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Silvicultural treatments for converting loblolly pine to longleaf pine dominance: Effects on planted longleaf pine seedlings

Huifeng Hu [a], G. Geoff Wang [a,*], Joan L. Walke [b], Benjamin O. Knapp [a]

[a] School of Agricultural, Forest and Environmental Sciences, Clemson University, 261 Lehotsky Hall, Clemson, SC 29634-0317, United States
[b] USDA Forest Service, Southern Research Station, Clemson University, 233 Lehotsky Hall, Clemson, SC 29634-0317, United States

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ABSTRACT

A field study was installed to test silvicultural treatments for establishing longleaf pine (*Pinus palustris* Mill.) in loblolly pine (*P. taeda* L.) stands. Harvesting was used to create seven canopy treatments, four with uniformly distributed canopies at different residual basal areas [Control (16.2 m^2/ha), MedBA (9.0 m^2/ha), LowBA (6.4 m^2/ha), and Clearcut (0 m^2/ha)] and three circular gaps defined by area [LG (~5281 m^2), MG (~3217 m^2), and SG (~1576 m^2)]. Within each canopy treatment, we applied three cultural treatments designed to benefit planted seedling early growth: no treatment (NT), herbicide (H), and herbicide plus fertilization (H + F). Three growing seasons after planting, seedling survival significantly differed among canopy treatments; compared to Controls, Clearcut plots had higher survival (80.6%). H and H + F treatments did not affect seedling survival in the first two years after application. Canopy removal generally increased seedling root collar diameter (RCD) but interacted with cultural treatments. NT within Controls had the smallest RCD, and H + F within Clearcuts had the largest RCD. Canopy treatments significantly affected the percentage of seedlings in height growth (i.e., terminal bud >15 cm high); Control plots had a significantly lower percentage of seedlings in height growth than other canopy treatments. H and H + F treatments also significantly increased the percentage of seedlings in height growth when compared to NT. Our results indicate that canopy removal improves early establishment of longleaf pine seedlings and that herbicides may additionally be used to increase early longleaf pine seedling growth. Our results are similar to those reported in previous studies conducted in mature longleaf pine stands.

1. Introduction

Throughout the southeastern United States, logging, land-use changes, and fire exclusion and suppression have resulted in the replacement of historically dominant longleaf pine (*Pinus palustris* Mill.) with faster growing, less fire-tolerant species, especially loblolly pine (*Pinus taeda* L.) (Frost, 2006). Because longleaf pine forests are among the most biologically diverse ecosystems in North America and serve as habitat for numerous federally protected threatened and endangered species [e.g., red-cockaded woodpeckers (RCW; *Picoides borealis*), gopher tortoise (*Gopherus polyphemus*)], much emphasis has recently been placed on restoring longleaf pine to its native range (U.S. Fish and Wildlife Service, 2003; Jose et al., 2006).

A necessary condition for longleaf pine ecosystem restoration is the establishment and development of a longleaf pine canopy. Longleaf pine establishment could be accomplished by clearcutting existing canopy trees and planting longleaf pine seedlings; however, overstory retention is increasingly used in forests traditionally managed for even-aged structure (Palik et al., 2003). It is believed that the residual stand structure associated with canopy retention better resembles the complex structure of forests after natural disturbances and therefore helps to maintain biodiversity and to perpetuate ecosystem functions dependent on that structure (Hansen et al., 1995; Franklin et al., 1997; Seymour and Hunter, 1999; Schliemann and Bockheim, 2011). In longleaf pine ecosystems, canopy retention helps to control hardwood encroachment and provides needlefall for fuels, both of which contribute to a fuel matrix that supports the characteristic frequent, low-intensity surface fire regime (Palik et al., 2002; Mitchell et al., 2006; Pecot et al., 2007). As such, underplanting longleaf pine beneath an overstory of other pine species can maintain ecological function throughout the development of the longleaf pine regeneration (Kirkman et al., 2007). Furthermore, because the widespread loss of longleaf pine forests has resulted in existing RCW populations using loblolly pine stands for nesting and foraging habitat, clearcutting is often not desirable in stands currently supporting RCWs (U.S. Fish and Wildlife Service, 2003).

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* Corresponding author. Tel.: +864 656 4864; fax: +864 656 3304.
E-mail address: gwang@clemson.edu (G.G. Wang).

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The uneven-aged structure of naturally regenerated longleaf pine stands and the results of recent studies that examined the response of naturally and artificially established longleaf pine seedlings in canopy gaps (Palik et al., 1997, 2003; Brockway and Outcalt, 1998; McGuire et al., 2001; Gagnon et al., 2003; Rodríguez-Trejo et al., 2003) suggest that longleaf pine could be restored with partial canopy retention, although the survival and growth of longleaf pine regeneration would be affected by competition from residual trees. Palik et al. (1997) reported that as little as 6 m^2/ha of overstory basal area reduced biomass of planted longleaf pine seedlings by up to 50% when compared to clearcut conditions on a coastal plain site in southwestern Georgia. The relationship between seedling size and basal area follows that of a general exponential decay curve (Palik et al., 1997, 2002). In addition, the spatial distribution of overstory retention influences the growth of planted longleaf pine seedlings. Palik et al. (2003) compared the effects of different canopy distributions that resulted in similar stand-level basal areas on longleaf pine regeneration and reported that seedling biomass was the largest with large-aggregate retention. However, no studies have explored the effects of loblolly pine canopy density or spatial distribution on underplanted longleaf pine seedlings. Longleaf pines have deeper taproots than loblolly pines, and differences in rooting habits may affect the competitive interactions between ovestory loblolly pines and planted longleaf pine seedlings (Baker and Langdon, 1990; Boyer, 1990). It is not clear if relationships between canopy pines and longleaf pine seedlings differ between loblolly and longleaf pine forests.

Additional management actions can be used to improve growing conditions for planted longleaf pine seedlings by reducing competition from understory vegetation and increasing the availability of resources (Haywood, 2000, 2005, 2007; Harrington et al., 2003; Ramsey and Jose, 2004; Jose et al., 2010). Haywood (2000) found that applying herbicide or mulches significantly increased seedling height growth and shortened the time longleaf pine seedlings were in the grass stage. Jose et al. (2010) reported that imazapyr (0.21 ai kg/ha) significantly increased longleaf pine seedling growth with a reduction in the abundance of shrub species. The low nutrient status of many sites that are well-suited for longleaf pine suggests that fertilization may be an option for improving site conditions. Previous studies have found that fertilization alone or in combination with vegetation control may increase the growth of longleaf seedlings (Gagnon et al., 2003) or have no effect (Ramsey et al., 2003; Haywood, 2007).

Recent longleaf pine regeneration studies have been conducted primarily in clearcuts (e.g., Haywood, 2000) or in mature longleaf pine stands (e.g., Palik et al., 1997). Protocols for restoring longleaf pine in loblolly pine stands while retaining a loblolly pine canopy are not available. The objective of our study was to determine the effects of selected silvicultural treatments on survival and growth of longleaf pine seedlings planted in mature loblolly pine stands on moderately well- to well-drained sites at Camp Lejeune, North Carolina. Specifically, we examined the effects of seven canopy and three cultural treatments on survival and growth of planted longleaf pine seedlings during the first three growing seasons after planting.

2. Methods and materials

2.1. Study site

This study was conducted at the United States Marine Corps Base Camp Lejeune, in Onslow County, NC (~34.68°N, 77.33°W). The study area is located within the Atlantic Coastal Flatlands Section of the Outer Coastal Plains Mixed Forest Province (Bailey, 1995) and falls within the White Oak watershed in Onslow County as defined by the North Carolina Department of Water Quality (USMCB Camp Lejeune, 2006). The climate is classified as warm humid temperate with hot, humid summers and mild winters. Mean annual temperature is 16 °C and annual precipitation averages 1420 mm, which is evenly distributed throughout the year, with a slight increase from June to September (National Climatic Data Center, Asheville, NC). Our study sites are on moderately well- to well-drained soils with low to moderately available water holding capacity and low nutrient holding capacity (Barnhill, 1992). Soil series in the study sites include the Baymeade-Urban land complex (loamy, siliceous, thermic Arenic Hapludults), Goldsboro fine sandy loam (fine-loamy, siliceous, thermic Aquic Paleudults), Marvyn loamy fine sand (fine-loamy, kaolinitic, thermic Typic Kanhapludults), Muckalee loam (coarse-loamy siliceous, thermic Typic Fluvaquents), Norfolk loamy fine sand (fine-loamy kaolinitic, thermic Typic Kandiudults), Onslow loamy fine sand (fine-loamy, siliceous, thermic Spodic Paleudults), and Wando fine sand (thermic coasted Typic Quartzipsamments) (Soil Survey Staff NRCS, 2011).

2.2. Experimental design

The study design was a randomized complete block split-plot, with location (loblolly pine stand) as the blocking factor. Each block consisted of seven main treatment plots to which a canopy treatment was randomly assigned. Seven canopy treatments included four treatments with uniformly distributed canopies at different residual basal areas and three circular gap treatments defined by area: Control (uncut, mean residual basal area of 16.2 m^2/ha), MedBA (single-tree selection to mean residual basal area of 9.0 m^2/ha), LowBA (single-tree selection to mean residual basal area of 6.4 m^2/ha), Clearcut (complete canopy removal), LG (group selection to create a circular canopy gap with mean radius of 41.0 m and size of 5281 m^2), MG (group selection to create a circular canopy gap with mean radius of 32.0 m and size of 3217 m^2), and SG (group selection to create a circular canopy gap with mean radius of 22.4 m and size of 1576 m^2). Treatment plots were 100 × 100 m (1 ha) with the exception of Clearcut (141 × 141 m; 2 ha) and LG (120 × 120 m; 1.4 ha). We selected seven mature loblolly stands as replicated blocks. Four blocks (Blocks 1–4) were located in 35 year-old loblolly pine plantations established on sites that were targeted for longleaf pine restoration by land managers, and the mean DBH (diameter at breast height) of Blocks 1–4 ranged from 25.5 to 34.0 cm. The remaining blocks (Blocks 5–7) were located in 60 year-old loblolly pine stands with large trees distributed at irregular spacing, and the mean DBH of Blocks 5–7 ranged from 38.5 to 45.5 cm. Base forestry personnel marked the timber for harvest using thinning from below to favor large, vigorous trees, and in gap plots all trees within the respective radius distance from gap center were harvested. Harvesting was completed in all blocks between February and May 2007. We measured residual basal area (BA) following harvest and found that the LowBA and MedBA treatments in two blocks (Blocks 3 and 4) were cut to similar residual BA levels, so both were considered to be the same canopy treatment (LowBA). We were unable to apply the LG treatment to one of the blocks (Block 5) due to spatial constraints. In addition, we abandoned one plot (LowBA in Block 4) in 2010 due to conflicts with military training. As a result, we used data from seven blocks and 47 canopy treatment plots for the study. Texture and nutrient content of soils are described in Table 1.

Prior to planting longleaf pine seedlings, the study sites were mechanically prepared by mowing all standing sub-canopy vegetation with a Fecon Bull Hog® rotary mower in the late summer of 2007 and by prescribed burning in fall 2007. Container-grown longleaf pine seedlings were planted by hand in December 2007

Table 1
Texture and nutrient content of soils for each block used in the study.

Block	1	2	3	4	5	6	7
BD ($g\ cm^{-3}$)	0.95	1.22	1.22	1.27	1.18	1.21	1.29
pH	4.9	4.7	4.8	4.5	4.4	4.4	4.7
CEC	9.2	13.0	8.7	11.9	9.8	11.0	7.3
OM (%)	1.4	1.4	1.5	1.6	1.0	0.7	0.8
TC (%)	1.21	1.48	1.46	1.56	1.36	0.98	0.93
TN (%)	0.05	0.04	0.05	0.05	0.04	0.04	0.04
P ($\mu g\ g^{-1}$)	6.0	5.1	4.9	5.3	11.1	28.3	18.8
K ($\mu g\ g^{-1}$)	53.9	48.9	53.8	46.9	41.9	39.1	45.8
Sand (%)	75.2	71.2	63.5	67.7	90.8	92.4	91.6
Silt (%)	19.0	22.0	30.1	26.5	5.4	3.5	3.9
Clay (%)	5.8	6.8	6.4	5.8	3.8	4.1	4.5
Soil type	NoB	NoB; MaC	NoB; MaC	On; NoB	WaB; Mk	BmB	BmB; GoA

Notes: BD: Bulk density; CEC: Cation exchange capacity; OM: Organic matter; TC: Total carbon; TN: Total nitrogen; P: Phosphorus; K: Potassium; NoB: Norfolk loamy fine sand; MaC: Marvyn loamy fine sand; On: Onslow loamy fine sand; WaB: Wando fine sand; Mk: Muckalee loam; BmB: Baymeade-Urban land complex; GoA: Goldsboro fine sandy loam.

at a spacing of 1.8 × 3.0 m (approximate 1800 seedlings/ha). Three months after planting (March 2008), 10 longleaf pine seedlings were randomly selected from each plot and root collar diameter (RCD) was measured. Initial RCD averaged 8.7 mm with a standard deviation of 0.6 mm.

Each uniform canopy treatment plot was divided into four equal sections and three of the sections were randomly selected for cultural treatment application. Within each section, cultural treatments were applied to a 30 × 30 m area centered on a 20 × 20 m subplot measurement area. Within each gap treatment plot, cultural treatments were applied directly to three selected rows of planted longleaf pine seedlings. Three cultural treatments included: NT (control with no cultural treatment applied), H (direct spray of 1% imazapyr with 1/4% non-ionic surfactant to target woody vegetation in October, 2008), and H + F (the H treatment plus broadcast 10-10-10 NPK fertilizer at a rate of 280 kg/ha in early May, 2009). Prescribed fires were applied to all experimental plots between January and March in 2010.

2.3. Data collection

In the beginning of the 2008 growing season, we randomly selected and marked 30 seedlings per uniform subplot, for a total of 90 seedlings in each uniform main plot. In each gap plot, we marked all longleaf pine seedlings within the gap from three selected rows and recorded the distance of each marked seedling to the row center, which resulted in about 44 seedlings per row in LG, 33 seedlings per row in MG, and 22 seedlings per row in SG. Survival of each seedling was monitored and growth of each seedling was measured at the end of each growing season (late September to early October of 2008–2010). Root collar diameter (RCD) was measured to the nearest millimeter using digital calipers. The distance from the root collar to the terminal bud was measured, and seedlings were considered to be in height growth (i.e., emerged from the grass stage) when >15 cm tall (Knapp et al., 2006).

2.4. Data analysis

One-way analysis of variance (ANOVA) (2008 data) and split-plot ANOVA (2009 and 2010 data) were used to quantify the effects of canopy and cultural treatments on survival and RCD at the end of each growing season. After each growing season, the number of seedlings in height growth per subplot (or per row in gaps) was calculated as a percentage of the living seedlings measured. Split-plot ANOVA was used to determine the effects of canopy and cultural treatments on the percentage of seedlings in height growth at the end of the 2009 and 2010 growing seasons.

The survival data were arcsine-transformed, the RCD data were transformed using natural logarithms, and the height growth data were log-transformed to improve normality (Krebs, 1999). All analyses were performed using SAS9.1 (SAS Institute, 2004) with mixed-models fit using PROC MIXED. In the case of a significant interaction between main-plot and split-plot effects, we used the SLICE statement to determine significant effects of one treatment (i.e., canopy or cultural) within each level of the other. Tukey's honestly significant difference (HSD) test was used to determine differences in pairwise comparisons among the canopy and cultural treatments for each variable. The level of statistical significance was set as $\alpha = 0.05$.

3. Results

3.1. Seedling survival

Survival of planted longleaf pine seedlings was significantly affected by canopy treatment at the end of each growing season (Fig. 1). At the end of the 2008 growing season, the Clearcut treatment resulted in greater survival than MG and SG ($p \leqslant 0.026$). At the end of the 2009 growing season, survival in the Clearcut plots was still greater than that in MG and SG ($p \leqslant 0.008$); in addition,

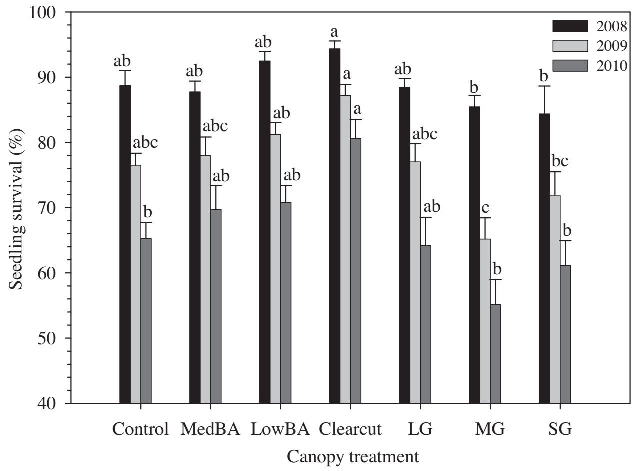

Fig. 1. Survival (Mean + 1SE) of planted longleaf pine seedlings by canopy treatment at the end of the 2008, 2009 and 2010 growing seasons. Means with the same letter in the same year indicate no significant difference ($\alpha = 0.05$).

LowBA plots had greater survival than MG plots ($p = 0.011$). At the end of the 2010 growing season, the Clearcut treatment resulted in the highest survival rate (80.6%), which was significantly greater than the Control, MG and SG treatments ($p \leqslant 0.037$).

No interactions were detected for seedling survival between the canopy and cultural treatments at the end of either the 2009 ($p = 0.835$) or the 2010 ($p = 0.545$) growing season. There were no differences in survival among the three cultural treatments in 2009 ($p = 0.220$) or in 2010 ($p = 0.116$) and mean survival rates across all cultural treatments were 76.7% and 66.7% at the end of the 2009 and 2010 growing seasons, respectively.

3.2. Root collar diameter growth

Seedling RCDs significantly differed among canopy and cultural treatments at the end of each growing season. At the end of the 2008 growing season, the Clearcut and LowBA treatments resulted in similar RCDs and both were greater than RCDs in SG and Control treatments ($p \leqslant 0.026$). At the end of the 2009 growing season, seedlings in Control plots had significantly smaller RCDs than those in Clearcut plots ($p = 0.005$). In addition, no interaction was detected between the canopy and cultural treatments ($p = 0.830$). Among the three cultural treatments, seedlings in H and H + F subplots had larger RCDs than those in NT ($p \leqslant 0.001$; Fig. 2). At the end of the 2010 growing season, there was an interaction effect between the canopy and cultural treatments ($p = 0.037$; Table 2). No significant differences among the three cultural treatments were detected for RCD in Control, LG, MG, or Clearcut treatments. In MedBA and SG plots, H and H + F subplots had larger RCDs than NT subplots. In LowBA plots, H subplots resulted in the largest RCDs and H + F subplots had larger RCDs than NT subplots. Within the NT cultural treatment, the Clearcut plots had larger RCDs than the SG and Control plots and the LG plots had larger RCDs than the Control plots. Within the H cultural treatment, the Clearcut and LowBA plots had larger RCDs than the Control plots, and within the H + F cultural treatment, the Control plots had significantly smaller RCDs than other canopy treatments (Table 2).

Table 2
Root collar diameter (RCD; mm) stratified by canopy and cultural treatments at the end of the 2010 growing season. Means are followed by standard errors in parentheses. Means with the same lowercase letter in each column indicate no significant difference ($\alpha = 0.05$). Means with the same capital letter in each row indicate no significant difference ($\alpha = 0.05$).

Treatment	NT	H	H + F
Control	15.8 A c (0.5)	17.8 A b (0.9)	17.0 A b (0.7)
MedBA	18.6 B abc (1.2)	21.9 A ab (1.5)	23.4 A a (1.2)
LowBA	18.8 C abc (1.0)	25.0 A a (2.7)	21.6 B a (0.6)
Clearcut	22.6 A a (1.4)	25.3 A a (2.1)	25.5 A a (2.1)
LG	20.3 A ab (0.7)	21.4 A ab (1.2)	23.0 A a (1.4)
MG	19.9 A abc (0.9)	21.4 A ab (1.0)	22.5 A a (1.1)
SG	17.7 B bc (1.7)	20.4 A ab (1.5)	22.5 A a (1.8)

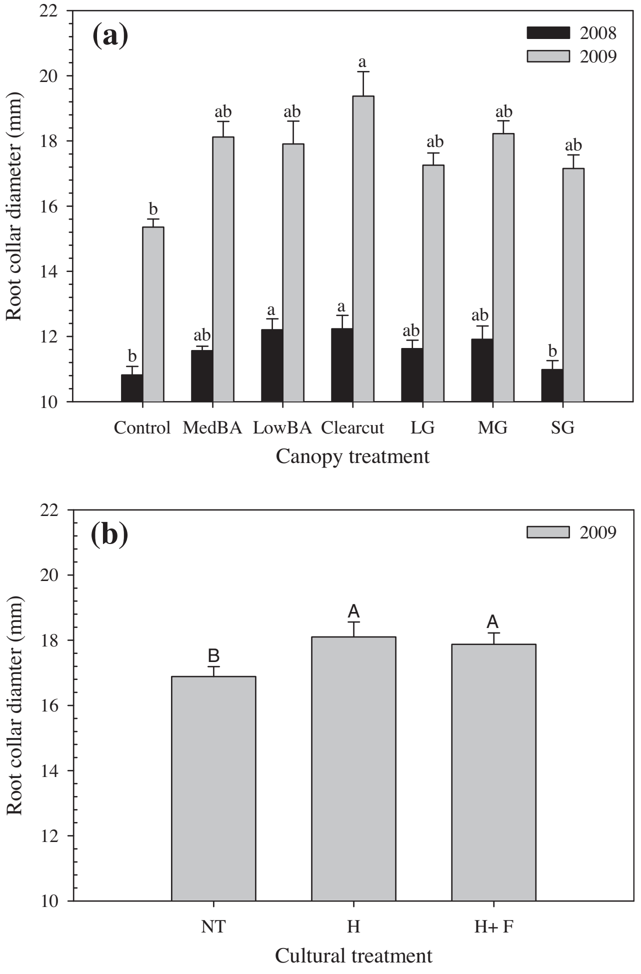

Fig. 2. Root collar diameter (RCD; Mean + 1 SE) of planted longleaf pine seedlings by (a) canopy and (b) cultural treatments at the end of the 2008 and 2009 growing seasons. Means with the same letter in the same year indicate no significant difference ($\alpha = 0.05$).

3.3. Percentage of seedlings in height growth

No seedlings emerged from the grass stage at the end of the 2008 growing season. The percentage of seedlings in height growth did not differ among the canopy treatments at the end of the 2009 growing season ($p = 0.268$) but differed at the end of the 2010 growing season ($p < 0.001$; Fig. 3). The Control treatment resulted in the lowest percentage of longleaf pine seedlings in height growth at the end of the 2010 growing season ($p \leqslant 0.034$).

No interactions were detected for the percentage of seedlings in height growth between the canopy and cultural treatments at the end of either the 2009 ($p = 0.558$) or the 2010 ($p = 0.272$) growing season. The percentage of seedlings in height growth did not differ among the cultural treatments at the end of the 2009 growing season ($p = 0.145$) but did differ at the end of the 2010 growing season ($p < 0.001$; Fig. 4). H + F and H treatments had more seedlings in height growth than the NT treatment at the end of the 2010 growing season ($p < 0.001$).

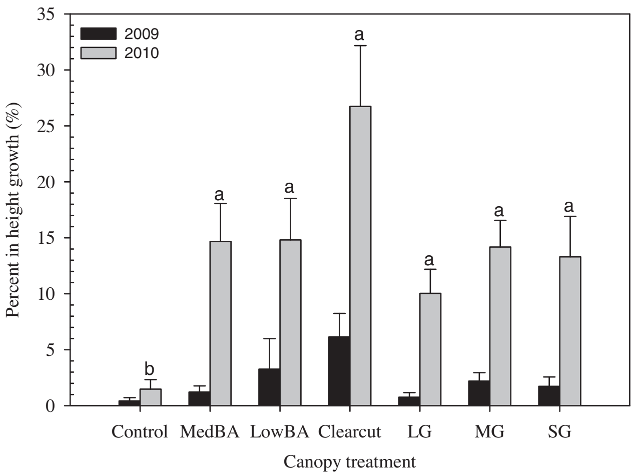

Fig. 3. The percentage (Mean + 1 SE) of longleaf pine seedlings in height growth by canopy treatment at the end of the 2009 and 2010 growing seasons. Means with the same letter indicate no significant difference ($\alpha = 0.05$).

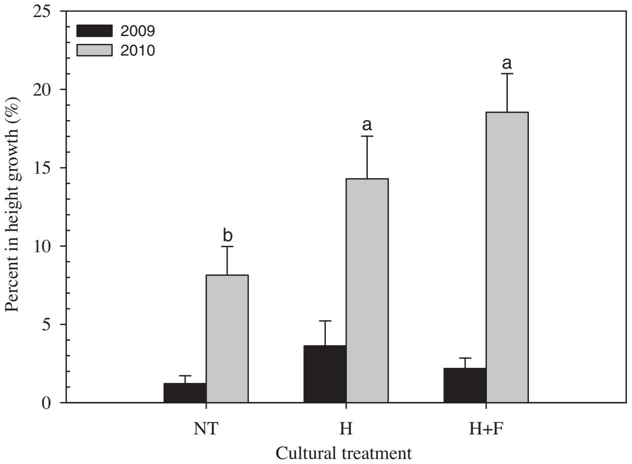

Fig. 4. The percentage (Mean + 1 SE) of longleaf pine seedlings in height growth by cultural treatment at the end of the 2009 and 2010 growing seasons. Means with the same letter indicate no significant difference ($\alpha = 0.05$).

4. Discussion

4.1. Effects of canopy treatments on longleaf pine seedling survival and growth

After the first three growing seasons, the Clearcut treatment resulted in the highest seedling survival and greatest seedling growth (i.e., seedling RCDs in Clearcut plots were 13%, 26% and 42–50% larger than those in Control plots at the end of the 2008, 2009 and 2010 growing seasons, respectively). This result is not surprising because longleaf pine is considered to be shade-intolerant, and competition from canopy trees can reduce survival and growth of longleaf pine regeneration (e.g., Boyer, 1990, 1993; Palik et al., 1997, 2003; Brockway and Outcalt, 1998; McGuire et al., 2001; Brockway et al., 2006). In our study, the survival rates of longleaf pine seedlings in Clearcut plots were 94.4%, 87.2% and 80.6% after the first, second and third growing season, respectively, which are within the range of survival rates previously reported on well-drained soils. For example, in flatwoods of central Louisiana, the survival rates of longleaf pine seedlings planted in clearcuts with different competition control methods ranged from 62% to 99% after the first growing season (Haywood, 2005, 2007) and ranged from 86 to 98% after three growing seasons (Haywood, 2000). In the lower coastal plain of Florida, the survival rates of longleaf pine seedlings planted in clearcuts with fertilization and/or different herbaceous weed control ranged from 53% to 93% after the first growing season and from 45% to 88% after the second growing season (Ramsey et al., 2003; Ramsey and Jose, 2004). At Camp Lejeune, Knapp et al. (2006) compared the effects of eight site preparation treatments on survival of longleaf pine seedlings planted on spodic soils and reported the mean survival rates of 70% after 1 year and 59% after 20 months.

Recent studies that explored the effects of alternative methods of canopy retention management designed to retain ecological services from existing pines during regeneration (e.g., Palik et al., 1997, 2003; McGuire et al., 2001; Pecot et al., 2007) suggest that regenerating longleaf pine can be accomplished within gap sizes as small as 0.10 ha (McGuire et al., 2001) or by using single-tree selection approaches to thin canopy trees to variable densities (Pecot et al., 2007). In our study, we used two single-tree selection approaches (MedBA and LowBA) and three gap sizes (LG, MG, and SG) and found that these five canopy treatments resulted in similar seedling survival and growth after the first three growing seasons (i.e., the mean seedling RCDs across these five treatment plots ranged from 19.0 mm to 22.5 mm at the end of the 2010 growing seasons). In our study, the mean survival rates of longleaf pine seedlings in these five treatment plots were 87.8%, 74.6% and 64.0% after the first, second and third growing season, respectively. On well-drained soils in southwestern Georgia, Palik et al. (1997) reported that the survival rate of planted seedlings averaged 97% after 12 months of growth within four gap sizes that ranged from 0.1 to 0.2 ha; Pecot et al. (2007) reported that mean seedling survival rates ranged from 67% to 73% over three growing seasons within 0.2 ha canopy gaps. However, other studies report low survival rates in canopy openings compared to survival under the intact canopy and suggest that canopy pines may provide facilitation effects for longleaf pine survival during dry conditions. For example, McGuire et al. (2001) reported that average survival rates were 54% and 9% after the first and second growing season within gaps that ranged from 0.1 to 1.6 ha. Similarly, Gagnon et al. (2003) reported that seedling survival ranged from 23% to 51% after the first growing season and from 19% to 36% after the second growing season within 0.3 ha gaps, and Rodríguez-Trejo et al. (2003) reported that survival rates averaged 23% and 15% after the first growing season within the gap sizes of 0.1 and 1.6 ha, respectively. According to data from the National Climatic Data Center (Wilmington International Airport, 34°16′N, 77°54′W), precipitation during our study period was somewhat greater than the 50-year mean (2008 = 154.4 cm; 2009 = 151.7 cm; 2010 = 148.7 cm; 50-year mean = 140.0 cm). As a result, our field sites did not experience drought conditions but experienced moderately wetter conditions through the study period. The survival rates from these five treatment plots were consistently similar to those in Control plots, suggesting that thinning the canopy with single-tree or group selections has no positive or negative effects under conditions (soils and adequate precipitation) similar to those in this study.

In our study, no seedlings had emerged from the grass stage after the first growing season, which was consistent with previous studies on well-drained soils of northwestern Florida (Ramsey et al., 2003; Ramsey and Jose, 2004) and central Louisiana (Haywood, 2005, 2007). However, seedlings started to emerge from the grass stage during the second growing season and the mean percentage of seedlings in height growth from six canopy removal treatment plots (15.8%) was 10.7 times higher than that in Control plots (1.5%) after the first three growing seasons, indicating that canopy removal did shorten the time of seedlings out of the grass stage and may accelerate stand development. Previous studies demonstrate that management actions can positively affect grass stage emergence, but differences in the treatment applied, the competitive pressures of the ground layer vegetation, and the criteria used to define height growth initiation make direct comparisons to previous studies complex (e.g., Haywood, 2000, 2005, 2007; Ramsey et al., 2003; Knapp et al., 2006). For example, Knapp et al. (2006) compared the effects of eight site preparation treatments on the percentage of seedlings in height growth and reported that the percentages of seedlings in height growth after 20 months ranged from 0% in untreated plots to 19% in plots that were treated with bedding, chopping, and herbicide. Past studies may present slightly different estimates of seedlings in the percentage of seedlings in height growth because a height of 12 cm has also been used to indicate height growth initiation (e.g., Haywood, 2000, 2007). In flatwoods of central Louisiana, Haywood (2000) tested seven herbaceous plant control treatments on the percentage of seedlings in height growth and reported that the percentage of seedlings in height growth ranged from 17% to 72% after three growing seasons and from 81% to 96% after five growing seasons. Although the treatments applied clearly affect the percentage of seedlings in height growth, site differences or differences in the vegetation community also affect seedling emergence. For example, Haywood (2007) used similar vegetation control treatments on two study sites and reported that the percentages of seedlings in height growth ranged from 0% to 24% on a grass-dominated site and from 86% to 99% on a shrub-dominated site after two growing seasons.

Because the widespread loss of longleaf pine forests has resulted in existing RCW populations using loblolly pine stands for nesting and foraging habitat, clearcutting is not desirable for land managers trying to establish longleaf pine at Camp Lejeune or other properties with RCW recovery goals. The partial canopy retention treatments (MedBA, LowBA, LG, MG, and SG) appear to be equivalent choices for establishing longleaf pine while maintaining loblolly pine canopy trees because of their similar roles in the establishment and growth of longleaf pine seedlings. However, restoring the longleaf pine ecosystem requires not only the establishment of longleaf pine but also the restoration of its characteristic herbaceous understory and its frequent, low intensity surface fire regime (Kirkman et al., 2007). The presence of canopy trees moderates growing conditions at the ground layer and strongly controls the structure and composition of the ground layer plant community. Reducing competition from canopy trees through heavy thinning (e.g., LowBA in our study) or creating larger gaps (e.g., LG and MG in our study) could increase ground herbaceous species richness and abundance in thinning plots (Harrington and Edwards, 1999; Harrington et al., 2003) and aboveground understory biomass in larger gaps (McGuire et al., 2001). However, previous studies have found that canopy removal and gap formation in longleaf pine forests could release understory hardwoods and may potentially shift ground layer communities away from herbaceous dominance (Pecot et al., 2007; Outcalt and Brockway, 2010). In our sites, natural loblolly pine regeneration released from canopy removal could compete with planted longleaf pine seedlings (Knapp et al., 2011; Huifeng Hu, unpublished data) and therefore light thinning (e.g., MedBA in our study) or creating smaller gaps (e.g., SG in our study) may be not only more appropriate for limiting hardwood encroachment but also for providing continuous pine needles as fuels to carry fires through the whole stand. Generally, our results support the strategy of gradual conversion to longleaf pine proposed by Kirkman et al. (2007), although future research needs to focus on the effect of partial canopy retention on ground layer vegetation and the effectiveness of carrying fires within loblolly pine forests.

4.2. *Effects of cultural treatments on longleaf pine seedling survival and growth*

In our study, we found that the herbicide application (H subplot treatment) did not affect seedling survival but had variable effects on RCD and the percentage of seedlings in height growth. Previous studies report similarly mixed results of herbicide treatments on longleaf pine seedling survival and RCD (Ramsey et al., 2003; Ramsey and Jose, 2004; Jose et al., 2010) but report a consistent increase in the percentage of seedlings in height growth associated with herbicide release (Nelson et al., 1985; Loveless et al., 1989; Haywood, 2000, 2005; Ramsey et al., 2003; Ramsey and Jose, 2004; Berrill and Dagley, 2010). Herbicide application has been found to decrease, increase, or cause no change in seedling survival and RCD growth (Ramsey et al., 2003; Ramsey and Jose, 2004; Jose et al., 2010). These conflicting results may be explained by the type of herbicides applied (Ramsey and Jose, 2004; Jose et al., 2010), the rate of herbicide applied (Ramsey and Jose, 2004), and the monitoring duration (Ramsey et al., 2003; Ramsey and Jose, 2004; Jose et al., 2010). For example, on well-drained soils in northwestern Florida, Jose et al. (2010) found that hexazinone application had no effect on longleaf pine seedling mortality during two growing seasons when compared to an untreated control, but imazapyr, sulfometuron methyl, and sulfometuron methyl plus hexazinone all significantly increased mortality. Ramsey et al. (2003) reported a significantly reduced mortality rate (10% lower than the control) following herbicide treatment during the first growing season and attributed the difference to less competition for water during the severe early summer drought of 2000. Ramsey and Jose (2004) reported that first-year RCD was significantly increased following application of hexazinone at rates of 0.56 and 1.12 ai kg/ha and sulfometuron methyl at a rate of 0.42 ai kg/ha but not by application of sulfometuron methyl at a rate of 0.21 ai kg/ha. However, after the second growing season, seedlings treated with hexazinone at rates of 0.56 and 1.12 ai kg/ha and sulfometuron methyl at a rate of 0.21 ai kg/ha all had significantly larger RCDs than the control, while seedlings treated with sulfometuron methyl at a rate of 0.42 ai kg/ha did not differ from the control. In addition, the original structure of understory vegetation also affects the results of herbicide application. In central Louisiana, Haywood (2005) found that the abundant herbaceous vegetation limited the growth of longleaf pine seedlings, and herbaceous plant control with herbicides significantly increased the percentage of seedlings in height growth through four growing seasons on a grass-dominated site but lost its effectiveness on a shrub-dominated site after two growing seasons.

The interaction between the canopy and cultural treatments found in 2010 in our study suggests that the overstory affects the results of herbicide application indirectly through its effects on the understory vegetation that competes with planted longleaf pine seedlings. Herbicides used in our study targeted hardwood species in the stands. Reducing hardwoods combined with reducing competition from canopy pines through whole canopy removal (e.g., Clearcut in our study) or creating larger gaps (e.g., LG and MG in our study) could facilitate rapid growth of natural loblolly pine seedlings (Knapp et al., 2011). The net effect would be no growth benefit to longleaf pine seedling RCD as observed in Clearcut, LG, and MG plots. We also observed that the H treatment did not increase seedling RCD in Control plots. Because overstory trees often limit the abundance of understory vegetation and longleaf pine seedling growth is strongly limited by competition with a dense overstory (Kirkman and Mitchell, 2006; Mitchell et al., 2006), it is likely that the herbicide release treatment was ineffective at increasing resource availability in unthinned plots. However, the H treatment significantly increased seedling RCD in MedBA, LowBA, and SG plots, suggesting that herbicide application would benefit the initial growth of planted longleaf pine seedlings under a loblolly pine canopy retained at an intermediate level.

In our study, we found that the H + F treatment increased or caused no change in seedling RCD, both results reported in previous studies in longleaf pine forests. In northwestern Florida, Ramsey et al. (2003) reported that fertilizer plus herbaceous woody control (the H + W treatment) did not affect the RCD of planted longleaf pine seedlings after the second growing season; Gagnon et al. (2003) reported that the similar treatment increased 47% of seedling RCD after the second growing season. When compared to the H treatment, the H + F treatment caused no change or a smaller seedling RCD, found in LowBA plots, suggesting that fertilizer did not benefit planted longleaf pine seedlings; furthermore, similar to previous studies (Loveless et al., 1989; Ramsey et al., 2003; Haywood, 2007), we did not find any fertilization effect on the percentage of planted longleaf pine seedlings in height growth.

5. Management implications

The canopy and cultural treatments tested in our study can be used to develop guidelines for land managers establishing longleaf pine in loblolly pine stands on moderately well- and well-drained sites in the Atlantic Coastal Plain of the southeastern United States. When canopy retention is not a management objective, clearcutting can be used to stimulate rapid seedling growth and high survival. However, when canopy retention is desired, partial canopy retention treatments (<~9 m^2/ha BA and gaps >~0.16 ha) are expected to result in similar survival and growth rates of underplanted longleaf pine seedlings. Application of herbicide was found to increase seedling RCD and shorten the time for longleaf pine seedlings to emerge out of the grass stage. However, the benefits resulted from herbicide application were affected by overstory canopy structure and could only be realized in reduced basal area and small gap treatments; therefore, we recommend that MedBA, LowBA and SG treatments in combination with herbicide application should be used to establish longleaf pine seedlings when canopy retention is desired. Recommendations from this study are based on the establishment of longleaf pine regeneration during the first three growing seasons, and it is not clear how our treatments will affect long-term stand development. Furthermore, the best silvicultural treatments for longleaf pine establishment may not necessarily be the best treatments for restoring other components of longleaf pine ecosystems. Therefore, future studies are needed to test how these silvicultural treatments affect the restoration of other critical components of longleaf pine ecosystems.

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