For. Sci. 62(5):574–585
http://dx.doi.org/10.5849/forsci.15-177

silviculture

Initial Mortality Rates and Extent of Damage to Loblolly and Longleaf Pine Plantations Affected by an Ice Storm in South Carolina

Don C. Bragg

A major ice storm struck Georgia and the Carolinas in February of 2014, damaging or destroying hundreds of thousands of hectares of timber worth hundreds of millions of dollars. Losses were particularly severe in pine plantations in west-central South Carolina, including many on the Savannah River Site (SRS). An array of paired, mid-rotation loblolly (*Pinus taeda* L.) and longleaf (*Pinus palustris* Mill.) pine plantations on the SRS provided an opportunity to evaluate species- and size-based tree responses to this storm. A preliminary assessment of these recently thinned plantations found that longleaf pines experienced higher mortality rates than loblolly pines; in part, this result was confounded with tree size (dbh). A more detailed analysis found that longleaf pines, even when controlled for dbh, experienced higher mortality rates and a greater degree of certain types of injuries than comparably sized loblolly pines. These results suggest that longleaf pine planted in glaze-prone regions of the southeastern United States may need to be managed with different planting densities, thinning regimes, and/or rotation ages than loblolly pine.

Keywords: glaze, *Pinus palustris*, *Pinus taeda*, Savannah River Site

Ice (also known as "glaze") storms are one of the most significant natural disturbances in eastern North America (Irland 2000, Smith 2000, Bragg et al. 2003, Changnon 2003); under certain circumstances, their impacts occur over hours to days across vast areas, and they can be as catastrophic to forests as hurricanes. Whereas long-term weather observations indicate that the northeastern United States and southeastern Canada have the highest frequency of freezing precipitation events (e.g., Bennett 1959, Changnon and Karl 2003, Cortinas et al. 2004), the southeastern United States also regularly experience ice storms (Bragg et al. 2003, Changnon 2003). Indeed, major glaze events periodically strike the region, damaging timber, property, and infrastructure, incurring massive cleanup costs and other negative consequences. Notable examples over the last quarter-century include a particularly devastating 1994 ice storm that damaged timber over millions of hectares from Texas to Alabama (1.6 million ha in Mississippi alone), inflicting more than $3 billion in losses (Lott and Sittel 1996); a pair of ice storms in December of 2000 that affected more than 3 million ha of forest in Arkansas, Oklahoma, and Texas, with more than $500 million in estimated impacts (Forgrave 2001); and a multiday glaze event in 2002 across the Carolinas and southeastern Virginia that damaged hundreds of thousands of hectares of timber worth more than a half-billion dollars (McCarthy et al. 2006).

To date, research on ice storm impacts to southeastern forests has focused on loblolly pine (*Pinus taeda* L.), slash pine (*Pinus elliottii* Engelm.), or upland hardwood ecosystems. Young pine plantations have been particularly well studied, given their vulnerability to this type of disturbance. However, research into the silvicultural factors (e.g., stocking, species composition, and thinning regimes) that may influence the nature and extent of glaze-related loss has largely been opportunistic and is often poorly replicated, insufficiently monitored, or otherwise inadequately controlled. When coupled with the inconsistent dynamics of the actual glaze event, much remains to be learned about the silvicultural and economic implications of catastrophic ice storms. As an example, foresters often wonder about the best approach for mitigating losses in small-diameter pine, particularly when little to no market exists for storm-damaged salvaged timber.

Foresters are also challenged by how to manage for injured trees that are expected to survive the glaze event. Poststorm response depends on the extent of the damage and the ability of a species to recover from the injuries inflicted (e.g., Bragg and Shelton 2010).

Manuscript received November 30, 2015; accepted April 22, 2016; published online June 30, 2016.

Affiliations: *Don C. Bragg (dbragg@fs.fed.us), USDA Forest Service, Southern Research Station, Monticello, AR.*

Acknowledgments: *I thank the following for their assistance on this project: John Blake, Ed Olson, Steven Butler, and Elizabeth Brooks (all of the USDA Forest Service's Savannah River Site); Timothy Harrington (Pacific Northwest Research Station, USDA Forest Service); James M. Guldin and Nancy Koerth (Southern Research Station, USDA Forest Service); and Tim Slay (consulting forester). Financial support for this project was provided by the USDA Forest Service's Southern Research Station and the Savannah River Site.*

For example, unless their crown loss or other injuries are particularly severe, loblolly pines damaged by ice storms usually rapidly regain their height, diameter, and basal area growth (e.g., Bell and Dunham 1987, Wiley and Zeide 1991, Aubrey et al. 2007). A recent ice damage simulation study (Dipesh et al. 2015) noted that planted loblolly pine with even substantial (up to 52%) crown loss had only brief and relatively limited decreases in basal area growth and damaged trees quickly recovered total height, although bole quality was still negatively affected.

Unlike loblolly pine, much less is known about how the slower growing longleaf pine (*Pinus palustris* Mill.) responds to ice storm damage. For instance, a handful of limited studies have reported that young longleaf pine fared better than slash pine but worse than loblolly pine after glaze injury (e.g., McKellar 1942, Muntz 1947, Van Lear and Saucier 1973). Some of this research gap is because young longleaf pine is less common in glaze-prone regions and much of the remaining longleaf is in mature, natural stands that are not particularly susceptible to ice damage. Nevertheless, longleaf pine's response to ice damage is a growing concern across much of the southeastern United States. Longleaf pine has been a species of interest for years, and recent gains in longleaf's coverage have been attributed to incentive-driven planting across its former range (e.g., Harrington 2011, America's Longleaf Restoration Initiative 2014, Rose 2015, South and Harper 2016). However, some conservationists worry that higher glaze-related losses may prompt an aversion to longleaf pine plantations by private landowners that could halt or even reverse this positive trend across much of the species' historical distribution.

After a February 2014 ice storm in eastern Georgia and the Carolinas, a number of observers asserted that planted longleaf fared noticeably worse than loblolly pine plantations. Although the veracity of these claims is still largely unknown, this ice storm did provide an opportunity to consider potential differences between loblolly and longleaf pine. Loblolly and longleaf plantations on the Savannah River Site (SRS) in western South Carolina established on the same sites at the same time and managed in an identical fashion allowed a comparison of these species in a semicontrolled environment. The objectives of this research included the following: to determine whether there were any significant differences between the ice damage response of these paired loblolly and longleaf pine plantations on the SRS; to understand the reasons behind any differences that arose; and to discuss relevant forest management implications.

Methods

Ice Storm History

What began as a cold rain in Georgia on Feb. 11, 2014, transitioned into frozen precipitation on Feb. 12 and 13, with the wintry weather extending into North Carolina before the storm system exited up the eastern coast of the United States (Malsick 2014). The thickest ice (up to 3.2 cm) from this storm accumulated in eastern Georgia and west-central South Carolina (Malsick 2014). Not surprisingly, timber damage was greatest in these areas, with nearly 680,000 ha of forests impacted and estimated losses of more than $425 million in Georgia and South Carolina alone (Johnson et al. 2014, South Carolina Forestry Commission 2014). As noted in many ice storms (e.g., Muntz 1947, Bragg and Shelton 2010), timber loss was most pronounced in young managed stands; the vast majority (87%) of the 28,000 ha of heavily damaged pine plantations in Georgia had been recently thinned (Johnson et al. 2014).

The SRS, an 80,267-ha US Department of Energy (US DOE) facility,[1] located in Aiken, Barnwell, and Allendale Counties in South Carolina (Figure 1), received some of the worst glazing and suffered significant tree damage (Harrington and Harrington 2016). According to after-storm assessments provided by the National Weather Service, most of the SRS area received 2–3 cm of ice and a dusting (about 1 cm) of snow (Malsick 2014). The SRS area is no stranger to damaging ice storms; events with 1 cm or more accumulation of glaze occur about once every 10–25 years (Blake et al. 2005). As an example, almost a decade earlier, the region experienced a major ice storm that deposited 2 cm of ice and affected more than 250,000 ha, inflicting more than $67 million in pine timber losses in South Carolina (Aubrey et al. 2007). Other notable ice storms struck the region in 1961, 1964, 1969, 1971, 1973, and 1979 (Hebb 1971, Van Lear and Saucier 1973, McNab and Carter 1981, Kilgo and Blake 2005, US Army Corps of Engineers 2015). Most of the glaze-affected trees on the SRS had bent or broken stems and branch loss. Few trees were uprooted, though (T. Harrington, US Forest Service, pers. comm., Mar. 4, 2015); the deep, sandy soils of the SRS site encouraged extensive root systems and rapid water drainage in the rooting zone, thereby limiting storm-related losses to windthrow or toppling.

Study Background

The current research focuses on the impacts of the February 2014 ice storm on a particular set of pine plantations installed by the US Department of Agriculture (USDA) Forest Service between 1988 and 1992 (Figure 1). This original study evaluated the influence of mycorrhizal inoculation and postplanting competition control on the survival and growth of loblolly and longleaf pine from excessively well-drained sites (for more details, see Cram et al. (1999)). The pine seedlings were machine planted in a randomized complete block design with three rows of 50–55 trees[2] each (a middle observation and two buffer rows) at a spacing of 3.05 m between rows and 1.83 m within rows. After planting, some mortality had occurred in every observation row before the 2014 ice storm, thereby reducing the number of trees in each replicate (see Table 1 for prestorm live pine counts). After 15 years, no consistent patterns of survival were generally observed in the original study between species or mycorrhizal treatment; however, modest differences attributable to planting stock (container versus bare root) on two sites and fire damage on another were noted (Cram et al. 2010). Loblolly pine was also significantly more productive than longleaf pine at all study locations (Cram et al. 2010).

After the formal closing of the mycorrhizal inoculation research project, parts of a few study locations were damaged or destroyed by unrelated disturbances, including a fire and some unexpected bulldozer work. In addition to these unplanned activities, a third-row thinning was conducted from fall 2011 to spring 2012 in all of the paired plantations. This thinning was not a part of the original study design, but rather an operational treatment intended to improve growth and yield. The harvest cut one of the two buffer rows around the treatment but did not remove any of the observation trees (John Blake, USDA Forest Service, Southern Research Station, pers. comm., June 24, 2014).

Post-Ice Storm Data Collection

A single block of all available paired loblolly and longleaf pine treatments was randomly selected at each of the original sample locations (Figure 1; Table 1) to assess how they fared in the February

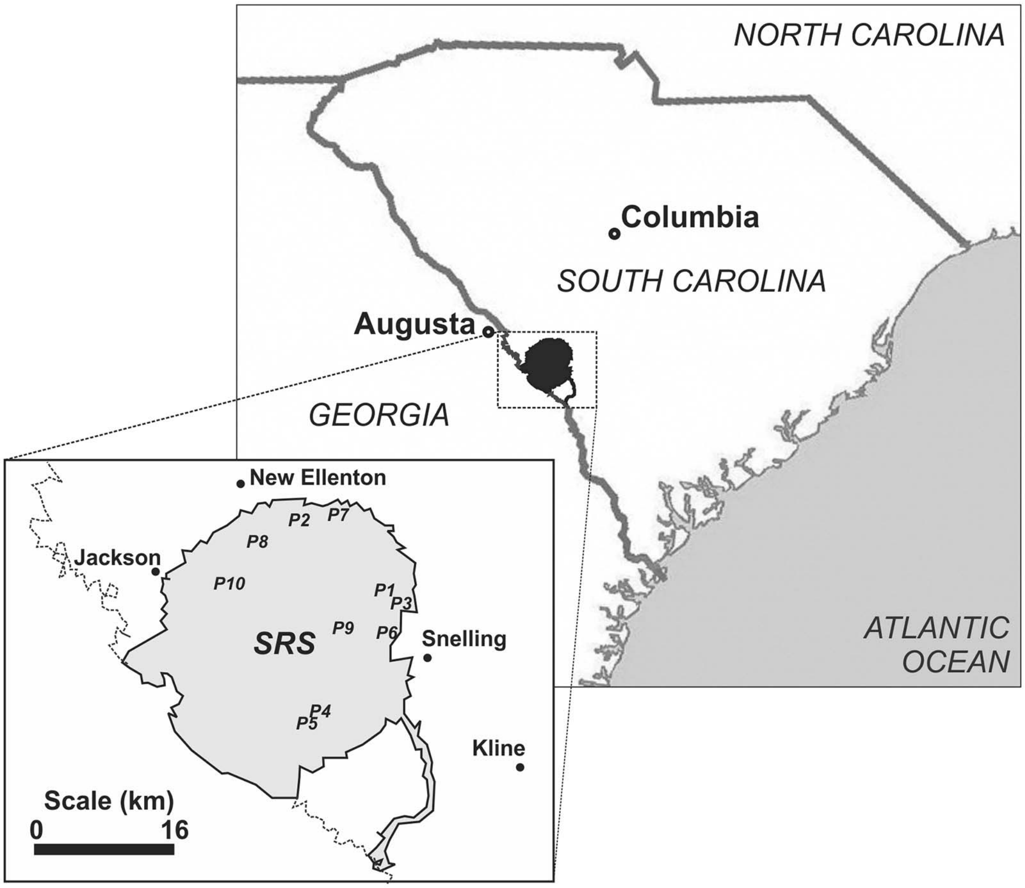

Figure 1. Map of the SRS in South Carolina, including approximate placement of sampling locations (P1–P10) used for this study of the February 2014 ice storm.

2014 ice storm. Between Aug. 28 and Sept. 17, 2014, a field crew went to every one of the original 50–55 planting points in the observation row of each selected block to determine whether a live tree was present when the storm began. This was possible because none of the damaged pines had been salvaged after the ice storm, and any pines that had died before the event had either decayed away or remained but were sufficiently degraded to be distinguishable from those more recently killed.

Once it was determined that a loblolly or longleaf pine was alive during the February 2014 ice storm, the tree had its dbh measured to the nearest 0.25 cm. Pines that succumbed to the storm (defined as having no live foliage at the time of the inventory) were noted. All mortality totals are cumulative; they consist of all pines that expired between the onset of the ice storm and the date of sampling. It was not possible to determine exactly when the sampled trees died. Some recent evidence of mortality was seen, as witnessed by freshly browned needles; however, most pines apparently died during the storm (if they lost 100% of their live crown) or in the first days or weeks after glazing. Notes were also made of any potential mitigating factors (such as the presence of canker or forked stems) that may have led to injury or death; however, there were too few observations to warrant further consideration of these factors.

Typically, small- to moderate-sized trees impacted by an ice storm experience both crown loss and some degree of bole bending. Uprooting can also be a major source of ice storm-related mortality under certain conditions (e.g., Bragg and Shelton 2010). However, the deep, sandy soils of the SRS greatly limited the amount of uprooting from this glaze event,[3] and I thus did not include this type of damage in my evaluations. All live and killed pines had two different damage ratings assigned, reflecting the extent of crown loss and bole bending visible at the time of measurement. These crown loss and lean categories reflected the results of other studies (e.g., Bragg and Shelton 2010) that noted similar long-term growth and survival patterns within these groupings. To ensure consistency and improve assessment speed, field crews were provided an example-based training manual. Pines that lost their entire live crown when the bole snapped below the base of the live crown or all live branches were stripped off were assigned to the 100% crown lost category. Otherwise, crews made ocular estimates guided by the training manual to allocate pines into one of the other crown loss categories (0–9.9, 10–49.9, and 50–99.9% crown lost). Field crews also assigned every pine one of three lean classes (0–9.9, 10–39.9, and >40°, measured with a clinometer).

Assumptions and Data Limitations

It is conceivable that the damage patterns observed in these small strip plots are not consistent with that experienced at larger scales. Furthermore, different types of thinning (e.g., operator select using diffusive removals) or different spacing patterns at planting time could also result in disparate outcomes for these same species at this stage in stand development, particularly if site and weather conditions varied considerably. After all, the extent of ice damage experienced in any given stand can vary dramatically and depends on factors such as localized weather and site conditions, stand structure,

Table 1. Sample location information and conditions after the February 2014 ice storm on the SRS, South Carolina.

Sample location (block)	Planting date	Age (yr)[a]	Pine species	Treatment codes[b]	Minimum dbh	Average	Maximum dbh[c]	No. of live pines	Pines killed (%)
					.(cm).				
P1 (8)	Jan.1988	27	Longleaf	NI	8.4	14.3	19.6	40	57.5
				NI + H	9.1	15.2	20.8	23	26.1
				PT	9.4	15.7	19.8	31	61.3
				PT + H	6.9	13.6	21.6	37	27.0
			Loblolly	NI	9.4	18.0	30.2	36	47.2
				NI + H	7.4	16.5	25.7	30	46.7
				PT	8.9	18.4	31.8	28	17.9
				PT + H	9.9	18.0	25.9	36	38.9
P2 (2)	Jan.1988	27	Longleaf	NI	4.8	14.9	19.8	45	40.0
				NI + H	7.6	14.7	22.9	41	29.3
				PT	5.6	14.5	20.1	46	6.5
				PT + H	6.4	14.2	20.1	46	32.6
			Loblolly	NI	7.4	15.8	28.2	46	26.1
				NI + H	11.4	16.6	25.7	39	41.0
				PT	9.1	17.5	24.6	38	42.1
				PT + H	8.9	16.1	26.2	45	57.8
P3 (4)	Jan.1989	26	Longleaf	NI	5.8	16.0	20.3	40	7.5
				NI + H	3.0	14.5	25.4	47	12.8
				PT	5.1	15.7	21.3	45	20.0
				PT + H	5.8	16.1	25.1	37	29.7
			Loblolly	NI	8.1	15.6	23.9	29	10.3
				NI + H	6.4	15.6	22.1	36	25.0
				PT	3.8	18.3	26.7	21	42.9
				PT + H	11.2	18.5	27.4	12	16.7
P4 (3)	Jan.1989	26	Longleaf	NI	12.4	18.3	33.0	38	28.9
				NI + H	7.6	15.7	22.9	35	45.7
				PT	6.4	15.3	22.9	25	40.0
				PT + H	6.6	15.7	23.1	26	38.5
			Loblolly	NI	8.4	18.1	31.2	37	43.2
				NI + H	13.7	20.2	27.4	40	20.0
				PT	8.4	20.3	26.9	44	15.9
				PT + H	10.9	20.8	29.7	46	21.7
P5 (5)	Jan.1990	25	Longleaf	NI	6.4	16.5	23.1	42	21.4
				NI + H	5.3	12.6	22.6	37	37.8
				PT	7.6	15.3	21.8	35	62.9
				PT + H	6.4	14.6	25.9	35	48.6
			Loblolly	NI	6.6	16.7	22.9	39	12.8
				NI + H	7.9	17.5	23.9	39	17.9
				PT	11.4	17.7	25.4	32	15.6
				PT + H	9.7	17.0	31.0	34	20.6
P6 (1)	Jan.1990	25	Longleaf	NI	4.8	15.9	28.2	37	29.7
				NI + H	6.6	15.0	21.3	33	48.5
				PT	9.1	15.6	20.6	31	45.2
				PT + H	10.2	18.4	24.9	30	23.3
			Loblolly	NI	7.4	16.9	28.4	35	28.6
				NI + H	11.9	18.2	39.6	35	14.3
				PT	12.2	18.2	23.1	29	13.8
				PT + H	9.7	16.8	27.2	29	34.5
P7 (7)	Jan.1991	24	Longleaf	NI	6.6	13.9	18.8	39	30.8
				NI + H	10.2	15.4	20.3	37	40.5
				PT	4.6	12.8	20.8	34	32.4
				PT + H	6.4	14.7	21.1	22	36.4
			Loblolly	NI	8.6	15.7	23.6	42	14.3
				NI + H	7.4	13.3	22.6	43	30.2
				PT	5.8	14.7	21.6	44	25.0
				PT + H	6.4	14.0	23.9	42	26.2
P8 (6)	Jan.1991	24	Longleaf	NI	10.9	16.4	22.9	22	31.8
				NI + H	7.4	15.6	20.1	30	30.0
				PT	9.1	17.9	24.6	23	8.7
				PT + H	7.1	15.9	22.4	17	64.7
			Loblolly	NI	7.4	16.6	23.1	27	48.1
				NI + H	7.4	15.9	24.6	40	20.0
				PT	10.2	18.6	25.9	44	6.8
				PT + H	7.4	15.8	24.1	31	48.4
P9 (2)	Jan.1992	23	Longleaf	NI	7.4	15.2	28.2	29	34.5
				PT	11.7	17.7	29.7	18	61.1
				CNT + NI	2.8	14.1	23.1	41	24.4
				CNT + PT	7.1	15.5	21.6	36	38.9
			Loblolly	NI	3.8	17.6	26.2	39	10.3
				PT	3.3	18.4	25.4	35	5.7
P10 (5)	Jan.1992	23	Longleaf	CNT + PT	7.6	14.9	21.6	36	30.6
			Loblolly	PT	8.6	17.9	25.9	35	42.9

The dbh values are poststorm, the number of live pines is the number alive at the onset of glazing, and the pine-killed percentage is of those live pines.
[a] Age at time of storm; includes the 1 year it took to raise the pine seedlings at the nursery prior to planting on the SRS.
[b] NI, naturally inoculated; PT, *Pisolithus tinctorius* inoculated; H, herbicide treatment; CNT, containerized seedlings.
[c] Includes pines killed by the ice storm; their dbh is at time of death (between February 14 and September 2014).

species composition, time since last glaze event, and recent silvicultural activities (e.g., Lemon 1961, Shepard 1978, Amateis and Burkhart 1996, Van Dyke 1999, Irland 2000, Bragg et al. 2003, Aubrey et al. 2007). Unfortunately, no data on location-specific ice accumulations were available, and it was not possible to observe the SRS stands during or immediately after the storm event. Undoubtedly, there would have been some variation in actual ice loading between the 10 sample locations on the SRS, but lacking site-specific instrumentation I assumed pines at all locations received the same quantity of glaze. I also assumed that the duration of ice loading was identical from one tree to the next and that no differences in post-ice storm mortality or recovery occurred as a function of geography or other stand-related conditions.

Some of the dead trees observed in September 2014 may have survived the ice storm, only to later die of completely unrelated factors; it was not possible to distinguish these from pines that expired due to glaze damage. However, because of the inherently low mortality rates of established, thinned pine plantations and a lack of unrelated exogenous mortality (the intervening growing season was not abnormally dry or hot, with no widespread insect or disease outbreaks), all trees that expired between February and September 2014 were assumed to have died either as a direct consequence of the ice storm (e.g., boles snapped below the live crown) or from injuries related to this event.

Finally, it is also likely that the measurements taken in late summer 2014 are conservative estimates of the degree of nonlethal injury inflicted by the February ice storm. Whereas crown loss is usually apparent long after the event, some branch and foliar regrowth would have occurred over the intervening days. Bent trees also start straightening almost immediately after the ice loads have been removed, especially after the growing season has begun. Given that these observations were taken months after the glaze event, many of the most pliable stems had recovered some if not all of their straightness.

Hypotheses and Data Analysis

A preliminary analysis using nonparametric Kruskal-Wallis tests found no significant differences between sample locations or inoculation status/site preparation technique in the percentage of pines killed by this ice event (data not shown; both $P > 0.3$), suggesting that no areas of markedly higher glaze accumulation or other location-specific treatment factors affected ice storm-related mortality rates. Although this initial analysis did not find statistically significant location or original treatment effects, there was evidence of species-based differences in survival (Figure 2). Hence, the first hypothesis tested was for differences in survival between loblolly and longleaf pines after this ice storm. Because I had no a priori expectation for mortality rates from this ice storm, my initial comparison was done by combining all observations and comparing overall survivorship using a 2×2 contingency table with the χ^2 test statistic (1 *df*, $\alpha = 0.05$) to determine whether species differed (Zar 1984).

There are a number of possible reasons why loblolly and longleaf pine of the same age, planted on the same site using the same techniques and managed similarly over time, could have exhibited different survival and damage extent in response to the February 2014 ice storm. These include critical variations in branch and/or bole architecture, crown surface area, differences in wood strength, and differences in bole size, among other factors. Of these, only a comparison of bole size (in this case, measured by dbh) was possible with the data available for this study. An additional preliminary evaluation of the data collected for this study (Figure 2) showed that the

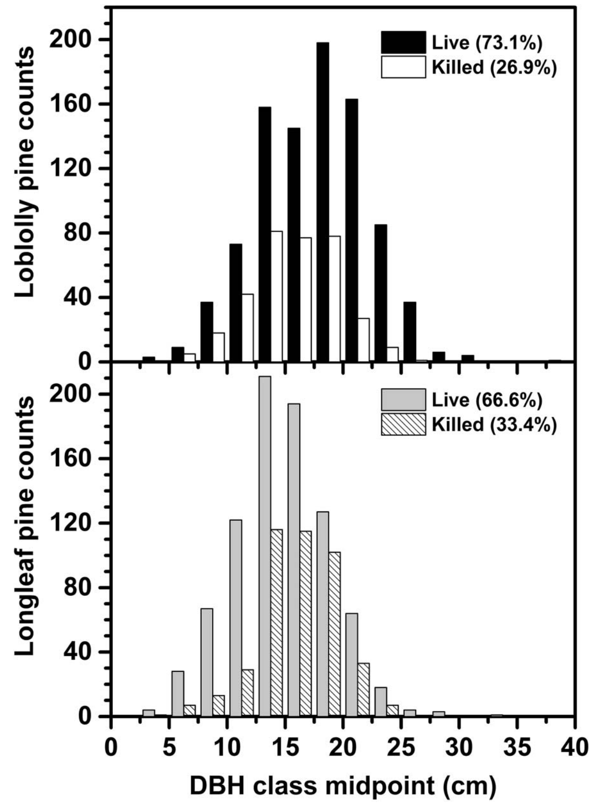

Figure 2. Histograms of the dbh distribution of all surviving and killed loblolly and longleaf pines measured after the February 2014 ice storm on the SRS.

loblolly pines were significantly greater in dbh than the longleaf pines. Given that dbh usually correlates with the type and severity of ice damage (e.g., Shepard 1975, Amateis and Burkhart 1996, Guo 1999, Aubrey et al. 2007, Bragg and Shelton 2010), it seemed logical to expect that bole size could be at least partially responsible for observed differences in survivorship and damage extent. Therefore, a second hypothesis considered whether loblolly and longleaf pine had similar rates of survivorship by various injury severities when controlled for bole size (using 5-cm dbh classes, but not including the smallest and largest classes due to their limited sample sizes). This hypothesis was tested using three-dimensional contingency tables and log-linear analysis of frequencies, with significance determined using a Pearson's χ^2 test statistic assuming $\alpha = 0.05$ (Zar 1984). In cases where differences were found, partial association analysis was done on the interactions to determine which of the variables (including interactions) were significant.

Results and Discussion

The following assessments of mortality and injury reflect the unique set of circumstances related to this ice storm; however, I believe they still suggest what may be expected on the SRS (and similar sites) for comparable events in the future.

Mortality Patterns

When the February 2014 ice storm struck, there were 2,523 pines (1,257 loblolly and 1,266 longleaf) alive in the sampled blocks. Although no background rate of mortality was available immediately before the ice storm, in the history of these stands

Table 2. Distributions of trees killed by the February 2014 ice storm one growing season later (September 2014) by species and damage categories, SRS, South Carolina.

Pine species damage category	Diameter class: All		0–4.9 cm		5.0–9.9 cm		10.0–14.9 cm		15.0–19.9 cm		20.0–24.9 cm		≥25.0 cm	
	n	%[a]	*n*	%[a]	*n*	%[a]	*n*	%[a]	*n*	%[a]	*n*	%[a]	*n*	%[a]
Longleaf (% killed)[b]	423	(33.4)	1	(20.0)	20	(17.4)	127	(28.8)	235	(40.9)	40	(32.8)	0	(0.0)
Percentage of killed longleaf pine sampled with leaning stems														
0.0–9.9°	392	92.7	0	0.0	17	85.0	118	92.9	217	92.3	40	100.0	0	0.0
10.0–39.9°	1	0.2	0	0.0	0	0.0	1	0.8	0	0.0	0	0.0	0	0.0
>40.0°	30	7.1	1	100.0	3	15.0	8	6.3	18	7.7	0	0.0	0	0.0
Percentage of killed longleaf pine sampled with lost crown														
0.0–9.9%	16	3.8	1	100.0	2	10.0	4	3.1	9	3.8	0	0.0	0	0.0
10.0–49.9%	12	2.8	0	0.0	1	5.0	4	3.1	7	3.0	0	0.0	0	0.0
50.0–99.9%	9	2.1	0	0.0	2	10.0	4	3.1	3	1.3	0	0.0	0	0.0
100%	386	91.3	0	0.0	15	75.0	115	90.6	216	91.9	40	100.0	0	0.0
Loblolly (% killed)[b]	338	(26.9)	0	(0.0)	23	(33.3)	117	(35.5)	161	(30.8)	36	(12.7)	1	(2.0)
Percentage of killed loblolly pine sampled with leaning stems														
0.0–9.9°	327	96.7	0	0.0	22	95.7	113	96.6	158	98.1	33	91.7	1	100.0
10.0–39.9°	2	0.6	0	0.0	0	0	2	1.7	0	0	0	0	0	0.0
>40.0°	9	2.7	0	0.0	1	4.3	2	1.7	3	1.9	3	8.3	0	0.0
Percentage of killed loblolly pine sampled with lost crown														
0.0–9.9%	13	3.8	0	0.0	2	8.7	6	5.1	2	1.2	2	5.6	1	100.0
10.0–49.9%	16	4.7	0	0.0	0	0.0	6	5.1	4	2.5	6	16.7	0	0.0
50.0–99.9%	20	5.9	0	0.0	2	8.7	7	6.0	7	4.3	4	11.1	0	0.0
100%	289	85.5	0	0.0	19	82.6	98	83.8	148	91.9	24	66.7	0	0.0

[a] Percentages may not sum to 100.0% due to rounding.
[b] In these rows only, % killed = percentage of pine killed by the ice storm by species and size class as a function of the total (still live + killed) in that class by that species.

annual mortality had rarely exceeded a few percent in any of the treatments, with the highest rates coming in the first years after planting (Cram et al. 1999, 2010). Glaze-induced mortality data are summarized by the various treatments at each sample location in Table 1. By September of 2014, 26.9% of these loblolly pine and 33.4% of the longleaf pine had expired as a consequence of the glazing (Table 1). A contingency table analysis of mortality rates by species produced a test statistic of 12.57, which exceeded the critical value ($\chi^2_{0.05,1} = 3.841$; $P < 0.001$), indicating that longleaf pine had experienced a significantly higher rate of mortality after this glaze event.

However, it was also apparent from the individual tree data (for all sampled stems) (Figure 2) that median loblolly pine diameters were greater than those of the longleaf pine (17.3 cm versus 15.2 cm; $P < 0.001$, Wilcoxon signed-rank test). Comparing mortality rates by 5 cm dbh classes indicated that both the smallest (<5 cm dbh) and largest (≥25 cm dbh) size classes experienced the lowest mortality rates (Table 2), but for different reasons. Although the small sample size ($n = 8$) of very-small-diameter pines limits the inferences possible, the rarity of small pines perishing in even severe ice events is not surprising. Unless crushed by larger trees falling on them, the smallest pines tend to survive because they are usually quite pliable and hence capable of bending completely over if gradually deformed, as happens with glaze accumulation (Shepard 1975, Aubrey et al. 2007, Bragg and Shelton 2010). Most of the very small pines distorted by ice or snow loading will return to vertical within a matter of weeks or months, usually with few lasting effects (Figure 3; see also Kuprionis 1970, Reamer and Bruner 1973, Aubrey et al. 2007). Unless afflicted by a mechanical weakness in the bole (e.g., decay), impinged on by strong winds, or subject to diminished root strength (e.g., shallow or saturated soils), large trees usually have sufficient bole strength to carry a large quantity of ice and often shed much of this load via the loss of foliage and branches (Bragg et al. 2003). However, because bigger trees have larger crowns and have lost much of the flexibility they had when they were smaller, they can be more prone to bole breakage (Aubrey et al. 2007), a lethal event for most conifers if it occurs below their live crown. Only one of the 57 pines larger than 25 cm dbh observed died between the February 2014 ice storm and the late summer 2014 sampling (Table 3); however, this loblolly pine had very little apparent damage, suggesting its demise may be only partially related to the ice storm.

In this study, 30–36% of loblolly pines between 5 and 20 cm dbh and 29–41% of longleaf pines between 10 and 25 cm dbh were killed by the ice storm (Table 2). The vast majority of these tree deaths occurred because of extreme injuries (e.g., loss of entire live crown due to bole breakage, severe lean, or both) (Tables 2 and 3). Intermediate-sized pines experienced the highest mortality rates because many of them had lost the pliability of smaller stems and their somewhat larger crowns accumulated higher ice loads. These observations are consistent with those of numerous other studies (e.g., Downs 1943, Wiley and Zeide 1991, Amateis and Burkhart 1996, Aubrey et al. 2007, Bragg and Shelton 2010).

Note that the mortality assessments made in late summer of 2014 probably did not capture all of the pines likely to eventually die from this glaze event. Work on different planted pines in other parts of the SRS affected by this same ice storm showed continued mortality of injured trees into at least the fall of 2015, especially in those with severe to extreme lean and/or crown loss (T. Harrington, USDA Forest Service, pers. comm., Nov. 20, 2015), and other studies have likewise documented delayed ice storm-related mortality in injured trees (e.g., Kuprionis 1970, Belanger et al. 1996, Bragg and Shelton 2010). Although the pines in this study were not revisited in 2015, delayed mortality was expected. Without additional measurements, it

Figure 3. Young loblolly pine when covered by frozen precipitation (top). Most of these pliable, small-diameter trees recovered within the first growing season after this event (bottom). [USDA Forest Service images adapted from Kuprionis (1970) and Bragg et al. (2003).]

will not be possible to determine whether longleaf pine will continue to experience a higher rate of mortality than loblolly pine.

Damage Patterns of Surviving Pines

Table 4 displays the different types of damage by species and size class for those pines still alive in the late summer of 2014. As noted in other research on glaze injury, large diameter (>15 cm dbh) surviving pines of both species had relatively low levels of damage. In these larger trees, the most prominent injury was crown loss. Between 10 and 20% of 15–24.9 cm dbh loblolly and longleaf pine experienced from 10 to 50% crown loss but rarely more than 7% of other types of severe lean or breakage (Table 4). The largest longleaf

Table 3. Distribution of damage magnitude categories as a function of dbh class and species in pines killed by the February 2014 ice storm, SRS, South Carolina.

			% dbh/species class in damage magnitude categories[a]				
dbh class	Pine species	dbh class totals	Minimal	Moderate	Major	Severe	Extreme
0.0–4.9 cm	Longleaf	1	0.0	0.0	100.0	0.0	0.0
	Loblolly	0	0.0	0.0	0.0	0.0	0.0
5.0–9.9 cm	Longleaf	20	5.0	0.0	10.0	5.0	80.0
	Loblolly	23	4.3	0.0	13.0	0.0	82.6
10.0–14.9 cm	Longleaf	145	0.0	1.4	3.4	4.1	91.0
	Loblolly	123	4.1	3.3	7.3	0.8	84.6
15.0–19.9 cm	Longleaf	217	0.5	0.0	4.1	1.8	93.5
	Loblolly	155	1.3	1.9	3.2	0.6	92.9
20.0–24.9 cm	Longleaf	40	0.0	0.0	0.0	0.0	100.0
	Loblolly	36	5.6	13.9	5.6	2.8	72.2
≥25.0 cm	Longleaf	0	0.0	0.0	0.0	0.0	0.0
	Loblolly	1	100.0	0.0	0.0	0.0	0.0

[a] Damage magnitude category definitions: minimal = 0.0–9.9° lean and 0.0–9.9% crown loss; moderate = 0.0–9.9° lean and 10.0–49.9% crown loss or 10.0–39.9° lean and 0.0–9.9% crown loss; major = 0.0–9.9° lean and 50.0–99.9% crown loss or > 40° lean and 0.0–9.9% crown loss or 10.0–39.9° lean and 10.0–49.9% crown loss; severe = 10.0–39.9° lean and 50.0–99.9% crown loss or > 40.0° lean and 10.0–49.9% crown loss; extreme = >40.0° lean and 50.0–100% crown loss. By definition, the most extreme type of damage recorded for either species, the loss of 100% of the live crown due to bole breakage, was classified as a lethal event.

Table 4. Distributions of trees still alive one growing season after (September 2014) the February 2014 ice storm by species and damage categories, SRS, South Carolina.

	Diameter class													
	All		0–4.9 cm		5.0–9.9 cm		10.0–14.9 cm		15.0–19.9 cm		20.0–24.9 cm		≥25.0 cm	
Pine species damage category	*n*	%[a]	*n*	%[a]	*n*	%[a]	*n*	%[a]	*n*	%[a]	*n*	%[a]	*n*	%[a]
Longleaf (% surv.)[b]	843	(66.6)	4	(80.0)	95	(82.6)	314	(71.2)	340	(59.1)	82	(67.2)	8	(100.0)
Percentage of still living longleaf pine sampled with leaning stems														
0.0–9.9°	618	73.3	3	75.0	49	51.6	193	61.5	284	83.5	81	98.8	8	100.0
10.0–39.9°	40	4.7	0	0.0	14	14.7	14	4.5	12	3.5	0	0.0	0	0.0
>40.0°	185	21.9	1	25.0	32	33.7	107	34.1	44	12.9	1	1.2	0	0.0
Percentage of still living longleaf pine sampled with lost crown														
0.0–9.9%	637	75.6	4	100.0	49	51.6	239	76.1	276	81.2	64	78.0	5	62.5
10.0–49.9%	157	18.6	0	0.0	40	42.1	56	17.8	44	12.9	14	17.1	3	37.5
50.0–99.9%[c]	49	5.8	0	0.0	6	6.3	19	6.1	20	5.9	4	4.9	0	0.0
Loblolly (% surv.)[b]	919	(73.1)	3	(100.0)	46	(66.7)	213	(64.5)	361	(69.2)	248	(87.3)	48	(98.0)
Percentage of still living loblolly pine sampled with leaning stems														
0.0–9.9°	874	95.1	2	66.7	28	60.9	191	89.7	358	99.2	247	99.6	48	100.0
10.0–39.9°	30	3.3	1	33.3	10	21.7	15	7.0	3	0.8	1	0.4	0	0.0
>40.0°	15	1.6	0	0.0	8	17.4	7	3.3	0	0.0	0	0.0	0	0.0
Percentage of still living loblolly pine sampled with lost crown														
0.0–9.9%	689	75.0	3	100.0	30	65.2	143	67.1	266	73.7	204	82.3	43	89.6
10.0–49.9%	172	18.7	0	0.0	12	26.1	50	23.5	70	19.4	36	14.5	4	8.3
50.0–99.9%[c]	58	6.3	0	0.0	4	8.7	20	9.4	25	6.9	8	3.2	1	2.1

[a] Percentages may not sum to 100.0% due to rounding.
[b] (% surv.) is the percentage of pine that survived the ice storm by species and size class for all damage classes combined as a function of the total (still live + killed) by those categories.
[c] By definition, any pine that lost 100% of its live crown was classified as killed by the ice storm.

pines (>25 cm dbh) experienced higher levels (37.5%) of moderate (10 to 50%) crown loss, although the limited number of specimens (8 trees total) in this size class constrains the interpretation of this result. The larger sample (48 trees) of loblolly pine greater than 25 cm dbh showed far fewer individuals with moderate to severe crown loss (just over 10%; Table 5). Smaller diameter (<15 cm) longleaf and loblolly pines had varying degrees of moderate (10–49.9%) crown loss: between 0 and 42%, with a prominent concentration between 17 and 27%. In addition, only a few (between 0 and 10%) of the small pines fell into the severest category (50–99.9%) of crown loss (Table 4). No consistent patterns appeared in these small pines regarding crown loss; this may also reflect the limited sample size in a number of the diameter classes, especially those less than 5 cm dbh.

Given that most of these pines experienced both crown loss and bent stem injuries, it is useful to merge the different broad damage types (bole lean and crown loss) into a unified spectrum of damage. Table 5 provides this combined assessment of the ratios of damage magnitude by species and dbh class for surviving pines. With only one exception, the majority of surviving trees had minimal damage (see footnote to Table 5 for how damage magnitude categories were defined) regardless of species or size class. The exception was for

Table 5. **Distribution of damage magnitude categories as a function of dbh class and species in pines that survived the February 2014 ice storm, SRS, South Carolina.**

			% of dbh/species class in damage magnitude categories[a]				
dbh class	Pine species	dbh class totals	Minimal	Moderate	Major	Severe	Extreme
0.0–4.9 cm	Longleaf	4	75.0	0.0	25.0	0.0	0.0
	Loblolly	3	66.7	33.3	0.0	0.0	0.0
5.0–9.9 cm	Longleaf	95	28.4	27.4	24.2	18.9	1.1
	Loblolly	46	41.3	28.3	19.6	10.9	0.0
10.0–14.9 cm	Longleaf	333	54.1	5.1	27.9	11.7	1.2
	Loblolly	231	60.2	26.4	11.3	2.2	0.0
15.0–19.9 cm	Longleaf	321	70.1	10.6	15.9	3.1	0.3
	Loblolly	343	74.1	18.7	7.3	0.0	0.0
20.0–24.9 cm	Longleaf	82	76.8	17.1	6.1	0.0	0.0
	Loblolly	248	81.9	14.9	3.2	0.0	0.0
≥25.0 cm	Longleaf	8	62.5	37.5	0.0	0.0	0.0
	Loblolly	48	89.6	8.3	2.1	0.0	0.0

[a] Damage magnitude category definitions: minimal = 0.0–9.9° lean and 0.0–9.9% crown loss; moderate = 0.0–9.9° lean and 10.0–49.9% crown loss or 10.0–39.9° lean and 0.0–9.9% crown loss; major = 0.0–9.9° lean and 50.0–99.9% crown loss or >40° lean and 0.0–9.9% crown loss or 10.0–39.9° lean and 10.0–49.9% crown loss; severe = 10.0–39.9° lean and 50.0–99.9% crown loss or >40.0° lean and 10.0–49.9% crown loss; extreme = >40.0° lean and 50.0–99.9% crown loss. By definition, the most extreme type of damage recorded for either species, the loss of 100% of the live crown due to bole breakage, was classified as a lethal event and is thus not given in this table.

Table 6. **Three-dimensional contingency tables and log-linear analysis of frequencies.**

	Contingency table and log-linear analysis		
Factors (and interactions)	*df*	χ^2	*P*
Simultaneously fitted factors assuming interactions are zero			
Species	10	3,531.6	<0.0001
Damage class	29	456.9	<0.0001
Dbh class	20	39.0	0.0068
Partial associations with interactions			
Species	1	3.2	0.0725
Damage class	5	1,409.5	<0.0001
Dbh class	4	2,118.9	<0.0001
Species × damage class	5	100.6	<0.0001
Species × dbh class	4	89.2	<0.0001
Damage class × dbh class	20	173.7	<0.0001

Values are based on the five damage categories and four main dbh classes (those from 5 to 25 cm) from Table 5, with significance determined with a Pearson's χ^2 test statistic and partial association analysis done on the interactions for the significant variables.

5–9.9 cm dbh longleaf and loblolly pines. In this size class, only 28.4% of longleaf pine and 41.3% of loblolly pine survivors had minimal damage, whereas values for all other categories were higher than those seen in most other size classes (Table 5). Slightly larger (10–14.9 cm dbh) longleaf pine also had relatively high amounts of major and severe damage, and this size loblolly pine also had an elevated amount of moderate damage (Table 5).

Three-dimensional contingency tests on surviving trees showed that all factors (species, damage type, and dbh class) were statistically significant (Table 6). Log linear-based analysis of partial associations further determined that most individual treatment effects and their interactions were highly significant ($P < 0.0001$), although with this analysis the species factor became marginally nonsignificant ($P = 0.0725$). As an example, longleaf pine was significantly ($P < 0.0001$) more likely to have moderate (10–39.9°) to severe (≥40°) lean than loblolly pine. Specifically, 5–9.9, 10–14.9, and 15–19.9 cm longleaf pine had 33.7, 34.1, and 12.9% of the surviving stems in those dbh classes in the severe lean category, respectively, compared to 17.4, 3.3, and 0% for loblolly pine (data from Table 4, contingency tests were based on categories given in Table 5 and analyzed in Table 6). The pattern was similar for moderate levels of lean. Whereas some have noted that longleaf pine were less susceptible to severe leaning than loblolly pine after a glaze event (e.g., Muntz 1947), the results of others comparing longleaf and loblolly pine agreed with this study (e.g., McKellar 1942).

Silvicultural Implications

Because of the considerable investments made in southern pine plantations, managers have long been advised to take a number of steps in ice storm-prone regions to lessen impacts. Perhaps the most basic way silvicultural decisions could influence forest response to glazing is through promoting those species most resilient to this inevitable, if unpredictable, event (e.g., McKellar 1942). As mentioned earlier, others have observed differences in ice damage they attributed to species, particularly for off-site taxa, although many of these studies have lacked sufficient controls to clearly demonstrate this factor. This research, with better control over stand age, planting, thinning, and location and with adjustment for tree size did find significant, if moderate, differences in survivorship and extent of damage between loblolly and longleaf pine.

Although the ability of locally adapted seed sources to perform better than off-site sources (even of the same species) has some merit for ice storm resistance, these patterns are probably more associated with tree condition than species. Other research (e.g., McKellar 1942, Hebb 1971, 1973, Harrington and Harrington 2016, Pile et al. 2016) has found that differences in branch architecture, foliage patterns, and carbon allocation strategies affect southern pine survivorship and damage patterns after glazing. For example, the thinner branches and smaller, less densely clustered needles of loblolly and sand (*Pinus clausa* [Chapm. ex Engelm.] Vasey ex Sarg.) pines limited ice buildup in these species (compared with longleaf or slash pines) through two mechanisms: the shedding of accrued weight via branch breakage and a lower amount of ice-accumulating surface area (McKellar 1942, Hebb 1973). Growth performance and species are also confounded, which can translate into meaningful size differences in mixed-species stands. In this study, more loblolly pine got big enough (even on the excessively well-drained soils of the SRS) over the last 23–27 years to lessen the damage experienced by this species. Simplified to a cantilevered beam and all other bole strength properties being equal, a tree of a larger diameter has greater capacity to support an ice load (Bragg et al. 2003, Aubrey et al. 2007).

Because of these relationships, a number of silvicultural practices in southern pine plantations can reduce losses attributable to ice damage regardless of species. Recently thinned, mid-rotation southern pine plantations are particularly vulnerable to damage (Muntz 1947, Bragg et al. 2003), so adjustments to the timing, intensity, and/or pattern of thinnings may help. For example, Brender and Romancier (1960) recommended thinning stands lightly and frequently from below or selective thinning to reduce losses from ice accumulation. Shepard (1975) suggested using selective, rather than row, thinning to help reduce glaze losses. T. Harrington (USDA Forest Service, pers. comm., Mar. 4, 2015) recommended early thinning of longleaf pine plantations (by age 10), coupled with hardwood control to decrease height/diameter ratios and allow pines to develop sufficient bole strength to support ice accumulations. Even though results from spacing trials impacted by ice storms have sometimes been ambiguous (e.g., Amateis and Burkhart 1996), another recommendation has been to use wide initial spacing to encourage faster tree growth, thereby allowing individuals to grow out of the most vulnerable size classes sooner (e.g., Shepard 1975). For genetically improved loblolly pines with straight bole and small branch ideotypes, low initial planting density rarely causes problems with bole quality because few develop excessively large branches, forks, or sweep. However, unimproved seedlings of most southern pines, including both longleaf and loblolly, struggle to remain straight-boled, produce small branches, and self-prune in low-density stands.

Judicious application of poststorm salvage can likewise reduce long-term impacts of a glaze storm. For surviving pines, permanent bole lean will be most problematic over the long term. Whereas major (>50%) crown loss can temporarily lower growth rates (e.g., Dipesh et al. 2015), produce stem defects (such as forking or decay), and increase future mortality rates, branch breakage does not significantly impact bolewood quality (Patterson and Hartley 2007) and rarely decreases end product yield unless the break occurred below the minimal acceptable sawlog length. However, unless a leaning stem quickly recovers verticality (straightness), the sweep incurred becomes permanently set and will probably keep the logs from becoming the more valuable sawtimber or veneer (Kuprionis 1970). Furthermore, a severely bent pine will continue to produce compression wood in an attempt to straighten the bole, thereby degrading the quality of the wood produced for years after the injury (Kuprionis 1970, Patterson and Hartley 2007). Therefore, pines that have lost even major portions of their crowns should be a lower salvage priority than those than those that have been badly bent.

Because it can be influenced by silviculture, it may seem logical, therefore, to mitigate the potential risk of incurring glaze-related losses. But do the precautionary measures capable of lessening the impacts of glazing make economic sense? Using a set of greatly simplified scenarios and assumptions, Goodnow et al. (2008) modeled the influence of different management approaches on the economic outcomes of an ice storm occurring either before or after thinning of a hypothetical loblolly pine plantation. In one of their scenarios, a landowner used a number of silvicultural treatments to reduce the nature of the damage; this was contrasted to a "myopic" landowner who made no such attempts. In this synthetic environment, Goodnow et al. (2008, p. 287) noted that "…potential gains from managing stands to mitigate ice damage are often smaller than potential losses that occur when storms fail to materialize… [landowners] may be best served by simply waiting until an ice storm occurs, and then adjusting their decisions after that period of time." In other words, the silvicultural tradeoffs (e.g., adjustments in planting density, thinning intensity and timing and rotation length changes) considered by Goodnow et al. to reduce glaze-related losses sufficiently decreased returns when the ice storm failed to occur to more than offset the benefits of more resilient loblolly pine plantations.

It is not clear how the results of Goodnow et al. (2008) translate to management of longleaf pine plantations, especially those established in areas of high risk for ice storms. Longleaf pine does not grow as quickly as loblolly pine and experiences damage from glaze differently. Furthermore, Goodnow et al. (2008) assumed a damaging ice storm frequency of once every 50–100 years, which is unrealistic across much of the southeastern United States (including the SRS). Many of those installing longleaf pine plantations may also have different management objectives to consider than maximizing volume production. For example, although the members of a longleaf pine-focused conservation organization surveyed by Lavoie et al. (2011) did not list ice storms as a restoration constraint, alterations to initial stocking and thinning practices (e.g., low-density stands to speed individual stem growth and carry higher ice loads) may prove problematic. Higher-value end products such as poles and pilings have been touted as a way to entice more landowners to plant longleaf pine (e.g., Dickens et al. 2007, Longleaf Alliance 2011), but the silvicultural practices needed to achieve this quicker bole growth are less conducive for pole and piling production due to lower bole quality and may also diminish revenue opportunities from pine straw (McIntyre and McCall 2014).

Conclusions

Damaging ice storms are a fact of life across most of the southeastern United States; foresters and landowners must make some allowance for the prospects of this disturbance event over the typical rotation of a pine plantation. Although it may be presumptive to call the Carolinas an "ice storm belt," the area is impacted frequently enough for glazing to be an ever-present threat to even short rotation pine plantations. Hence, foresters should be aware of the full range of factors that may contribute to glaze-related losses. During the past few decades, the SRS has been struck by multiple ice storms with very different results: the storm that occurred in 2004 apparently had little to no effect on the loblolly and longleaf plantations used in this study, as there was no mention of this event in recent publications (Kilgo and Blake 2005, Cram et al. 2010). However, the February 2014 ice storm left the same (although older and recently thinned) plantations with considerable losses. Loblolly pine was not immune from damage or mortality either, but the species handled glazing somewhat better than comparably sized longleaf pine. An even more severe ice storm in 2014 could have erased any significant differences between these species; higher glaze accumulation or stronger winds during the storm, for example, might have devastated both species to the point that their losses were indistinguishable.

More research is needed to determine the best silvicultural options for the development of ice storm-resilient southern pine stands. In particular, treatments designed specifically to meet the management objectives for longleaf pine plantations in ice-prone regions are justifiable. The higher rate of damage found by this assessment may suggest that conventional thinning regimes (e.g., third-row removals) are inadvisable for comparable longleaf pine plantations. Furthermore, customized solutions for longleaf pine in glaze-prone regions that emphasize higher initial stockings and more conservative thinnings are possible and may be particularly advisable for landowners not driven solely by fiber production objectives. Determining the efficacy of any silvicultural regime modified to increase ice storm resilience in longleaf pine should include thorough examination of landowner goals and objectives with the likelihood of successful outcomes.

Endnotes

1. The SRS is a National Environmental Research Park managed and operated for the US DOE by Savannah River Nuclear Solutions; under an interagency agreement, the USDA Forest Service manages the natural resources on the 68,155 ha not reserved for industrial and nuclear missions (Kilgo and Blake 2005, Savannah River Nuclear Solutions 2012).
2. These were called "planting points" and represented the location where a pine had been planted in the original inoculation study.
3. In an unrelated assessment, only 0.6% of longleaf pines killed by this ice storm on the SRS had succumbed to uprooting (T. Harrington, USDA Forest Service, pers. comm., Mar. 4, 2015).

Literature Cited

AMATEIS, R.L., AND H.E. BURKHART. 1996. Impact of heavy glaze in a loblolly pine spacing trial. *South. J. Appl. For.* 20(3):151–155.

AMERICA'S LONGLEAF RESTORATION INITIATIVE. 2014. *2014 Range-wide accomplishment report.* ALRI Longleaf Partnership Council. 15 p. Available online at www.longleafalliance.org/publications/2014-ALRI-Accomplishment-Report-final.pdf; last accessed Nov. 20, 2015.

AUBREY, D.P., M.D. COLEMAN, AND D.R. COYLE. 2007. Ice damage in loblolly pine: Understanding the factors that influence susceptibility. *For. Sci.* 53(5):580–589.

BELANGER, R.P., J.F. GODBEE, R.L. ANDERSON, AND J.T. PAUL. 1996. Ice damage in thinned and nonthinned loblolly pine plantations infected with fusiform rust. *South. J. Appl. For.* 20(3):136–142.

BELL, R.D., AND P.H. DUNHAM. 1987. *Response of a ten-year-old, plantation-grown loblolly pine subjected to ice damage.* Res. Rep. 65, Westvaco Forest Science Laboratory, Ravenel, SC. 17 p.

BENNETT, I. 1959. *Glaze: Its meteorology and climatology, geographical distribution and economic effects.* Tech. Rep. EP-105, Quartermaster Research and Engineering Center, Natick, MA. 234 p.

BLAKE, J.I., C.H HUNTER, JR., AND B.A. BAYLE. 2005. Climate and air quality. P. 20–30 in *Ecology and management of a forested landscape: Fifty years on the Savannah River Site*, Kilgo, J.C., and J.I. Blake (eds.). Island Press, Washington, DC.

BRAGG, D.C., AND M.G. SHELTON. 2010. Recovery of planted loblolly pine 5 years after severe ice storms in Arkansas. *South. J. Appl. For.* 34(1):13–20.

BRAGG, D.C., M.G. SHELTON, AND B. ZEIDE. 2003. Impacts and management implications of ice storms on forests in the southern United States. *For. Ecol. Manage.* 186:99–123.

BRENDER, E.V., AND R.M. ROMANCIER. 1960. Glaze damage in loblolly pine plantations. *South. Lumberman* 201(2513):168.

CHANGNON, S.A. 2003. Characteristics of ice storms in the United States. *J. Appl. Meteorol.* 42:630–639.

CHANGNON, S.A., AND T.R. KARL. 2003. Temporal and spatial variations of freezing rain in the contiguous United States: 1948–2000. *J. Appl. Meteorol.* 42(9):1302–1315.

CORTINAS, J.V., JR., B.C. BERNSTEIN, C.C. ROBBINS, AND J.W. STRAPP. 2004. An analysis of freezing rain, freezing drizzle, and ice pellets across the United States and Canada: 1976–90. *Weather Forecast.* 19(2): 377–390.

CRAM, M.M., J.G. MEXAL, AND R. SOUTER. 1999. Successful reforestation of South Carolina sandhills is not influenced by seedling inoculation with *Pisolithus tinctorius* in the nursery. *South. J. Appl. For.* 23(1): 46–52.

CRAM, M.M., K.W. OUTCALT, AND S.J. ZARNOCH. 2010. Growth of longleaf and loblolly pine planted on South Carolina sandhill sites. *South. J. Appl. For.* 34(2):79–83.

DICKENS, E.D., B.C. MCELVANY, D.J. MOORHEAD, AND M. FRYE. 2007. *Growing poles in southern pine stands.* Georgia Forest Productivity Rep. 010R-07. 10 p. Available online at www.bugwood.org/productivity/; last accessed Nov. 20, 2015.

DIPESH, K.C., R.E. WILL, T.C. HENNESSEY, T.B. LYNCH, R.A. HEINEMANN, R.T. HOLEMAN, AND D.E. WILSON. 2015. Effects of simulated ice storm damage on midrotation loblolly pine stands. *For. Sci.* 61(4):774–779.

DOWNS, A.A. 1943. *Minimizing glaze damage in pine.* USDA For. Serv., Tech. Note 55, Appalachian Forest Experimental Station, Asheville, NC. 5 p.

FORGRAVE, R. 2001. State's ice-storm costs top $547 million. *Ark. Democrat-Gazette* Nov. 2, 2001.

GOODNOW, R., J. SULLIVAN, AND G.S. AMACHER. 2008. Ice damage and forest stand management. *J. For. Econ.* 14:268–288.

GUO, Y. 1999. Ice storm damage to a sweetgum plantation fertilized with nitrogen and phosphorus. *South. J. Appl. For.* 23:224–229.

HARRINGTON, T.B. 2011. Overstory and understory relationships in longleaf pine plantations 14 years after thinning and woody control. *Can. J. For. Res.* 41:2301–2314.

HARRINGTON, T.B., AND T.A. HARRINGTON. 2016. Early density management of longleaf pine reduces susceptibility to ice storm damage. P. 313–316 in *Proc. of the 18th Biennial southern silvicultural research conference*, Schweitzer, C.J., W.K. Clatterbuck, and C.M. Oswalt (eds.). USDA For. Serv., e-Gen. Tech. Rep. SRS-212, Southern Research Station, Asheville, NC.

HEBB, E.A. 1971. Resistance to ice damage—A consideration in reforestation. *Tree Planters' Notes* 22(2):24–25.

HEBB, E.A. 1973. Ice and cold damage to sand pine—Weighing the risk. P. 213–225 in *Sand pine symposium proceedings.* USDA For. Serv., Gen. Tech. Rep. SE-2, Southeastern Research Station, Asheville, NC.

IRLAND, L.C. 2000. Ice storms and forest impacts. *Sci. Total Environ.* 262:231–242.

JOHNSON, J., C. BATES, AND G. WHITE. 2014. *Timber impact assessment: Georgia ice storm, February 11–13, 2014.* Georgia Forestry Commission. 7 p. Available online at www.gfc.state.ga.us/resources/publications/Timber%20Impact%20Assessment%20Georgia%20Ice%20Storm%20February%2011-14%202014.pdf; last accessed Nov. 20, 2015.

KILGO, J.C., AND J.I. BLAKE (EDS.). 2005. *Ecology and management of a forested landscape: Fifty years on the Savannah River Site.* Island Press, Washington, DC. 479 p.

KUPRIONIS, J. 1970. *Recovery of loblolly, slash, and shortleaf pines bent by snowfall and/or ice.* Bull. 4, Louisiana Polytechnic Institute, School of Agriculture and Forestry, Ruston, LA. 34 p.

LAVOIE, M., L. KOBZIAR, A. LONG, AND M. HAINDS. 2011. Problems and needs for restorationists of longleaf pine ecosystems: A survey. *Nat. Areas J.* 31(3):294–299.

LEMON, P.C. 1961. Forest ecology of ice storms. *Bull. Torrey Bot. Club* 88:21–29.

LONGLEAF ALLIANCE. 2011. *The economics of longleaf pine management: A road to making dollars and sense.* Longleaf Alliance, Andalusia, AL. 12 p. Available online at www.longleafalliance.org/archives/documents/economics/longleaf.pdf; last accessed Nov. 20, 2015.

LOTT, J.N., AND M.C. SITTEL. 1996. *The February 1994 ice storm in the southeastern US.* National Climatic Data Center, Asheville, NC. 7 p. Available online at www.ncdc.noaa.gov/oa/pub/data/special/iwais96.pdf; last accessed November 20, 2015.

Malsick, M. 2014. *February 12–13, 2014 ice and snow event open-file report.* South Carolina Department of Natural Resources, Land, Water and Conservation Division, South Carolina State Climatology Office, Charleston, SC. 11 p.

McCarthy, H.R., R. Oren, H.-S. Kim, K.H. Johnsen, C. Maier, S.G. Pritchard, and M.A. Davis. 2006. Interaction of ice storms and management practices on current carbon sequestration in forests and potential mitigation under future CO_2 atmosphere. *J. Geophys. Res.* 111(D15103):1–10.

McIntyre, R.K., and B.B. McCall. 2014. *Longleaf pine economics: Large-acreage landowner perspectives and opportunities.* North Carolina Longleaf Coalition report. 63 p. Available online at www.nclongleaf.org/pdfs/nfwf_economics_final_06_20_14.pdf, last accessed Nov. 20, 2015.

McKellar, A.D. 1942. Ice damage to slash pine, longleaf pine, and loblolly pine plantations in the Piedmont section of Georgia. *J. For.* 40:794–797.

McNab, W.H., and A.R. Carter. 1981. Sand pine performance on South Carolina sandhills. *South. J. Appl. For.* 5(2):84–88.

Muntz, H.H. 1947. Ice damage to pine plantations. *South. Lumberman* 175(2200):142–145.

Patterson, D.W., and J. Hartley. 2007. Properties of wood from ice-storm damaged loblolly pine trees. *For. Prod. J.* 57(1):48–51.

Pile, L.S., C.A. Maier, G.G. Wang, D. Yu, and T.M. Shearman. 2016. Responses of two genetically superior loblolly pine clonal ideotypes to a severe ice storm. *For. Ecol. Manage.* 360:213–220.

Reamer, L.D., and M.H. Bruner. 1973. *The recovery of loblolly pine after snow damage.* Dept. of For. Bull. 10, Clemson Univ., Clemson, SC. 5 p.

Rose, A.K. 2015. *Forests of South Carolina, 2013.* USDA For. Serv., Resour. Update FS-36, Southern Research Station, Asheville, NC. 4 p.

South Carolina Forestry Commission. 2014. *2014 winter storm timber damage assessment.* 7 p. Available online at www.state.sc.us/forest/2014winterstorm.htm; last accessed Feb. 12, 2016.

Shepard, R.K., Jr. 1975. Ice storm damage to loblolly pine in northern Louisiana. *J. For.* 73(7):420–423.

Shepard, R.K., Jr. 1978. Ice storm damage to thinned loblolly pine plantations in northern Louisiana. *South. J. Appl. For.* 2(3):83–85.

Smith, W.H. 2000. Ice and forest health. *North. J. Appl. For.* 17(1):16–19.

South, D.B., and R. Harper. 2016. A decline in timberland continues for several southern yellow pines. *J. For.* 114(2):116–124.

Savannah River Nuclear Solutions. 2012. *Savannah River Site.* 9 p. Available online at www.srs.gov/general/news/facts.htm; last accessed Nov. 20, 2015.

US Army Corps of Engineers. 2015. *Ice storm GIS 2.3d* [Database]. Available online at rsgisias.crrel.usace.army.mil/ice/; last accessed Nov. 20, 2015.

Van Dyke, O. 1999. *A literature review of ice storm impacts on forests in eastern North America.* Tech. Rep. 112. Ontario Ministry of Natural Resources, Southcentral Science Section, Peterborough ON, Canada. 29 p.

Van Lear, D.H., and J.R. Saucier. 1973. *Comparative glaze damage in adjacent stands of slash and longleaf pine.* For. Res. Ser. No. 27, Department of Forestry, Clemson Univ., Clemson, SC. 7 p.

Wiley, S., and B. Zeide. 1991. Investigation of growth 14 years after glaze damage in a loblolly pine plantation. P. 272–281 in *Proc. of the Sixth biennial southern silvicultural research conference*, Coleman, S.S., and D.G. Neary (eds.). USDA For. Serv., Gen. Tech. Rep. SE-70, Southeastern Research Station, Asheville, NC.

Zar, J.H. 1984. *Biostatistical analysis,* 2nd ed. Prentice Hall, Englewood Cliffs, NJ. 718 p.