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Responses of two genetically superior loblolly pine clonal ideotypes to a severe ice storm

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ABSTRACT

An increase in the frequency and magnitude of extreme weather events, such as major ice storms, can have severe impacts on southern forests. We investigated the damage inflicted by a severe ice storm that occurred in February 2014 on two loblolly pine (*Pinus taeda* L.) ideotypes in Cross, South Carolina located in the southeastern coastal plain. The "narrow crown" ideotype allocates more resources to stem growth while the "broad crown" ideotype allocates more of its resources to leaf area. We sampled each clone in August of 2014 and assessed damage based on four mutually exclusive damage categories: crown damage (visual estimation of percent damage); bent bole (bending shape and angle); snapped bole (distance from ground to snapped height); and uprooted. Damage category was statistically different between clones ($\chi^2 = 120.36; p = 0.001$); 67% of the individuals of the narrow crown ideotype suffered crown damage compared to 94% of the broad crown ideotype; 27% of the individuals of narrow crown ideotype suffered immediate mortality after the bole snapped, compared to only 3% for the broad crown. Of the individuals that incurred crown damage, the degree of damage sustained was statistically different by clonal type ($F = 8.73; p < 0.01$). The broad crown ideotype incurred greater crown damage than the narrow crown (38.0 ± 1.34 and 31.8 ± 1.6, respectively). Damage that resulted in a bent bole was minimal, with 4% for the narrow crown ideotype and 3% for the broad crown. The observed clonal differences in response to damage that incurred from an extreme ice storm may be attributed to differences in morphology and carbon allocation strategies between the two ideotypes. These differences are important to carbon sequestration projects and ideotype development in regions that are prone to extreme glazing events.

1. Introduction

Catastrophic natural disturbances can result in severe impacts to forest resources (Bragg et al., 2003) and carbon sequestration projects (Galik and Jackson, 2009). Because major disturbances can transfer live biomass to dead respiring pools and change the size distribution of forests to smaller diameters and lower biomass stocks (Chambers et al., 2007a), even small increases in the frequency and/or intensity could substantially diminish terrestrial carbon sinks (Chambers et al., 2004; Johnsen et al., 2014), resulting in positive feedbacks to climate warming (Reichstein et al., 2013). Therefore, catastrophic natural disturbances, such as ice storms, hurricanes and fire, pose the greatest challenge to carbon offset projects due to their inherent unpredictability and the potential scale that often characterize such disturbances (Galik and Jackson, 2009). For example, one study reported that a single ice storm was estimated to have damaged the equivalent of approximately 10% of the forest carbon sequestered annually in the US (Birdsey and Heath, 1995).

Ice storms are among the most frequent and injurious large-scale disturbances in temperate forests (Irland, 2000; Smith, 2000). Among the temperate forests in the world, the eastern US experiences the most frequent ice damage, with the highest freezing rain occurrence observed in the eastern portion of the Appalachian Mountains, from northeast Georgia to Virginia (Robbins and Cortinas, 1996). Although less frequent than the northeast, ice storms also impact the southeastern US (Changnon, 2003), where southern yellow pines are an important economic resource and form some of the most intensively managed and productive plantations in the world (Allen et al., 2005). Glaze damage to southern pine species due to sufficient ice accumulation may cause stem

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bending, breaking, or uprooting (Belanger et al., 1996; Warrillow and Mou, 1999), with the amount of damage attributed to a wide variety of factors including stand and tree conditions, soil characteristics, variation in ice formation, and wind speed. In addition to direct mortality, ice storm damage can increase forest susceptibility to insect and disease (Bragg et al., 2003).

Loblolly pine (*Pinus taeda* L.) is the most economically important tree species in the southeastern US (Zeide and Sharer, 2001). In the past 50 years, loblolly pine plantations have increased from approximately 0.7 to over 13 million hectares. At the same time, advances in silviculture and tree improvement increased yields from 104 to 414 m^3 ha^{-1} (Fox et al., 2007). In 2007, approximately $14 million was spent to breed and improve southern yellow pine species (McKeand et al., 2007). There is an inherently high risk to such large investments in tree improvement and breeding if the development does not include ways to mitigate the impact of natural disturbances on genotypes. As timber and regional carbon storage demands increase in the future, the use of genetically superior loblolly pine genotypes is expected to play an increasingly critical role in forest management (Fox et al., 2007; Johnsen et al., 2014). However, current breeding and tree improvement programs are focusing on creating genotypes capable of producing high timber yield and disease resistance by selecting certain physiological and morphological traits over others, which could have significant implications to disturbance response. Understanding how these selected traits differ in their response to catastrophic natural disturbances is important to forest management and carbon sequestration projects because widespread planting of a susceptible clone in disturbance prone areas could have severe consequences, and how these genetically superior genotypes will respond to disturbances such as ice storms has never been evaluated. Indeed, one of the greatest challenges for forest management and planning is to quantify the acceptable level of risk associated with establishing clonal plantations across the broader landscape (McKeand et al., 2006).

The ice storm that occurred on February 11–13, 2014 resulted in an estimated direct timber loss of approximately 607,000 forest hectares and an estimated 360 million dollar loss of timber value in South Carolina alone (South Carolina Forestry Commission, 2014). Among many of the forest stands affected was a long-term carbon sequestration research project conducted by the US Forest Service (Tyree et al., 2009, 2013; Maier et al., 2012, 2013). By taking advantage of this well-designed study and data measured prior to the ice storm, we investigated how loblolly pine clones of two distinct ideotypes responded to glazing from a severe ice storm. We hypothesized that each clone would respond differently to ice accumulation based on their differences in morphology and carbon allocation strategies. Specifically, we hypothesized that the clonal ideotype with greater branch and foliar biomass and greater leaf area (i.e., Clone 32) would suffer greater glaze damage.

2. Methods

2.1. Site description

This study utilized the Cross Carbon Study in the town of Cross, located in Berkeley County, SC (33°16_N, 80°10_W), which is 24 m above sea level (Tyree et al., 2009; Maier et al., 2012). The Cross Carbon Study was designed to examine differences in growth efficiency, carbon allocation, and storage for two contrasting clones of loblolly pine. The dominant soil series is a Seagate series (sandy over loamy, siliceous, active, thermic Typic Haplohumods) (US Department of Agriculture: Natural Resource Conservation Service, 2012) with moderate levels of organic matter (0.5–2%) and is devoid of rocks. The soils are somewhat poorly drained, and have a fluctuating water table that approaches the surface after harvest. The average January and July temperatures are 8 and 27 °C, respectively, with an average annual rainfall of 1358 mm.

2.2. Experimental design

The previous stand was a 21-year-old loblolly pine plantation. In May 2004, the stand was whole-tree harvested and chipped (Maier et al., 2012). Site preparation included shearing of residual material in July and bedding in November of 2004.

The original study design was a 2 × 2 factorial, randomized, complete block design with three replicates. The two factors were clone ideotype (93 or 32) and logging residue. The two levels of logging residue were no logging residue incorporated into the soil (*C* = control) and the incorporation of logging residue into the mineral soil at a rate of 25 Mg oven-dry weight/ha that was concentrated into the beds (LR). Each 0.18 ha (48 × 38 m) plot was planted with 243 container-grown seedlings in 9 rows at 1.8 m spacing within rows and 4.3 m between rows. Bedding and incorporation of logging residue was completed in November of 2004 and clones were planted in January of 2005. Two ArborGen® loblolly pine clones that exhibit superior height growth but represent two distinct ideotypes were selected for the original study. Clone 93 (ArborGen® varietal Clone AA93), or the "narrow crown" ideotype, allocates more of its resources to stem growth. Clone 32 (ArborGen® varietal Clone AA32), or the "broad crown" ideotype allocates more of its resources to leaf area (Tyree et al., 2009; Maier et al., 2013). The stands were nine years old in January 2014, one month prior to the ice storm. Both clones had similar stem biomass, but Clone 32 (broad crown ideotype) had 13% greater foliage and 15% greater biomass, while Clone 93 (narrow crown ideotype) had 14% greater coarse-root biomass (>2 mm) (Maier, unpublished data). By 2013, the crowns had been in canopy closure for several years, with maximum (September) and minimum (January) leaf area of 3.6 and 3.1 for Clone 93 and 2.5 and 2.1 for Clone 32, with little individual mortality (<4% of all individuals) prior to the storm.

Diameter at breast height (DBH) and tree height were measured using a diameter tape (to the nearest 0.1 cm) and a laser (to the nearest 0.1 m), respectively, in December 2013. We re-measured each tree in September of 2014 to determine the impact of the February 2014 ice storm on the two loblolly pine clones. To reduce the influence of any edge effects from ice damage, we established 20 × 30 m plots within the original design, leaving a 5-tree buffer on the row and 3-row buffer from the side. We measured DBH and assigned a damage class to each tree within the plot (Fig. 1). The damage categories included: Crown Damage (CD) as a visual estimate of percent damage (in 5% increments, up to 95%; if 95% or greater it was determined to be a snapped bole) to the live crown, Bent Bole (BB), Snapped Bole (SB), and Uprooted (UR). For the BB category we measured bending shape or degree of angle. Angle, or degree of bend, was determined by deriving angles a_1 [$a_1 = \cos^{-1}(X_1/H_2)$] and a_2 [$a_2 = a\cos(H_1^2 + C^2 - \text{hyp}^2)/(2 \times H_1 \times C^2)$] from the measured height to bend on the bole of the tree (H_1), height from ground to terminal (H_2), and distance from bole to terminal (X_1) (Fig. 2). The angle of bend is the deviation from 90° of a straight growing tree, with angles closer to 90° resulting in less bend in the main stem. The second angle (a_2) was used to determine the degree of departure from a straight bole and was compared between the two clonal ideotypes. For SB we measured height (m) to the snapped point, and measured tree height on UR individuals. A SB was only recorded if the entire live crown was removed (greater than 95% percent CD, with no remaining branches); otherwise it was considered percent CD with the terminal leader recorded as broken. Mortality was assumed for

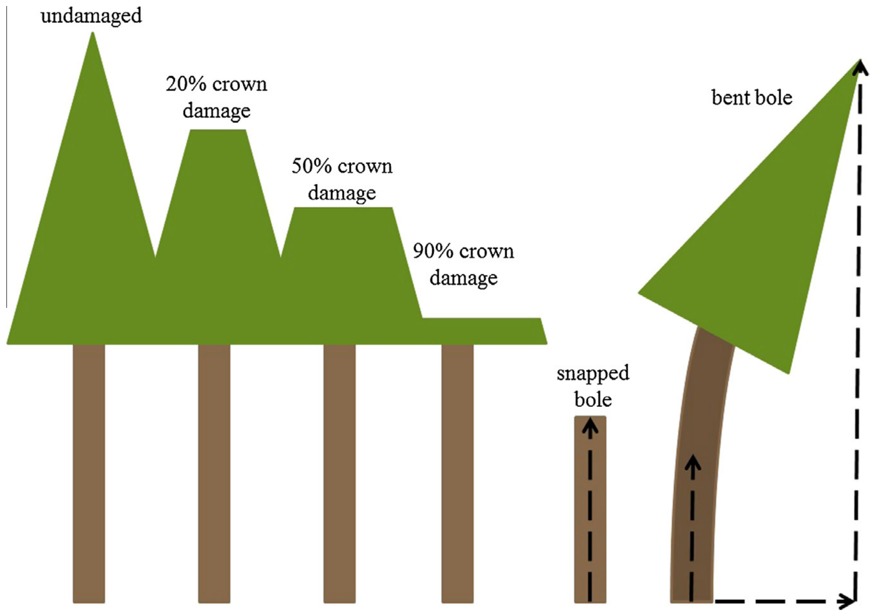

Fig. 1. Ice storm damage assessment categories. Percent crown damage (CD) was a visual estimation of the percent crown loss to the ice storm. Snapped bole (SB) was recorded when the snap occurred below the crown, removing 100% of the crown, with no remaining branches. Height (m) to the snap point was measured. Bent bole (BB) was recorded when the tree bent under the weight of the ice. Measurements were taken to determine bending shape and angle.

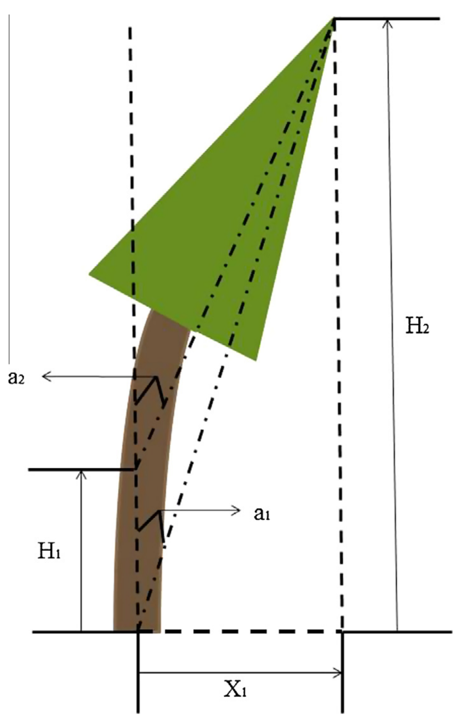

Fig. 2. Determining degree of bend in ice damaged clonal loblolly pines. Degree of bend was determined by deriving angles (a_1 and a_2) from the measured height to bend on the bole of the tree (H_1), height from ground to terminal (H_2), and distance from bole to terminal (X_1). Angle a_2 was used to determine the degree of departure from a straight growing tree (90°).

individuals resulting in 90% or greater crown loss, including all individuals where the bole was completely snapped.

2.3. Ice storm event

The Berkeley County area received approximately 6.35–25.4 mm of ice accumulation during a 48 h period, with the town of Cross, SC receiving 25.4 mm of ice, from two separate storms that impacted the region (Malsick, 2014; South Carolina Forestry Commission, 2014). The first storm came through the Northern Midlands and Pee Dee Regions of South Carolina on February 11th and the second more severe storm impacted the entire southeast the following day (NOAA, 2014). The coastal plain region of the southeastern US, on average, experiences 1–2 freezing rain or sleet events per year with increasing frequencies north and west (Gay and Davis, 1993).

2.4. Data analysis

Data was analyzed in SAS/STAT® 9.3.1 and JMP® 11 (SAS Institute Inc., Cary, NC). Data are reported as least squared means and standard error of the mean. Where appropriate, data have been transformed to meet the assumptions of hypothesis testing, but values are reported in original scale to ease interpretability. Any p-value less than an alpha of 0.05 was considered evidence of a significant result.

A chi-squared test was used to determine differences in mortality between the two clones. To determine differences between distributions of damage categories among clones, treatments, and diameter distributions, a categorical analysis was performed using PROC FREQ. Global differences and pair-wise comparisons were analyzed with chi-squared tests. Uprooted individuals were not included in the model comparing the distributions in damage categories due to low sample size (Clone 93 $n = 0$; Clone 32 $n = 4$). We designed statistical models using PROC GLM determine differences in DBH, height, height to diameter ratio, and percent crown damage between clonal types, treatments, and their interaction with blocking as a factor in the model. An ANOVA was used to develop F-statistics with follow-up pair-wise comparisons using Tukey's HSD to test the terms in each model. To determine the effects of crown damage on growth, we modeled growth (change in diameter from 2013 to 2014 measurements) with percent crown damage, clone (clone as a binary (0,1) variable: Clone 32 = 0; Clone 93 = 1), total tree height in 2013 (Ht), DBH in 2013 (DBH13), and whether or not the terminal was broken (TB as a binary (0,1) variable: 0 = terminal intact; 1 = terminal broken) as predictors in a multiple linear regression model using PROC REG using STEPWISE and Mallow's $C(p)$ for model selection. Model terms were included if significant, as defined by a p-value less than an alpha of 0.05. We also modeled height to diameter ratio for both clonal ideotypes and each clone separately using PROC REG. To improve fit in the model the response variable growth was log transformed. We used a non-linear exponential model to determine the correlation between DBH and snap height of Clone 93 using PROC NLIN.

3. Results

Of the 507 individuals of Clone 93 sampled, 19% had no or sustained less than 5% crown damage. Of the 509 sampled individuals of Clone 32, only 8% suffered no or less than 5% crown damage. Overall mortality was significantly different between clonal types ($\chi = 84.46$; $p < 0.001$). Mortality for Clone 93 was 32.6% for Clone 93 and 9.5% for Clone 32.

When comparing DBH between clones, there was an interaction between the clonal type and the residue treatment ($F = 6.4$; $p = 0.011$). LR increased DBH for Clone 93 ($F = 8.43$; $p = 0.004$) but not for Clone 32 ($F = 0.39$; $p = 0.53$). As a result, the DBH of Clone 93 in C (16.7 ± 0.1 cm) was smaller than that of Clone 93 in LR (17.3 ± 0.1 cm) while DBH was similar for Clone 32 in both C (17.5 ± 0.1 cm) and LR (17.3 ± 0.1 cm) ($F = 2.85$; $p = 0.09$). Similarly, there was an interaction between clonal type and treatment on height ($F = 21.75$; $p < 0.01$). Clone 93 had increased height growth (C = 17.2 ± 0.1 m; LR = 17.7 ± 0.1 m) while Clone 32 had decreased height growth (C = 16.8 ± 0.1 m; LR = 16.6 ± 0.1 m) from the addition of the logging residue. However, Clone 93 was consistently taller than Clone 32 prior to the ice storm ($F = 82.59$; $p < 0.01$), regardless of the logging residue treatments. The ratio between height and diameter was significantly different between the two clones ($F = 127.78$; $p < 0.001$). Clone 93 had a higher average height to diameter ratio (103.9 ± 0.4) than Clone 32 (96.9 ± 0.4). There was no effect of treatment ($F = 2.09$; $p = 0.15$), or treatment by clone interaction for determining height to diameter ratio ($F = 2.09$; $p = 0.15$).

3.1. Damage by category

Overall, for the individuals that sustained damage, the damage type (SB, BB, and CD) was statistically different between the two clones ($\chi^2 = 120.36$; $p < 0.01$). For Clone 32, 94% ($n = 476$) of the damage was crown damage, with only 3% of the damage resulting in a bent bole ($n = 14$) and 3% in a snapped bole ($n = 14$). For clone 93, 67% ($n = 337$) of the damage was crown damage, 27% of the damage resulted in a snapped bole ($n = 135$), and 4% of the damage resulting in a bent bole ($n = 21$). Pair-wise comparisons between the two clonal types indicate damage that resulted in a snapped bole ($\chi^2 = 95.37$; $p < 0.01$), or crown damage was statistically different ($\chi^2 = 23.77$; $p < 0.01$), but the damage that resulted in a bent bole was not statistically significant ($\chi^2 = 1.4$; $p = 0.24$).

Damage by treatment between clones was similar to overall damage without treatment as a factor (Fig. 3). Within the Control treatment, damage was statistically different by clonal type ($\chi^2 = 83.48$; $p < 0.01$) Clone 32 had 95% crown damage, 4% bent bole damage, and 1% snapped bole damage. Clone 93 had 64% crown damage, 5% bent bole damage, and 31% snapped bole damage. Within the LR treatment, damage was statistically different by clonal type ($\chi^2 = 40.73$; $p < 0.01$). Clone 32 had 94% crown damage, 2% bent bole, and 4% snapped bole damage. Clone 93 had 73% crown damage, 4% bent bole, and 23% snapped bole damage. There was no clone by treatment interaction for type of damage incurred ($\chi^2 = 8.19$; $p = 0.08$).

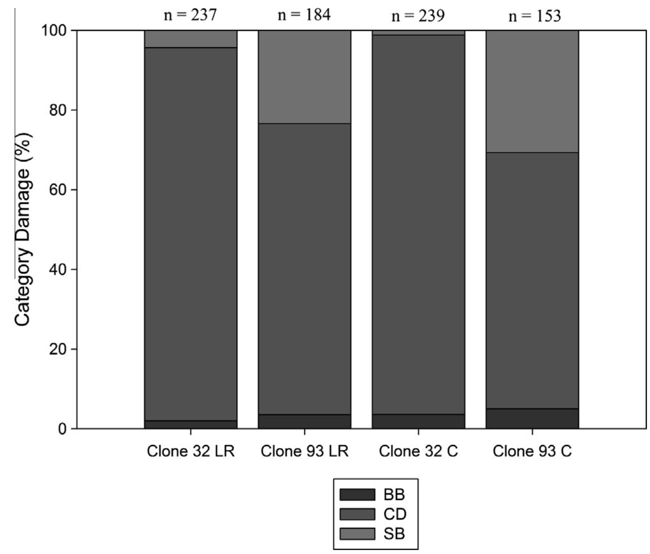

Fig. 3. Percent damage category (BB = bent bole; CD = crown damage; SB = snapped bole) by clone (Clone 32 = "broad crown"; Clone 93 = "narrow crown") and treatment type (C = control; LR = logging residue).

3.2. Crown damage

The full factorial model was significant ($F = 3.35$; $p = 0.0053$) with the main effects of clone ($F = 8.73$; $p = 0.0032$) and treatment ($F = 4.6$; $p = 0.0323$) as significant terms in the model. The effect of block and the interaction of clone by treatment were non-significant in the model. Clone 93 suffered significantly less percent crown damage than Clone 32 (31.78 ± 1.6% and 38.0 ± 1.34% respectively). The LR treatment had significantly greater percent crown damage than the control treatment (37.1 ± 1.4% and 32.5 ± 1.5% respectively). For the individuals that sustained crown damage, the incremental growth from December 2013 to September 2014 was affected by the percent crown damage sustained by the clone ideotype, the stem size (DBH and height) prior to the storm measured in December 2013, and whether or not the terminal was broken. The full model explained 49% of the variability in growth ($F = 154.02$; $C(p) = 6.0$; MSE = 0.040; $p < 0.001$).

$$\begin{aligned}\ln \text{Growth} = {} & 0.16754 - 0.00482(\text{CD}) - 0.006618(\text{clone}) \\ & + 0.01279(\text{DBH13}) + 0.00021128(\text{Ht}) \\ & - 0.10980(\text{TB})\end{aligned}$$

However, percent crown damage alone explained approximately 45% of the variation in growth over the period ($F = 657.22$; $C(p) = 61.92$; MSE = 0.042; $p < 0.001$) (Fig. 4).

3.3. Bent Bole

There was no statistical difference between angle of bend and clonal ideotype ($F = 2.57$; $p = 0.12$), although Clone 32 did have a greater degree of bend (67.37° ± 2.48), than Clone 93 (72.52° ± 2.03). Similarly, there was no statistical difference in degree of bend and treatment type ($F = 0.02$; $p = 0.89$). The majority of individuals that bent for both clonal types occurred between 12 and 18 cm DBH and were also significantly different by size class for each clone ($\chi^2 = 13.1$, $p = 0.017$; Fig. 5).

3.4. Snapped Bole

The snap point in relation to DBH for Clone 93 was determined using an exponential model (Fig. 6). As DBH increases, height of

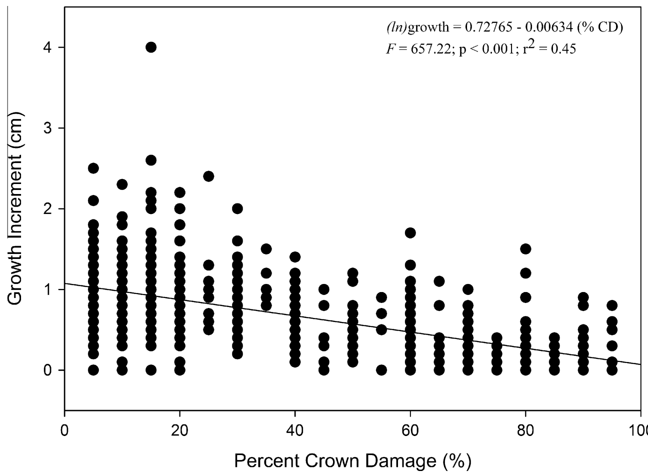

Fig. 4. Relationship between percent crown damage and growth (cm) between measurement periods (December 2013 and September 2014).

snapped point increases at an exponential rate ($F = 17611.6$; $p < 0.01$). The height of snap was determined as: $H = \exp(0.2892 * \text{DBH})$. There was not enough data to estimate a relationship between DBH and snap height of Clone 32. The diameter range for snapped bole was similar to that of the range for bent bole, but occurred at even larger diameters (12–22 cm; Fig. 7).

The height to diameter ratio was nearly significant in determining the snapping point height when considering both clonal ideotypes ($F = 3.67$; $p = 0.057$), however, this only accounted for 2% ($R^2 = 0.02$) of the variability in snap height. When modeled separately, height to diameter ratio was non-significant in determining snapping point for Clone 32 ($F = 0.88$; $p = 0.37$), however, it was significant for determining the snapping point for Clone 93 ($F = 9.33$; $p < 0.01$). As the height to diameter ratio increased, the point at which the bole snapped decreased ($\text{SBH} = 10.0289 - 0.047665 * \text{ht:diam}$), but the height to diameter ratio only explained 7% ($R^2 = 0.07$) of the variability in snap height.

4. Discussion

In southern pines, lethal damage can occur when most of the live crown is lost or the tree is severely bent or uprooted (Bragg et al., 2003). In addition to environmental conditions such as the

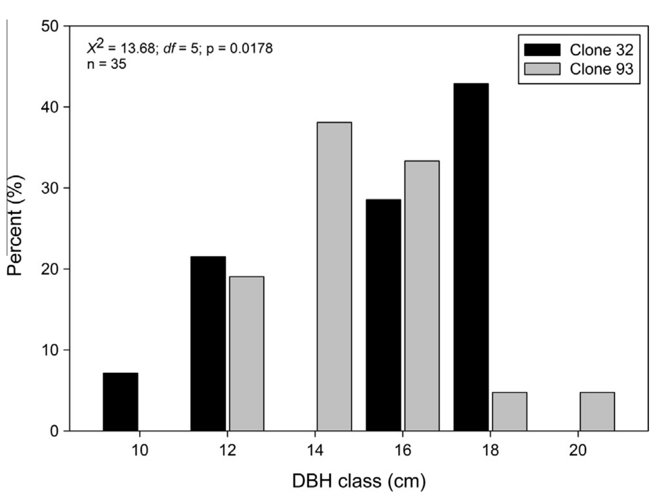

Fig. 5. Diameter class distribution for the percent bent bole (BB) by DBH class by clone (Clone 32 = "broad crown"; Clone 93 = "narrow crown").

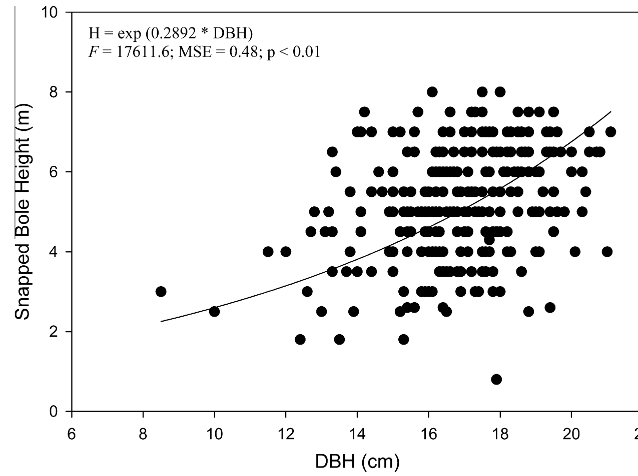

Fig. 6. Relationship between DBH (cm) and the height of snap point (m) for Clone 93 ("narrow crown" ideotype).

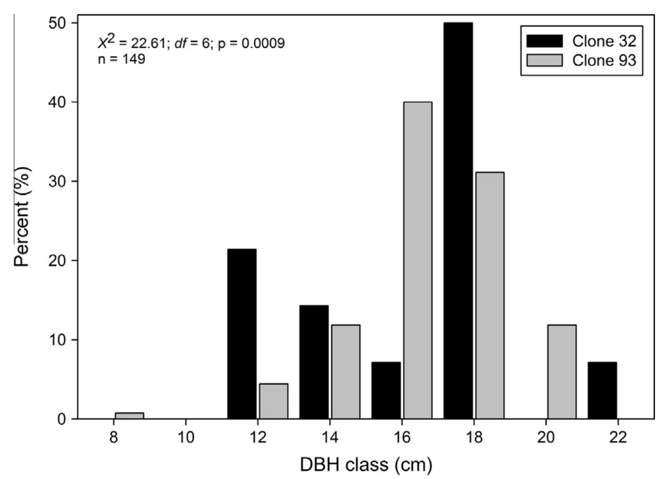

Fig. 7. Diameter class distribution for the percent snapped bole (SB) by DBH class by clone (Clone 32 = "broad crown"; Clone 93 = "narrow crown").

amount of ice accumulation, length of ice persistence, soil conditions, and wind presence and speed, the susceptibility of a tree to ice damage depends on the individual tree and species characteristics including: tree size, wood strength, elasticity, growth form, and surface area (Croxton, 1939; Carvell et al., 1957; Bruederle and Stearns, 1985; Hauer et al., 1993). In our study, ice damage incurred varied between the two clones. The proportion of individuals damaged was similar for each clone; however, the type of damage differed significantly, which supports the importance of individual tree and ideotype characteristics. The differences in carbon allocation strategies between these two distinct loblolly ideotypes may have contributed to the observed differences in ice damage.

4.1. Morphological differences and ice storm response

The development of specific clonal ideotypes based on crown architecture or structure is important to the individual tree's ability to capture light and the performance of the stand due to competition (Martin et al., 2005). Clonal type 32 is characterized as an "isolation ideotype" that competes aggressively with neighboring trees by developing a wide spreading crown with a rapid growth rate that accelerates crown closure and reduces the period where vegetation management is necessary (Cannell, 1978). In contrast, Clonal ideotype 93 is characterized as a "crop ideotype" with more compact crowns and smaller branches that allow for efficient light interception without a high degree of competition with neighboring trees (Cannell, 1978). This ideotype is considered to be highly efficient and desirable for high density pulpwood and high quality saw timber production (Martin et al., 2005).

In our study, the two clonal types differed in the type of damage they sustained. Clone 32 had 94% of the damage it sustained in the form of crown damage, while Clone 93 had only 67% of the damage it sustained in the form of crown damage. The significantly greater crown damage in Clone 32, when compared to Clone 93, may be attributed to its greater allocation of carbon to foliage production, which results in larger surface area and more ice accumulation occurring on small branches. At 8 years old, Clone 32 had 14% more foliar biomass and 18% more branch biomass than Clone 93 (Maier et al., 2013). As ice accumulates on branches, many small branches would break (breaking point), resulting in crown damage. In contrast, Clone 93 allocates more carbon to height growth along a smaller stem diameter (i.e., larger height to diameter ratio) which may result in greater ice accumulation along the fewer but larger branches and the main stem resulting in the overall weight to cause the stem to snap (breaking point) instead of individual branches breaking.

The goal for the development and establishment of loblolly pine clones is to increase productivity through rapid growth. However, fast growing plantations, such as clonal loblolly pine plantations, may have a large portion of juvenile wood (Bettinger et al., 2009). Juvenile wood generally has lower specific gravity, shorter fiber length, and higher levels of moisture and lignin (Megraw, 1985). The specific gravity of young loblolly pines was found to be 25% less in the crown than it was near the base of the tree (Lenhart et al., 1977). Clone 93 was taller and had a smaller diameter than Clone 32 prior to the ice storm. A large proportion of juvenile wood coupled with a higher height to diameter ratio observed in Clone 93 is likely the cause of the stem snapping during the severe ice storm, which is indirectly supported by the significant relationship between height and diameter and height of snap for Clone 93. The larger diameter and shorter stature of Clone 32 may have reduced bole snapping, even with similar proportions of juvenile wood.

Trees that are not killed immediately, may have reduced growth or die after subsequent growing seasons. For those trees that suffer damage from ice storms, the growth of individual trees following ice storm damage is strongly dependent on the total crown loss (Belanger et al., 1996). In an 18–20 year old loblolly pine plantation, 28% of those critically injured (greater than 70% crown loss) died within the first growing season following a severe ice storm, while only 2% of less damaged individuals died (Bragg et al., 2002). In our study, growth significantly decreased with increased crown damage for both ideotypes, and when the crown sustained 55% damage, growth was reduced by half (Fig. 4). About 10% ($n = 82$) of Clone 93 and 13% ($n = 101$) of Clone 32 sustained damage of 70% or more to the live crown. If the crown is unable to recover, the growth of individuals with a high degree of crown damage may be severely reduced to the extent that they are no longer economically viable and subsequently should be considered for removal from the stand. Long-term monitoring would be needed to observe the ultimate fate of those injured trees in terms of their recovery or eventual mortality.

Ice damage to loblolly pine has been correlated to tree diameter. Shepard (1975) reported that individuals with smaller diameters were more likely to bend or be uprooted than individuals with larger diameters, which were more susceptible to snapping. Previous studies have reported that stem breakage of loblolly pines is most susceptible when DBH is between 12 and 25 cm (Downs, 1943; Wiley and Zeide, 1991; Amateis and Burkhart, 1996; Belanger et al., 1996; Zeide and Sharer, 2001; Bragg et al., 2003, 2004), and stem breakage below the live crown is fatal to southern pines (Abel, 1948). Our results were in general agreement with these previous findings, with the diameter range for snapped bole occurring at larger diameters (12–22 cm) than bent bole.

Because our field sampling occurred six months after the ice storm, the number of trees that bent might have been underestimated in our data as trees that suffered only minor bending have likely recovered. Aubrey et al. (2007) reported that after 28 weeks since ice storm damage occurred, 83.3 ± 6.3% of bent trees of loblolly pine returned to vertical. In our study, the individuals that bent during the ice storm but recovered afterwards could have also sustained internal damage, which is not reported in our results.

While we only found that a small number of individuals were uprooted, and that such a small sample size has prevented further statistical analysis, it is worth noting that the contribution of greater allocation to fine and coarse roots in Clone 93 ($n = 0$) may have aided in reduced uprooting compared to Clone 32 ($n = 4$). Clone 93 partitioned more biomass to roots than Clone 32, with 16 % more coarse root biomass and approximately 21% greater fine root biomass at age 8 (Maier et al., 2013). The implication of rooting characteristics to ice damage was also found in previous studies. For example, it was suggested that the shallow root system of Virginia pine (*Pinus virginiana* Mill.) might have contributed to the observed uprooting in an ice storm when compared to other pine species (Warrillow and Mou, 1999). Therefore, root development and belowground biomass allocation may warrant further investigation for the development of clonal ideotypes in response to disturbance events.

4.2. Management implications

Southern pine plantations are likely to play an increasingly critical role in meeting regional carbon storage demands (Johnsen et al., 2014). If future climate change results in more intense weather events leading to more extreme disturbances (IPCC, 2007), live tree forest carbon stocks may decline while dead wood decomposition following mortality may increase, potentially resulting in a positive feedback loop that could further elevate atmospheric CO_2 levels (Chambers et al., 2007b). For example, Hurricane Katrina damaged approximately 320 million large diameter trees (>10 cm DBH) resulting in a loss of 105 Tg of C, which is equivalent to 50–140% of the net annual U.S. carbon sink from forest trees (Chambers et al., 2007b). Although ice storms are inherently variable with a lack of known probability and occurrence (Goodnow et al., 2008), management with the use of clonal loblolly stock should consider ideotype traits and silvicultural options that may reduce risk over the rotation, especially in areas prone to severe ice storms.

The use of clonal loblolly pine in plantation forestry is projected to increase along with using mixed product stands to achieve multiple management objectives throughout the rotation. Often the potential gains for managing stands to mitigate ice damage are smaller than the potential losses when storms fail to materialize (Goodnow et al., 2008). However, management considerations could be made that mitigate damage risk while also considering other resource objectives. The increased interest in growing multiple end products on the same hectare (e.g., FlexStand™ ArborGen Inc., Ridgeville, SC) may have the potential to offset damage incurred from ice storms, especially if stands are intermixed with less susceptible species (e.g., shortleaf, *Pinus echinata* Mill.). However, it has also been suggested that mixing vulnerable and resistant species (e.g., slash pine, *P. elliottii* Englem., with loblolly or shortleaf) may increase losses when more susceptible trees fall into otherwise resistant trees (Abel, 1948). Further studies are, therefore, needed.

5. Conclusion

The two studied loblolly pine clones responded differently to an extreme ice storm. The broad crown ideotype (Clone 32) had much less mortality due to snapped bole and much more crown damage than the narrow crown ideotype (Clone 93). For those trees that suffered crown damage, the % crown loss for Clone 32 was also higher than Clone 93. These different responses may be attributed to the differences in morphology and carbon allocation strategies between the two ideotypes.

When managed for carbon sequestration or timber production, the broad crown ideotype may provide reduced risk in ice prone areas over the rotation. The broad crown ideotype may sustain greater amounts of crown damage, but its main stem is less likely to snap, causing immediate mortality, when compared to the narrow crown ideotype. Land managers should consider the susceptibility of different ideotypes to extreme weather events or other disturbances when establishing a plantation.

Given more intensively selected, less genetically diverse clones are likely to established, and the increased uncertainty and environmental instability from global climate change could result in greater exposure of forest trees to disturbance events, the development of clonal ideotypes should consider their resistance not only to biological stressors such as pests and disease, but also to weather related disturbance events such as ice storms.

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