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Impacts and management implications of ice storms on forests in the southern United States

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Abstract

This review explores the ecological and silvicultural impacts of ice storms on forests in the southern United States. Different environmental factors like weather conditions, topography, vegetation, stand density, and management practices influence the degree of glaze damage a particular forest may experience. Additionally, the frequent contradictions in the relationships between these factors and the resulting damage suggests a complexity that makes each ice storm unique and difficult to predict. We recommend a series of silvicultural responses to ice storms, including density management, planting species selection, post-event evaluation, salvage, stand rehabilitation, and long-term monitoring of forest health.
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1. Introduction

Natural disturbances strongly influence forest composition, structure, and dynamics (Oliver, 1981; Pickett and White, 1985; Everham and Brokaw, 1996; Rogers, 1996). Severe wind, drought, fire, snow and ice, debris flows, flooding, pests, and pathogens damage or destroy billions of dollars of timber and other property annually. Ice accumulation (also called "glaze") is one of the most frequent and injurious disturbances in temperate regions (Irland, 2000; Smith, 2000). Because they usually develop from the clash of weather systems, ice storms often occur on a monumental scale. For example, in January of 1998 an ice storm struck southeastern Canada and the northeastern United States (US). Over 10 million forested hectares were damaged (Irland, 1998; Nordin, 1998; Miller-Weeks et al., 1999), placing ice storms on par with other major natural catastrophes (Deuber, 1940; Lautenschlager and Nielsen, 1999).

Ice storms periodically strike the southern US, a region whose prominence in global timber production has placed considerable pressure on forest managers to minimize disruptions (Sheffield and Dickson, 1998). Reducing losses to catastrophic glazing requires better guidance for landowners, foresters, and other resource managers to ensure that proper silvicultural and economic decisions are made. Literature reviews for northern and eastern North American forests have

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been recently completed (e.g., Van Dyke, 1999; Irland, 2000; Smith, 2000), but information on ice damage in the South is still largely unconsolidated. Therefore, objectives of this paper include the examination of the biophysical and ecological attributes of ice storms in the southern US and the development of glaze-related silvicultural recommendations.

2. Ecology of ice storms

2.1. Ice storm climatology

The National Weather Service declares an ice storm after at least 0.6 cm of ice accumulates (Irland, 2000). However, glaze events are not usually considered remarkable without extensive property damage. An ice storm can be separated into two unique components: the meteorological event that produces the glaze and the response of the biota to this accumulation. Though it is virtually impossible to discuss one without considering the other, this section will focus on the climatology of ice storms.

2.1.1. Weather conditions

Ice storms develop under specific atmospheric conditions and may last for hours to days (Okada, 1914; Christie and Chartier, 1943; Lemon, 1961). Typically, warm, moist air overruns a shallow body of cold air. The air near the ground cools surfaces below the freezing point of water, causing liquid precipitation to freeze on impact. Rain may also become supercooled in its fall from the warmer clouds, causing it to freeze immediately upon contact (Harshberger, 1904; Lemon, 1961; Gay and Davis, 1993). Localized icing events may be triggered when an influential factor like elevation interacts with the proper atmospheric conditions (Ashe, 1918; Nicholas and Zedaker, 1989; Jones and Mulherin, 1998).

Depending on how rapidly the landscape warms, glaze may remain for a considerable period of time, accentuating the damage (von Schrenk, 1900; Illick, 1916; Christie and Chartier, 1943). Destruction may be further compounded by wind, snow, or rain that often accompany icing (Harshberger, 1904; Illick, 1916; Christie and Chartier, 1943; Cayford and Haig, 1961; Semonin, 1978; De Steven et al., 1991). Heavy, wet snows affect vegetation in much the same way (Curtis, 1936; McKay and Thompson, 1969; Reamer and Bruner, 1973; Nykänen et al., 1997) and can also inflict considerable damage on forests (Illick, 1916; Anonymous, 1939; Nykänen et al., 1997).

As with other natural disturbances, ice storms inconsistently impact the landscape, especially in the degree of ice loading that occurs (e.g., Sanzen-Baker and Nimmo, 1941; Christie and Chartier, 1943; Lemon, 1961; Belanger et al., 1996). Total glaze accumulation depends on the intensity of the precipitation, the duration of the storm, and the temperature range and fluctuation during the event, amongst other factors (Rogers, 1924; Lemon, 1961; Belanger et al., 1996; Smith, 2000). Ice buildup can range from barely measurable to greater than 15 cm (Lemon, 1961; Halverson and Guldin, 1995; Nordin, 1998). Most reports typically provide the maximum accumulation observed because this usually results in the greatest damage (Table 1).

2.1.2. Spatial extent and frequency

Catastrophic ice storms of the magnitude of the 1998 event that struck Canada and the northeastern US are quite rare. The South, while not as prone to glaze storms as other regions (Cool et al., 1971), also experiences large-scale icing (e.g., von Schrenk, 1900; Anonymous, 1969; Fountain and Burnett, 1979; Warrillow and Mou, 1999). White (1944) reported an ice storm that covered 3 million hectares in Texas and Louisiana, with at least 1 million hectares suffering "severe" damage. Halverson and Guldin (1995) described a particularly severe glazing that produced heavy damage from eastern Arkansas through northern Mississippi—an area approximately 270 km long and up to 170 km wide. During December of 2000, Arkansas endured two ice storms that damaged an estimated 40% of the 7.4 million hectares of the state's forests (Forgrave, 2001). Fortunately, the most severe losses tend to be confined to relatively small areas (Bennett, 1959; Russell, 1966; Boerner et al., 1988).

Some locations in North America report glazing once every 1–2 years, though most areas experience >5 year return intervals (Bennett, 1959; Goebel and Deitschman, 1967; Cool et al., 1971; Wiley and Zeide, 1991; Gay and Davis, 1993; Irland, 2000). Forests inland from the Gulf of Mexico may expect some type of glaze damage once every 5–12 years (Bennett, 1959; Mattoon, 1915; Wahlenberg, 1960; Cool et al., 1971; Schultz, 1997), while ice storms are virtually

Table 1
A select listing of major glaze storms and their maximum reported ice accumulations by geographic area

Region (study)	Maximum ice (cm)	Year of event	Area(s) most affected
Northeastern US and Canada			
Downs (1938)	7.6	1936	New York, Pennsylvania
Christie and Chartier (1943)	15.2	1942	New York
Lemon (1961)	5.0	1949	New York
Melancon and Lechowicz (1987)	1.5	1983	Quebec
Seischab et al. (1993)	>2.0	1991	New York
Proulx and Greene (2001)	>16.5	1998	Southeast Canada, northeast United States
Midwestern US			
Buttrick (1922)	11.4	1922	Michigan
Boggess and McMillan (1954)	5.0	1952	Illinois
De Steven et al. (1991)	11.9	1976	Wisconsin
Boerner et al. (1988)	3.0	1986	Ohio
Hauer et al. (1993)	2.0	1990	Illinois
Rebertus et al. (1997)	2.5	1994	Missouri, Iowa, Kansas
Western US			
Irland (2000)	3.7	1996	Washington, Idaho
NOAA (2001)	12.7	1996	Oregon, Washington
Southern US			
Williamson (1934)	2.5	1934	Tennessee
Reed (1939)	2.5	1938	Texas
McNayr (1944)	2.5	1944	Louisiana
Kiviat (1949)	7.6	1949	Arkansas, Missouri
Burton and Gwinner (1960)	2.5	1960	Tennessee
Van Lear and Saucier (1973)	>2.5	1973	South Carolina
Nicholas and Zedaker (1989)	10.2	1987	North Carolina
Halverson and Guldin (1995)	20.1	1994	Arkansas, Mississippi
Warrillow and Mou (1999)	12.7	1994	Virginia
NOAA (2001)	10.2	2000	Arkansas, Oklahoma, Texas
Europe			
Sanzen-Baker and Nimmo (1941)	>10.0	1940	Southcentral Britain, Wales, Seine-Inférieure (France)

unheard of along many coastal areas (Gay and Davis, 1993). Occasionally, multiple ice storms occur in the same general area only days apart (Christie and Chartier, 1943; Nicholas and Zedaker, 1989; Warrillow and Mou, 1999). For example, Brender and Romancier (1965) noted that three glaze storms affected the Hitchiti Experimental Forest in Georgia within a year, and four damaging ice storms struck southwestern Virginia over a 2-month period (Rhoades, 1999).

2.2. Vegetation responses to ice storms

Glazing can impart tree damage range from the loss of tissues to structural failure or fatal injury. Biomechanics help explain the likelihood that an individual will be affected under an idealized set of circumstances, but cannot completely account for the actual damage inflicted upon a given tree.

2.2.1. Biomechanics of ice damage

The structural integrity of an individual under ice loading ultimately depends on its ability to withstand collapse—the greater the resistance, the less likely the tree is to fail. This is especially true since wood that is cold, "green," or less dense has notably lower resistance to breakage than warm, seasoned wood of the same species (von Schrenk, 1900; Panshin and de Zeeuw, 1970; Cannell and Morgan, 1989). The most relevant wood property related to resistance is modulus of rupture (MOR) or the maximum bending load to failure (Panshin and de Zeeuw, 1970). MOR is sensitive to wood specific gravity and moisture content, so even a slight decrease in specific gravity (G) can yield a pronounced reduction in strength:

$$\mathrm{MOR} = aG^{1.25} \tag{1}$$

where the coefficient (a) equals 177 when the wood is air dry and 121 when green (Panshin and de Zeeuw, 1970). Using Eq. (1), the green resistive strength of a low density sample ($G = 0.40$) is 38.5 MPa compared to 50.9 MPa for wood with a $G = 0.50$, while a $G = 0.70$ approaches 80 MPa.

Specific gravity can vary within a species and even along the dimensions of an individual tree. For example, early wood is less dense than late wood and juvenile wood has a lower specific gravity than mature wood (Megraw, 1985). The specific gravity of bole wood in the crown of young loblolly pines was approximately 25% less than that found near the base of the tree (Lenhart et al., 1977) and the specific gravity of roots for some southern pine species was markedly lower than bole wood (Gibson et al., 1986). These differences help to explain why the upper stem and roots of trees are more vulnerable to loading damage than the lower bole.

The biomechanics of ice loading have been adapted from cantilevered beams subject to large deflections (Petty and Worrell, 1981; Morgan and Cannell, 1987; Cannell and Morgan, 1989; Peltola et al., 1999). To do this, one must assume that the beams have no defects or variability in density and the forces acting upon them are not highly irregular. Failure occurs when bole stress (bending force, or F_B) exceeds the maximum bending moment (R_C) possible for a tree of a given size and species (Petty and Worrell, 1981; Peltola et al., 1999):

$$F_B > R_C \tag{2}$$

In other words, structural integrity fails at the point along the branch, bole, or roots where the accumulated stress exceeds the tree's resilience to damage. Peltola et al. (1999) developed an additive model to estimate F_B:

$$F_B = \sum_{z=0}^{h} T_{\max}(z) \tag{3}$$

where the maximum turning point at a specified location ($T_{\max}(z)$) is

$$T_{\max}(z) = W \times P_f \times \left[\left(\frac{C_d \times \rho \times u(z)^2 \times A(z)}{2} \right) + (M(z) \times g) \right] \tag{3a}$$

In Eq. (3a), W is an empirically derived wind gust loading factor, P_f a gap positional factor, C_d a crown drag coefficient, ρ the density of the air, $u(z)^2$ the average wind speed at location z, $A(z)$ the projected area of the tree against the wind (adjusted for streamlining and ice accretion), $M(z)$ the biomass and accumulated precipitation weight, and g the acceleration due to gravity. Critical beam resistance (R_C, in Pa) can be estimated from:

$$R_C = \frac{\pi \times \mathrm{MOR} \times D^3}{32} \tag{4}$$

where D is the diameter (in m) of the branch, stem, or root (Petty and Worrell, 1981; Cannell and Morgan, 1989; Peltola et al., 1999). From Eq. (4), it can be seen that R_C is proportionally related to MOR and exponentially related to D. Thus, large trees with strong wood (high MOR) require considerably greater mass of accumulating ice or snow before failure (Fig. 1).

Eqs. (3) and (4) account for most of the critical factors involved with ice damage. $A(z)$ and $M(z)$ cannot remain fixed over time like the other parameters because the surface area and mass of the tree above height z fluctuate as ice accumulates or material is shed (Jones, 1996; Peltola et al., 1999). Trees exposed to more wind experience greater F_B than sheltered individuals (Larson, 1963). For example, foliated trees have appreciably greater surface area than those without leaves, and thus are more vulnerable to ice, snow, and wind damage (Rogers, 1923; Butler and Swanson, 1974; Petty and Worrell, 1981; Peltola et al., 1999) unless their wood is very strong (Rogers, 1923). Bending force can also be affected by leverage resulting from branch or stem architecture. Trees with branches that droop, are relatively thick, or have pliable stems and limbs are thought to better withstand glazing since they can shed ice or transfer the bending force to other parts of the tree, the ground, or even neighboring individuals (Harshberger, 1904; Rogers, 1924; Metcalfe, 1949; Cannell and Morgan, 1989; Smith, 2000).

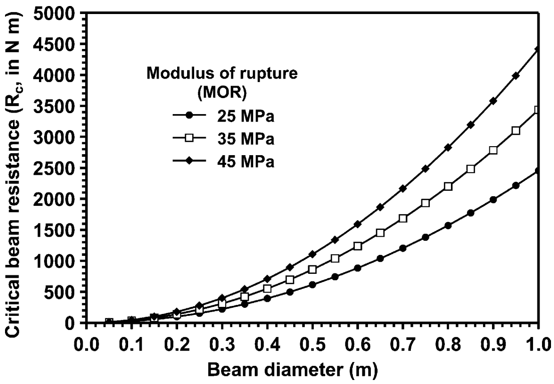

Fig. 1. Critical beam resistance (in N m) as a function of modulus of rupture (in MPa) and beam diameter (see Eq. (4)).

As with any model, Eqs. (2)–(4) oversimplify ice loading. Weak points from decay, knots, or other defects, inconsistency in wood quality, temperature-related pliability, irregular load attenuation due to branch or foliage loss, limited rooting depth, or saturated soils could noticeably alter this idealized model (Petty and Worrell, 1981). For instance, Sisinni et al. (1995) reported that intermediate to large (>25 cm dbh) street trees were heavily damaged following a severe ice storm, injuries attributed to unsound limbs, low flexibility, and poor form.

2.2.2. Glaze-induced mortality

Glazing is the predominant canopy disturbance in many areas (Smith, 2000), but few stands are completely destroyed by an ice storm. Mortality related to ice accumulation can vary widely due to factors like event severity, tree tolerance to ice accumulation, and post-event trauma (e.g., insects, disease, fire). Lethal damage can occur in southern pines if most of the live crown is lost or the tree is severely bent or uprooted. Bragg et al. (2002) tracked 18–20-year-old planted loblolly pine (*Pinus taeda* L.) during the first growing season following a severe ice storm. They found that 28% of the critically injured (>70% crown loss or >60° bowed) loblolly pine expired by the end of this period, while <2% of less damaged individuals died. Hardwoods have a much greater capacity to resprout and rarely have foliage during the peak ice storm season, so they are less likely to perish from glazing. Nevertheless, the same risk factors (e.g., spindly stature) that affect conifers can also kill hardwoods (Blum, 1966). Young trees may be more vulnerable to mortality from freezing, especially in nurseries or when planted much further north than their customary range (Hebb, 1973).

2.2.3. Non-lethal individual tree damage

Even if not necessarily lethal, ice accumulation has serious physical consequences for vegetation.

Fig. 2. Inelastically bent 18–20-year-old loblolly pine in a recently thinned plantation. Many of these trees will not straighten appreciably, and some will eventually break below the live crown.

Individuals most likely to survive ice loading share a number of key attributes: stout boles, strong wood, symmetrical crowns, limited accumulating surfaces, favorable branching patterns, good rooting conditions, and local support. A pronounced weakness in any of these factors leaves the tree vulnerable. For example, loblolly pine tolerates icing better than slash (*Pinus elliottii* Engelm.) or longleaf (*Pinus palustris* Mill.) because of greater stem flexibility and shorter needles (McKellar, 1942; Wahlenberg, 1960; Brender and Romancier, 1965).

Ice loading can critically injure tree roots, sometimes to the point of uprooting. Trees with extensive root damage have little potential for recovery (Hyman, 1985), although individuals with less pronounced failures may persist for years. Some species can resprout when prone, and hence may survive even complete toppling.

Bole compression injuries have been found in seemingly undamaged trees (e.g., Forest Products Research Laboratory, 1941). Severe bole wounds can lead to saprot, reduced growth, the formation of compression wood, eccentric growth rings, and empty intercellular voids between rings (Rendle et al., 1941; Spaulding and Bratton, 1946; Kuprionis, 1970). Since wood is a relatively pliable material, trees can be permanently damaged by being inelastically bent by soil movement, wind, snow, or ice accumulation (Fig. 2). Stout boles are more capable of supporting ice accumulation, although they are more likely to break (rather than bend) once the resistance of the wood has been exceeded (Shepard, 1975; Amateis and Burkhart, 1996). Stem breakage below the live crown (Fig. 3) is fatal to southern pines (Abel, 1948), but not necessarily so in many hardwoods because of sprouting. If even slightly bowed by glazing, phototropism causes woody plants to attempt to straighten their boles by the formation of reaction wood (Rendle et al., 1941). However, permanent bole deformation may occur when a growing tip is lost and apical dominance is transferred to axillary buds (Fig. 4). Evidence of some storms can persist for decades. For instance, Ashe (1918, p. 374) recounted "... a number of old trees bowed ... an almost certain sign of past ice damage ..." and later "... a young stand ... bent into an inextricable tangle ... the signs of this storm will be written in this stand for a century ...".

As suggested by pruning studies, southern pines tolerate a considerable loss of their crown (e.g., Bull, 1943; McClay, 1953). Lemon (1961, p. 23) stated that ice between 0.6 and 1.3 cm thick would remove small or "faulty" branches, while an accumulation of 1.3–2.5 cm would produce "conspicuous" breakage. Branching pattern affects individual response to glaze damage (Fig. 5), especially when weak crotches or pronounced forks produce a leverage point on the stem or branches (Rogers, 1924; Metcalfe, 1949; Hauer et al., 1994; Amateis and Burkhart, 1996). The excurrent growth of most pines and hardwoods with pronounced apical dominance (e.g., sweetgum, *Liquidambar styraciflua* L.) is thought to be more conducive for shedding ice and snow than the decurrent form (e.g., Rogers, 1924; Guo, 1999; Van Dyke, 1999). The vase-shaped form of many elms and oaks has been identified as particularly susceptible to ice damage (Rogers, 1924; Reed, 1939; Van Dyke, 1999). Form-related

Fig. 3. This loblolly pine could not bear the load of ice it received and fatally snapped below the crown. However, note the general lack of major damage in this ~30-year-old plantation.

Fig. 4. The ''crooks'' in these mature loblolly pine (arrows) were likely caused by the same ice storm years ago that broke the original leader. It is not unusual to see this consistency in damage in overstory dominants of older stands.

Fig. 5. Hardwoods are often stripped on large branches, especially if partially decayed.

amelioration of ice loads is a useful survival mechanism because many kilograms of ice can build on even small limbs (Rogers, 1922; Brender and Romancier, 1965; Semonin, 1978).

Following glazing, Lutz (1936) found external callous lesions on young, smooth-barked hardwoods that apparently formed when the leaning, ice-covered trees overstretched their bark. Young southern pines can also suffer bark damage and seep pitch following severe bending. Spaulding and Bratton (1946) linked saprot along the boles of northern hardwoods to sudden exposure of vulnerable surfaces to intense sunlight following a severe ice storm. The presence of cankers (Belanger et al., 1996; Cool et al., 1971) and decay (Bruederle and Stearns, 1985; Sisinni et al., 1995) may increase susceptibility to future ice damage.

2.3. Ice damage related to local environments

Injury may result from the complex interactions between site conditions, stand attributes, and other external aggravating factors. Even the presence of woody vines can influence the damage suffered by increasing the ice accumulating surface area (Siccama et al., 1976) or by causing constriction-related defects in the stem.

2.3.1. Stand density

An examination of the reported effects of stocking on ice damage has produced many conflicting reports (Table 2). For example, Amateis and Burkhart (1996) assessed an 11-year-old unthinned loblolly pine spacing trial for ice damage and did not detect any relationship between spacing and the degree of stand damage. Others have found that dense stands were more vulnerable to glazing (e.g., Boggess and McMillan, 1954; Cayford and Haig, 1961; Van Dyke, 1999). Even for open-grown trees there is no agreement. For instance, Cool et al. (1971) believed open-grown

Table 2
Observed effects of tree, stand, site, and weather characteristics on the degree of ice damage

Characteristics	Damage[a]	Reference	Conditions
Tree variables			
Old age	+	Van Dyke (1999)	Any species
Forked trees	+	Amateis and Burkhart (1996)	Loblolly pine
Very small trees (3.2 < dbh < 9.5 cm)	+	Proulx and Greene (2001)	Northern hardwoods (for any icing, though less at heavy icing)
Small trees (dbh < 17.8 cm)	+	Proulx and Greene (2001)	Northern hardwoods (bending)
Intermediate size (13.1 < dbh < 17.8 cm)	+	Proulx and Greene (2001)	Northern hardwoods (snapping)
Large trees	+	Proulx and Greene (2001)	Northern hardwoods (many branches lost)
Larger trees	+	Van Dyke (1999)	Dense pine plantations
Dominant trees	+	Van Dyke (1999)	Prominent crowns
Greater than average size	+	Van Dyke (1999)	Any species
Low height/dbh ratio	−	Van Dyke (1999)	Pine plantations
Low crown/stem ratio	+	Cool et al. (1971)	Southern pine stands
Compact, cone-shaped crowns	−	Van Dyke (1999)	Conifers
Broad, flat crowns	+	Van Dyke (1999)	Hardwoods
Asymmetric crowns	+	Fountain and Burnett (1979), Van Dyke (1999), Williston (1974)	Any species
Excurrent growth	+	Van Dyke (1999)	Narrow crowns
Acute branch angles	−	Van Dyke (1999)	Any species
Opposite branching	+	Van Dyke (1999)	Any species
Numerous small branches	+	Van Dyke (1999)	Any species
Shallow rooting habit	+	Warrillow and Mou (1999)	Virginia pine
Vine coverage	+	Siccama et al. (1976)	Mixed species
Decay/insect damage	+	Van Dyke (1999)	Any species
Fusiform rust infection	0	McKellar (1942), Abel (1948)	Pine plantations
Fusiform rust infection	+	Fountain and Burnett (1979), Williston (1974)	Pine plantations
Wood strength	0	Van Dyke (1999)	Any species
Trees grown from seeds collected from coastal stands	+	Jones and Wells (1969)	Loblolly pine plantations
Stand variables			
Planted versus natural stands	−	Wahlenberg (1960)	Loblolly pine
14 < stand age < 25 years	−	Cayford and Haig (1961)	Red and Scots pine plantations
Stand age < 10 years	+	Cool et al. (1971)	Pine stands (bending)
Open-grown trees	−	Cool et al. (1971)	Southern pine stands
Open-grown trees	+	Van Dyke (1999)	Any species
Dense stands	+	Cayford and Haig (1961)	Red and Scots pine plantations
Dense stands	0	Cool et al. (1971)	Southern pine
Dense stands	0	Amateis and Burkhart (1996)	Small loblolly pine (<13 cm dbh), high winds
Dense stands	−	Zarnovican (2001)	28-year-old hardwoods, 13 years after thinning
Stand density	+	Boggess and McMillan (1954), Van Dyke (1999)	Pine plantations
Stand density	0	Abel (1949), Van Dyke (1999)	Pine plantations (high winds)
Low density, high dbh (>25 cm)	−	Shepard (1975)	Loblolly pine
Medium density medium dbh (18–25 cm)	+	Shepard (1975)	Loblolly pine
High density, low dbh (<18 cm)	−	Shepard (1975)	Loblolly pine
Recent thinning (<3 years)	+	Belanger et al. (1996), Burton and Gwinner (1960), Cool et al. (1971), Shepard (1978), Walker and Oswald (2000)	Loblolly pine

Table 2 (*Continued*)

Characteristics	Damage[a]	Reference	Conditions
Recent row thinning	+	Van Dyke (1999)	Pine plantations
Thinning intensity	+	Brender and Romancier (1960)	Loblolly pine (conclusion conflicts with provided data)
Edges	−	Kienholz (1941)	Jack pine
Edges	+	Proulx and Greene (2001)	Northern hardwoods (bend and snap into clearing)
Edge versus interior trees	+	Burton and Gwinner (1960)	Pine stands
Edge versus interior trees	0	Proulx and Greene (2001)	Northern hardwoods
Site conditions			
Elevation	+	Christie and Chartier (1943)	Any species
Frost pockets	+	Walker and Oswald (2000)	Localized
Slope	+	Proulx and Greene (2001)	Northern hardwoods (bend and snap downhill)
Colder slopes	+	Van Dyke (1999)	North and east slopes
Steep slopes	+	Van Dyke (1999)	Rugged terrain
Soft wet soil	+	Van Dyke (1999)	Localized
Rooting depth	−	Rhoades (1999)	Any species
Weather factors			
Ice accumulation	+	Proulx and Greene (2001)	Stand edge and interior; northern hardwoods
Ice retention	+	Schultz (1997)	Any species
Strong winds	+	Proulx and Greene (2001), Van Dyke (1999), Cool et al. (1971)	Any species

[a] + and − indicate greater and smaller than average damage, respectively, and 0 implies no effect.

southern pines were less vulnerable to ice damage, while Van Dyke (1999) reported the opposite. As suggested by Eq. (4) and Fig. 1, thicker trees are more apt to resist ice loads than spindly individuals. Thinning stands releases trees from competition, allowing them to increase in size faster and hence become more resistant to ice damage (Zeide and Sharer, 2000). However, until trees adjust to these thinned conditions by adding more bolewood and roots, they are particularly vulnerable to glazing (Downs, 1943).

Density may also influence ice damage in unexpected ways. Cain and Shelton (2002) reported that collisions from falling neighbors was the most obvious risk factor in a natural, unthinned 18-year-old stand of loblolly and shortleaf (*Pinus echinata* Mill.) pine. Thinning reduces collision effects by placing greater spacing between trees. Sometimes the glazed crowns of closely packed neighbors form a large, solid mass (e.g., von Schrenk, 1900; Kienholz, 1941), which may contribute to mutual support or group failure. If the trees gain support from neighbors or their own branches reaching the ground, then the ice load is better distributed and the damage may be lessened (Rogers, 1924; Metcalfe, 1949). However, if structural failure affects even a single tree in this aggregate, its inertia can cause the whole mass to fail (Kienholz, 1941; Fenton, 1959).

2.3.2. *Stand age/tree size*

Boerner et al. (1988) and Smith (2000) noted greater levels of damage with increasing tree age, but others hold that the larger size of older trees imparts more structural rigidity and hence greater resistance to damage (e.g., Amateis and Burkhart, 1996). Hebb (1973) suggested that older (and hence larger) trees were more likely to break than bend when loaded with ice. Guo (1999) found that in 22-year-old sweetgum plantations individuals of a larger diameter than their neighbors had a higher probability of damage. The December 2000 Arkansas ice storms resulted in limited crown damage in older (~30-year-old) loblolly plantations, with only scattered stem breakage or uprooting (Bragg et al., in press). Intermediate-aged (12–20-year-old) plantations on similar sites experienced major stem breakage, crown loss, and uprooting, while the youngest (<8-year-old),

Fig. 6. Young, snow-covered loblolly and shortleaf pine (a) will straighten considerably even before the next growing season (b), and will be visually indistinguishable from undamaged trees in a few years. Note how the largest trees barely even buckled under the snow load.

initially flattened by the ice, straightened with little obvious injury (Fig. 6).

2.3.3. Edge effects

The influence of edge effects on ice storm damage also appears contradictory. Kienholz (1941) noticed that jack pine (*Pinus banksiana* Lamb.) along the outer edges of an unthinned plantation sustained less damage than the interior of the stands, which he attributed to the greater bole diameters of the perimeter trees. However, others have reported more damage along the stand edges due to greater wind exposure (Seischab et al., 1993; Päätalo et al., 1999), and stems along openings often develop asymmetrical crowns, increasing their vulnerability (Abel, 1948; Burton and Gwinner, 1960; Williston, 1974; Fountain and Burnett, 1979).

2.3.4. Site-based risk factors

Limited rooting support contributes significantly to ice storm damage. Since much of the turning force on a tree is transferred down the bole into the roots, a prominent belowground weakness would be a likely spot for failure. Factors leading to restrictions in rooting depth (e.g., genetics, shallow bedrock, high water table, fragipans) limit a tree's ability to withstand ice loads (Rhoades, 1999). For example, Warrillow and Mou (1999) suspected that Virginia pine's (*Pinus virginiana* Mill.) shallow rooting habit contributed to its poor survivorship following icing.

Topography can also magnify glaze injury (Abell, 1934; Carvell et al., 1957; Boerner et al., 1988; Walker and Oswald, 2000), especially if higher elevations are more prone to freezing rain. Elevation and certain aspects may increase exposure to stronger winds, resulting in higher damage (Nicholas and Zedaker, 1989; Lafon et al., 1999; Warrillow and Mou, 1999). Unique conditions can increase ice damage frequency, as has been reported for the ''cold-air damming'' in the mountains of southwestern Virginia (Lafon et al., 1999) or frost pockets leading to localized areas of elevated injury (Walker and Oswald, 2000).

2.4. Further ecological impacts of ice storms

2.4.1. Understory trees

In multilayered stands, overstory trees can shelter midcanopy and smaller individuals (Rebertus et al., 1997). Rhoades (1999) reported only limited injury to understory trees even though the overstory of mixed hardwood-pine stands was heavily damaged by a series of ice storms. Although seedlings are normally very resilient to bending, their recovery may be prevented if trapped or broken by fallen debris. For instance, Duguay et al. (2001) found 78% of saplings and small trees were snapped or pinned by debris. Losses of understory trees can be offset by increased resources (especially light), allowing formerly suppressed survivors to achieve canopy positions following a severe icing event (Duguay et al., 2001). However, overstory removal may contribute to lethal release shock in suddenly exposed individuals or leave top-heavy advanced pine regeneration susceptible to later glazing (Nelson, 1951).

2.4.2. Response by wildlife to glazing

Wildlife first must endure the perils of the storm—low temperatures, ice buildup, falling debris, and reduced mobility. Birds are especially vulnerable. Walker and Wiant (1966, p. 47) noted that woodpeckers were killed in ''great numbers'' by ice storms; likewise, Kirby (1954, p. 5) reported that a Mississippi ice storm had ''. . . killed most of the woodpeckers and other birds. They were found by the basketfull [sic] . . . frozen to death''. Horned grebes (*Podiceps auritus* Linn.) have experienced substantial mortality from glazing (Eaton, 1983) and Errington (1936) linked elevated mortality of bobwhite quail (*Colinus virginianus* Linn.) to an ice storm.

Ice storms also modify wildlife habitat (McLellan, 1998). Changes to habitat quality associated with ice storms usually favor wildlife species that prefer the early stages of succession. Ice damage often forces land managers to carry lower stocking levels than would be desirable for maximum timber production, including stands liquidated before the end of their intended rotation. Reductions in stand basal area have been shown to improve forage production of vegetation important to bobwhite quail (Peitz et al., 1997) and whitetail deer (*Odocoileus virginianus* Zimm.) (Peitz et al., 2001), but these gains decline over time. Ice storms also increase the number of habitat-forming snags and coarse woody debris (Hunter, 1990; Lamson and Leak, 1998) and initiate stem and branch decay, providing conditions favorable for cavity development (Lamson and Leak, 1998).

Glazing indirectly impacts both wildlife and natural plant regeneration by its impact on fruit and seed production. Short-term negative effects on revegetation occur if reproductive structures set during the fall are destroyed in the storm. The seeds of southern pines and red oaks require two growing seasons to mature, so two crops could be affected by the loss of twigs bearing flower buds and maturing cones or acorns. This is problematic because the failure of even a single year of mast can decimate some wildlife populations. However, other evidence suggests that light or moderate stem injury may actually stimulate future crops. For example, Wheeler and Bramlett (1991) found that partial girdling of the stem improved strobili production in a loblolly pine seed orchard, and the girdling of stems and branches is a fairly common practice to stimulate flowering for commercial fruit production (Trueman and Turnbull, 1994).

2.4.3. Woody debris loads

Severe ice storms and related secondary mortality can create a tremendous quantity of woody debris. Van Lear and Saucier (1973) compared longleaf and slash pine plantations in South Carolina and found 2 m^3/ha in broken tops and upright snags in the longleaf stands, compared to 52 m^3/ha for slash pine. Woody debris constituted one-third of the annual litterfall from a bottomland hardwood stand following glazing (Brown and Peterson, 1983). Hooper et al. (2001) reported 34 m^3/ha of downed woody biomass after an ice storm in an old-growth northern hardwood stand, and an old-growth oak-hickory stand produced an average of 5 m^3/ha (range = 0–33 m^3/ha) of woody debris directly from ice damage (Rebertus et al., 1997).

2.4.4. Structural, compositional, and successional changes

Ice storms can dramatically alter forest structure and dynamics through the loss of certain size classes or species or shifts in species success. In extreme cases, whole cohorts of regeneration are lost and exposed canopy dominants are killed (Carvell et al., 1957; Halverson and Guldin, 1995). Predictable successional changes may also arise from secondary responses (see next section) to the glaze storm (e.g., Downs, 1938; Rhoads et al., 2002). Williams (1998) modeled ice damage and southern pine beetle outbreaks for Table Mountain (*Pinus pungens* Lamb.) and pitch (*Pinus rigida* Mill.) pine-dominated stands in the southern Appalachians, with both disturbances converting pine-hardwood to primarily oak forests.

Trees vary in crown size, crown shape, growth habit, and wood strength; thus, species vary considerably in their tolerance to ice damage (Croxton, 1939; Lemon, 1961). When an ice storm affects a mixed stand, the species that can better withstand ice loading have a competitive advantage. Shade-tolerant hardwoods may become more important if the stand receives only minor to moderate damage, with limited canopy openings and no post-glaze disturbances like fire or insect outbreak (e.g., Halverson and Guldin, 1995). A severe ice storm can re-initiate secondary succession, especially when an aggressive colonizer is present (Whitney and Johnson, 1984; De Steven et al., 1991). Whitney and Johnson (1984) found examples of both successional pathways following an ice storm in southwestern Virginia—pine forests were hastened toward oak stands by the damage to the pine overstory, while yellow-poplar (*Liriodendron tulipifera* L.) stands were maintained by improved regeneration following glaze-related release.

2.5. Interactions with other disturbance agents

Any disturbance that causes widespread decline in forest health and creates large volumes of dead material improves the conditions for other damaging agents, including insects, disease, and fire. These secondary events may prove at least as damaging as the original ice storm by killing injured trees and healthy survivors. For example, Cain and Shelton (1996) reported that an ice storm contributed to a southern pine beetle (*Dendroctonus frontalis* Zimm.) outbreak in a mature pine-hardwood stand in southern Arkansas, with beetle-caused mortality of dominant and codominant pines accelerating succession towards hardwoods.

Hyman (1985) believed one of the greatest hazards to ice-damaged timber in the South are the pine beetles (see also Rhoades, 1918; Kirby, 1954; Cain and Shelton, 1996). Pest buildup following an ice storm is associated with weakened surviving trees and abundant insect breeding sites. Gooch (1943) associated severe southern pine beetle outbreaks in Virginia during 1936–1937 with a 1934 ice storm that struck the same area. Cool et al. (1971) reported that up to 90% of heavily glaze-injured trees had endured bark beetle attack. Walker and Wiant (1966) believed that ice storm-related mortality of woodpeckers combined with damaged trees to encourage southern pine beetle outbreaks (see also Kirby, 1954).

However, the complex interactions between tree health, the environment, and insect populations means that insect problems are not inevitable (McNulty et al., 1998). For example, Muntz (1947) observed that no serious insect outbreaks followed the 1944 and 1947 ice storms in central Louisiana, and Cool et al. (1971) reported only limited damage to healthy trees from engraver beetles and black turpentine beetles (*Dendroctonus terebrans* Oliv.) following a South

Carolina ice storm. One of the main defense mechanisms of pines is increased resin flow after physical injury. Blanche et al. (1985) found greater resin flow for 7 months after simulated logging damage to loblolly pines, which could reduce their susceptibility to bark beetles.

Glaze-related wounds permit infection by a wide array of disease fungi, especially when the injuries are large and do not heal rapidly (Rhoades, 1918; Campbell, 1937; Spaulding and Bratton, 1946; Greifenhagen and Hopkin, 2000). Stain fungi quickly colonize exposed wood, causing quality (but not structural) reductions within weeks (Cool et al., 1971). Other ice storm-related injuries leading to fungal infections include sunscald (Spaulding and Bratton, 1946) and bark stress cracks (Lutz, 1936). Hardwoods are especially susceptible to decay arising from wounds or post-storm sunscald (Campbell and Davidson, 1940; Hepting et al., 1940; Roth, 1941; Spaulding and Bratton, 1946; Greifenhagen and Hopkin, 2000). However, Rexrode and Auchmoody (1982) found little long-term loss to heartrot from glaze-related crown injuries in black cherry. Mattoon (1915) attributed some red heart (*Phellinus pini* Ames) in shortleaf pine to injuries from earlier ice storms. Deuber (1940) expected the spread of Dutch elm disease (*Ophiostoma ulmi* (Buism.) Nannf.) following widespread glaze injury.

Ice storms increase potential fire risk by elevating fuel loads and limiting stand access (Irland, 2000). The Mississippi Forestry Commission (1994) estimated that the 1994 ice storm increased fuel loads 3–6 times above normal. Unless salvaged, these accumulations rapidly dry and elevate fire risk until sufficiently decomposed. However, the thinning of overstocked stands by glazing may lessen long-term fire risk through improved stand vigor and reduced aerial fuels.

2.6. Consideration of inconsistencies and contradictions

When reviewing a major natural disturbance like an ice storm, it is not unusual to observe inconsistency in damage patterns. Table 2 summarizes the observed effects different factors have on the extent of glazing injury for trees and stands. Notice that many of the studies came to opposing conclusions about their influence. For instance, Kienholz (1941) reported less damage to trees along the edge of a stand, while Proulx and Greene (2001) found more. These inconsistencies and even outright contradictions arise from the complexity and uncertainty associated with local environmental conditions and the vegetation being affected (Cool et al., 1971; Hebb, 1973). Additionally, reports often do not have sufficient detail to discern what factors were responsible for the observed damage.

Density-related contradictions can often be resolved by considering the circumstances. For instance, the first conclusion reported by Belanger et al. (1996, p. 136) is that ‘‘. . . stem breakage and storm-related mortality were greater in thinned than in non-thinned portions of the plantations’’. The authors derive far-reaching conclusions from this observation, questioning the utility of thinning. However, it is not the thinning but the timing of the ice storm that caused problems. After all, reduced height/diameter ratio characteristic of less dense forests diminishes damage. The plots assessed by Belanger et al. (1996) were thinned shortly before the storm, and the remaining trees did not have time to adjust their taper. The likely cause of damage in this case was not lower stand density but a combination of a sudden exposure to glaze on a slender form (see also Wiley and Zeide, 1991).

Other intuitively significant factors may not contribute to the damage as expected. As an example, fusiform rust (*Cronartium fusiforme* Hedgc. and Hunt) produces swollen cankers on the boles and branches of many southern pines. These cankers can reduce wood strength and are often identified as the point of failure when a tree is stressed by ice, snow, or wind (Brender and Romancier, 1960; Van Lear and Saucier, 1973; Skoller et al., 1983). However, McKellar (1942) and Abel (1948) reported that fusiform cankers did not significantly contribute to stem breakage in 6–12-year-old loblolly, shortleaf, slash, and longleaf plantations. Similarly, Jones (1969) found almost 10 times the number of injured slash pines than loblolly pines in a Georgia plantation, even though the loblolly pines had twice the rate of visible fusiform stem cankers. Hence, the contribution of fusiform rust to glaze damage depends on the tree species affected and prominence and location of the canker.

Another potential source of discrepancies is ice thickness. Many studies are vague about this variable because it is hard to accurately measure and glaze deposition can be quite spatially variable. It is clear that few differences would exist if ice is several meters thick, because such a layer would obliterate the trees regardless of their characteristics. Hence, truly catastrophic damage is indiscriminate. On the other hand, at lesser ice loads many other tree, stand, and site characteristics come into play, often precluding reliable conclusions. Standardized measurement and reporting criteria should help alleviate some of these contradictory results.

3. Socioeconomic implications

The most costly ice storms reported to date (in unadjusted US dollars) include the Great Northeastern Ice Storm of 1998 (at least $ 2.5 billion) (Nordin, 1998), the 1994 Mississippi storm ($ 1.8 billion in timber and utility losses) (Halverson and Guldin, 1995; Jacobs, 2000), and the December 2000 Arkansas ice storms (almost $ 550 million) (Forgrave, 2001). Ice storms cause major problems for private residences and other urban settings (Hauer et al., 1993, 1994), transportation networks (Mattoon, 1915; Harlin, 1952), power grids (Burnham, 1922; Christie and Chartier, 1943), orchards (Burnham, 1922), nut producers (O'Barr, 1994), and sugarbushes (USDA Forest Service, 1998). Communities already mired in poverty may be poorly equipped to recover from a major ice storm, especially if dependent on timber or tourism.

Catastrophic natural disturbance can impact land expectation and expected present values of plantations, affecting their optimal rotation age (Reed and Errico, 1985; Haight et al., 1996). There are also some insurance or tax casualty implications for storm-damaged timber (Haney et al., 2001). Salvage cuttings following an ice storm sharply increase as landowners attempt to reclaim damaged timber before it is consumed by insects, decay, or fire. During this recovery period, timber supply can outstrip demand, thus reducing its market value (Straka and Baker, 1991; McEvoy and Lamson, 1998). Prestemon and Holmes (1997) found that pine sawtimber stumpage had recovered to pre-Hurricane Hugo levels less than 2 years after the storm. However, pine pulpwood stumpage fell 60% following the hurricane and only about half of this loss was recouped 6 years after the storm. Prestemon and Holmes (1997) believed that an already saturated pulpwood market unable to absorb the volume of storm-damaged timber triggered this extended drop. McEvoy and Lamson (1998) speculated that unsubstantiated claims on the poor quality of salvaged timber may further lower stumpage prices.

A particularly severe disturbance over a large area can impact long-term local wood supply. For example, if most pole-size trees are lost in an ice storm, then there may be a period when fiber is locally unavailable and demand outstrips supply, boosting prices. The more size classes that are lost, the greater the impact on local prices. Small timber owners are more vulnerable to catastrophe-related price fluctuations than large-scale, well distributed landholders (Prestemon and Holmes, 2000). Cooperative efforts between public, private, and industrial landowners have been suggested to help local markets adjust to the influx of storm-damaged wood following natural catastrophes (Kyle, 1960; Cool et al., 1971).

4. Silvicultural recommendations

4.1. Preventative measures

Ice storms are an inevitable feature of forestry in the South. However, considerable savings in time, effort, and resources are possible when the risks of ice accumulation are recognized. The following characteristics accentuate ice damage in pine plantations:

1. recent thinning (within 2 years for pines);
2. high stand density and low live crown ratio;
3. average dbh approximately 18–25 cm (trees about 10–20-year-old);
4. presence of disease or defect (e.g., cankers, root rot, forks);
5. species and origin of planting stock; and
6. susceptible locations.

These features are the most silviculturally controllable, and thus provide the greatest opportunity for management. Since plantations and stands of natural origin are similarly vulnerable when composition, stocking, size, or disease are taken into account (Muntz, 1947; Wahlenberg, 1960), the measures discussed in this section are relevant for both.

4.1.1. Initial stocking, thinning, and other treatments

The implementation of good forestry is one of the best measures to minimize ice damage (Downs, 1938). For example, Zeide and Sharer (2000, 2002) stressed that loss to glazing could be reduced by increasing bole taper during the most vulnerable period (between ages 10 and 20 years) in the life of loblolly pine. They recommended the following treatments to achieve this: (1) planting on wide (2.7 m × 3.0 m or 2.4 m × 3.4 m) spacing with large, improved seedlings; (2) controlling competing vegetation early (<5-year-old) in the stand's history and after the second thinning; (3) thinning at age 13 and 18 years to 13.8 m^2/ha, and to 16.1 m^2/ha every 5 years thereafter; (4) starting with the third thinning, prescribe burn before each harvest; and (5) tailoring management objectives to the possibilities and limitations of the environment.

Dense, young, unthinned stands have many slender, top-heavy individuals (Downs, 1943; Nelson, 1951; Wahlenberg, 1960; Burton, 1981) that are particularly vulnerable. Hebb (1973) suggested relatively wide initial spacing of sand pine (*Pinus clausa* (Chapm. ex Englem.) Vasey ex Sarg.) plantations, with no thinning of pulpwood stands, as a means to reduce ice damage. As with any set of silvicultural treatments, there are trade-offs that need to be recognized. Widely spaced plantations grow more rapidly but are limbier, and thus may require pruning to provide knot-free wood (Guldin and Fitzpatrick, 1991). Maintaining fewer trees per hectare may also underutilize the yield potential of a site (Wakeley, 1954), a trade-off that some have resisted given the relative rarity of damaging ice storms.

Thinning or pruning young stands can increase the risk or severity of glaze damage if the storm happens soon after treatment (McCulloch, 1943; Nelson, 1951; Wahlenberg, 1960; Hebb, 1973). For example, Shepard (1981) attributed much of the loss in recently thinned 12–13-year-old loblolly and slash pine plantations in northern Louisiana to the lack of support from adjacent stems. However, if properly timed, thinning can improve a stand's ability to weather an ice storm. Downs (1943) recommended thinning dense stands less than 15 cm dbh immediately (in two steps, if necessary) unless the trees were noticeably spindly. Muntz (1947) and Brender and Romancier (1960) favored repeated light thinnings from below if the area is subject to frequent glaze accumulation. Thinning from below removes high risk small trees while row thinning and thinning from above leaves more vulnerable individuals, thus increasing loss to ice buildup (Wahlenberg, 1960; Shepard, 1978). Curtis (1936) and Amateis and Burkhart (1996) encouraged judicious harvesting of asymmetrically distributed crowns or forked trees, as these irregularities increase the odds of damage. Trees with obvious cankers or signs of root disease should also be targeted for removal (Fountain and Burnett, 1979).

4.1.2. Planting stock selection

Choosing the species to plant on a given site depends largely on the desired markets, the performance of the planting stock, and the intentions of the landowners. One should also consider potential threats like glaze storms before investing resources into stand establishment and maintenance (Goebel and Deitschman, 1967; Van Lear and Saucier, 1973; Williston, 1974). For example, Hebb (1971) recounted a 1969 ice storm that devastated young planted slash and sand pines in South Carolina but left loblolly plantations with only minor losses. Slash and sand pine have been frequently identified as vulnerable to glazing when planted outside of their natural distribution (e.g., Muntz, 1948; Abel, 1949; Wahlenberg, 1960; Brender and Romancier, 1965; Jones, 1969; Hebb, 1971, 1982; Van Lear and Saucier, 1973). Irland (2000) made similar observations for black locust (*Robinia pseudoacacia* L.) and willow (*Salix* spp.).

Planting species with favorable wood properties, the use of disease-resistant taxa, and the recognition of species-related crown and foliar configurations can further reduce losses to ice storms. Loblolly pine withstands glazing better than slash pine, but does poorer than shortleaf pine and eastern redcedar (*Juniperus virginiana* L.) (Abel, 1948; Huckenpahler, 1948; Brender and Romancier, 1965; Goebel and Deitschman, 1967). The short foliage and strong wood of shortleaf pine and eastern redcedar probably confers their improved performance (Illick, 1916; Cool et al., 1971; Goebel and Deitschman, 1967). Kuprionis (1970) suspected that some southern pines possessed a heritable inclination for bending under load (e.g., slash pine). Foliage retention, orientation, and surface area, branch and bole architecture, and rooting patterns are other possible selectable attributes for improving glaze resistance (Larson, 1963; Kuprionis, 1970). Genetic improvement for greater disease resistance should also improve ice load tolerance (Skoller et al., 1983). However, the compromise between loblolly pine performance, specific gravity, fusiform resistance, and susceptibility to glazing (Skoller et al., 1983; Wells and Lambeth, 1983) must be balanced with potential impacts on growth and yield. For example, Wells and Lambeth (1983) found that loblolly started from seed sources west of the Mississippi River had greater resistance to fusiform rust (see also Skoller et al., 1983) and higher overall survival, but also grew appreciably slower than eastern sources.

But how is the "best" species determined? Some authors have developed rankings of species by their resistance to ice damage (e.g., Illick, 1916; Bennett, 1959; Seischab et al., 1993; Hauer et al., 1994). These rankings should be considered only marginally useful since regional and intraspecific differences exist and thus contradictory statements on taxonomic vulnerability are common. Rather, avoid species or even seed sources with a predisposition for vulnerable crown shapes, branching patterns, or the production of low specific gravity wood, recognizing that some feel that the higher growth rates of more glaze susceptible seed sources could offset potential ice storm losses (e.g., Huckenpahler, 1948; Jones, 1969; Jones and Wells, 1969). Mixing vulnerable and resistant species (e.g., slash with loblolly or shortleaf pine) can increase losses when weak trees topple into otherwise resistant individuals (Abel, 1948).

4.1.3. Geographic and geomorphic setting

Climatic conditions that result in large, damaging glaze events depend in part on features like proximity to moisture, warming or cooling influences, and physiography (Smith, 2000). These factors can be used to anticipate the risk of loss. For example, Wahlenberg (1960) recommended planting loblolly over slash pine in areas greater than 240 km from the Gulf of Mexico because of its greater resiliency to ice damage (see also Brender and Romancier, 1965). However, even a relatively glaze-resistant species like loblolly pine may have problems if their seed source originated from a warmer region (Jones and Wells, 1969).

Avoidance of sites with increased risk of ice damage relative to local physiographic conditions can reduce the loss from glaze storms. Locally higher elevations often accumulate more ice than lowlands because of lower air temperatures and higher precipitation (e.g., Rendle et al., 1941; Christie and Chartier, 1943). Exposed upper slopes are also at risk of greater damage in ice storms (Sanzen-Baker and Nimmo, 1941; Smith, 2000; Rhoads et al., 2002), since the stronger winds at these locations add to the magnitude of the event. Rhoades (1999) reported greater glaze damage to trees on steep slopes and in valley bottoms attributable to fine soil textures and limited rooting depth. If establishing a plantation on sites where glazing is frequent, managers should shun species that lack resiliency and avoid silvicultural regimes that produce susceptible individuals (e.g., high planting densities, inappropriate timing or intensity of thinnings). As an example, Zeide and Sharer (2000) suggested that loblolly pine stands be managed on pulpwood rotations in areas where unfavorable rooting conditions and frequent ice storms made reaching sawtimber size difficult.

4.2. Stand recovery

A timely recovery effort can turn a potential disaster into an unanticipated but acceptable natural thinning. While recovery efforts should begin as soon as conditions permit, they must not be approached haphazardly (McEvoy and Lamson, 1998). Delays in entering ice-damaged stands increase the possibility of further economic loss, elevated fire risk from downed fuels, and the chance of insect outbreaks. Unfortunately, many parts of the South are excessively wet during the ice storm season, often limiting accessibility and hampering salvage efforts. The ability to recover damaged timber also depends on the capacity of local markets to absorb a considerable volume of small-diameter wood (Cool et al., 1971; McEvoy and Lamson, 1998).

4.2.1. Damage assessment

A journey through the woods immediately after a severe glaze event often leaves an impression of absolute devastation. Bent and broken trees appear everywhere, and it seems that all pole-sized or smaller trees have been critically injured. Very young plantations may be completely flattened. Many landowners drive past their property and mistakenly interpret the damage along the fringes as representative of the entire tract. Rather than making a hasty judgement on the future of the stand, a more measured response based on a post-storm inventory should be used to guide management. At this stage, the best advice is not to assume that the stand has been completely lost (Cool et al., 1971; Hebb, 1973; Williston, 1974; Allen et al., 1998). Experience has shown that many of the injured trees, especially the smaller ones, will recover considerably over the next few months (Williston, 1974). For example, Russell (1967) recalled a loblolly pine plantation in north-central Louisiana in which nearly every tree suffered a broken top. The landowner was willing to wait a year before deciding how to treat the stand. In the end, no salvage was done, but regular thinning of low quality pines allowed the stand to be carried to its expected rotation (Russell, 1967).

The first recovery step following a severe ice storm is an assessment of the damage. Most stands can be evaluated using slight modifications to standard inventories (private landowners with limited resources should consult recent extension publications for help—e.g., Allen et al., 1998; Lamson and Leak, 1998; LandOwner Resource Centre, 1999a,b). After conditions are deemed safe to enter the forest, conduct a 5 or 10% cruise with either plot or point-based sampling methods. Take an unbiased approach to avoid oversampling locations like roadsides, large gaps, or other places influenced by edge effects. Measurements will depend on management objectives, but may include mortality, crown loss, tree lean, root failure, bole breakage, fuel loading/fire danger, damage to non-timber resources, and the loss of access.

Ideally, a contingency plan addressing timber damage from catastrophic natural disturbance should exist a priori indicating which events would trigger a given response (Irland, 2000), but even the best plans cannot fully account for market fluctuations, accessibility issues, or other uncertainties related to the natural environment. Managers should consider the potential of an ice storm to alter future silvicultural options (Irland, 2000; Zeide and Sharer, 2002). For example, if non-lethal stem breakage is common, how would this type of injury impact the development of the stand? If many boles are broken at 4 m aboveground in a sawtimber stand, does enough residual stocking capable of producing a 5 m sawlog remain to meet this objective? Long-term monitoring may be necessary to detect insect outbreaks or disease-related problems.

4.2.2. Salvage

Salvage of damaged timber is the first instinct of most forest managers, even though this effort may be hindered if the wood is of insufficient quantity, quality, or value (Daley, 1964; Rexrode and Auchmoody, 1982). If damage is limited to non-lethal bending of stems and minor branch or top loss with no major insect infestations, the injured stand has more time for evaluation, which may allow improvements in accessibility or market conditions.

Managers should target the most valuable and highest risk stands first, because extended delays allow for stain fungi, weight loss due to drying, insects, and other problems that decrease product value. For example, insect losses can be reduced after ice storms by salvaging severely damaged trees and monitoring pest activity (Barry et al., 1998). Bark beetles can significantly reduce the salvageable life of snags and broken tops (Cool et al., 1971), and engraver beetles (*Ips* spp.) also threaten ice-damaged stands (Wakeley, 1954; Cool et al., 1971). In stands dominated by major (>75%) crown loss, trees broken below the live crown, and/or uprooted or strongly bowed (>45°) individuals should be removed as soon as feasible to capture their value and lower the risk of secondary disturbance (e.g., Brewer and Linnartz, 1973).

Salvage strategies would not appreciably differ for natural or uneven-aged pine stands, assuming long-term regeneration has not been affected. Salvage in uneven-aged stands is aided by frequent harvests. Hardwoods, conversely, may need a different approach. Many hardwood species produce epicormic branches if the canopy opens sufficiently. These laterals degrade log quality, and thus may support clearing heavily impacted hardwood stands.

4.2.3. Keep the stand, or begin anew?

Determining if an affected stand should continue to its full rotation or if it should be cleared and a new stand established is critical to managing ice-damaged timber. Rarely are ice storms so devastating that they completely destroy a stand—rather, they usually act as unplanned thinnings, and may leave enough residual stocking to permit its retention (Shepard, 1978; Zeide and Sharer, 2002). Straka and Baker (1991) emphasized the potential of rehabilitating storm-damaged timber, even if noticeably understocked, as a less costly alternative to starting over with a new stand.

Cool et al. (1971) set thresholds for stand retention at (1) more than half of the stems undamaged or (2) at least 30 m^3/ha in undamaged trees. Different landowners will have different thresholds, based on their management goals and the factors contributing to their cost of stand establishment. The salvage effort following the December 2000 Arkansas ice storms exemplify this difference in strategy. One timber company specializing in sawtimber and plywood retained pole-sized plantations if they had at least 75 quality loblolly pines per hectare, while another cleared stands with less than 200 crop trees per hectare (both salvaged severely damaged trees).

Another consideration towards retaining or replacing a glaze-damaged stand is the quality of material left for future harvest. Although evidence suggests that most moderately bent trees will straighten appreciably following an ice storm (Blum, 1966; Williams, 1966; Brewer and Linnartz, 1973), internal tissue damage can be highly detrimental to log quality. For instance, Dunham and Bourgeois (1996) reported on some attributes of hurricane-bent loblolly pine. Though properties like specific gravity or moisture content did not differ markedly, loblolly pines with a pronounced lean (>45°) produced significantly more compression wood and had 21% lower toughness. Young stems were more likely to fully recover from being bent (unless their inclination had exceeded 45°), primarily because of their greater pliability. The formation of compression wood on the lower side of leaning trees leads to high longitudinal shrinkage, discoloration, and eccentric rings (Rendle et al., 1941; Panshin and de Zeeuw, 1970). Glaze-injured trees may also experience log quality degradation from decay or stain fungi (Lutz, 1936; Campbell and Davidson, 1940; Hepting et al., 1940).

Ice storms can influence individual tree productivity. Significant losses in photosynthetic surface area lead to reduced diameter growth until foliage is replaced (Kuprionis, 1970; Smith and Shortle, 2003). As an example, Wiley and Zeide (1991) followed a damaged loblolly pine plantation for 14 years after an ice storm and found reduced long-term diameter increment. However, height growth may be stimulated by top damage. Guo and VanderSchaaf (2002) found that post-ice storm phosphorus fertilization of top-damaged sweetgum significantly boosted height but not diameter increment. Both Wiley and Zeide (1991) and Guo (1999) noticed significantly greater height increment in ice-damaged loblolly pine and sweetgum, respectively. Neither study concluded that the reduction in survivor growth justified the clearing of the stands.

4.3. Stand rehabilitation

The potential for rehabilitating even-aged pine stands following ice damage is determined by the residual stocking of crop trees expected to recover. Baker and Shelton (1998c) found that 5-year-old natural and planted loblolly pine with 450 trees/ha will produce 75% of the yield of fully stocked plantations in 10 years, but may have to be pruned to yield quality sawtimber. Even poorer stocked pine stands have a high potential for sawtimber production. For example, a loblolly plantation on a good site in southern Arkansas precommercially thinned to 250 trees/ha at 9-year-old produced nearly 175 m^3/ha in sawlogs through 30 years (Williston, 1978). Lower stocking thresholds may be possible in older even-aged pine, especially if trees have been pruned. Table 3 shows how the basal area and sawtimber volume of even-aged stands with 75–250 trees/ha vary with average stand diameter. Stands of 125–175 pulpwood-sized trees per hectare can produce 120–250 m^3/ha of sawlogs when the pines average 40–45 cm dbh. Thus, 125 trees/ha acre seems to be a reasonable minimum stocking in pulp-sized stands that would allow landowners to reach a full sawtimber rotation.

Another alternative would be to establish and manage a two-aged stand similar to a shelterwood with reserves. This option would probably work best in stands with marginal stocking (40–75 trees/ha) of quality crop trees. Natural regeneration is possible if the residual trees are of seed-producing size (>30 cm dbh), or seedlings could be underplanted. Ideally, retained trees should be in large pulpwood or small sawlog size classes (20–35 cm dbh) where tree value rapidly increases. Once the residual trees in the rehabilitating stand are identified, there are a number of options that can improve stand recovery and financial return.

The multiple size classes present in uneven-aged stands confer some resiliency to ice damage and facilitate stand rehabilitation. For example, Guldin (2002) reported that a 1974 ice storm in southern

Table 3
Effects of mean tree dbh and number of trees on basal area and volume in hypothetical even-aged stands of loblolly pine

Average dbh (cm)	Number of trees per hectare							
	75	100	125	150	175	200	225	250
Basal area (m^2/ha)								
10	0.6	0.8	1.0	1.2	1.4	1.6	1.8	2.0
15	1.3	1.8	2.2	2.7	3.1	3.5	4.0	4.4
20	2.4	3.1	3.9	4.7	5.5	6.3	7.1	7.9
25	3.7	4.9	6.1	7.4	8.6	9.8	11.1	12.3
30	5.3	7.1	8.8	10.6	12.4	14.1	15.9	17.7
35	7.2	9.6	12.0	14.4	16.8	19.3	21.7	24.1
40	9.4	12.6	15.7	18.9	22.0	25.1	28.3	31.4
45	11.9	15.9	19.9	23.9	27.8	31.8	35.8	39.8
50	14.7	19.6	24.6	29.5	34.4	39.3	44.2	49.1
Merchantable volume[a] (m^3/ha)								
10	1	1	2	2	2	3	3	3
15	7	9	12	14	16	18	21	23
20	16	21	27	32	37	43	48	54
25	29	38	48	57	67	77	86	96
30	45	60	75	90	105	120	135	150
35	65	87	108	130	152	173	195	216
40	88	118	147	177	206	236	265	295
45	115	154	192	230	269	307	346	384
50	145	193	241	290	338	386	434	484
Sawtimber volume[a] (m^3/ha)								
10	–	–	–	–	–	–	–	–
15	–	–	–	–	–	–	–	–
20	–	–	–	–	–	–	–	–
25	13	17	21	25	30	34	38	42
30	32	42	53	63	74	84	95	106
35	51	68	85	102	119	136	153	170
40	72	96	121	145	169	193	217	241
45	97	130	162	195	227	260	292	325
50	127	169	211	254	296	338	380	423

[a] Based on inside-bark volume equations of Farrar et al. (1984). Sawtimber trees are ≥25 cm dbh. Merchantable and sawtimber volumes are to a 9 and 19 cm top, respectively.

Arkansas devastated the pulpwood component of uneven-aged stands of loblolly and shortleaf pine but only lightly damaged the sawtimber component. Although this loss contributed to a deterioration in uneven-aged structure, there was no net reduction in growth and yield over the following 25 years. Following Hurricane Hugo, Straka and Baker (1991) showed that rehabilitation of poorly stocked uneven-aged stands provided a low-capital alternative with reasonable rates of return when compared to plantation conversion. According to Baker and Shelton (1998a), uneven-aged stands can be rehabilitated from as low as 20% stocking and 1.1–2.2 m^2/ha of basal area if the stands have a reverse-J size class distribution and crop trees of sufficient quality and vigor. The rapid recovery was due to the presence of multiple size classes and the remarkable growth exhibited by released loblolly (Baker and Shelton, 1998b).

Extension publications usually recommend the removal of trees with >75% crown loss because of poor recovery, while those with less than 50% crown loss usually recover adequately (e.g., Cox, 1998; LandOwner Resource Centre, 1999b). If a tree has at least half of its original crown, the remaining crown is symmetrical, the bole is of good quality, and there does not appear to be a great risk of insect outbreak, these individuals can be left until a more opportune time to harvest them arises. Pruning may help recovery following an ice storm. Roberts and Clapp (1956) removed all branches below the leader to reduce the stress of branch weight in young, ice-damaged slash pine. Most of the pruned slash pine had straightened in a year, while few untreated individuals had appreciably responded.

5. Conclusions

This review of the literature on ice storm damage leads to a number of conclusions. First, ice storms are complex perturbations and the damage expressed is a function of this complexity. Because so many factors influence the degree of injury any given tree or stand may receive, our ability to anticipate damage is usually limited to broad generalizations. For example, spindly trees are more vulnerable to icing than stout ones, and forests on exposed sites are more likely to suffer damage than those in protected locations. However, it is possible to identify susceptible trees and stands if knowledge of their structural integrity and site conditions is available.

Second, although ice storms are unpredictable events, we can anticipate their potential impact and plan accordingly. Since the risk of ice damage in the south grows with increasing latitude, selection of species adapted to ice loads common to the region should provide a more robust stand. The practice of low-cost forestry shows promise for reducing the economic impact of catastrophic disturbances (Straka and Baker, 1991; Haight et al., 1996). Overstocked stands suffer considerably from glazing, yet well-managed, regularly thinned forests yield fast growing, healthy, and sound trees that can survive inclement weather.

Finally, damaging ice storms in the southern US are inevitable, so developing an effective response strategy beforehand should help minimize their impacts (Zeide and Sharer, 2002). As devastating as an ice storm may appear, it should not be viewed as an insurmountable obstacle to good forestry practices, even for private non-industrial forest landowners. Evaluate the post-event stand, clear access lanes, salvage heavily damaged or dead individuals if possible, monitor forest health, and adjust future silvicultural treatments accordingly. Coordinated management, marketing, and research efforts (e.g., Kyle, 1960; Lautenschlager and Nielsen, 1999) should also help local communities and industries cope with catastrophic ice storms.

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