within two growing seasons. Yellow-poplar and pine (*Pinus*) were most damaged, and white oak, scarlet oak (*Quercus coccinea* Muenchh.), chestnut oak (*Quercus prinus* L.), red maple, and hickory were most resistant to the ice loading. All species except red maple and yellow-poplar showed a positive correlation between degree of crown loss and likelihood of mortality. Yet mortality for red maple and yellow-poplar was only 6 percent and 5 percent, respectively, among heavily affected trees. Both developed many epicormic sprouts (Whitney and Johnson 1984). Contrary to this, Downs (1938) reported that a severe ice storm in Pennsylvania caused heavy black cherry losses at 1,900 to 2,100 ft in elevation, a 20-percent decrease in the total number of stems of all species, and a 43-percent decrease in trees ≥10 in. d.b.h. in the second-growth stands.

OPINIONS ABOUT SPECIES SUSCEPTIBILITY TO ICE DAMAGE

Table 1 ranks several common hardwoods according to susceptibility to ice damage. Table 2 shows their potential to produce epicormic branches. These tables expand on information initially presented by Van Dyke (1999). They show that not all researchers agree on the exact susceptibility of any given species (Boerner et al. 1988, Seischab et al. 1993). This may reflect differences in the methods of damage estimation, study locations, tree ages, and sizes of the stands and trees. Differences in epicormic numbers within a species result from genetic influences as well (Bowersox and Ward 1968, Auchmoody 1972, Grisez 1978, Remphrey and Davidson 1992). Further, increased sprouting in proximity to pre-treatment branches may reflect the genetic tendency of certain trees to sprout, possibly irrespective of a change in stand density (Ward 1966). Warrillow and Mou (1999) found the most significant difference in ice-related injury within species at sites having moderate overall damage.

MANAGEMENT RECOMMENDATIONS

Allen et al. (1998) warned against hasty actions in treating affected stands. Ice loading rarely kills hardwoods stripped of branches. Instead, dormant buds sprout to form epicormic shoots. So waiting at least 1 yr will reveal what trees show signs of recovery. During the interim, managers can identify stands and areas having different levels of damage. Based on the inventory, they can assign priorities to different stands and prepare a treatment list to sequence the salvage and rehabilitation cuttings (Fig. 22). Tree species should be taken into account, because they differ in potential to rebuild crowns. Heavily damaged and broken trees should be salvaged (Illick 1916, Sisinni et al. 1995, Allen et al. 1998, Lamson and Leak 1998, Boulet et al. 2000), but managers have one to three growing seasons before discoloration and decay significantly affect wood quality (McEvoy and Lamson

Photo used with permission by Ralph D. Nyland

Figure 22.—Rehabilitation treatments based on a thorough post-storm assessment can return many stands to a productive status, so the forest continues to satisfy a landowner's ownership objectives.

1998). That allows ample time to inventory the extent of injury and plan the best followup treatment.

Smith and Shortle (2003) suggested that because rates of crown building and recovery of diameter growth vary with species as well as degree of crown loss, landowners should not make decisions about harvesting affected stands based solely on the initial reduction of diameter increment. Their findings, along with other available evidence, suggest that most forest landowners should wait before salvaging damaged trees, watch for signs of tree recovery, and monitor the extent of discoloration and decay (Lamson and Leak 1998, McEvoy and Lamson 1998, Miller-Weeks and Eagar 1999, Shortle and Smith 1998, Shortle et al. 2003). Most of the time, severely damaged stands (e.g., with many badly broken, split, bent, or uprooted trees), as well as trees having greater than three-fourths crown loss, should be salvaged so landowners can recover the volume (Spaulding and Bratton 1946). Sanitation cutting may also prove necessary in stands prone to fungus and insect invasion.

Preventive measures for safeguarding against potential ice storm damage might include removing holdovers/wolf trees, reducing the proportion of susceptible species, preserving an even canopy, favoring species that develop at similar rates, and modifying local silviculture to take elevation and aspect into account with regard to

Table 1.—Species susceptibilities to ice damage[a]

Susceptibility			Location	Citation
Low	Medium	High		
	Red maple, sugar maple	Black cherry, white ash	Northern New York	Kraemer 2003
Sugar maple	Yellow birch	American beech	New Hampshire	Rhoads et al. 2002
In stands with overall branch breakage ≥5 percent, red maple, bigtooth aspen, and red oak were the most severely injured hardwoods.			Northern New York	Manion et al. 2001
On sites dominated by trembling aspen, red maple trees had an average of 29 percent of their branches broken by the ice storm and black cherry had 55 percent breakage. In severely damaged sugar maple dominated stands, white ash, red maple, American beech, and eastern hemlock had 24 percent to 53 percent branch breakage.			Northern New York	Rubin and Manion 2001
Sugar maple, white ash		Yellow birch	Eastern Quebec, Canada	Zarnovican 2001
Species most prone to damage by ice also rebuild their crowns the best. Severely damaged white ash and black cherry will likely survive better than equally damaged sugar maple.				Boulet et al. 2000
Species varied by state and storm severity, but ash, aspen, basswood, black cherry had above average damage.			Northeastern United States	Miller-Weeks and Eagar 1999
		Scarlet oak (dominant overstory species)	Southwestern Virginia	Rhoads 1999
	Red maple		Central Virginia Appalachians	Warrillow and Mou 1999
The probability of sustaining damage increased significantly with stem diameter for basswood, hophornbeam, and northern red oak, but not for white oak.			Northern Missouri	Rebertus et al. 1997
Greatest damage to least: Japanese pagoda, green ash, silver maple, London plantetree, callery pear, Norway maple, honeylocust, red maple, littleleaf linden, sugar maple.			Rochester, New York	Sisinni et al. 1995
Red, sugar, and Norway maple, swamp white, northern red and white oak, Kentucky coffeetree, silver and littleleaf linden, black walnut, American sweetgum	White ash, silver maple, bur oak	Siberian elm, honeylocust, Bradford pear, common hackberry, pin oak, sycamore, green ash and tulip-poplar	Champaign-Urbana, Illinois	Hauer et al. 1993
Hickory, ash, white oak, elm	Red maple, sugar maple, American beech, poplar, basswood	Black cherry, northern red oak, black oak, willow.	Western New York	Seischab et al. 1993
Number of major branches broken and their total biomass were significantly greater for American beech than the sugar maple compared to each species' contribution to the crown canopy layer.			Montreal, PQ, Canada	Melancon and Lechowicz 1987
	Red maple, sugar maple	Black cherry, white ash	Southern Wisconsin	Bruederle and Stearns 1985
Sugar maple	Black cherry, white ash	Red maple	Pennsylvania, New Jersey, New York, and southern New England	Siccama et al. 1976
White ash	Sugar maple	Black cherry		Lemon 1961
		Black cherry, chestnut oak, northern red oak, yellow-poplar	Northern West Virginia	Carvell et al. 1957
		Sugar maple, white ash, American beech, basswood	New York, New England, and Canada	Spaulding and Bratton 1946

continued

Table 1.—continued

Susceptibility			Location	Citation
Low	**Medium**	**High**		
Catalpas, Norway maple, oaks	Sugar maple	Red maple, silver maple, tulip-tree, poplars, willows	Pennsylvania to Boston	Deuber 1940
The third most common species, sugar maple, had 102 observations with 41 percent injured little, 26 percent injured moderately, and 33 percent badly broken. 26 *Prunus* spp. Trees were observed with 42 percent injured little, 16 percent injured moderately, and 42 percent badly broken. During the next growing season, observations indicated that many of the damaged trees had recovered reasonably well.			Missouri and Illinois	Croxton 1939
Oak, hickory, sugar maple, sycamore, white ash	American beech, birches, red maple, yellow-poplar	Aspen, basswood, black cherry, willow	New York and Pennsylvania	Downs 1938
Black locust, red maple, and scarlet oak were injured more severely than black oak and white oak.			Western North Carolina	Abell 1934
American hornbeam, bur oak, eastern hophornbeam, northern catalpa, shagbark hickory, swamp white oak, white oak			Wisconsin	Rogers 1923
The main stem of species such as oaks and hickories often break within the crown and develop a broad flat mushroom-shaped crown.			Appalachian Mountains south of Pennsylvania	Ashe 1918
All species suffered severe damage equally, especially in the areas with the greatest ice accumulation (several oak species, chestnut, basswood, yellow-poplar, hickory, white pine, and yellow pine.)			Western North Carolina and northwestern South Carolina	Rhoads 1918
Resistance to ice damage from least to most: chestnut, tulip-tree, red maple, oaks, ash, birch, elm, and hickory			Western New Jersey and eastern Pennsylvania	Illick 1916
Greatest damage to least: silver maple, weeping willow, Carolina poplar, American beech, elms, hickories, white oak, plane trees (especially the oriental species), Kentucky coffee tree (almost no damage.)			Pennsylvania	Harshberger 1904

[a] This table expands on information initially presented by VanDyke (1999).

Table 2.—Potential for epicormic branching by species[a]

Low	Medium	High	Stimulus	Citation
No significant relationship between crown loss estimates and numbers of epicormic branches/clusters for black cherry, red maple, sugar maple, and white ash.			Ice storm	Kraemer 2003
		White ash, black cherry	Ice storm	Lamson 2001
Sugar maple	Black cherry is prone to epicormic sprouting	Red maple, white ash	Ice storm	Meating et al. 2000
		Black cherry	Deferment cuttings	Miller 1996
Green and white ash	Shumard oak and yellow-poplar were variable by tree	Cherrybark oak sprout numbers increased the most after 1 yr	Seed-tree method and partial cut	Stubbs 1986
		Red maple, yellow-poplar	Ice storm	Whitney and Johnson 1984
Red maple, sugar maple, yellow-poplar	Black cherry, chestnut oak	White oak	Clearcut	Trimble and Seegrist 1973
White ash	Red maple, sugar maple	Black cherry	Clearcut border trees	Smith 1966
Yellow-poplar	Black cherry	Red oak	Group harvest border trees	Smith 1965
American beech	20-yr-old sugar maple developed a significantly greater number of epicormic branches than the 10-yr-old sugar maple.	Yellow birch	Trees bordering patch cuts	Blum 1963
Greatest to least in numbers of epicormics: hickory, chestnut oak, yellow-poplar, a basswood-white ash-sweet birch group, red maple, and northern red oak.			Thinning	Jemison and Schumacher 1948
Sugar maple		White ash	Ice storm	Spaulding and Bratton 1946
Tulip-poplar, basswood, cucumbertree, and chestnut form epicormics on stubs of large broken branches. The main stem of species such as oaks and hickories often break within the crown and develop a broad, flat mushroom-shaped crown afterward.			Ice storm	Ashe 1918

[a]This table expands on information initially presented by VanDyke (1999).

Photo used with permission by Ralph D. Nyland

Figure 23.—Thinning and other treatments that take out no more than about 30 percent of stocking at any time may make trees more resistant to effects of glazing.

ice storms. Practices like these should help reduce future losses (Downs 1938). One study on North American Maple Project plots across the ice storm area revealed that sugarbushes at low elevations, and having fewer and larger sugar maple trees growing in mixture with other species, had a greatly reduced risk of crown loss and broken tops than unmanaged stands (DesRochers and Allen 2001). This suggests that thinning and other methods that reduce crowding in stands to appropriate levels (e.g., taking out no more than 30 percent of stocking at any time) may help to make trees more resistant to effects of glazing, or at least not more susceptible (Fig. 23).

Landowners could use patch cutting to remove severely injured trees in stands with a heterogeneous pattern of damage. Logging operations must not cause injuries to the butt logs of standing trees, because that would affect the value more than any broken limbs in the crown (Lamson and Leak 1998). Frequent light crown thinning (<30 percent by volume) would not open the stand too much and would strengthen dominant and codominant trees. This intensity appears best when taking potential future ice storms into account (Carvell et al. 1957, Wisher and Ostrofsky 2001, Zarnovican 2001, Nielsen et al. 2003). Trees with a balanced crown and well-distributed branches around the main stem will likely withstand future ice storms better than ones with unbalanced crowns (McEvoy and Lamson 1998).

Photo used with permission by Ralph D. Nyland

Figure 24.—By estimating the crown spread before damage and comparing it to the remaining crown, managers can get a reasonable measure of crown loss and judge the potentials for tree and stand recovery.

Boulet et al. (2000) provide guidelines that landowners and forest managers can use to assess ice storm damage, and they offer detailed silvicultural guidelines for managing injured trees and forests. They suggest that by estimating the crown spread before damage and comparing it to the remaining crown (Fig. 24), managers can get a reasonable measure of crown loss. Their illustrations of trees affected to various degrees will assist in the estimation. But users must also consider the vigor of injured trees, amount of residual crown, abundance of twigs, condition of the bole, and vigor before the storm. Consensus suggests salvage cutting where most trees lost 80 percent or more of the crown. In all cases, harvesting crews must protect advance regeneration, soil, and residual trees from logging damage. Yet landowners must often wait 2 to 3 yr after a storm to adequately assess the potential for recovery before deciding how to treat a stand.

ACKNOWLEDGMENTS

Funding for the project was provided by the U.S. Forest Service, Northeastern Area State and Private Forestry, through the New York State Department of Environmental Conservation. Additional assistance was provided by SUNY-ESF. We thank John C. Brissette and Kevin T. Smith of the Northern Research Station of the U.S. Forest Service for reviews and other assistance in preparing the manuscript.

LITERATURE CITED

Abell, Charles A. 1934. **Influence of glaze storms upon hardwood forests in the southern Appalachians.** Journal of Forestry. 32(1): 35-37.

Allen, Douglas C.; Smallidge, Peter J.; Staats, Lewis. 1998. **Preliminary guidelines for forest owners following the January ice storm.** New York Forest Owner. March/April: 71-72.

Ashe, W.W. 1918. **Note on the preceding.** Monthly Weather Review. 46: 374.

Auchmoody, L.R. 1972. **Epicormic branching: seasonal change, influence of fertilization, and frequency of occurrence in uncut stands.** Res. Pap. NE-228. Upper Darby, PA: U.S. Department of Agriculture, Forest Service, Northeastern Forest Research Station. 8 p.

Barry, Patrick J.; Doggett, Coleman; Anderson, Robert L.; Swain, Kenneth M., Sr. 1993. **How to evaluate and manage storm-damaged forest areas.** R8-MB 63. Atlanta, GA: U.S. Department of Agriculture, Forest Service. Management Bulletin. 12 p.

Beil, James. 2001. **Extent of damage in New York State and Department of Environmental Conservation's response.** In: Allen, Douglas C., ed. Proceedings of the New York Society of American Foresters ice storm symposium. 1999 January 29; Cortland, NY. NA-TP-03-01. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northeastern Area State and Private Forestry: 25-29.

Bennett, Iven. 1959. **Glaze—its meteorology and climatology, geographical distribution, and economic effects.** Tech. Rep. EP-105. U.S. Army, Headquarters Quartermaster Research and Engineering Command, Quartermaster Research and Engineering Command Center, Environmental Protection Research Division. 217 p.

Blum, Barton M. 1963. **Excessive exposure stimulates epicormic branching in young northern hardwoods.** Res. Note NE-9. Upper Darby, PA: U.S. Department of Agriculture, Forest Service. Northeastern Forest Research Station. 6 p.

Boerner, R.E.J.; Runge, Shari D.; Cho, Do-soon; Kooser, James G. 1988. **Localized ice storm damage in an Appalachian Plateau watershed.** American Midland Naturalist. 119(1): 199-208.

Bofinger, Jennifer. 2001. **New Hampshire ice storm damage assessment and response.** In: Allen, Douglas C., ed. Proceedings of the New York Society of American Foresters ice storm symposium. 1999 January 29; Cortland, NY. NA-TP-03-01. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northeastern Area State and Private Forestry: 73-75.

Books, David J.; Tubbs, Carl H. 1970. **Relation of light to epicormic sprouting in sugar maple.** Res. Note NC-93. St. Paul, MN: U.S. Department of Agriculture, Forest Service. North Central Forest Experiment Station. 2 p.

Boulet, Bruno; Trottier, François; Roy, Gabriel. 2000. **Management of ice storm damaged stands.** Charlesbourg, PQ: Quebec Ministère des Ressources Naturelles. 10 p.

Bowersox, Todd W.; Ward, WilberW. 1968. **Auxin inhibition of epicormic shoots in white oak.** Forest. Science. 14(2): 192-196.

Brinkman, Kenneth A. 1955. **Epicormic branching on oaks in sprout stands.** Tech. Pap. 146. U.S. Department of Agriculture, Forest Service, Central States Forest Experiment Station. 8 p.

Bruederle, Leo P.; Stearns, Forest W. 1985. **Ice storm damage to a southern Wisconsin mesic forest.** Bulletin of the Torrey Botanical Club. 112(2): 167-175.

Buttrick, Philip L. 1922. **Storm damage to Michigan forests.** Journal of Forestry. 20: 527-532.

Campbell, W.A. 1937. **Decay hazard resulting from ice damage to northern hardwoods.** Journal of Forestry. 35(12): 1156-1158.

Campbell, W.A.; Davidson, Ross W. 1940. **Top rot in glaze-damaged black cherry and sugar maple on the Allegheny Plateau.** Journal of Forestry. 38(12): 963-965.

Carvell, K.L.; Tryon, E.H.; True, R.P. 1957. **Effects of glaze on the development of Appalachian hardwoods.** Journal of Forestry. 55(2): 130-132.

Chapeskie, David. 2001. **Ice storm damage to sugarbushes in Ontario.** In: Allen, Douglas C., ed. Proceedings of the New York Society of American Foresters ice storm symposium. 1999 January 29; Cortland, NY. NA-TP-03-01. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northeastern Area State and Private Forestry: 21-29.

Conover, D.F.; Ralston, R.A. 1959. **Results of crop-tree thinning and pruning in northern hardwood saplings after nineteen years.** Journal of Forestry. 57(8): 551-557.

Coons, Clarence F. 1999. **Effects of ice storm damage and other stressors on sugar bush health and sap productivity. Literature review and synthesis.** Toronto, ON: Ontario Ministry of Natural Resources, Ice Storm Economic Recovery and Assistance Program. 75 p.

Croxton, W.C. 1939. **A study of the tolerance of trees to breakage by ice accumulation.** Ecology. 20(1): 71-73.

DeGaetano, Arthur T. 2000. **Climatic perspective and impacts of the 1998 northern New York and New England ice storm.** Bulletin of the American Meteorological Society. 81(2): 237-254.

DeSteven Diane; Kline, Joanne; Matthiae, Paul E. 1991. **Long-term changes in a Wisconsin *Fagus-Acer* forest in relation to glaze storm disturbance.** Journal of Vegetation Science. 2: 201-208.

DesRochers, Pierre; Allen, Douglas C. 2001. **Impact of the January 1998 ice storm on some maple stands in the North American Maple Project.** In: Allen, Douglas C., ed. Proceedings of the New York Society of American Foresters ice storm symposium. 1999 January 29; Cortland, NY. NA-TP-03-01. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northeastern Area State and Private Forestry: 41-59.

Deuber, Carl G. 1940. **The glaze storm of 1940.** American Forests. 46(5): 210-211, 235.

Downs, Albert A. 1938. **Glaze damage in the birch-American beech-maple-hemlock type of Pennsylvania and New York.** Journal of Forestry. 36(1): 63-70.

Duguay, Stephanie M.; Arii, Ken; Hooper, Michael; Lechowicz, Martin J. 2001. **Ice storm damage and early recovery in an old-growth forest.** Environmental Monitoring and Assessment. 67: 97-108.

Faccio, Steven D. 2003. **Effects of ice storm-caused gaps on forest breeding bird communities in central Vermont.** Forest Ecology and Management. 186: 133-145.

Foster, David R. 1988. **Species and stand response to catastrophic wind in central New England, U.S.A.** Journal of Ecology. 76(1): 135-151.

Godman, Richard M.; Mattson, Gilbert A. 1970. **The sprouting potential of dormant buds on the bole of pole-sized sugar maple.** Res. Note NC-88. St. Paul, MN: U.S. Department of Agriculture, Forest Service, North Central Forest Experiment Station. 4 p.

Grisez, Ted J. 1978. **Pruning black cherry in understocked stands.** Res. Pap. NE-395. Broomall, PA: U.S. Department of Agriculture, Forest Service, Northeastern Forest Experiment Station. 9 p.

Guo, Yanfei. 1999. **Ice storm damage to a sweetgum plantation fertilized with nitrogen and phosphorus.** Southern Journal of Applied Forestry. 23(4): 224-229.

Guo, Yanfei; Vanderschaaf, Curtis. 2002. **Effect of nitrogen and phosphorus fertilization on growth of a sweetgum plantation damaged by an ice storm.** In: Outcalt, Kenneth W., ed. Proceedings of the eleventh biennial southern silvicultural research conference. Gen. Tech. Rep. SRS-48. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station: 223-226.

Harshberger, John W. 1904. **The relation of ice storms to trees.** Contributions of the Botany Laboratory of the University of Pennsylvania. 2: 345-349.

Hauer, Richard J.; Hruska, Mary C.; Dawson, Jeffrey O. 1994. **Trees and ice storms: the development of ice storm-resistant urban tree populations.** Spec. Pub. 94-1. Urbana-Champaign, IL: Department of Forestry, University of Illinois. 12 p.

Hauer, Richard J.; Wang, Weishen; Dawson, Jeffrey O. 1993. **Ice storm damage to urban trees.** Journal of Arboriculture. 19(4): 187-193.

Hooper, Michael C.; Arii, Ken; Lechowicz, Martin J. 2001. **Impact of a major ice storm on an old-growth hardwood forest.** Canadian Journal of Botany. 79(1): 70-75.

Hopkin, Anthony; Williams, Tim; Sajan, Robert; Pedlar, John; Nielson, Cathy. 2003. **Ice storm damage to eastern Ontario forests: 1998-2001.** Forestry Chronicle. 79(1): 47-53.

Horn, Henry S. 1971. **The adaptive geometry of trees.** Princeton, NJ: Princeton University Press. 144 p.

Huppuch, Charles D. 1961. **Epicormic branching on sycamore.** Res. Note SE-166. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southeastern Forest Experiment Station. 1 p.

Illick, Joseph S. 1916. **A destructive snow and ice storm.** Forest Leaves. 15: 103-107.

Irland, Lloyd C. 1998. **Ice storm 1998 and the forests of the northeast: a preliminary assessment.** Journal of Forestry. 96(9): 32-40.

Irland, Lloyd C. 2000. **Ice storms and forest impacts.** Science of the Total Environment. 262(3): 231-242.

Jemison, George M.; Schumacher, F.X. 1948. **Epicormic branching in old-growth Appalachian hardwoods.** Journal of Forestry. 46(4): 252-255.

Jones, Jason; DeBruyn, Ryan D.; Barg, Jennifer J.; Robertson, Raleigh J. 2001a. **Assessing the effects of natural disturbance on a neotropical migrant songbird.** Ecology. 82(9): 2628-2635.

Jones, Jason; Pither, Jason; DeBruyn, Ryan D.; Robertson, Raleigh J. 2001b. **Modeling ice storm damage to a mature mixed-species hardwood forest in eastern Ontario.** Ecoscience. 8(4): 513-521.

Jones, Kathleen F. 1998. **A simple model for freezing rain ice loads.** Atmospheric Research. 46: 87-97.

Jones, Kathleen F. 2001. **The physics of ice formation: ice on trees.** In: Allen, Douglas C., ed. Proceedings of the New York Society of American Foresters ice storm symposium. 1999 January 29; Cortland. NA-TP-03-01. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northeastern Area State and Private Forestry: 1-10.

Kidon, Jennifer; Fox, Glenn; McKenney, Daniel; Chapeskie, Dave. 1998. **Eastern Ontario ice storm maple producer's survey: summary and results.** Can. Work. Pap., Guelph, ON: Department of Agricultural Economics and Business, University of Guelph. 20 p.

Kraemer, Martin J. 2003. **Hardwood crown loss and subsequent rebuilding in northern New York following the January 1998 ice storm.** Syracuse, NY: State University of New York College of Environmental Science and Forestry. 240 p. M.S. Thesis.

Lafon, Charles W. 2004. **Ice-storm disturbance and long-term forest dynamics in the Adirondack Mountains.** Journal of Vegetation Science. 15: 267-276.

Lafon, Charles W.; Graybeal, Daniel Y.; Orvis, Kenneth H. 1999. **Patterns of ice accumulation and forest disturbance during two ice storms in southwestern Virginia.** Physical Geography. 20(2): 97-115.

Lafon, Charles W.; Speer, James H. 2002. **Using dendrochronology to identify major ice storm events in oak forests of southwestern Virginia.** Climate Research. 20: 41-54.

Lamson, Neil. 2001. **Recommended forest management responses to the January 1998 ice storm.** In: Allen, Douglas C., ed. Proceedings of the New York Society of American Foresters ice storm symposium. 1999 January 29; Cortland, NY. NA-TP-03-01. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northeastern Area State and Private Forestry: 105-107.

Lamson, Neil; Leak, William B. 1998. **Silvicultural approaches for managing ice-damaged stands.** Ice Storm 1998 Information Sheet 4. Durham, NH: Forestry Information Center, University of New Hampshire, Cooperative Extension. 2 p.

Lautenschlager, R.A.; Nielsen, Cathy. 1999. **Ontario's forest science efforts following the 1998 ice storm.** Forestry Chronicle. 75(4): 633-641.

Lautenschlager, R.A.; Winters, John A. 2001. **Quantifying ice damage by counting branches on damaged sugar maple trees.** Forestry Chronicle. 77(4): 637-642.

Lautenschlager, R.A.; Pedlar, John H.; Winters, John A.; Nielson, Cathy M. 2003b. **Ice storm damage: effects of competition and fertilization on growth of sugar maple trees.** Forestry Chronicle. 79(1): 63-69.

Lemon, Paul C. 1961. **Forest ecology of ice storms.** Bulletin of the Torrey Botanical Club. 88(1): 21-29.

Manion, Paul D.; Griffin, David H. 2001. **1998 ice damage in New York forests: assessment of impact on forest health.** In: Allen, Douglas C., ed. Proceedings of the New York Society of American Foresters ice storm symposium. 1999 January 29; Cortland, NY. NA-TP-03-01. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northeastern Area State and Private Forestry: 31-39.

Manion, Paul D.; Griffin, David H.; Rubin, Benjamin D. 2001. **Ice damage impacts on the health of the northern New York state forest.** Forestry Chronicle. 77(4): 619-625.

Marquis, David A. 1986. **Thinning Allegheny hardwood pole and small sawtimber stands.** In: Smith, H. Clay; Maxine C. Eye, eds. Proceedings of the workshop on guidelines for managing immature Appalachian hardwood stands. SAF Pub. 86-02. Morgantown, WV: West Virginia University Books: 68-84.

McEvoy, Thom J. 2002. **How to fend off storm damage.** Journal of Forestry. 100(2): 4.

McEvoy, Thom J.; Lamson, N. 1998. **Harvesting ice-damaged timber.** Ice Storm 1998 Information Sheet 9. Durham, NH: Forestry Information Center, University of New Hampshire, Cooperative Extension. 2 p.

Meating, Joe; Van Dyke, Olesia; Boyd, Andrew; Wright, King. 2000. **Management of ice storm damaged woodlots and plantations.** Tech. Rep. 117. Ontario Ministry of Natural Resources, Scientific Development and Transfer, Southcentral Science Section. 96 p.

Melancon, Serge; Lechowicz, Martin J. 1987. **Differences in the damage caused by glaze ice on codominant *Acer saccharum* and *Fagus grandifolia*.** Canadian Journal of Botany. 65(6): 1157-1159.

Miller, Gary W. 1996. **Epicormic branching on central Appalachian hardwoods 10 years after deferment cutting.** Res. Pap. NE-702. Radnor, PA: U.S. Department of Agriculture, Forest Service, Northeastern Forest Research Station. 9 p.

Miller-Weeks, Margaret; Eagar, Chris. 1999. **The northeastern ice storm 1998: highlights of a forest damage assessment for New York, Vermont, New Hampshire, and Maine.** Concord, NH: North East State Foresters Association, and Durham, NH: U.S. Department of Agriculture, Forest Service, State and Private Forestry. 32 p.

Miller-Weeks, Margaret; Linnane, Jim. 2001. **January 1998 ice storm: USDA Forest Service's response for damage assessment and landowners assistance.** In: Allen, Douglas C., ed. Proceedings of the New York Society of American Foresters ice storm symposium. 1999 January 29; Cortland. NA-TP-03-01. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northeastern Area State and Private Forestry: 61-65.

Millward, Andrew A.; Kraft, Clifford E. 2004. **Physical influences of landscape on a large-extent ecological disturbance: the northeastern North American ice storm of 1998.** Landscape Ecology. 19: 11-111.

Milton, Jennifer; Bourque, Alain. 1999. **A climatological account of the January 1998 ice storm in Quebec.** Can. EN57-34/1-1999. Ville Saint-Laurent, PQ: Atmospheric Science and Environmental Issues Division, Environment Canada.

Mou, Pu; Warrillow, Michael P. 2000. **Ice storm damage to a mixed hardwood forest and its impacts on forest regeneration in the ridge and valley region of southwestern Virginia.** Journal of the Torrey Botanical Society. 127(1): 66-82.

Nielsen, Cathy; VanDyke, Olesa; Pedlar, John. 2003. **Effects of past management on ice storm damage in hardwood stands in eastern Ontario.** Forestry Chronicle. 79(1): 70-74.

Noland, Thomas L. 2003. **1998 ice storm impact on sugar bushes of eastern Ontario.** Forestry Chronicle. 79(1): 75-81.

Noland, Thomas L.; McVey, Geoff; Chapeskie, Dave. 2005. **1998 ice storm effects on the health and productivity of sugar bushes of eastern Ontario: Part 2.** Maple Digest. 17A(1): 13-21.

Noland, Thomas L.; McVey, Geoff; Chapeskie, Dave. 2006. **Ice storm and fertilization effects on root starch, sap productivity and sweetness, diameter growth, and tap hole closure in sugar maple stands of eastern Ontario.** For. Res. Note 68. Sault Ste. Marie, ON.: Ministry of Natural Resources, Ontario Forest Research Institute. 6 p.

Olthof, Ian; King, Douglas J.; Lautenschlager, R.A. 2001. **Leaf area index change in ice-storm-damaged sugar maple stands.** Forestry Chronicle. 77(4): 627-635.

Parker, William C. 2003. **The effect of ice damage and post-damage fertilization and competition control on understory microclimate of sugar maple (*Acer saccharum* Marsh.) stands.** Forestry Chronicle. 79(1): 82-90.

Peterson, Chris J.; Pickett, S.T.A. 1991. **Treefall and resprouting following catastrophic windthrow in an old-growth hemlock-hardwoods forest.** Forest Ecology and Management. 42(3&4): 205-217.

Proulx, Olga J.; Greene, David F. 2001. **The relationship between ice thickness and northern hardwood tree damage during ice storms.** Canadian Journal of Forest Research. 31(10): 1758-1767.

Rebertus, Alan J.; Shifley, Stephen R.; Richards, R. Hoyt; Roovers, Lynn M. 1997. **Ice storm damage to an old-growth oak-hickory forest in Missouri.** American Midland Naturalist. 137(1): 48-61.

Reed, J.F. 1939. **Some factors affecting sleet damage to shade trees in the southern great plains.** Ecology. 20(4): 586-589.

Remphrey, W.R.; Davidson, C.G. 1992. **Spatiotemporal distribution of epicormic shoots and their architecture in branches of *Fraxinus pennsylvanica*.** Canadian Journal of Forest Research. 22(3): 336-340.

Rexrode, C.O.; Auchmoody, L.R. 1982. **46 years after the storm…glaze-damaged black cherry.** Pennsylvania Forests. 72(3): 8-9.

Rhoads, Anne G.; Hamburg, Steven P.; Fahey, Timothy J.; Siccama, Thomas G.; Hane, Elizabeth N.; Battles, John; Cobill, Charles; Randal, Jesse; Wilson, Geoff. 2002. **Effects of an intense ice storm on the structure of a northern hardwood forest.** Canadian Journal of Forest Research. 32(10): 1763-1775.

Rhoads, Richard W. 1999. **Ice storm damage in a small valley in southwestern Virginia.** Castanea. 64(3): 243-251.

Rhoads, Verne. 1918. **Ice storms in the southern Appalachians.** Monthly Weather Review. 46: 373-374.

Rogers, Walter E. 1922. **Ice storms and trees.** Torreya. 22: 61-63.

Rogers, Walter E. 1923. **Resistance of trees to ice storm injury.** Torreya. 23(6): 95-99.

Rogers, Walter E. 1924. **Trees in a glaze storm.** Tycos-Rochester. XIV(1): 5-8.

Root, Clarence J. 1924. **The glaze storm of December 17-18, 1924, in Illinois.** Monthly Weather Review. 52: 585.

Rubin, Benjamin D.; Manion, Paul D. 2001. **Landscape-scale forest structure in northern New York and potential successional impacts of the 1998 ice storm.** Forestry Chronicle. 77(4): 613-618.

Seeley, D.A. 1922. **In Michigan.** Monthly Weather Review. 50: 80-82.

Seischab, Franz K.; Bernard, John M.; Eberle, Mark D. 1993. **Glaze storm damage to western New York forest communities.** Bulletin of the Torrey Botanical Club. 120(1): 64-72.

Shigo, Alex L. 1986. **A new tree biology dictionary.** Durham, NH: Shigo and Trees, Assoc. 132 p.

Shigo, Alex L. 1991. **Modern arboriculture.** Durham, NH: Shigo and Trees, Assoc. 423 p.

Shortle, Walter; Smith, Kevin T. 1998. **How to determine percent live crown loss in hardwoods before leaf-out.** Ice Storm 1998 Information Sheet 1. Durham, NH: Forestry Information Center, University of New Hampshire, Cooperative Extension. 2 p.

Shortle, Walter; Smith, Kevin T.; Dydzik, K.R. 2003. **Tree survival and growth following ice storm injury.** Res. Pap. NE-723. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northeastern Research Station. 4 p.

Siccama, Thomas G.; Weir, George; Wallace, Kit. 1976. **Ice damage in a mixed hardwood forest in Connecticut in relation to Vitis infestation.** Bulletin of the Torrey Botanical Club. 103(4): 180-183.

Sisinni, Susan M.; Zipperer, Wayne C.; Pleninger, Andrew G. 1995. **Impacts from a major ice storm: street-tree damage in Rochester, New York.** Journal of Arboriculture. 21(3): 156-167.

Skilling, Darroll D. 1957. **Is the epicormic branching associated with hardwood pruning wounds influenced by tree crown class?** Tech. Note No. 510. St. Paul, MN: U.S. Department of Agriculture, Forest Service, Lake States Forest Experiment Station. 2 p.

Sleeth, B. 1938. **Decay in black cherry damaged by glaze.** Note 20. (original not seen). U.S. Department of Agriculture, Forest Service, Allegheny Forest Experiment Station. 2 p.

Smith, H. Clay. 1965. **Effects of clearcut openings on quality of hardwood border trees.** Journal of Forestry. 63(12): 933-937.

Smith, H. Clay. 1966. **Epicormic branching on eight species of Appalachian hardwoods.** Res. Note NE-53. Upper Darby, PA: U.S. Department of Agriculture, Forest Service, Northeastern Forest Experiment Station. 4 p.

Smith, H. Clay. 1977. **Changes in tree density do not influence epicormic branching of yellow-poplar.** Res. Note NE-239. Upper Darby, PA: U.S. Department of Agriculture, Forest Service, Northeastern Forest Experiment Station. 3 p.

Smith, Kevin T.; Shortle, Walter C. 2003. **Radial growth of hardwoods following the 1998 ice storm in New Hampshire and Maine.** Canadian Journal of Forest Research. 33: 325-329.

Smith, Kevin T.; Shortle, Walter C.; Dudzik, K.R. 2001. **Patterns of tree injury and response.** NA-TP-02-01. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northeastern Research Station, Northeastern Area State and Private Forestry. 4 p.

Smith, William H. 2000. **Ice and forest health.** Northern Journal of Applied Forestry. 17(1): 16-19.

Spaulding, Perley; Bratton, Allen W. 1946. **Decay following glaze storm damage in woodlands of central New York.** Journal of Forestry. 44(7): 515-519.

Spencer, J.H. 1929. **Ice storm of December 17-18, 1929, at Buffalo, N.Y.** Monthly Weather Review. 57: 508-509.

Staats, Lewis J. 2001. **The 1998 ice storm: its impact and recovery program in New York.** In: Allen, Douglas C., ed. Proceedings of the New York Society of American Foresters ice storm symposium; 1999 January 29; Cortland, NY. NA-TP-03-01. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northeastern Area State and Private Forestry: 15-19.

Stubbs, Jack. 1986. **Hardwood epicormic branching—Small knots but large losses.** Southern Journal of Applied Forestry. 10(4): 217-220.

Ter-Mikaelian, Michael; Lautenschlager, R.A. 2001. **Predictive equations for leaf area and biomass for sugar bushes in eastern Ontario.** Forestry Chronicle. 77(4): 643-649.

Timmer, Vic R.; Teng, Yuanxin; Pedlar, John. 2003. **Soil and leaf analysis of fertilized sugar maple stands after ice storm damage.** Forestry Chronicle. 79(1): 99-105.

Trimble, George R., Jr.; Seegrist, Donald W. 1973. **Epicormic branching on hardwood trees bordering forest openings.** Res. Pap. NE-261. Upper Darby, PA: U.S. Department of Agriculture, Forest Service, Northeastern Forest Research Station. 6 p.

Van Dyke, Olesia. 1999. **A literature review of ice storm impacts on forests in Eastern North America.** Tech. Rep. 112. Ontario Ministry of Natural Resources, Scientific Development and Transfer, Southcentral Science Section. 29 p.

Wahlenberg, W.G. 1950. **Epicormic branching of young yellow-poplar.** Journal of Forestry. 48(9): 417-419.

Ward, Wilber W. 1966. **Epicormic branching of black and white oaks.** Forest Science. 12(3): 290-296.

Warrillow, Michael; Mou, Pu. 1999. **Ice storm damage to forest tree species in the ridge and valley region of southwestern Virginia.** Journal of the Torrey Botanical Society. 126(2): 147-158.

Whitney, H.E.; Johnson, W.C. 1984. **Ice storms and forest succession in southwestern Virginia.** Bulletin of the Torrey Botanical Club. 111(4): 429-437.

Winship, Charles E.; Smallidge, Peter J. 1998. **Trees & ice—After the storm of 1998. Forestry information for private forest landowners and maple producers.** Ithaca, NY: Cornell University, Cornell Cooperative Extension, Department of Natural Resources. 70 p.

Wisher, Julie; Ostrofsky, William D. 2001. **Response of trees to ice injury in thinned and unthinned hardwood stands.** In: Proceedings of the 2000 National Convention, Society of American Foresters; 2000 November 16-20; Washington, DC. Bethesda, MD: Society of American Foresters: 474-475.

Zarnovican, Richard. 2001. **Glaze damage in a young yellow birch stand in southern Quebec, Canada.** Northern Journal of Applied Forestry. 18(1): 14-18.

Kraemer, Martin J.; Nyland, Ralph D. 2010. **Hardwood crown injuries and rebuilding following ice storms: a literature review.** Gen. Tech. Rep. NRS-60. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station. 29 p.

Ice storms occur frequently in northeastern North America. They damage and kill trees, change the structural characteristics of a forest, and may importantly alter the goods and services that owners realize from their land. This literature review summarizes 90 years of relevant information, mainly from fairly short term studies published between 1904 and 2006. It documents ice storm severity and the effects on hardwood branch loss, primarily among upper canopy trees; methods for estimating and classifying hardwood crown damage; and factors influencing epicormic branch formation on hardwood trees. It also summarizes management recommendations for dealing with crown loss and for managing stands after damage by ice storms.

Key words: Ice storm, storm injuries to trees, hardwood forests, tree damage

www.nrs.fs.fed.us