FATE OF RESIDUAL CANOPY TREES FOLLOWING HARVESTING TO UNDERPLANT LONGLEAF PINE SEEDLINGS IN LOBLOLLY PINE STANDS IN GEORGIA

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Abstract—Over the past few decades, reports of forest health problems have concerned scientists and forest managers in loblolly pine forests of the southeastern United States. Several interacting factors likely contribute to observed reductions in loblolly pine health, including low resource availability on many upland sites that were once dominated by longleaf pine. Currently, land managers are interested in converting such sites back to longleaf pine, while maintaining ecosystems services that are now provided by loblolly pine. Recent research suggests that underplanting longleaf pine in loblolly pine stands may be a viable solution for stand conversion, but it is not clear how such treatments affect the longevity or condition of residual canopy trees. In this study, we compared the effects of three levels of uniformly-distributed stand density (uncut Control, ~16 m^2/ha basal area; MedBA, ~9 m^2/ha basal area; LowBA, ~6 m^2/ha basal area) and three gap sizes (LG, radius of 40 m; MG, radius of 30 m; and SG, radius of 20 m) on the survival, growth, and canopy condition of residual trees through five years after harvest. Survival was not significantly affected by treatment ($p = 0.5899$), with an average of 96.8 percent survival. Tree growth during the study period was significantly greater on the LowBA plots than on the Control plots. By the end of the study period, LowBA plots had greater live crown ratios and less crown dieback than Control plots. Our results suggest that harvesting loblolly pine trees for underplanting longleaf pine does not accelerate pine decline in the short-term but does have the potential for growth release of residual trees.

INTRODUCTION

Longleaf pine (*Pinus palustris* Mill.) historically dominated the southeastern United States, occurring on site types that included xeric sandhills, coastal plain flatwoods, and mountainous portions of Georgia and Alabama (Peet 2006). Frequent surface fire regimes were common to longleaf pine ecosystems and maintained longleaf pine dominance throughout its range. In contrast, loblolly pine (*P. taeda* L.) was more commonly restricted to wetter sites that experienced relatively infrequent fire (Schultz 1999). Following widespread logging in the 1800s and early 1900s and fire exclusion policies of the early to mid-1900s, upland sites that had once supported longleaf pine were commonly reforested with loblolly pine through natural or artificial regeneration (Schultz 1999). As these stands developed through time, largely in the absence of fire, their resulting structure, composition, and function were notably different from frequently burned longleaf pine ecosystems. With current interest in the conservation value and ecosystem services provided by longleaf pine ecosystems, land managers throughout the southeast are interested in restoring longleaf pine to loblolly pine stands on upland sites.

Although longleaf pine seedlings are conventionally considered intolerant of competition (Boyer 1990), recent publications have discussed benefits of using a gradual approach to convert slash pine (*P. elliottii* Engelm.) (Kirkman and others 2007) and loblolly pine stands (Hu and others 2012, Knapp and others 2013) to longleaf pine by reducing canopy densities and underplanting longleaf pine seedlings. Retaining canopy pines during the restoration process may be desirable for several reasons. First, canopy pines reduce the rate of growth of hardwood seedlings and saplings that are commonly abundant on sites requiring restoration (Jack and others 2006, Kirkman and others 2007, Knapp and others 2014). In addition, needlefall from canopy pines provides an important source of fine fuel for frequent fire management (Mitchell and others 2009). Finally, the existing pines may be providing important wildlife habitat. This is the case at Fort Benning in Georgia and Alabama, where populations of the federally-endangered red cockaded woodpecker (*Picoides*

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borealis; RCW) currently utilize loblolly pine trees for nesting and foraging habitat as longleaf pine restoration occurs throughout the landscape (Fort Benning 2014).

Interest in converting loblolly pine stands to longleaf pine is heightened on sites believed to be susceptible to pine decline, a condition in which loblolly pines have a rapid reduction in growth followed by mortality (Ryu and others 2013). Reports of pine decline have been documented since the 1960s, with symptoms including short, chlorotic needles, sparse crowns, fine root deterioration, and reduced radial growth (Eckhardt and Menard 2008, Eckhardt and others 2010). Pine decline has been associated with the presence of insect and fungal species, including bark beetles (*Hylastes* spp.) and species of *Leptographium* fungi (Otrosina and others 1999, Eckhardt and others 2007). In addition, pine decline has been associated with low-quality sites that generally result in increased resource stress on trees and may be better suited for longleaf pine than loblolly pine (Eckhardt and Menard 2008, Eckhardt and others 2010, Ryu and others 2013). Given that pine decline appears to be incited by a complex of interacting stressors, it is possible that forest management practices that improve stand vigor, such as thinning in overstocked stands, may reduce susceptibility to decline (Eckhardt and others 2010).

The relatively xeric, upland sites commonly targeted for conversion from loblolly pine to longleaf pine are also likely to be the most susceptible to loblolly pine decline due to resource stress. The objectives related to a gradual conversion to longleaf pine on such sites may be compromised by unexpected mortality of residual canopy trees, especially if loblolly pine canopy trees are retained for other ecosystem services during restoration. The goal of this study was to evaluate the short-term effects of alternative harvesting treatments, used in conjunction with underplanting longleaf pine seedlings, on residual loblolly pine trees. Specifically, we quantified changes in 1) canopy health metrics; 2) survival; and 3) growth through five years following the harvesting treatments.

METHODS

This study was conducted at Fort Benning Military Installation in Muscogee and Chattahoochee Counties, GA and Russell County, AL (~32.38 °N, 84.88 °W). Fort Benning occupies approximately 74,000 ha, of which 30,000 ha are classified as pine forest. Longleaf pine is currently present on approximately 20,000 ha, and longleaf pine restoration is a primary objective of forest management on upland sites (Fort Benning 2014). The northern two-thirds of Fort Benning is classified as Sand Hills and the southern one-third is classified as Upper Loam Hills (Baily 1995). Upland soils in the area are generally low in organic matter and nutrient holding capacity, although the Upper Loam Hills region has higher silt and clay content than the coarse-textured, sandy soils of the Sand Hills.

The study used a randomized, complete block design, with each block located in a different loblolly pine stand on upland sites at Fort Benning. Each of five blocks were divided into seven experimental units that were 100 m × 100 m (1 ha), and experimental units were randomly assigned one of seven overstory harvesting treatments. Three treatments resulted in approximately uniform distribution of the residual canopy, including Control (uncut; residual basal area ~ 16 m^2/ha), MedBA (residual basal area of 9 m^2/ha), and LowBA (residual basal area of 6 m^2/ha). Harvesting focused on removing smaller trees or trees of poor form. Three treatments used group-selection to create canopy gaps of three sizes, including LG (large gap; radius of 40 m and total area of approximately 5027 m^2), MG (medium gap; radius of 30 m and total area of approximately 2827 m^2), and SG (small gap; radius of 20 m and total area of approximately 1257 m^2). An additional clearcut treatment was used in the experiment but is not relevant to this study because all canopy trees were removed. Harvesting was completed by December 2007, and container-grown longleaf pine seedlings were planted throughout the study area at 1.8 m × 3.7 m spacing in January 2008.

Immediately following harvesting in 2007, residual overstory trees (diameter at breast height (dbh) ≥ 10 cm) were each identified with an aluminum tag, and the species and dbh (cm) were recorded for each tree. In plots with uniformly distributed trees (Control, MedBA, and LowBA), all trees within each plot were measured. In group-selection plots (LG, MG, and SG), all trees within 20 m from the edge of the canopy gap were measured. The condition of each tree crown was assessed in July 2008 and again in July 2012 following protocol developed for the USDA Forest Service Forest Health Monitoring Program (Schomaker and others 2007). In this study, we report on the “uncompacted live crown ratio”, measured as the ratio of live crown length to aboveground tree length (reported as percent of total tree length), “crown dieback”, measured as the proportion of the crown that has experienced recent dieback from the upper and outer edges (reported as percent of crown area), and “crown density”, measured as the amount of crown stem, branches, twigs, shoots, buds, foliage, and reproductive structures that block light penetration through the crown (reported as percent of crown area) (Schomaker and others 2007). In addition, we measured the crown diameter across the drip-line of each tree along two axes, the first of which was the widest crown diameter and the second being its perpendicular axis. In July 2012, the dbh of each tree was recorded, and the cause of death was noted for any tree that had died during the study period.

The data were summarized at the plot-level to determine effects of harvesting treatment on crown condition, survival, and growth. We used mixed-model Analysis of Variance (ANOVA) with a random block effect to determine treatment effects on uncompacted live crown ratio, crown dieback, and crown density in 2008 and in 2012. Using trees remaining alive in 2012, we calculated the difference from 2008 to 2012 for each variable and similarly tested for treatment effects on the change during the study period. Mixed-model ANOVA was used to test treatment effects on survival percentage from 2007 to 2012 and on dbh in 2007, 2012, and the change in dbh from 2007 to 2012. For each model with a significant treatment effect, pair-wise comparisons among treatments were made using Tukey's HSD test. To determine if crown condition or tree size were indicators of future mortality, each tree was classified as alive or dead based on status in 2012. Because of the low sample size for dead trees, we grouped trees across all treatments, and we tested for differences in crown condition metrics and dbh in 2007 between the two groups. Finally we used simple linear regression to determine relationships between dbh growth (change in dbh from 2007 to 2012) and crown condition metrics. We determined statistical significance when $p \leq 0.05$ for all analyses.

RESULTS

The harvesting treatments significantly reduced the basal area of the LowBA plots relative to all other treatments, resulting in approximately 6.4 m^2/ha basal area (table 1). The MedBA plots had significantly lower basal areas than the Control and all gap plots. The Control plots and the residual trees surrounding the group openings in LG, MG, and SG did not differ in basal area following harvest. The number of trees per hectare followed similar patterns among the treatments, with higher variability. There was no difference in the size (dbh) of the residual canopy trees following harvesting treatments (table 1).

During the first measurement period following harvest (2008 for the crown condition variables and 2007 for dbh), there were no significant differences in live crown ratio, crown dieback, crown density, or dbh (table 2). In 2012, there were significant treatment effects on live crown ratio and crown dieback. Live crown ratio was significantly greater on LowBA plots than on Control plots, and crown dieback was significantly lower on MedBA and LowBA plots than on Control plots. There were no effects of harvesting treatment on the stand-level averages of dbh or the crown densities of residual trees in 2012 (table 2). The response of live crown ratio, measured as change from 2008 to 2012, was significantly greater on LowBA, MG, and SG plots when compared to Control plots (fig. 1A). Changes in crown dieback (fig. 1B) and crown density (fig. 1C) were not affected by treatment and were highly variable within the treatments. The change in dbh from 2007 to 2012 was significantly greater on LowBA plots than on Control or MG plots (fig. 1D). Change in dbh was significantly related to the change in crown diameter from 2008 to 2012 and to live crown ratio in 2008 (fig. 2).

Survival of residual trees from 2007 through 2012 was high (mean = 96.8 percent) and did not significantly differ among treatments (table 2). The cause of mortality was not evident for the majority of the 59 trees that had died during the study period, although 20 percent of the dead trees had snapped boles by 2012. Three of the dead trees (5.1 percent) had apparent lightning strikes. The live crown ratios and crown densities from 2007 were significantly lower for trees that had died by 2012 than for trees that remained alive (table 3). Likewise, crown dieback from 2007 was significantly greater for trees that had died by 2012. There was no difference in the dbh from 2007 for trees that were alive vs dead in 2012 (table 3).

Table 1—Means and standard errors of stand structure attributes in 2007 (following initial harvest), including basal area (m^2/ha), trees per hectare, and dbh (cm). The p-values indicate significance from the global ANOVA test, and the same superscript letter within a column indicates no significant difference from pair-wise comparisons

	Basal area (m^2/ha)		Trees per hectare		DBH (cm)	
Treatment	Mean	SE	Mean	SE	Mean	SE
Control	17.5^A	1.2	293.4^A	68.7	30.7	3.0
MedBA	9.4^B	0.4	136.5^{BC}	23.4	31.2	2.8
LowBA	6.4^C	0.5	94.5^C	20.1	31.0	2.6
LG	16.5^A	0.9	269.9^A	31.3	30.8	2.1
MG	16.2^A	1.0	232.8^A	29.6	31.7	2.0
SG	15.0^A	1.1	203.7^{AB}	28.1	32.3	2.7
p-value	< 0.0001		0.0005		0.9779	

Table 2—Mean and standard errors of crown condition variables (live crown ratio, crown dieback, crown density) in 2008 and 2012, diameter at breast height in 2007 and 2012, and percent survival from 2007 through 2012. The p-values indicate significance from the global ANOVA test, and the same superscript letter within a row indicates no significant difference from pair-wise comparisons

	Control		MedBA		LowBA		LG		MG		SG		
Response variable	Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE	p-value
Live crown ratio (%)													
2008	36.2	1.4	38.6	0.8	38.2	1.4	37.1	1.0	36.0	1.3	37.3	0.6	0.4989
2012	37.0^{B}	1.5	40.7^{AB}	0.8	42.4^{A}	1.1	39.1^{AB}	0.9	39.6^{AB}	1.3	40.6^{AB}	1.1	0.0473
Crown dieback (%)													
2008	10.9	0.7	9.2	0.9	9.8	1.3	10.5	1.7	12.0	0.5	11.2	0.7	0.4287
2012	8.9^{A}	0.6	7.0^{B}	0.5	7.0^{B}	0.2	7.6^{AB}	0.5	7.4^{AB}	0.6	7.5^{AB}	0.3	0.0213
Crown density (%)													
2008	46.4	1.8	47.4	2.3	48.6	1.6	47.6	1.5	50.0	2.1	48.5	1.4	0.2989
2012	44.6	2.4	44.0	2.6	47.8	1.1	43.7	1.8	44.2	2.3	43.5	3.1	0.5502
DBH (cm)													
2007	30.7	3.0	31.2	2.8	31.0	2.6	30.8	2.1	31.7	2.0	32.3	2.7	0.9779
2012	32.7	3.3	34.7	2.7	34.2	2.7	33.1	2.3	33.5	2.1	35.0	2.7	0.9224
Survival													
2007 - 2012 (%)	99.0	0.7	95.5	2.1	96.6	1.0	97.0	1.2	97.5	1.2	95.2	2.8	0.5899

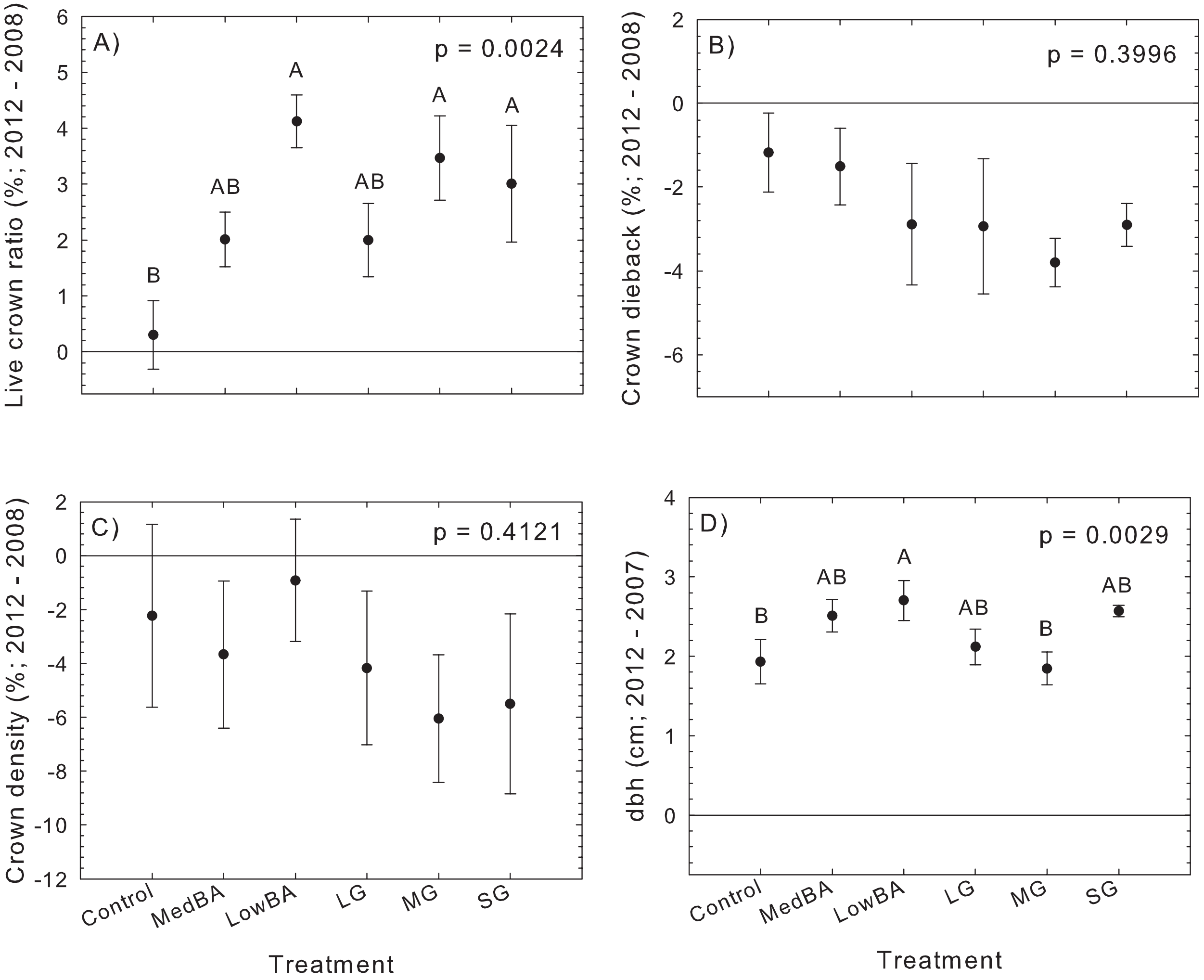

Figure 1—Means and standard errors by treatment for the change from 2008 to 2012 for A) live crown ratio (%), B) crown dieback (%), C) crown density (%), and D) change from 2007 to 2012 for diameter at breast height (dbh; cm). Within each panel, the p-values indicate significance from the global ANOVA test, and the same letter indicates no significant difference from pair-wise comparisons.

DISCUSSION

Unpredictable forest health may complicate efforts to integrate canopy retention into regeneration or restoration practices. Prescriptions for gradually converting stands of loblolly pine to longleaf pine have suggested target ranges of residual stand density intended to provide a balance between the desirable (e.g., reducing growth rates of hardwood regeneration) and undesirable (e.g., reducing growth rates of underplanted longleaf pine seedlings) effects on restoration targets (Knapp and others 2013, Knapp and others 2014). Although observations of pine decline have raised concerns about the longevity of loblolly pine forests at Fort Benning (Ryu and others 2013), we found little evidence of mortality from declining pine health in our study. The five-year mortality rate based on all trees sampled in this study was 4.8 percent, with wind damage (i.e., snapped boles) accounting for 20 percent of the mortality. In natural longleaf pine forests of the Gulf Coastal Plain region, lightning has been reported to cause greater mortality than wind damage (Platt and others 1988, Palik and Pederson 1996). Outcalt (2008) reported that lightning killed 1 tree/8 ha/year in longleaf pine forests in South Carolina, which was similar to the rate of lightning mortality observed in this study. It is possible that the higher incidence of wind snap in our study was related to the canopy reduction by harvesting, although no clear patterns between treatment and wind snap emerged in our study.

The crown condition metrics used in this study have been used to assess pine decline at Fort Benning (Menard 2007, Ryu and others 2013) and in central Alabama (Eckhardt and others 2007), and we found few indications of poor health. Live crown ratios greater than 30 percent generally indicate that crown size is

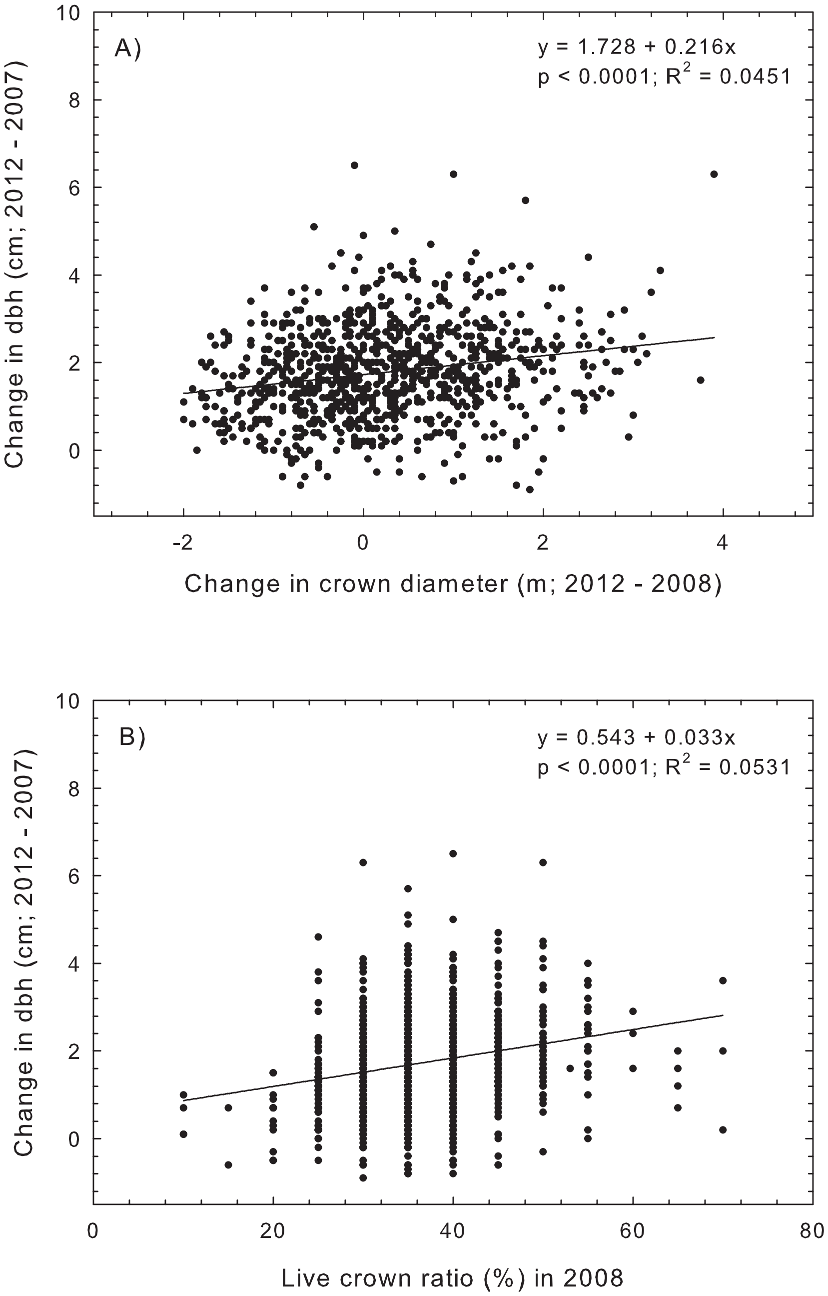

Figure 2—Scatterplots and linear regressions between diameter growth (change in dbh from 2007 to 2012) and A) change in crown diameter from 2008 to 2012 and B) the live crown ratio (%) in 2008.

Table 3—Means and standard errors of crown condition (live crown ratio, crown dieback, and crown density) and dbh at the initial measurement period for trees that were alive in 2012 and trees that were dead in 2012. All trees sampled were alive at the initial measurement period. The p-values indicate significant differences in the initial condition between live and dead trees in 2012 for each respective variable

	Status of tree in 2012				
	Live (n = 1163)		Dead (n = 59)		
Variable	Mean	SE	Mean	SE	p-value
Live crown ratio (%)	37.18	0.23	33.41	1.33	0.0031
Crown dieback (%)	10.80	0.24	21.36	3.09	< 0.0001
Crown density (%)	47.65	0.26	40.65	1.82	< 0.0001
Diameter at breast height (cm)	31.35	0.29	30.62	1.52	0.7891

not limiting to tree growth (Smith and others 1997), suggesting that stand densities prior to the harvesting treatments were not restricting crown development. Alexander and Palmer (1999) reported crown dieback values of around 5 percent from a series of loblolly pine plots in the southeastern United States but discuss that trees are not considered unhealthy if dieback is < 20 percent. The crown density values reported in our study are similar to values reported in a region-wide description of loblolly pine crown condition from Forest Inventory and Analysis plots measured in the late 1990s (Randolph 2006). Moreover, Menard (2007) reported crown density values similar to those found on our sites for loblolly pine trees that were asymptomatic for pine decline but crown densities from 35 to 40 percent for symptomatic pines at Fort Benning. Despite finding few indicators of poor tree health, the trees that died within our study period exhibited lower vigor at the first measurement period following harvest when compared to the trees that lived. In particular, crown dieback of trees that died averaged around 20 percent, providing support for the threshold discussed by Alexander and Palmer (1999), and crown density was closer to 40 percent, as found by Menard (2007).

Our results indicate that the harvesting stimulated a growth response from the residual trees, observed through the positive change of live crown ratio and dbh on the LowBA treatment. Trees generally respond to increased resource availability by increasing foliar production and crown size, resulting in the eventual allocation of carbon to diameter growth (Oliver and Larson 1996). This pattern was further supported in our data by the positive relationships between diameter growth response following harvesting and the change in crown size and the initial live crown ratio, although these relationships were weak. Our results also suggest that reducing canopy density resulted in increased tree vigor, with increased live crown ratio and reduced crown dieback on LowBA plots. In a region-wide analysis, Klos and others (2009) also found that stand density was negatively related to growth but positively related to mortality of pines. Given the relatively short response period of this study (five years), it is not clear if the magnitude of growth/vigor responses will become greater through time. However, loblolly pine stands with lower density are likely more resistant to stressors like drought (Klos and others 2009) and southern pine beetle (Belanger and others 1993).

CONCLUSION

There were few indications of forest health problems associated with pine decline on these study sites. However, this study did not cover a full range of site and stand conditions on which loblolly pine decline has been described, and it is not clear if similar results would occur on sites with higher tree stress or if pine decline was present initially. The associations of the crown condition metrics with tree mortality in this study support their utility in assessing tree vigor in loblolly pine forests. Treatments that reduced canopy density resulted in apparent increases in diameter growth and tree vigor, supporting previous reports that reducing stand density can likewise reduce risk of pine decline (Eckhardt and others 2010). Our results suggest that recommendations for reducing stand density to underplant longleaf pine seedlings during conversion of loblolly pine stands are compatible with improving the vigor of residual trees.

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