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Effects of Simulated Ice Storm Damage on Midrotation Loblolly Pine Stands

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We simulated ice damage by shooting a portion of live crown from midrotation (ages 14–16 years) loblolly pine (*Pinus taeda* L.) stands in southeastern Oklahoma to study the postice damage effects in thinned, thinned-pruned, and nonthinned-nonpruned stands. Four years after damage, diameter growth was faster in the thinned plots than the nonthinned plots as expected. Relative basal area growth (rBA_{growth}; basal area growth over the 4-year period/initial basal area) decreased as the fraction of live crown ratio loss (LCR_{loss}) increased in all stands. While the slope of the relationship was similar among silvicultural treatments, the intercept for the nonthinned plots was lower. The result was that a 50% loss of live crown predicted rBA_{growth} reductions of 28% in thinned and 64% in nonthinned plots. Canopy opening due to the simulated damage did not have a positive growth effect on the undamaged trees. We did not detect any differences in stem taper, probably because the study included data for only a 4-year recovery period. We conclude that stands can recover from moderate ice storm damage without large loss in production and that thinned stands have less reduction in basal area growth than nonthinned stands.

Keywords: thinning, pruning, live crown ratio loss, relative basal area growth, taper

Natural disturbances, such as ice storms, cause significant changes in forest dynamics (Warrillow and Mou 1999, Bragg et al. 2003). Pine forests, a major forest cover type in the southern United States (Schultz 1997), periodically experience ice storms (Aubrey et al. 2007), the latest major events being in 1994, 2000 (twice), and 2007. Because pines retain foliage throughout the year, they have large surface area for ice accumulation, which can lead to considerable damage (Schultz 1997, Aubrey et al. 2007, Guldin 2011). Major damage by ice storms include reduced timber production and altered wildlife habitat, which are also accompanied by secondary damage such as soil erosion, wildfires, plant invasions, disease and pest outbreaks, and degradation to recreational areas (Meyers and McSweeney 1995, Warrillow and Mou 1999).

The area of pine plantation in the South has substantially increased from almost none in 1952 to nearly 16 million ha in 2010 (Wear and Greis 2012). Improved planting stock and intensive management practices have been important keys to the success of pine plantation management (Atwood et al. 2002, Fox et al. 2004). Loblolly pine (*Pinus taeda* L.) is the fastest growing and most economically important species among the southern pines (Samuelson et al. 1992, Schultz 1997, Zeide and Sharer 2002, Diéguez-Aranda et al. 2006, Dipesh et al. 2015). Of the seedlings planted in the South, more than 80% are loblolly pine (McKeand et al. 2003).

Loblolly pine stands are susceptible to ice storms (Samuelson et al. 1992, Aubrey et al. 2007), and ice storms might be more damaging in the northern part of southern forests (Guldin 2011). Although loblolly pine is relatively more tolerant to ice than some other pine species such as longleaf pine (*P. palustris* Mill.), slash pine (*P. elliottii* Englem.), and sand pine [*P. clausa* (Chapm. Ex Englem.)], hail or ice storms may severely affect the growth of loblolly pine, causing stem breakage, severe tree bending, or uprooting (Belanger et al. 1996). Loss of 70% crown, as well as severe stem bending or uprooting, is usually fatal to loblolly pine (Bragg et al. 2003). Therefore, loblolly pine plantations near or beyond the northern limit of the natural range may fail due to winter damage (Groninger et al. 2000), and successful management of loblolly pine

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This article uses metric units; the applicable conversion factors are: centimeters (cm): 1 cm = 0.39 in.; meters (m): 1 m = 3.3 ft; square meters (m^2): 1 m^2 = 10.8 ft^2; hectares (ha): 1 ha = 2.47 ac.

Table 1. Study sites and the key characteristics (USDA Natural Resource Conservation Service 2013) for loblolly pine stands in southeastern Oklahoma used to examine the effects of simulated ice damage on growth.

Closest community	Latitude, longitude	Soil type	Soil texture (≤40 cm)	Soil pH	Water table depth (cm)	Plantation year	No. of trees/plot	Treatment
Hochatown	34°09'N,94°46'W	Pickens and Carnasaw-Clebit	Gravelly silty loam-silty clay loam	5.2–5.6	>200	1992	227	TP
Hochatown	34°05'N,94°46'W	Carnasaw-Clebit	Loam-silty clay loam	5.2	>200	1994	221	NTNP
Eagletown	34°07'N,94°34'W	Carnasaw-Clebit	Loam-silty clay loam	5.2	>200	1994	232	OT
Eagletown	34°08'N,94°34'W	Pickens and Carnasaw-Clebit	Gravelly silty loam-silty clay loam	5.2–5.6	>200	1994	236	TP
Union Valley	34°08'N,94°30'W	Carnasaw-Clebit	Loam-silty clay loam	5.5	>200	1994	245	NTNP
Union Valley	34°04'N,94°30'W	Saffell	Gravelly fine sandy loam	5.0	>200	1994	260	OT

Treatments applied were thinned-pruned (TP), only thinned (OT), or nonthinned-nonpruned (NTNP).

plantations at these locations is questionable because of exposure to severe ice storms (Schultz 1997).

Silvicultural practices such as thinning and pruning manipulate the availability of the resources such as light, water, and nutrients and improve tree diameter growth rate of residual trees (Jokela et al. 2004, Sword Sayer et al. 2004, Allen et al. 2005). Under intensive management, loblolly pine plantations may receive commercial thinning as early as age 10 years and every 5–7 years after the first thinning before being harvested (Schultz 1999). Similarly, loblolly pine plantations may be artificially pruned, often in conjunction with thinning. Loblolly pine plantations in the southern United States may suffer from ice storms at some point during their rotation. How thinning and pruning affect tree recovery after ice damage is speculative. Following ice damage, managers must decide whether to clearcut for replanting, salvage the damaged trees, or do nothing (Bragg et al. 2003).

There are models predicting ice storm damage (Goodnow 2002) as well as studies on immediate effects of ice damage in loblolly pine. For example, wood of bent stems of loblolly pine is weakened by ice storms, although specific gravity is not affected (Dunham and Bourgeois 1996). Similarly, diameter growth of the damaged loblolly pine trees is reduced in the first few years after damage (Belanger et al. 1996). However, detailed quantitative assessments of loblolly pine tree and stand response to varying levels of ice damage in conjunction with prestorm data is usually not available. Therefore, it is important to monitor for a sufficiently long time and compare stand and tree growth after damage with predamage size and crown position. This will quantify the effect that different degrees of ice damage have on growth and determine sizes and types of trees that are best able to recover from damage. We also are limited by an understanding of how previous silvicultural activities, e.g., thinning and pruning, influence ice storm damage and recovery. Information on tree taper following ice damage is lacking but is important due to its influence on bole volume (Newnham 1992, Muhairwe 1994).

We determined the effects of varying levels live crown loss on tree growth (height, diameter, basal area) over 4 years within nonthinned-nonpruned, recently thinned, and recently thinned-pruned midrotation stands in southeastern Oklahoma near the northern and western margin of the loblolly pine commercial range. Our objectives were to determine how basal area growth and taper of individual trees was affected by the extent of damage to the live crown and whether thinning and pruning influenced these responses. We also compared the effects of damaging 25, 50, 75, and 100% of trees within a stand on tree and stand growth to determine whether growth of undamaged trees increased as the percentage of damaged trees within a stand increased. This research helps serve as a guide for forest managers to understand stand dynamics after ice storms and therefore help them decide the best actions to take.

Methods

Study Area

In March 2008, six midrotation loblolly pine stands were identified in McCurtain County in southeastern Oklahoma. Because one stand was later disturbed by a logging crew, a replacement stand was added in early 2009. These stands are owned by Weyerhaeuser Company (Federal Way, WA), administered by their Kiamichi Tree Farm (Broken Bow, OK), and ranged in planting year from 1992 to1994. Average 24-hour minimum temperature at the study area is −2.2° C (January) and average 24-hour maximum temperature (August) is 36.1° C with approximately 131 cm of annual precipitation (Oklahoma Climatological Survey 2013 [2001–2010 data]). Number of frost free days at the sites ranges from 190 to 230 days. Soil characteristics and water table depth at the locations were similar (Table 1).

Study Design and Measurements

The study was established as a split-plot design. Two replications of three stand-level treatments each (thinned-pruned = TP, only thinned = OT, nonthinned-nonpruned = NTNP) served as whole-plots and were established in late winter and early spring of 2008. Trees were planted at a spacing of 2.6 × 3.05 m (approximately 1,260 trees ha^{-1}). For the thinned plots, thinning was conducted operationally less than a year before study establishment and reduced tree density to approximately 310 trees ha^{-1}. Thinning method removed a row approximately every 12.5 m, smaller trees from the remaining rows, and the larger trees that did not have the potential to become sawtimber. Operational pruning was conducted using pole saws shortly after thinning and removed the lower branches to a height of 6.5 m.

Each site was divided into five split-plots (split-plot area ranging from 221 to 537 m^2, 28 to 68 trees per split-plot) for ice damage simulation. Each split-plot was randomly assigned to have 0, 25, 50, 75, or 100% of trees damaged. Prior to ice damage simulation (early 2008), trees were measured for height, dbh (1.4 m aboveground level), and crown height (base of live crown). Tree and crown heights were measured using a Haglöf Vertex IV Hypsometer with Transponder T3 (Haglöf, Längsele, Sweden) to the nearest 0.1 m. Diameter tapes were used to measure tree dbh to the nearest 0.1 cm. Trees within the split-plots were selected randomly for ice damage simulation. Selected individual trees had 4–52% of their live crown ratio removed by shooting the main stem multiple times with a rifle. Immediately after shooting, diameter at the break point and length

Table 2. Tree dimensions of undamaged (UND) and damaged (DAM) loblolly pine trees both before treatment and 4 years after ice damage simulation in southeastern Oklahoma.

		Dbh (cm)		Height (m)			Live crown ratio (LCR)		
	Tree condition	2008	2012	2008 Pretreatment	2008 Posttreatment	2012	2008 Pretreatment	2008 Posttreatment	2012
TP	UND	20.2 (0.4)	25.9 (0.4)	12.3 (0.1)	NA	14.6 (0.3)	0.52 (0.02)	NA	0.53 (0.01)
	DAM	20.3 (0.2)	25.9 (0.3)	12.5 (0.1)	10.3 (0.1)	14.2 (0.3)	0.53 (0.02)	0.42 (0.01)	0.50 (0.01)
OT	UND	19.4 (0.6)	26.0 (0.6)	11.7 (0.3)	NA	13.9 (0.2)	0.52 (0.01)	NA	0.43 (0.01)
	DAM	18.9 (0.3)	24.4 (0.3)	11.6 (0.2)	9.0 (0.2)	13.1 (0.2)	0.55 (0.01)	0.43 (0.004)	0.50 (0.01)
NTNP	UND	19.1 (0.5)	21.8 (0.5)	13.1 (0.3)	NA	16.5 (0.3)	0.52 (0.01)	NA	0.43 (0.01)
	DAM	18.7 (0.3)	20.6 (0.3)	13.1 (0.3)	10.7 (0.3)	15.4 (0.4)	0.53 (0.01)	0.42 (0.01)	0.46 (0.01)

Values in the parentheses indicate standard errors. Before the ice damage, loblolly pine stands were either thinned-pruned (TP), only thinned (OT), or nonthinned-nonpruned (NTNP).

of the broken section were recorded. Height, dbh, and crown height measurements were again taken after the fourth growing season following the ice damage simulation. Stem diameter was measured at 5.3 m height using Gator Eyes Laser Pointers (Haglöf, Inc., of Sweden) four growing seasons after simulated ice damage. Ice damage simulation and every measurement in the replacement site were done a year later than the other five for comparison at a common time since treatment.

Calculations and Analyses

To account for the initial tree sizes on the growth response, we calculated relative basal area growth (rBA_{growth}) of individual trees [(basal area after four growing seasons − basal area before ice damage simulation)/basal area before ice damage simulation]. We also calculated fraction of live crown ratio loss (LCR_{loss}; i.e., fraction of live crown reduction for the damaged trees). Tree taper was calculated as the ratio of diameter at 5.3 m height to dbh.

To test the effects of crown damage on stem growth, we conducted analysis of covariance (ANCOVA) that included the split-plot structure for the main effects of silvicultural treatment (whole-plot; $n = 2$) and the percentage of trees damaged (split-plot; $n = 6$). This allowed us to test the whole-plot and split-plot factors as well as their relationship to the covariate (slope differences among treatments). Our response variable was rBA_{growth}, and the covariate was LCR_{loss} (PROC GLM of SAS 9.2; SAS Institute, Inc. 2011). The means were separated using Fisher's protected least significant difference (LSD) test. We used 0.10 probability level of significance. We also determined the response of undamaged trees in relation to silvicultural treatment and the percentage of damaged trees using a split-plot analysis.

Results

At time of treatment, tree height averaged 12.4 m (standard error [*s.e.*] = 0.2 m) and tree dbh averaged 19.5 cm (*s.e.* = 0.2 cm). Live crown ratio (LCR) before treatment was 0.53 (*s.e.* = 0.01; Table 2). At time of treatment, height, dbh, and LCR were not statistically different among silvicultural treatments ($P > 0.13$) or percentage of trees damaged in split-plot treatments ($P > 0.34$).

On average, 2.4 m (*s.e.* = 0.1 m) of the crown was removed to simulate ice damage, with the absolute amount ranging from 0.5 to 6.8 m. This resulted in approximately 35% of the live crown length removed and a reduction in average live crown ratio from 0.53 to 0.42 (Table 2). Immediately after simulation, the damaged trees were approximately 18% shorter than the undamaged trees.

Table 3. ANCOVA summary table showing the effects of silvicultural treatments (ST, whole-plot) and percentage of trees damaged (PTD, split-plot) on the relative basal area growth of the damaged loblolly pine stands after 4 years in southeastern Oklahoma; fraction of live crown ratio (LCR_{loss}) was used as a covariate.

Source	DF	MS	*P* value
Silvicultural treatments (ST)	2	1.6220	0.09
Error I	3	0.2768	
Percentage of trees damaged (PTD)	3	0.0918	0.009
ST*PTD	6	0.0325	0.11
Error II	9	0.0124	
LCR_{loss}	1	0.3804	<0.0001
LCR_{loss}*ST	2	0.0101	0.63
LCR_{loss}*PTD	3	0.0627	0.05
LCR_{loss}*ST*PTD	6	0.0351	0.21

The analysis was done at $\alpha = 0.10$ level.

After 4 years of growth, undamaged trees averaged 14.9 m (*s.e.* = 0.2 m) in height and 24.6 cm (*s.e.* = 0.3 cm) in dbh (Table 2). The damaged trees were only 0.8 m shorter than the undamaged trees but the difference between damaged and undamaged trees was statistically significant ($P < 0.0001$). The damaged trees had a dbh of 23.9 cm (*s.e.* = 0.2 cm), which was significantly smaller than the undamaged ones ($P = 0.01$). Damaged trees recovered their crown size after 4 years of treatment such that both damaged (0.50, *s.e.* = 0.01) and undamaged trees (0.53, *s.e.* = 0.01) had similar live crown ratios ($P = 0.92$; Table 2).

Relative basal area growth of individual trees decreased with increased LCR_{loss} regardless of silvicultural treatment ($P < 0.0001$; Table 3). The relationship between rBA_{growth} and LCR_{loss} was shifted downward for trees in the NTNP stands compared to the OT and TP stands ($P = 0.09$; Figure 1), but the slopes did not differ among treatments ($P = 0.63$). When the relationship for each silvicultural treatment was examined separately, the equations were $rBA_{growth} = -0.48*LCR_{loss} + 0.328$, $r^2 = 0.20$ for the NTNP treatment; $rBA_{growth} = -0.48*LCR_{loss} + 0.795$, $r^2 = 0.05$ for the OT treatment; and $rBA_{growth} = -0.30*LCR_{loss} + 0.696$, $r^2 = 0.03$ for the TP treatment. Average rBA_{growth} over 4 years for the damaged trees in OT stands, TP stands, and NTNP stands were 0.68, 0.64, and 0.23, respectively.

Relative basal area growth differed among the split-plot treatments containing a different percentage of trees damaged ($P = 0.009$), with values of 0.55 (*s.e.* = 0.02), 0.53 (*s.e.* = 0.02), 0.52 (*s.e.* = 0.03), and 0.50 (*s.e.* = 0.02) for the 100, 75, 25, and 50% treatment plots, respectively. Split-plot treatments that had 100 and 75% of trees damaged had rBA_{growth} higher than the split-plot treatment with 50% damage, whereas growth in the split-plot treatment

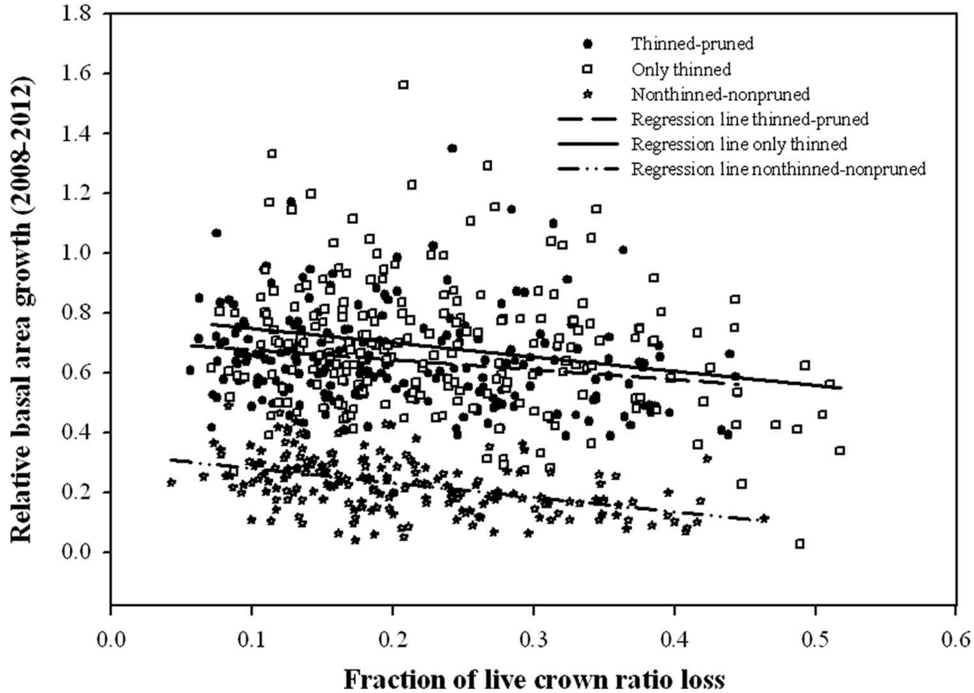

Figure 1. Relationship between relative basal area growth and fraction of live crown ratio loss in thinned-pruned (TP), only thinned (OT), and nonthinned-nonpruned stands (NTNP).

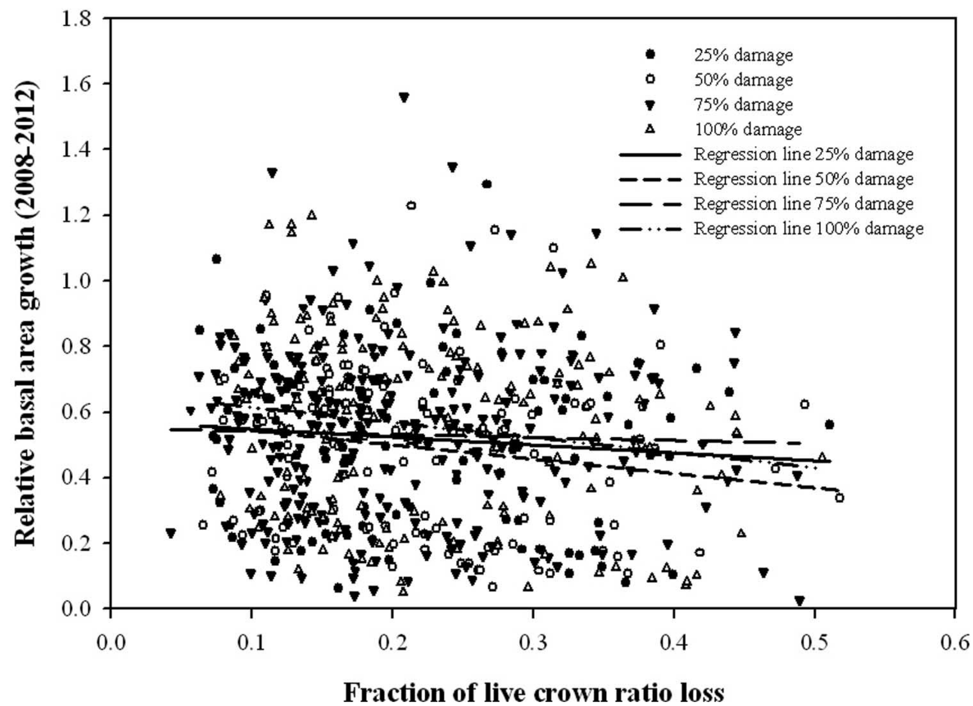

Figure 2. Relationship between relative basal area growth and fraction of live crown ratio loss in stands with 25, 50, 75, and 100% of trees damaged.

with 25% damage was similar to the others. However, the slopes of the relationship between rBA_{growth} and LCR_{loss} differed among the various split-plot treatments with a different percentage of trees damaged ($P = 0.05$; Figure 2). Equations were $rBA_{growth} = -0.42*LCR_{loss} + 0.645$, $r^2 = 0.02$ for the 100% of trees damaged treatment; $rBA_{growth} = -0.11*LCR_{loss} + 0.556$, not significant (*n.s.*) for the 75% of trees damaged treatment; $rBA_{growth} = -0.44*LCR_{loss} + 0.587$, r^2=0.03 for the 50% of trees damaged treatment; and $rBA_{growth} = -0.22*LCR_{loss} + 0.571$, *n.s.* for the 25% of trees damaged treatment.

When comparing rBA_{growth} among the undamaged trees, rBA_{growth} was similar for the OT stands (0.81, *s.e.* = 0.04) and TP stands (0.65, *s.e.* = 0.03) and lower in the NTNP (0.28, *s.e.* = 0.01) stands ($P = 0.01$). Relative basal area growth of the undamaged trees within the split-plots with 75, 50, 25, and 0% damage were 0.61 (*s.e.* = 0.10), 0.58 (*s.e.* = 0.10), 0.63 (*s.e.* = 0.12), and 0.54

($s.e. = 0.09$), respectively, with rBA_{growth} differing between the 0% and 25% treatments ($P = 0.06$). There was an interaction between the percentage of trees damaged and silvicultural treatment ($P = 0.07$) because the order of ranking for rBA_{growth} for the different percentage damage stands varied among silvicultural treatments. When each stand type (OT, TP, and NTNP) was analyzed separately, the effect of the percentage of trees damaged on rBA_{growth} was not significant ($P > 0.13$).

Tree taper of damaged trees was not affected by LCR_{loss} ($P = 0.34$). Tree taper of the stand types was similar ($P = 0.97$) among the TP (0.85), OT (0.84), and NTNP (0.80) treatments. Similarly, the percentage of trees damaged did not significantly affect taper of the damaged trees; taper in the 25% (0.85), 50% (0.83), 75% (0.83), and 100% (0.82) damage levels were similar ($P = 0.96$).

Discussion

Although an average of 2.4 m of the tops were removed at time of treatment, we found that the damaged trees had mostly recovered in height compared to the undamaged trees when measured 4 years later (0.8 m difference). Loblolly pine is a fast-growing species and top damage usually stimulates height recovery. Typically, at least one lateral branch bends upward to become the terminal leader (Belanger et al. 1996, Bragg et al. 2003, Aubrey et al. 2007). However, top damage can reduce wood quality and increase susceptibility of future damage at the point of stem breakage. Compared to height growth, which can accelerate to compensate for damage, dbh growth rate is reduced in damaged trees (Belanger et al. 1996). In our study too, the damaged trees had smaller dbh than the undamaged ones.

Less live crown means less leaf area and, thus, less carbon gain available for tree growth. In our study, we removed up to 52% of the live crown ratio from the top. This reduction in live crown ratio equates to approximately 66% reduction in live crown length; the reduction in live crown length was on average 27% greater than the calculated reduction in live crown ratio. In a eucalyptus pruning study by Pinkard (2003), trees started to exhibit stem growth reduction at 20% loss of leaf area. The upper part of the crown is the most productive, and its removal significantly reduces tree growth (Pinkard and Beadle 2000). Similar to our study, Belanger et al. (1996) reported basal area growth decreased with increased loss of live crown due to stem breakage.

When all factors were included in our analysis, i.e., silvicultural treatment and percentage of trees damaged as well as LCR_{loss}, the r^2 was 0.64, indicating the importance of accounting for silviculture practices when trying to predict stem growth. However, variables that we could not account for such as available growing space adjacent to individual trees and altered crown architecture may also influence the growth of the damaged trees (Smith 2000).

Although the slopes between rBA_{growth} and LCR_{loss} were not significantly different for the thinned and nonthinned stands, the trees in the nonthinned stands suffered a proportionately greater decrease in rBA_{growth} because the regression relationship for these stands had a lower intercept. For instance, using the average slope of the three relationships (-0.42) and an intercept of 0.33 for the NTNP and 0.75 for the thinned stands (average of OT and TP) (Figure 1), a 25% reduction in LCR reduces rBA_{growth} by 33% in the NTNP and 13% in the thinned stands. A 50% reduction in LCR reduces rBA_{growth} by 64% for NTNP and 28% in the thinned stands. Thus, depending on the extent of ice damage, immediate thinning of nonthinned stands should be considered to reduce the negative effects on dbh growth. Thinning also provides the opportunity to remove the most-damaged individuals.

Our study on the response to simulated ice damage in thinned and nonthinned plots indicates that prior thinning may influence the extent of ice damage incurred during storms. From a modeling study, Goodnow (2002) determined that smaller diameter loblolly pine trees, e.g., younger, lower site index, higher planting density, nonthinned, were more susceptible to ice damage. Therefore, thinning can be used to reduce the potential effects of ice damage by accelerating diameter growth of midrotation stands. However, stands exposed to an ice storm immediately after thinning experience more damage (Belanger et al. 1996, Zeide and Sharer 2002, Bragg et al. 2003). While recently thinned stands increase dbh growth, they also develop larger crown area and can accumulate large volumes of ice during storms, thus exposing individual trees to more ice damage (Belanger et al. 1996, Aubrey et al. 2007).

The relationship between live crown ratio removal and basal area growth varied among the stands with a different percentage of trees damaged. These differences, while statistically significant, were small and difficult to interpret. In addition, the size of response did not consistently increase nor decrease as the percentage of trees damaged increased. Because of these inconsistencies, we are unable to make any firm conclusions based on our data with regard to the split-plot treatments.

Growth of undamaged trees might accelerate as the proportion of damaged trees increases if competition for light decreases for the undamaged trees. However, the percentage of trees damaged in a stand did not affect the growth of the undamaged trees. This finding suggests that although the upper canopy of stands was more open following simulated ice damage, the undamaged trees had plenty of light regardless of the damage to adjacent trees. In particular, the thinning treatments (OT and TP) reduced competition for light such that the simulated ice damage probably did not have a large effect on light capture of undamaged trees.

Pruning of already thinned stands did not have a significant effect on the growth of damaged or undamaged trees. No effects were measured probably because very little live crown was removed during pruning. The live crowns of the trees in the only thinned stands began at approximately 5.5 m. Removing the less productive, lower live branches up to 6.5 m during pruning did not appear to have any large effect. As our study simulated ice storm damage, we could not measure the effects of pruning on ice damage during actual storms, which may shift the center of gravity upward and lead to more damage.

Thinning increases taper (Karlsson 2000). In contrast, pruning may result in more cylindrical trees because it reduces the crown length (Muhairwe et al. 1994). We did not find any effects of thinning, pruning, or crown loss on taper based on proportional change of diameters at the two fixed points. The relatively short 4-year period may not have been long enough for treatment effects to develop.

Conclusion

Understanding how loblolly pine responds to ice damage is important for the management of damaged stands. We conclude that after ice damage, midrotation stands should be assessed for crown loss because basal area growth after the damage is influenced by it. However, loss of a large proportion of live crown results in a relatively small decrease in basal area growth, especially in thinned stands, and tree height mostly recovers after a few years. Therefore, unless a majority of the crown is lost, it is probably best to allow the stand to continue to grow. If the stands have not yet been thinned, thinning can be used to remove the most-damaged trees. Even if it is necessary to leave some residual trees that are damaged, accelerated diameter growth due to thinning will minimize the effects of crown damage. Moderate crown loss does not affect stem form after 4 years of recovery.

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