Recovery of Planted Loblolly Pine 5 Years after Severe Ice Storms in Arkansas

Don C. Bragg and Michael G. Shelton

ABSTRACT

Following a severe ice storm, one of a landowner's first considerations regarding the future of their damaged stands should be on the recovery potential of injured crop trees. The ice storms that struck Arkansas in December 2000 provided an opportunity to monitor 410 injured loblolly pines (*Pinus taeda* L.), representing a wide range of damage in 18–20-year-old plantations. Five-year mortality rates were $<3\%$ for trees with low to moderate injury, 16% for major damage, and 55% for critical damage. Of the most seriously affected pines, root-sprung trees had the highest periodic mortality rate (85%). Annualized diameter growth was significantly affected by the tree's dbh class (positively) and intensity of damage (negatively). This research suggests that pines with low to moderate levels of damage can prove to be acceptable growing stock, whereas critically injured individual trees are not. Trees with major damage could be either retained or salvaged, depending on residual stand stocking, the operability of the salvage, and existing market conditions. Finally, recommendations from this study should enable landowners to better respond to their loblolly pine plantations damaged by ice storms.

Keywords: disturbance, glaze damage, salvage, silviculture, stand rehabilitation

Ice storms are frequent, if unwanted, visitors across much of the southern United States, often causing widespread timber and infrastructure damage over large areas in a matter of hours to days. In recent decades, ice storms have affected millions of acres of forest lands, with billions of dollars of direct economic costs (e.g., Irland 2000, Jacobs 2000, Aubrey et al. 2007). Their extensive damage places ice storms on par with other, more publicized disturbance events, such as hurricanes—for instance, a relatively modest ice storm that struck parts of North Carolina in 2002 resulted in an estimated loss of 58 million tons of oven-dry tree biomass (McCarthy et al. 2006), compared with the 230 million tons felled by Hurricane Katrina (Chambers et al. 2007). Given that either of these storm totals represents a considerable fraction of the estimated 240–330 million tons of biomass accumulated annually in trees across the entire United States (Pacala et al. 2001), it is apparent that heavy icing can affect environmental processes on a global scale.

Ice accumulation (also called glazing) can range from thin coatings that slightly bend branches to heavy accretions thick enough to snap or uproot full-sized trees of all species. Ice storm frequency and severity vary considerably across the southern United States, with fewer storm events occurring close to the Gulf of Mexico (Bennett 1959, Lemon 1961, Gay and Davis 1993). Although they do not always receive extensive damage from these storms, most of the inland Gulf Coastal Plain forests can expect to see some significant ice accumulation once every 5–15 years (Bennett 1959, Wahlenberg 1960, Schultz 1997). It is also possible to get multiple damaging ice storms in the same region during the same year, as has been reported in Arkansas (Bragg et al. 2003), Georgia (Brender and Romancier 1965), and Louisiana (Shepard 1978). Unfortunately, there is no way to predict the magnitude of an ice storm, as the accumulation of glaze, the strength of any accompanying wind, and other factors (e.g., the wetness of the soil) depend on site-specific conditions that change constantly. Suffice to say, much of the region can expect at least some ice damage to its forests during any given sawtimber rotation.

Landowners affected by ice storms face a dilemma commonplace after most large-scale disturbances—what is the best silvicultural strategy to take following widespread damage to their stands? This is of particular concern to those with intensively managed pine plantations because of the large monetary investments made in establishing and maintaining these stands. One approach calls for salvaging as much as possible, even clearing the stand altogether, and then starting over again. This may be the only course of action if the stand has become dramatically understocked or has a particular risk of forest health problems. However, it is possible that the combined receipts from the salvage and casualty claims (whether as tax deductions or insurance claims) may be insufficient to cover the investment in the stand, resulting in a net loss. This is especially true if the plantations have not reached commercial status, or would yield only low-value outputs such as pulpwood.

If possible, it seems preferable to work with the surviving trees and allow these stands to grow into more valuable product classes. To start the recovery process, an assessment must first be made of the damaged stand to determine whether the stocking is adequate to carry the stand to rotation. The easiest part of this inventory is the quantification of the obviously dead and down materials. But what of the remaining live trees? Many have been seriously damaged by the glazing, and their recovery is uncertain. Even if these trees survive, their injuries may prove so significant that their growth is suppressed for many years afterward, and the quality of the wood

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formed after the event may be unacceptable for high-value products, such as dimensional lumber or plywood. Clearly, more information is needed about the relationship between the recovery of injured trees and the type and extent of damage so that landowners can make sound silvicultural decisions. To this end, this study monitored the 5-year performance of 410 ice-damaged trees from six 18–20-year-old loblolly pine plantations in south-central Arkansas.

Materials and Methods

The Arkansas Ice Storms of 2000

Two massive ice storms struck the Arkansas region in late 2000, affecting >17 million ac of forest and inflicting >$500 million in damage (Forgrave 2001, Bragg et al. 2003). The first storm occurred on December 12–13, 2000, and affected much of the southern half of Arkansas (National Climatic Data Center [NCDC] 2001). Although ice totals varied considerably, maximum accumulations approached 4 in. and ranged from 1.2 to 2.4 in. across most of the study area (NCDC 2001). This initial storm, which did virtually all of the damage to the stands reported in this article, was followed about 2 weeks later by another icing event that struck other parts of west-central Arkansas (e.g., the Ouachita National Forest) severely but was not as damaging in southern Arkansas (NCDC 2001).

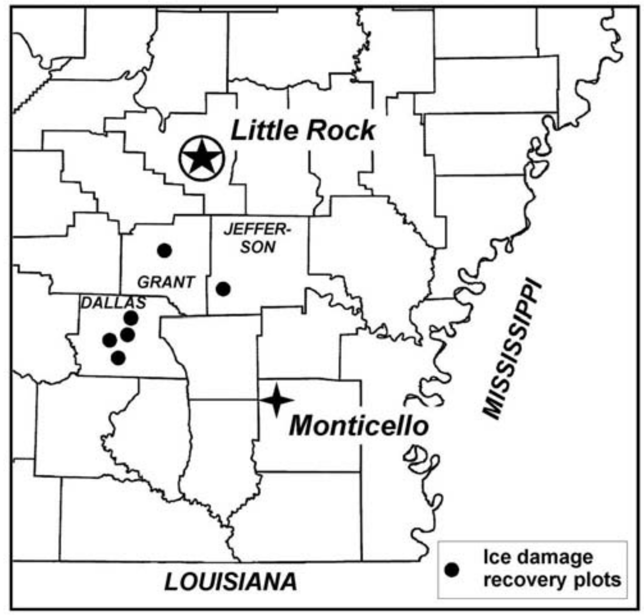

Figure 1. Map of study plots placed in loblolly pine plantations in three counties in south-central Arkansas following the December 2000 ice storms.

Table 1. Basic statistics of the 410 loblolly pines chosen in 2001 from six Arkansas plantations affected by the December 2000 ice storms, including a sample tree count by 2-in.-dbh diameter classes.

		Diameter distribution	
Dimension	dbh	Midpoint of dbh class	Number of individuals
	(in.)		
Minimum	3.6	1	0
Maximum	13.8	3	3
Average	8.0	5	47
Standard deviation	1.7	7	137
		9	163
		11	53
		13	6
		15	1

Study Area

The study area is part of the Upper West Gulf Coastal Plain and is dominated by gently rolling hills of eroded Eocene deposits and Pleistocene terraces separated by narrow bottomlands of Holocene alluvium. The natural vegetation of the region is primarily pine-hardwood mixtures of varying compositions. However, a large portion of the uplands (especially the properties controlled by the timber industry or investment organizations) have been converted to intensively managed loblolly pine plantations. The loblolly plantations in this study were owned by International Paper Company (IP) at the time of the ice storms and had an intended sawtimber rotation age of 30–35 years (depending on site conditions).

Immediately after the ice storms, representatives of IP, the University of Arkansas–Monticello, and the US Forest Service met to discuss research opportunities. In addition to identifying a range of different-aged pine plantations for a quick assessment of damage as a function of stand condition (reported in Bragg et al. 2004), IP agreed to set aside certain small parcels for long-term recovery work. Six study sites of 1–5 ac were reserved for this study—four were located in Dallas County, one in Grant County, and one in Jefferson County in south-central Arkansas (Figure 1). These stands were 18–20-year-old plantations that had been thinned once in the years immediately preceding the storms but were not fertilized (Bragg et al. 2002). Loblolly plantations of this condition and age were selected primarily because they sustained extensive damage and represented the conventional management approach of most industrial landowners in the region. These parcels were not deliberately salvaged following the ice storms of 2000 to avoid any mechanical damage to the pines being studied. The study ended in 2006 following the sale of these lands by IP.

Sample Tree Selection

Loblolly pines, especially those with bent stems, began to recover immediately following the storm, and thus April was the latest we believed we could identify and accurately measure these injured trees. Expedience and the wide range of damage to the pines, coupled with the complex injuries often sustained by individual trees (for example, some had been bent, lost branches, and had their tops sheared off), made it virtually impossible to set up specific hypothesis tests on what damage type proved most problematic prior to the initiation of the growing season. Therefore, rather than spending an inordinate amount of time trying to locate and track a small number of stems, we chose as many examples of the primary damage types as possible.

In all instances, the pines selected for this study had green foliage when sampled in the spring of 2001. Each tree was measured for its dbh and type of damage (detailed in the next paragraph) and then marked with white paint. Numbered aluminum tags were also placed in the ground adjacent to each tracked pine to aid in later identification. An approximate stem map was then created using the distance and bearing of each marked pine from one or more station points. These trees were revisited every spring for the next 5 years to determine their survival, growth, and recovery from injury. Table 1

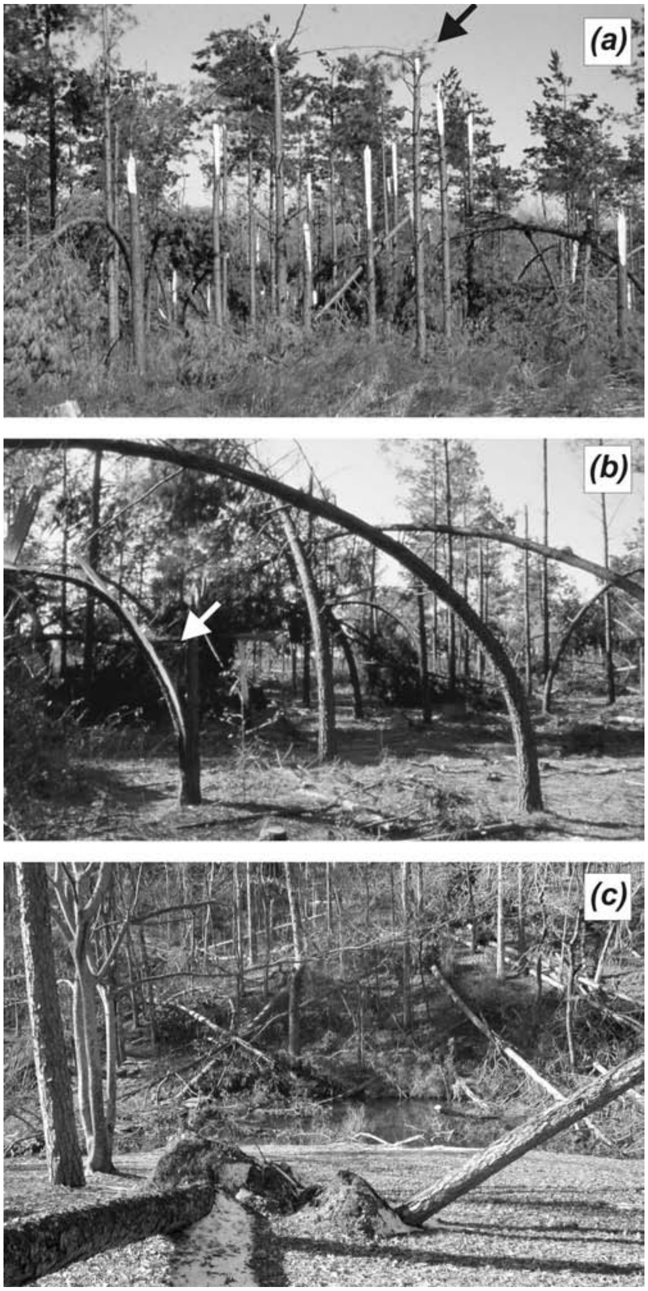

Figure 2. Examples of the damage types and severities found after the December 2000 ice storms in Arkansas. In (*a*), most of the clearly broken stems failed below the live crown, killing these pines (and thus excluding them from this study). However, individual trees with even one small live branch (black arrow) were included, as were the less damaged trees (background). Severely bent stems (*b*) were included if they had not broken (white arrow). "Root-sprung" or uprooted pines (*c*) displayed full or partial failure of root support (in this example, large shortleaf pines [*Pinus echinata* Mill.] near Hot Springs, AR). Photos (*a*) and (*b*) by Don C. Bragg; photo (*c*) courtesy of James M. Guldin.

Table 2. Ice damage classification system used to evaluate loblolly pine trees from the study plantations affected by the December 2000 ice storms (modified from Bragg et al. 2002).

	Major injury		
Damage class	Branch/crown loss (%)		Root-sprung/bending (°)
Insignificant[a]	<10	or	<10
Minor	10–24	or	10–19
Moderate	25–44	or	20–39
Major	45–69	or	40–59
Critical	70–99[b]	or	60–90

[a] Includes pines with no visible signs of damage (even though at least some injury was likely).
[b] Given the requirement of this study to follow only trees that had the potential to recovery, an individual tree with 100% loss of branches was considered to have an immediately lethal injury and hence was not included in this study.

provides some basic descriptive statistics of the sample of trees monitored in this study. Note that selected pines were not chosen according to their proportion in the stand but rather were identified as representative of a particular type and degree of nonlethal damage.

Several types of survivable glaze damage were differentiated (Figure 2, *a–c*). Loblolly pines that broke below their live crown were considered killed by the storm and thus, with no potential for recovery, these individuals were not tracked further. However, broken individuals that had at least one live branch remaining were included. Initially, pines that had their leader snapped off and those that only lost some of their subordinate branches were distinguished. In the end, these were combined into a broader crown loss type because there were virtually no differences in their growth or survival. Perhaps the most dramatic injury associated with ice loading occurs when the stem bends without concurrent root failure. A range of bending in pines was included, so long as the stem did not experience catastrophic bole splintering. Pine can also survive being root-sprung (also called uprooting—the full or partial failure of root support, causing the tree to topple over).

Bragg et al. (2002) categorized damage severity using a multilevel description that was modified slightly to evaluate 5-year patterns of survival (Table 2). This damage categorization considers not only the specific type of injury (e.g., crown loss versus root sprung/bending) but also the severity of the injury, it and places trees into one of five classes ranging from insignificant to critical. Although such a system may mask any unique mortality or growth response patterns as a function of the type of injury, previous experience (Bragg et al. 2002) suggests that enough similarities exist to justify this aggregation.

Growth Rate Analysis

Individual tree growth rates were annualized by dividing the increment of each of the 332 loblolly pines that survived the entire observation period by 5. This metric was used because it is conventionally applied to evaluate loblolly pine growth performance under different silvicultural treatments, and no stand-level information was available for comparisons. We hypothesized that the growth rate of surviving pines would be affected by the level of injury received (more damage, less growth) and as a function of individual tree size (bigger trees will grow faster). Although these data were not from a true random sample of all the injured pines found in these plantations, there was no deliberate bias in how trees were chosen, so a two-factor analysis of variance (ANOVA) with five damage classes (Table 2) and three dbh classes (<7.9, 8.0–9.8, and ≥9.9 in.) should permit the differentiation of growth performance, if present. When the ANOVA detected a significant impact, means were separated using Tukey's honestly significant difference test on the annualized dbh growth rates.

Table 3. **Type of damage, number of individual loblolly pines within each type, and proportion still alive at the end of the 5-year observation period following the December 2000 ice storms.**

Damage type[a]	Initial sample size	Number of survivors, year 5	Percentage alive, year 5
Crown loss[b]	148	127	85.8
Stem bent	204	159	77.9
Root-sprung	13	2	15.4
No visible damage[c]	45	44	97.8
Totals	410	332	81.0[d]

[a] Individuals were selected that were affected primarily by the damage type for which they are listed.
[b] Includes trees whose primary injury visible during evaluation was the loss of branches and/or the growing leader. Some of these trees may have also exhibited some stem bending, but it was not the dominant type of damage at that time.
[c] It is likely that virtually every pine in the ice-affected areas received at least some injury. Furthermore, because the initial evaluation was conducted about 4 months after the storm, some recovery from bending may have already occurred, masking this type of injury.
[d] Weighted mean.

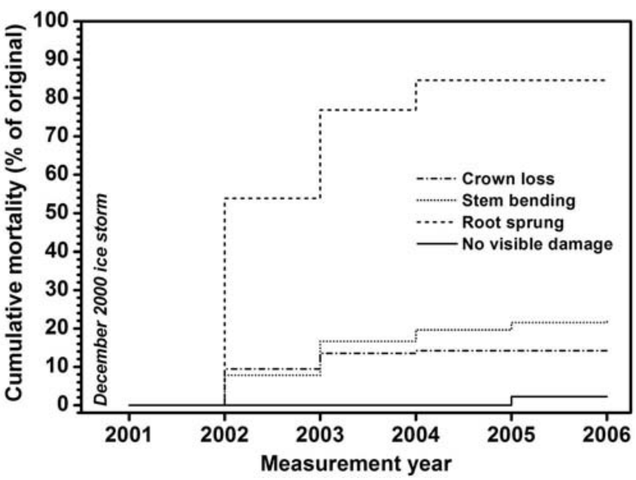

Figure 3. Cumulative mortality by damage type over the 5-year observation period of loblolly pines damaged by the December 2000 ice storms in Arkansas.

Results and Discussion

Mortality Patterns

The clearest patterns for the four damage types tracked were the high proportion of mortality experienced by the root-sprung category and the low mortality found in the "undamaged" stems (Table 3). Almost 54% of the root-sprung trees died by the end of the first year (2002), increasing to 77% in 2003, and then stabilizing at 85% by 2004 (Figure 3). However, the growth of vines and other low-growing vegetation, coupled with increasing crown closure from the surviving pines of this ice storm, is expected to eventually shade out and kill the last few root-sprung survivors.

Only 1 of the 45 undamaged individuals (2.2%) died during the 5-year observation period (Figure 3), succumbing to unknown causes during the fourth year after the ice storm. This is a remarkably good survival rate for pine plantations of this age and condition, especially considering the damage inflicted by the glaze event. High survival can probably be attributed to the thinnings these stands experienced—both the planned thinning conducted prior to the ice storm and the unplanned natural thinning following glazing. A pine that survives an ice storm with little damage compared with its neighbors quickly finds itself in a much more favorable competitive position. Growth may be slightly reduced during the first year after the storm as the tree recovers and resists insect attacks, but barring

Table 4. Mortality rates by the severity of damage after the first (measured in 2002) and fifth (measured in 2006) growing seasons following the December 2000 ice storms.

Damage class[a]	Initial (2001) sample[b]	2002 number of: Survivors	2002 number of: Dead[c]	2006 number of: Survivors	2006 number of: Dead
Insignificant	115	115	0 (0.0%)	114	1 (0.9%)
Minor	71	71	0 (0.0%)	69	2 (2.8%)
Moderate	48	48	0 (0.0%)	48	0 (0.0%)
Major	57	53	4 (7.0%)	48	9 (15.8%)
Critical	119	86	33 (27.7%)	53	66 (55.5%)

[a] Defined in Table 2.
[b] These numbers differ from Bragg et al. (2002) due to slight modifications in how damage classes were assigned.
[c] Percentage of initial (2001) sample size.

catastrophic events in an ice storm's aftermath, most survivors quickly take advantage of the newly available resources.

Other types of tree damage produced elevated, if variable, levels of mortality. Many critically injured pines died during the first 2 years before the rate of death slowed and stabilized. The stresses of being severely bent or suffering the heavy loss of branches and foliage claimed 7 and 10% of the damaged pines after the first year (Figure 3), gradually increasing to 22 and 14% by the end of the fifth year, respectively. Most of the mortality occurred during the first 2 years for both damage types, although bent trees continued to die during most of the observation period. Severely leaning trees suffered both from the immediate trauma of the ice storm, as well as delayed mortality following the event—a few of the badly bent pines broke below their live crowns many months after the ice storm.

Mortality rates were also influenced by the severity of the injury received. Of the 234 sampled pines that experienced insignificant to moderate damage (Table 4), only 3 had died after 5 years (1.3%, or about 0.26% annually). This rate is comparable to what may have been expected from an undamaged, recently thinned plantation. In fact, it is likely that at least one of these pines died by some factor other than this ice storm (perhaps competition). Seventy-five of the 78 pines (96%) that died over the course of the observation period had experienced major or critical levels of damage (Table 4), and 66 of these had received critical damage. In other words, almost 16% of trees with major damage and >55% of the critically injured loblolly pines died within 5 years of the December 2000 ice storm, with most expiring in the first 2 years (Figure 3).

Straightening of Bent Trees

Of the 13 root-sprung trees, less than half survived the first year following the ice storm. Rather than recovering any straightness, the survivors generally increased their bend until they died. The two pines that survived the entire 5-year observation period did not change their angle, as their crowns already touched the ground, and hence they could not lean any more. Given that root-sprung trees, by definition, have experienced significant support failure, their increasing bend over time was not surprising.

Bent (but not uprooted) loblolly pines have a considerable capacity to recover their straightness. These results are consistent with the trends noted by others (e.g., Kuprionis 1970, Brewer and Linnartz 1973, Reamer and Bruner 1973), with increasing degree of initial bending corresponding strongly to the decrease in subsequent straightening (Figure 4). Of the 159 bent pines that survived to the end of the observation period, virtually all of the individuals (regardless of tree diameter) that had been bent to no more than 30° had

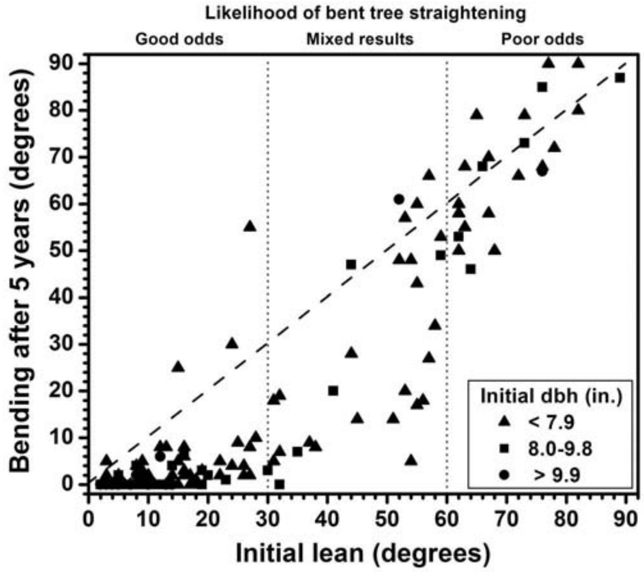

Figure 4. Recovery of stem straightness by size class for the 159 pines that survived at least 5 years following the December 2000 ice storms in Arkansas. Symbols below the dashed, angle-equivalence line indicate straightening, whereas those above the line indicate increased bending.

straightened to 15° or less of lean after 5 years. Stems experiencing between 30° and 60° of initial bending varied considerably more, with most showing at least some recovery but very few dropping to <15°. Stems bent >60° by the glazing recovered very little, and a large proportion of these badly damaged pines actually increased their lean during the observation period (Figure 4).

Survivor Growth

Given the severity of this ice storm, virtually every surviving pine experienced some type of injury, ranging from insignificant (e.g., the limited loss of small branches and needles or a slight bend) to critical (e.g., uprooting, severe bending, or the loss of virtually all live crown). The magnitude of the injury and tree size are known to influence the growth performance of pines that withstand ice storms for years after the event (e.g., Kuprionis 1970, Wiley and Zeide 1991). For example, root-sprung pines, whose damage was considered the most critical of those that survived the glazing, fared worse when diameter growth was examined. Neither of the root-sprung survivors grew in diameter at all during the 5-year observation period.

Both damage class and dbh class influenced growth rate ($P < 0.0001$ for each effect; interaction $P = 0.2208$) (Table 5). As expected, as the degree of injury increased, the tree's ability to grow rapidly during this initial recovery period was progressively limited. Undoubtedly, most of this increment loss can be attributed to the reduction in photosynthetic surface area (in the case of broken branches) and the reallocation of resources when attempting to straighten bent boles or add roots, in addition to the subordinate position of the crowns of bent trees. For the most severely injured pines, the loss of crown or the pronounced and unrecoverable bend in the stem drastically and significantly reduced dbh growth (Table 6). Most of the pines with minor to moderate injury were able to gradually improve their growth performance during the observation period, and those experiencing an insignificant level of damage primarily lost increment only during the first year after the ice storm (Figure 5).

For trees with more limited damage, most size classes had approximately the same potential for average (0.3–0.4 in.) and maximum dbh increments (~0.5–0.7 in., Table 6). Pines in the smallest diameter class were more likely to experience strongly diminished growth rates (minimum increments <0.04 in./year) regardless of damage severity, which suggests that the subordinate canopy position of these small trees helped to constrain their productivity. Although most survivors with adequate crown likely were able to exploit the thinning of the stand that happened following glazing, the largest trees benefited disproportionately from this reduction in stand density. With only one exception, the class with the greatest dbh (pines ≥9.9 in.) grew faster than smaller size classes (data not shown). However, in the six study sites, finding large-diameter pines with moderate to critical levels of damage was difficult, and this is reflected in the limited sample of this size class.

What to Salvage and What to Keep

The first step following a severe ice storm is to determine the degree of damage to the pine plantation. Typically, a landowner only has weeks to months before stain or other fiber degradation occurs, rendering dead timber worthless to many buyers. Landowners should also recognize that local timber markets are usually quickly saturated with excessive quantities of damaged timber following large-scale catastrophic natural disturbances. This may inhibit their ability to perform any type of salvage, short of paying someone to clean up their properties. The following discussion is based on the premises that commercial salvage is possible (e.g., no regulatory or access limitations), there is enough volume for the salvage to be considered operable, and that local markets will accept their harvested timber.

If possible, the damage assessment should be followed by immediate salvage of the commercial timber killed outright by the ice storm. In a related study, 18–20-year-old loblolly pine plantations in the same area and struck by the same ice storm experienced 10–20% lethal losses to broken boles (Bragg et al. 2004), and other stands experienced 50% or greater mortality as an immediate impact of the ice accumulation. Whether or not this loss yields enough salvageable material to interest a logger depends on a number of circumstances, including market prices, access to the downed timber, and the degree of wood quality degradation found in the dead pines.

The most severely damaged yet still living timber should also be harvested immediately, given that these trees are most likely to die from their injuries over the next few years (Table 4) and will show the least growth (Table 6) during this period. Root-sprung individuals, for example, expired at the highest rate and grew only negligibly after injury. Thus, root-sprung trees should be harvested immediately since they have no potential to recover.

Likewise, badly bent trees have virtually no chance to straighten adequately enough to justify their long-term retention. But how much bending is too much? Patterson and Hartley (2007) recommended that all pines initially bent more than 20° be salvaged to minimize future wood quality problems. In regards to survivorship or even growth, with the exception of critically injured trees, moderate to severe bending does not appear to drastically increase mortality. Hence, retaining strongly bent trees to avoid short-term depressed market conditions should not be a major problem.

Table 5. Analysis of variance test on the effects of damage severity class, diameter class, and their interaction on annualized dbh increment for loblolly pines in plantations following the December 2000 ice storms.

Source	Degrees of freedom	Sum of squares	Mean square	F value	Probability $>F$
Model	14	29.5722	2.1123	21.55	<0.0001
Error	317	31.0662	0.0980		
Corrected total	331	60.6384			
Type III sum of squares					
Damage class	4	13.7041	3.4260	34.96	<0.0001
dbh class	2	3.3618	1.6809	17.15	<0.0001
Damage × dbh class	8	1.0539	0.1317	1.34	0.2208

Table 6. Means separation (Tukey's honestly significant difference) tests on the annualized dbh growth rate differences among damage severity classes and dbh classes for loblolly pine plantations following the December 2000 ice storms.

	Annualized dbh growth rate (in.)				
Effect	n	Average[a]	SD	Minimum	Maximum
Damage class[b]					
Insignificant	114	0.38^{A}	0.14	0.00	0.74
Minor	69	$0.35^{A,B}$	0.15	0.00	0.72
Moderate	48	0.30^{B}	0.14	0.02	0.52
Major	48	0.21^{C}	0.11	0.02	0.40
Critical	53	0.09^{D}	0.09	0.00	0.48
dbh class (in.)					
<7.9	138	0.23^{A}	0.15	0.00	0.60
8.0–9.8	138	0.31^{B}	0.17	0.00	0.72
≥9.9	56	0.39^{C}	0.15	0.02	0.74

[a] Means within each effect followed by the same letter are similar ($P = 0.05$).
[b] Defined in Table 2.

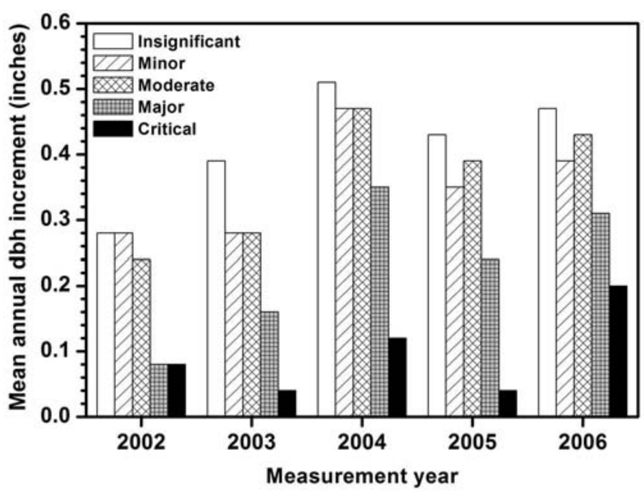

Figure 5. Annual growth rate for 8.0–9.8-in.-dbh loblolly pines by damage class following the December 2000 ice storms in Arkansas.

If additional fiber volume is needed to make a salvage sale viable, then trees that were bent at least 60° are good candidates to cut, as their chances for recovery of bole straightness are negligible. This level could drop to 40° of initial bend if still more volume was needed—below this threshold, evidence suggests that young, otherwise healthy loblolly pine have a good chance to return to near-vertical conditions, and may be better left for future yields. A further caveat is that a tree's ability to recover from glaze-related injury is somewhat size dependent. As pines grow larger, their bole elasticity tends to decrease. Thus, a 12-in.-dbh pine with 40° of bend is less likely to straighten (or will straighten less) than a 6-in.-dbh pine bent to the same angle.

Another salvage consideration relates to the desired end product. If the management objective of the stand is simply to produce biomass for chips or pulpwood, then it matters little where the damage occurred along the bole of injured trees, so long as growth performance is adequate. However, if sawtimber or veneer is the intended end product, otherwise productive survivors that had their bole break below the minimum sawlog length (typically 16 ft plus trim in Arkansas) or retain a substantial amount of sweep due to bending are of little future commercial value (Williston 1974). Hence, we recommend that postevent inventory be multitiered, with categories designed to tally trees that were killed outright, trees that survived but are unacceptable as any type of crop tree, trees that are acceptable for biomass or chipping only, and trees that are expected to meet the requirements of higher value end products.

Survival of Damaged Pines

Tables 4 and 5 illustrate how the most harmed trees (i.e., those with critical damage, regardless of the injury type) represent an unacceptable level of risk. Hence, in addition to stems broken off below the live crown, loblolly pines with bends greater than 60°, those that have lost ≥70% of their live crowns, and all root-sprung trees should be salvaged as soon as possible. This should be reflected in the poststorm cruising of damaged timber, as the thresholds for acceptable stand stocking are based largely on the number of potential crop trees (e.g., Baker and Shelton 1998). Conversely, stems with bends of less than 40° or pines with at least 55% of their crowns still intact (i.e., the moderate and lower damage classes) are, according to this study, of minimal mortality risk.

Loblolly pines with major damage (45–69% crown loss or 40–59 degree bends) tended to die at a markedly higher rate than less damaged individuals, but substantially lower (by about 40 percentage points) than critically injured trees. Pines with major damage can act as a wild card in deciding how to treat damaged plantations, especially if significant forest health risks, such as wildfire or southern pine beetle (*Dendroctonus frontalis* Zimm.), are unlikely. Given that ice storms can glut local timber markets with low-value wood fiber and produce at least temporary stumpage price declines (Straka and Baker 1991, Prestemon and Holmes 2000), it may benefit the landowner to defer harvesting until prices increase. Pines with major damage are less than ideal growing stock—some will die during recovery, their growth is noticeably depressed, and survivors with bending will begin producing reaction wood. However, these negative factors will almost certainly be offset by higher stumpage prices after the local markets have corrected themselves following the storm event.

Mitigating Wood Quality and Growth Impacts

Removal of the most severely damaged trees should simultaneously eliminate both stems with the greatest chance of developing poor wood quality and stems with the slowest growth rate. This alone should alleviate concerns of mill operators of receiving large quantities of wood of dubious quality in the decades following a major ice storm. Another advantage to cutting heavily damaged timber is preventative—slow-growing, recently injured pines are also more susceptible to infestation by southern pine beetles (Kirby 1954, Ku et al. 1980, Barry et al. 1998), creating a new forest health risk in the aftermath of ice storms.

Most research (including this study) indicates that long-term pine growth is reduced to some degree by ice damage (e.g., Wiley and Zeide 1991, Belanger et al. 1996). However, these results suggest that when controlled for diameter and level of damage, only the pines with the most severe damage failed to return to acceptable levels of productivity within 5 years of the glaze injury (Figure 5). Deciding which pines to retain is fairly straightforward for slightly injured trees (they recover swiftly after glazing) and for stems with major to critical levels of bending, which will straighten very little regardless of their size (Figure 4). However, the decision of whether or not to allow moderately injured pines to recover for the full rotation is more difficult and involves an evaluation of the potential end product in addition to growth.

Delaying harvesting may be particularly valid if the stands are approaching mid-rotation or late rotation—if crop tree stocking remains adequate (adequacy of stocking depends on landowner goals) and the risk of forest health problems is limited, it would be better to carry acceptable trees to the end of their rotation than clearing and establishing a new stand (Shepard 1978). Loblolly pine stands have a remarkable capacity to respond to substantial understocking with accelerated growth, allowing for a return to acceptable stocking levels quickly (e.g., Burton 1981, Baker 1989, Wiley and Zeide 1991). Revenues may be lower than they would be if a fully stocked stand was taken to rotation, but the high value of sawlogs or veneer compared with smaller dimension products should offset much of the decrease in the return on the original investment.

Planning for the Future

Beyond knowing that much of the southern United States experiences a damaging glaze event once every decade or two, ice storms are highly unpredictable, and hence, it is impossible to anticipate them before conventional intermediate treatments such as thinnings. It would be ideal, for instance, to know an ice storm was imminent prior to thinning dense pine stands, as this makes them vulnerable for a number of years (Downs 1943, Shepard 1978). Since this kind of foresight is not possible, landowners are strongly encouraged to take preventative measures that limit the impact of ice storms.

Minimizing the length of time pines remain in particularly vulnerable size classes has long been recommended as a course of action to help limit damage to ice storms (Bragg et al. 2003). This strategy generally favors maintaining relatively low density stands for as much of the rotation as possible, which can be accomplished via lower planting densities and periodic light thinnings to ensure stem growth rates are maximized while trees are allowed to acclimate to less dense stand conditions. With ice damage, a poorly timed thinning can be worse than no thinning at all (Downs 1943, Shepard 1978). Exposing spindly trees to the weather may lead to major losses following glazing because these trees lack the bole integrity to support accumulated ice and can no longer depend on support from adjacent stems (Downs 1943, Nelson 1951). Furthermore, open stands have the tendency to produce more large branches on the crop trees, lowering log quality unless pruning is used to keep the bole free of branches. However, high levels of pruning have been shown to increase the degree of ice damage (Burton 1981). Pruning may improve ice damage recovery, though, if performed judiciously after the storm (Roberts and Clapp 1956). Care should also be taken in choosing the species (if a conversion from loblolly to another species is being considered) or provenance of the pines to be planted in glaze-prone areas, as not all taxa or cultivars respond equally to ice accumulation (McKellar 1942, Muntz 1947, Jones and Wells 1969).

Conclusions

Advice on recovering storm-damaged stands has been provided for years (e.g., Downs 1943, Barry et al. 1998, Stanturf et al. 2007). There is no single metric that can be considered when evaluating an ice damaged stand for silvicultural treatment. Rather, the manager must consider a number of factors, including short- and long-term survivorship likelihoods, productivity of retained trees as a function of the type and degree of injury, and end product wood quality. These components must be evaluated to decide whether the remaining stand is worth continuing to some point in the future (possibly to the end of the original rotation, or perhaps some years before this) or whether a better strategy would be to start over—salvaging whatever value may be present and establishing a new stand.

Silvicultural decisions regarding ice damage mitigation should not be monolithic—each landowner has different "comfort zones" or preferences for how to respond to the storm, and the specific conditions found in affected stands can vary considerably. This study, in conjunction with other related assessments (e.g., Bragg et al. 2002, 2004, Patterson and Hartley 2007), was designed to address questions on the management and long-term disposition of loblolly pine plantations following catastrophic ice storms. Ultimately, improvement of the decisionmaking of landowners who have recently experienced a severe ice storm is sought, given that certain actions taken hastily after the event can prove counterproductive (Russell 1967, Williston 1974, Fountain and Burnett 1979).

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