Site preparation for longleaf pine restoration on hydric sites: Stand development through 15 years after planting

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A B S T R A C T

Longleaf pine (Pinus palustris Mill.) restoration is an important land management goal throughout the southeastern U.S. On hydric sites within the Atlantic Coastal Plain, restoration may involve site preparation prior to planting to overcome challenges to seedling establishment, such as abundant competition and poor soil drainage. Investment in site preparation assumes that treatments will result in long-term benefits to stand development, yet lasting impacts of site preparation on longleaf pine are not well understood. We sampled longleaf pine plantations in Onslow County, North Carolina through three years and at 15 years after site preparation and planting. The eight study treatments we tested include an untreated control, six combinations of two vegetation control treatments (chopping or herbicide) with three soil manipulation treatments (mounding, bedding, or flat-planting (no treatment)), and a chopping-herbicide-bedding treatment. Our findings indicate that site preparation significantly improved survival and growth of longleaf pine through 15 years. Herbicide resulted in greater growth, higher survival, and earlier grass stage emergence than chopping. Similarly, soil manipulation treatments resulted in improved stand establishment outcomes relative to flat-planting (no treatment). Effects of site preparation treatments on diameter growth were observed early and maintained through the end of the study period, while effects on survival were not observed within the first three years. Differences in stand height among treatments were more strongly driven by growth rates following grass stage emergence than timing of emergence. Our results demonstrate that site preparation improves longleaf pine stand establishment on hydric sites, although the intensity of site preparation treatments recommended for restoration depends on management objectives.

1. Introduction

Restoration of longleaf pine (Pinus palustris Mill.) ecosystems is an important land management objective throughout the southeastern U.S. Prior to European settlement, longleaf pine occupied an estimated 37 million hectares (Frost, 2006). By 2010, however, one of North America’s most extensive forest ecosystems had been reduced to approximately 4.5% of its pre-settlement range (Oswalt et al., 2012). This reduction was due to a number of anthropogenic factors, including timber harvest and naval stores production, land conversion for urban and agricultural uses, grazing by hogs and other livestock, and, perhaps most importantly, fire exclusion (Frost, 2006; Landers et al., 1995). In addition to this dramatic reduction in areal extent, the cultural, ecological, and economic value of longleaf pine contribute to interest in its restoration. Longleaf pine ecosystems include some of the most diverse plant communities in North America (Walker and Peet, 1983; Walker and Silletti, 2006), and many plant species within these ecosystems demonstrate high endemism and rarity (Glitzenstein et al., 2001; Walker, 1998, 1993). In addition, longleaf pine produces high quality timber and suitable habitat for both game species and wildlife species of conservation concern (Brockway et al., 2015; Landers et al., 1995; Mitchell et al., 2006). Longleaf pine forests may be simultaneously managed for timber and biodiversity (Freeman and Jose, 2009; Mitchell et al., 2006), and this pairing of economic and ecological benefits has...
been critical to increasing interest in longleaf pine restoration across the southeastern U.S. (Lander et al., 1995; Mitchell et al., 2006).

Restoration often occurs on sites where mature longleaf pine is no longer present or is a minor component of the overstory, which necessitates the use of artificial regeneration. This practice has become so common that over 25% of contemporary longleaf pine forests were established through artificial regeneration (Oswalt et al., 2012). A major impediment to successful establishment of longleaf pine is its intolerance to competition, particularly as a grass stage seedling (Boyter, 1990; Brockway et al., 2006). During this stage, seedlings allocate growth to root development rather than stem elongation and can be outcompeted and overtopped by fast growing vegetation (Boyter, 1990). This challenge is amplified on hydric sites, such as flatwoods, where soil moisture limits seedling growth and competition from woody plants is abundant (Brockway et al., 2006; Glitzenstein et al., 2003; Peet, 2006).

Longleaf pine would have naturally regenerated on hydric sites under a treatment are subsequently lost. Nilsson and Allen (2003) described a Type C response occurs when initial growth gains from the treatment are maintained through time but do not continue to increase. Type C response occurs when initial growth gains from the treatment are subsequently lost. Nilsson and Allen (2003) described a fourth trajectory, Type D, which occurs when growth of an untreated stand surpasses that of the treated stand. Studies on slash and loblolly pine have reported conflicting results on long-term growth responses following site preparation (Nilsson and Allen, 2003; Outcalt, 1984; Zhao et al., 2009). Although short-term studies on longleaf pine have generally found that site preparation improves seedling growth, it is not known if those early increases result in meaningful differences in stand development. Given the unique seedling development of longleaf pine, reports from within a few years of planting may not provide enough time for seedlings to emerge from the grass stage. Thus, it is not known if site preparation may result in (1) earlier grass stage emergence, (2) improved growth following grass stage emergence, or (3) a combination of the two.

The objective of this study was to quantify responses of planted longleaf pine to site preparation treatments through 15 years on poorly drained, hydric sites. The study served as a follow up to an earlier study by Knapp et al. (2006, 2008) that monitored seedling growth and survival through three years after planting. We addressed three specific questions: (1) How does site preparation affect longleaf pine tree size and density at the stand level 15 years after planting? (2) Are early gains obtained from site preparation maintained beyond the seedling establishment phase and into stand development? (3) Are differences in stand development among treatments the result of earlier emergence from the grass stage, increased growth rates after grass stage emergence, or a combination of the two?

2. Methods

2.1. Study area

This study was conducted on Marine Corps Base Camp Lejeune (34°36’N, 77°24’W) in Onslow County, North Carolina. Camp Lejeune is located within the Atlantic Coastal Flatwoods section of the Outer Coastal Plain Mixed Forest province (McNab et al., 2007). The study sites were located on Leon sand (sandy, siliceous, thermic Aeric Aquort), a poorly drained Spodosol with a fluctuating water table that may be at or near the surface (Barnhill, 1992; NRCS, 2014). Spodosols are the primary soil order of flatwoods and are characterized by their sandy, acidic, and infertile nature (Brockway et al., 2015; Peet, 2006).

Leon sand is one of the most extensive soil series on Camp Lejeune (Barnhill, 1992; Frost, 2001) and is of large extent throughout the Southeast (NRCS, 2014). Timber production has been a primary land use objective throughout Camp Lejeune’s history (MCBCL, 2015), and the sites selected for this study were previously used for slash and loblolly pine plantations, which were harvested six months to two years prior to treatment installation. In recent decades, Camp Lejeune has prioritized restoration of longleaf pine on hydric flatwoods sites (MCBCL, 2015). Although hydric flatwoods are less common throughout the range of longleaf pine than mesic and xeric sites (Kirkman et al., 2017), longleaf pine restoration on hydric sites is common (e.g., Freeman and Jose, 2009; Glitzenstein et al., 2003; Hiers et al., 2012; Jose et al., 2010; McCaskill and Jose, 2012) and is particularly important because of the diverse plant communities that occur on such sites (Frost, 2001; Peet, 2006; Walker and Peet, 1983).

The natural vegetation community on frequently burned Leon sand in this area is species-rich longleaf pine wet savanna (Frost, 2001). This bilayered community consists of an overstory dominated by longleaf pine and an understory containing a diverse array of grasses, sedges, forbs, and fire-dwarfed shrubs (Frost, 2001). Wiregrass (Aristida stricta Michx.) dominates the herbaceous layer, and bluebells (Andropogon spp. and Schizachyrium spp.) are also common (Frost, 2001; Peet, 2006). The estimated pre-settlement fire return interval was 1–3 years, and with such frequent fire Leon sand supports rare species such as roughleaf loosestrife (Lysimachia asperulifolia Poir.) and Venus flytrap (Dionaea muscipula Ellis) (Frost, 2001). These sites also typically contain other insectivorous plants, such as pitcher plants (Sarracenia spp.) and sundews (Drosera spp.) (Frost, 2001; Peet, 2006). Common shrubs
include inkberry (Ilex glabra (L.) A. Gray), dwarf and blue huckleberries (Gaylussacia dumosa and frondosa (Andrews) Torr. & A. Gray), and a few blueberry species (Vaccinium spp.) (Frost, 2001; Peet, 2006).

### 2.2. Experimental design

This study utilized a randomized complete block design, consisting of eight site preparation treatments replicated across five blocks for a total of 40 experimental units. Study treatments were randomly assigned to experimental units with dimensions of 55 m × 86 m (~0.5 ha), with 20 m buffers between units to prevent treatment overlap and reduce edge effects. Study treatments consisted of combinations of two vegetation control treatments (herbicide and chopping) and three soil manipulation treatments (mounding, bedding, and flat-planting [no additional treatment]) to create a 2 × 3 factorial design of six treatments. The two additional study treatments were an untreated control (no vegetation control and flat-planting) and a bedding treatment with both levels of vegetation control. The eight resulting study treatments (Table 1) are herein referred to by their initials: F (flat-planting and no vegetation control), HF (herbicide and flat-planting), CF (chopping and flat-planting), CH (chopping and mounding), HB (herbicide and bedding), CB (chopping and bedding), and CHB (chopping, herbicide, and bedding).

Prior to site preparation, all blocks were harvested and sheared to remove standing vegetation. Study treatments were then applied in summer 2003. Vegetation control treatments were applied first, followed by the soil manipulation treatments. The chopping treatment was implemented using a 2.4 m Lucas Drum Chopper pulled by a TD15 Dresser crawler tractor. The herbicide treatment included 0.70 kg/ha of imazapyr and 0.56 kg/ha of triclopyr, which were mixed and broadcast at a rate of 280 L/ha. Mounds approximately 1.2 m wide were created using a New Forest Technology custom mounding bucket on a Caterpillar 320BL excavator. For consistency, the mounds were created in rows, rather than in the discontinuous, random distribution that is commonly associated with mounding site preparation. Beds approximately 2.1–2.4 m wide were created using a Rome 6-disc Bedding Harrow with three discs on each side. All blocks were burned in October or November 2003 to remove remaining vegetation and further prepare the sites for planting. Container-grown longleaf pine seedlings from locally collected seed were hand planted in December 2003. There was variation in initial planting density across treatments, particularly on mounded treatments where space between mounds resulted in less planting space than bedded and flat-planting treatments. All blocks were burned again in March 2006, and after that, two more burns occurred at 4-7-year intervals, depending upon the block.

### 2.3. Data collection

After planting, a full census was conducted to record the number of seedlings planted in each experimental unit. A sub-sample of 45 seedlings from each experimental unit was then randomly selected for repeated growth and survival measurement. Survival was measured through two years after planting, with two measurements periods in August 2004 and 2005. Root collar diameter (RCD) was measured through three years after planting, with four measurement periods occurring in June and December 2004, December 2005, and December 2006 (see Knapp et al., 2006, 2008 for more details).

In summer 2018, a sample population of trees was selected from each experimental unit to quantify stand density and tree size. Five circular subplots were systematically located within each experimental unit, with one subplot located at the experimental unit center and each of the other four subplots spaced between each respective corner and the center. Each subplot had a radius of 10 m, resulting in approximately a third of each experimental unit being sampled. Within each subplot, every tree was identified to species and measured for height and diameter at breast height (DBH). There was some volunteer seeding in of longleaf, slash, and pond pine (Pinus serotina Michx.); however, this was always a minor component of the developing stands and our analyses considered only the planted longleaf pine.

In summer and winter 2017, we conducted stem analysis on a random sample of longleaf pine trees from each experimental unit to quantify annual height growth of individual trees. We established a transect running longways across the middle of each rectangular experimental unit and located six equally spaced points along the transect. We then selected the longleaf pine nearest each point for destructive sampling for stem analysis. Each selected tree was felled in the field and cut into sections at 10 cm intervals from the ground line to 1.5 m and every 25 cm thereafter. These intervals gave us a fine resolution toward the base of the tree, where transitions between growth years were closer. Each sample was prepared by sanding with progressively finer grit, following the protocol of the Missouri Tree-Ring Laboratory (J. Marschall, personal communication, 2017), and tree age was determined for each section (at known heights) using a stereo microscope to count annual rings.

### 2.4. Data analysis

We fit linear mixed models to each stand-level response variable of interest (i.e., total height, DBH, trees per hectare, grass stage seedlings per hectare, and basal area), with treatment as a fixed effect and the hierarchical, nested sampling design (i.e., subplots within experimental units within blocks) as a random effect. We used a height of 15 cm (from ground line to terminal bud) as the threshold to classify grass stage emergence (Boyer, 1988; Wang et al., 2016). We conducted one-way analysis of variance (ANOVA) on each of the fitted mixed models to test for differences among the eight study treatments for each response variable of interest. When one-way ANOVA indicated that treatments significantly differed (α = 0.05), post-hoc Tukey-adjusted pairwise comparisons were used to determine which treatments significantly differed. Additionally, we used a 2 × 3 factorial ANOVA, excluding the F and CHB treatments, to determine the effect of individual factors (e.g., chopping vs. herbicide) on each response variable of interest and to test for interactions between the vegetation control treatments and soil manipulation treatments. With significant treatment or interaction effects, we used post-hoc Tukey-adjusted pairwise comparisons to determine which individual factors significantly differed, as appropriate.

To understand how longleaf pine responses to site preparation changed through time, we integrated the stand-level measurements taken 15 years after planting with data collected in the original study, which measured seedlings through three years after planting (from 2003 through 2006). We computed two response variables of interest: survival and relative diameter. Survival in the initial two-year measurement period was calculated by applying the survival rates from sub-sampled seedlings to the number of planted seedlings recorded in the initial census. Survival at 15 years was calculated by scaling longleaf pine density within the subplots up to the experimental unit level and then dividing those estimates by the number of seedlings planted in summer 2008.
each experimental unit. To integrate root collar diameter measurements (RCD) from 2003 to 2006 with DBH measurements recorded in 2018, we calculated the respective diameter (RCD or DBH) for each treatment relative to the untreated control (F). Relative diameter was calculated for each measurement period using the following equation:

relative diameter = \frac{treatment mean - control mean}{control mean}

Therefore, a treatment mean diameter that is twice as large as the control mean diameter results in a relative diameter value of one. We fit linear mixed models to both survival and relative diameter and then used repeated measures ANOVA to test for differences among treatments and through time and to test for interactions between treatment and time. Significant main effect and interaction terms (α = 0.05) from repeated measures ANOVA were followed by post-hoc Tukey-adjusted pairwise comparisons to determine which treatments and time periods significantly differed.

For the stem analysis data, we determined the age at each height level by counting annual rings and adjusting internode tree heights using the Carman method (Carman, 1972; Dyer and Bailey, 1987). Tree height growth through time was reconstructed for the six sampled trees per experimental unit. Patterns of mean height and mean annual height growth through time were determined for each treatment, with non-overlapping 95% confidence intervals indicating statistically significant differences in growth patterns. We computed two additional response variables of interest: age of emergence from the grass stage and mean rate of height growth after emergence. Age of emergence from the grass stage was determined by counting the number of years a tree took to reach 15 cm in height (Boyer, 1988; Wang et al., 2016). The rate of height growth after emergence was determined by computing the mean annual height growth after the tree exceeded 15 cm in height. We fit linear mixed models for both age of emergence and post-emergence growth rate. We then conducted one-way ANOVA, followed by Tukey-adjusted pairwise comparisons, on both mixed models to test for differences among the eight study treatments. We also conducted a 2 × 3 factorial ANOVA, excluding the F and CHB treatments and followed by Tukey-adjusted pairwise comparisons, to determine the effects of individual treatment levels on the response variables.

Data were analyzed in R (R Core Team, 2018). The lme function in the nlme package (Pinheiro et al., 2018) and the glmer function in the lme4 package (Bates et al., 2015) were used for fitting linear mixed models, with the former being used in most cases and the latter being used to specify a Poisson distribution where necessary. The anova function in the stats package (R Core Team, 2018) was used for running ANOVA tests. The lsmeans function from the emmeans package (Lenth, 2019) and the CLD function from the multcompView package (Graves et al., 2015) were used for post-hoc, Tukey-adjusted pairwise comparisons. When factorial or repeated measures ANOVA resulted in a significant (α = 0.05) interaction term, we used the testInteraction function in the phia package (De Rosario-Martinez, 2015) to conduct post-hoc interaction significance tests. The dplyr package (Wickham et al., 2019) was used for data manipulation, the ggsurvplot function in the survminer package (Kassambara and Kosinski, 2018) was used for plotting survival, and the ggplot2 package (Wickham, 2016) was used to create all other figures.

3. Results

3.1. Stand-level effects of site preparation at year 15

Fifteen years after planting, site preparation resulted in significant differences in mean height (p < 0.001) and DBH (p < 0.001) among the eight study treatments (Fig. 1A and B). We found that CHB (chop, herbicide, and bed), HM (herbicide and mound), and HB (herbicide and bed) resulted in the greatest tree size at age 15, with mean heights exceeding 5 m and mean DBH near 8 cm. These three treatments resulted in significantly greater heights than HF (herbicide and flat-planting), CF (chop and flat-planting), and F (flat-planting and no vegetation control) and significantly greater DBH than CF and F. In contrast, CF and F resulted in the smallest trees, with mean heights of less than 2 m and mean DBH less than 5 cm. Based on factorial ANOVA, both soil manipulation and vegetation control treatments affected height (p < 0.001) and DBH (p ≤ 0.001) of planted longleaf pine (Table 2), and there was no significant interaction between the treatment types for height (p = 0.469) or DBH (p = 0.773). Bedding and mounding resulted in greater height and DBH than flat-planting (no soil manipulation), with differences in height and DBH exceeding 2 m and 2 cm, respectively. Herbicide resulted in greater height and DBH than chopping, with differences in height and DBH exceeding 1 m and 1 cm, respectively.

Site preparation treatments also resulted in significant differences in longleaf pine tree density (p < 0.001) and grass stage seedling density (p = 0.001) at age 15. HB, CHB, CB (chop and bed), and HF (herbicide and flat-planting) had greater than three times the number of trees/ha compared to F (Fig. 1C), while F resulted in more grass stage seedlings/ha than CHB and HM (Fig. 1D). F averaged 28 grass stage seedlings/ha, while grass stage seedlings were absent from all but one experimental unit for CHB and HM. Based on factorial ANOVA, soil manipulation (p = 0.010) and vegetation control treatments (p = 0.026) affected the number of trees/ha, and there was no significant interaction between the treatment types (p = 0.659). Bedding resulted in greater tree density than mounding, and herbicide resulted in greater tree density than chopping 15 years after planting (Table 2). For grass stage seedling density, differences among soil manipulation treatments were significantly different (p = 0.006), but there was no significant difference between vegetation control treatments (p = 0.264) and no significant interaction between treatment types (p = 0.162). Flat-planting resulted in greater grass stage seedling density than mounding and bedding (Table 2).

Basal area, which integrates tree size and density at the stand level, was also significantly different among the eight study treatments (p < 0.001). Mean basal area for CHB and HB, which approached 3.5 m²/ha, was significantly greater than that of CM, CF, and F, which were near or below 1 m²/ha (Fig. 1E). Soil manipulation (p = 0.009) and vegetation control treatments (p = 0.001) affected basal area, and there was no significant interaction between the treatment types (p = 0.848). Bedding resulted in significantly greater basal area than flat-planting, and herbicide resulted in significantly greater basal area than chopping 15 years after planting (Table 2).

3.2. Effects of site preparation through time

Repeated measures ANOVA indicated that time significantly affected longleaf pine survival (p < 0.001) through 15 years after planting, while treatment did not (p = 0.281). Survival decreased through time, and mean survival across all treatments was 72.5% at eight months after planting, 59.1% at 20 months, and 32.7% at 15 years. The interaction between time and treatment approached significance (p = 0.061), likely because survival did not significantly differ among treatments after the first and second growing seasons (Knapp et al., 2006) but did differ in year 15 according to one-way ANOVA (p = 0.002). At this measurement period, the herbicide treatments – HB, HM, HF, and CHB – resulted in higher survival compared to the untreated control (Fig. 2).

The interaction between treatment and time was significant (p < 0.001) for relative diameter of longleaf pine through 15 years after planting. There were no significant differences among treatments at seven or 12 months after planting (p ≥ 0.855), but there were differences at two, three, and 15 years after planting (p < 0.001). After two years, CHB and HB consistently had greater relative diameter than CF and F (Fig. 3). By year 15, CHB, HM, HB, CB, and CM had significantly greater relative diameter than CF and F. Notably, there were
no significant changes in relative diameter for any individual study treatment after year two \((p = 0.382)\).

### 3.3. Effects of site preparation on height growth reconstruction

One-way ANOVA indicated that there were significant differences in age of emergence from the grass stage among the eight study treatments \((p < 0.001)\). CF, which had a mean emergence age of 9.25 years after planting, emerged significantly later than the other seven treatments (Fig. 4A). The other treatments had emergence ages ranging from 3.72 to 5.29 years and did not significantly differ from each other. Based on factorial ANOVA, soil manipulation \((p < 0.001)\) and vegetation control \((p < 0.001)\) affected emergence age. The interaction between the treatment types approached significance \((p = 0.054)\) because CF resulted in much later emergence than any of the other treatments. Bedding and mounding resulted in earlier grass stage emergence than flat-planting, while herbicide resulted in earlier emergence than chopping (Table 3).

One-way ANOVA also found significant differences in mean annual height growth after grass stage emergence among the eight study treatments \((p < 0.001)\). HM and HB, with mean height growth exceeding 0.5 m/year, grew significantly faster than F and CF, which had mean growth rates of 0.33 m/year and 0.23 m/year, respectively (Fig. 4B). CF had significantly lower annual height growth than all
treatments except for F and CM. Based on factorial ANOVA, soil manipulation ($p < 0.001$) and vegetation control ($p < 0.001$) significantly impacted post-emergence growth, while the interaction between the two treatment types was insignificant ($p = 0.195$). Bedding and mounding resulted in a greater annual growth rates than flat-planting, and herbicide produced greater annual growth than chopping (Table 3).

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Mean height (m)</th>
<th>Mean diameter at breast height (cm)</th>
<th>Mean trees per hectare</th>
<th>Mean grass stage seedlings per hectare</th>
<th>Mean basal area ($m^2$/ha)</th>
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</thead>
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<tr>
<td>Flat</td>
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<td>5.77 b</td>
<td>383 ab</td>
<td>20.4 a</td>
<td>1.01 b</td>
</tr>
<tr>
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<td>4.79 a</td>
<td>7.79 a</td>
<td>321 b</td>
<td>8.3 b</td>
<td>1.75 ab</td>
</tr>
<tr>
<td>Bedding</td>
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<td>7.78 a</td>
<td>535 a</td>
<td>4.5b</td>
<td>2.55 a</td>
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<td>&lt; 0.001</td>
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<td>0.006</td>
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<tr>
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<td>6.46 b</td>
<td>349 b</td>
<td>13.2 a</td>
<td>1.08 b</td>
</tr>
<tr>
<td>Herbicide</td>
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<td>7.76 a</td>
<td>477 a</td>
<td>8.9 a</td>
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<td>0.026</td>
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</tr>
</tbody>
</table>

Same letters indicate no significant difference within a treatment type and response variable based upon Tukey-adjusted pairwise comparisons; $p$-values are from 2 × 3 factorial ANOVA tests.

Fig. 2. Mean survival for each study treatment (defined in Table 1) at three points in time: 8 months, 20 months, and 15 years after planting.

Fig. 3. Diameter of each study treatment (defined in Table 1) relative to the control (F) at five points in time, from seedling establishment into stand development.

Stem analysis allowed us to reconstruct height growth of each sampled longleaf pine through time (Fig. 5). The year in which each treatment line begins on the x-axis indicates the earliest grass stage emergence age of trees sampled in that treatment. All treatments were significantly taller through time than CF, due to that treatment’s late emergence and slow growth. For the last four years of growth, HB was significantly taller than F, and during that same period, HM approached significantly greater height than F. Stem analysis also allowed us to reconstruct mean annual height growth after grass stage emergence for each treatment (Fig. 6). For years 1–3, HB had significantly greater height growth than F, while HM had significantly greater height growth than F during years 2–5. Annual height growth continued to increase slightly over time for F, while growth generally levelled off after
Our results show that site preparation had strong effects on longleaf pine stand development through 15 years after treatment (Fig. 7). Among all treatments, the untreated control (F) generally resulted in the smallest height and DBH, the lowest tree density, and the greatest number of seedlings still in the grass stage, although CF did not differ from the untreated control. Thus, all methods of site preparation considered in this study, aside from a single pass of chopping, improved long-term longleaf pine stand establishment compared to no treatment. Other studies have also found significantly improved growth of longleaf pine seedlings (Addington et al., 2012; Freeman and Jose, 2009; Knapp et al., 2006) with site preparation. Moreover, our results demonstrate a pattern of increasing magnitude of response with increasing site preparation intensity, which is consistent with other studies that have examined longleaf pine responses to vegetation control and soil manipulation (Knapp et al., 2006; Loveless et al., 1989). Study treatments that resulted in the greatest tree size and density included both herbicide and soil manipulation, while treatments that produced intermediate size and density included either herbicide or soil manipulation. The treatments that resulted in the smallest tree size and lowest density – CF and F – included neither herbicide nor soil manipulation.

Chopping was not effective for improving conditions for longleaf pine establishment. This is consistent with other studies, which have found that chopping resulted in reduced longleaf pine seedling growth (Freeman and Jose, 2009; Knapp et al., 2006) and increased woody vegetation (Miller, 1980) compared to other vegetation control treatments. Although chopping causes minimal soil disturbance, has low impact on herbaceous vegetation, and immediately reduces standing woody vegetation, a major drawback is that it promotes sprouting of woody species (Lowery and Gjerstad, 1991). Freeman and Jose (2009) suggested that chopping plus fire may be sufficient for longleaf pine establishment through 15 years after treatment.

4–5 years for the other treatments.

4. Discussion

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Chopping was not effective for improving conditions for longleaf pine establishment. This is consistent with other studies, which have found that chopping resulted in reduced longleaf pine seedling growth (Freeman and Jose, 2009; Knapp et al., 2006) and increased woody vegetation (Miller, 1980) compared to other vegetation control treatments. Although chopping causes minimal soil disturbance, has low impact on herbaceous vegetation, and immediately reduces standing woody vegetation, a major drawback is that it promotes sprouting of woody species (Lowery and Gjerstad, 1991). Freeman and Jose (2009) suggested that chopping plus fire may be sufficient for longleaf pine establishment through 15 years after treatment.

4–5 years for the other treatments.

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establishment in flatwoods, even though seedling growth may be slow. However, our findings did not support this expectation through 15 years after planting on similar flatwoods sites. Perhaps this contrasting result is due to interactions between treatments and fire, but an analysis of such interactions is beyond the scope of this study because we lack long-term, replicated data on fire behavior. The contrasting result might also be due to a fire return interval that was too long to control abundant woody competition in our study. The first burn occurred two years after site preparation, but the next two burns occurred at 4-7-year intervals, depending upon the block. This is much less frequent than the study sites’ estimated pre-settlement fire return interval of 1–3 years (Frost, 2001). The need for frequent fire, especially during restoration on flatwoods sites, is emphasized because even a slight reduction in frequency could allow shrub encroachment (Glitzenstein et al., 2003).

Our findings show that herbicide applied for site preparation can have lasting improvements on growth and survival of planted longleaf pine. Although previous studies have consistently observed increased longleaf pine seedling growth (Addington et al., 2012; Boyer, 1988; Freeman and Jose, 2009; Knapp et al., 2006; Loveless et al., 1989) and earlier grass stage emergence (Boyer, 1988; Freeman and Jose, 2009; Loveless et al., 1989) as a result of herbicide application for site preparation and release, few studies have reported responses beyond six years after planting. Additionally, previous studies have reported that longleaf pine seedling survival is either unaffected (Addington et al., 2012; Loveless et al., 1989) or reduced by herbicide (Boyer, 1988; Freeman and Jose, 2009) within the first few years following planting. Although survival did not differ among treatments through two years

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**Fig. 6.** Mean annual height growth after grass stage emergence for each study treatment (defined in Table 1). Individual treatment panels include a line for the treatment mean and an envelope of the 95% confidence interval. The plot with all eight treatments shows only treatment means. Lines are smoothed on a three-year mean to reduce noise. Treatment lines are cut off after all five experimental units are no longer represented in the data.
after planting in our study (Knapp et al., 2006), herbicide contributed to the highest survival among treatments by year 15. This finding emphasizes the importance of a longer-term perspective when evaluating responses to site preparation and suggests that treatments that encourage early grass emergence may be important for increasing long-term survival.

Soil manipulation treatments resulted in increased longleaf pine growth compared to flat-planting (no treatment) through 15 years after treatment, which is consistent with previous studies of early growth for slash (Haywood, 1987; Outcalt, 1984; Pritchett, 1979) and longleaf pine seedlings (Knapp et al., 2006; Loveless et al., 1989). Survival and density responses to soil manipulation in our study were less clear. Bedding has been shown to increase survival of slash pine seedlings (Pritchett, 1979) but not of longleaf pine seedlings (Knapp et al., 2006; Loveless et al., 1989), while mounding has not been shown to increase survival of slash (Haywood, 1987) or longleaf pine seedlings (Knapp et al., 2006). In our study, treatments with soil manipulation tended to have higher survival in year 15 than the untreated control, yet only those treatments that included herbicide were significantly greater than the control. Stand density in year 15 on bedded sites was significantly greater than mounded sites, but this was likely due to lower initial planting density on mounds (mean = 886 trees/ha) compared to beds (mean = 1,371 trees/ha) because survival in year 15 was similar among bedded and mounded treatments.

Stem analysis indicated that herbicide and soil manipulation treatments provided both immediate (earlier grass stage emergence) and long-term (increased growth rate after emergence) advantages for longleaf pine establishment. The short-term benefit obtained from vegetation control is consistent with our expectation that reduced competition results in greater seedling growth and earlier grass stage emergence (Knapp et al., 2006, 2008). However, competition control from herbicide or mechanical treatments should diminish through time following vegetation recovery. For example, Freeman and Jose (2009) found that shrub cover was similar between treated and untreated areas four years after herbicide application on flatwoods sites in Florida. Boyer (1990) suggested that duration of the grass stage has a critical impact on subsequent longleaf pine growth and stand development, with delayed emergence resulting in lower long-term growth rates (Boyer, 1983). Twenty years after a single herbicide release treatment, Michael (1980) reported volume differences that represented an 8-year growth advantage for longleaf pine on treated sites. Although this could be due to more years of growth from earlier grass stage emergence, our results suggest that early competition control results in long-term, sustained increases in growth rate. In contrast to the recovery of vegetation following a single mechanical or chemical application, soil manipulation treatments may have persistent effects for several decades (Brockway et al., 2015). Although mounds and beds are likely to settle over time (Londo and Mroz, 2001), these treatments may have lasting impacts on hydrology. Given that the majority of the root system of longleaf pine is within the upper 30 cm of soil (Boyer, 1990; Heyward, 1933), it is possible that the drier conditions at the soil surface continue to directly benefit tree growth through time. Drier soil might also indirectly benefit longleaf pine by producing less optimal conditions for woody competitors that thrive in wetter soils.

Our findings suggest that the growth rate after grass stage emergence is more important than the timing of emergence for determining patterns of stand development through year 15. For example, the untreated control (F) did not differ from any treatment other than CF in timing of grass stage emergence, yet resulted in the fewest trees/ha and smallest mean tree size. One explanation for this pattern may be the survivorship bias implicit in our sampling approach. By studying a random sample of trees 15 years after planting, we were limited to studying only those trees that were still alive at sampling, thus basing conclusions on successful trees. On the untreated control, which experienced a high level of mortality during the study period, the stem analysis results suggest that for trees to survive to age 15, they must emerge from the grass stage early. If they fail to do so, competitors will presumably overtake the grass stage seedlings, resulting in suppression and eventual mortality. Because competition and poor drainage were not improved on the control, post-emergence growth remained low for trees that did manage to survive.

Several of our findings suggest that the more intensive site preparation treatments used in this study resulted in a Type A response (Morris and Lowery, 1988; Nilsson and Allen, 2003) through 15 years after treatment. For example, survival did not differ among treatments during early seedling establishment, but by year 15, survival ranged from 11.7% on F to 44.7% on HB. The results for growth differences were much more pronounced; differences in relative diameter among treatments were significant in year two and persisted at the same magnitude through year 15. Finally, stem analysis indicated that annual height growth remained consistently higher through time on treated sites compared to F and CF. Long-term responses of longleaf pine to site preparation have not been well studied, but the Type A response observed in our study is consistent with the growth response of loblolly pine through 18 years after intense site preparation reported by Nilsson and Allen (2003). In contrast, slash pine has generally exhibited a Type C response after bedding on flatwoods sites (Outcalt, 1984; Zhao et al., 2009). Differences in annual growth rates observed in our study...
magnify the cumulative differences in tree size among treatments, suggesting that differences among treatments are likely to persist or increase.

5. Management implications

Longleaf pine management may encompass a range of specific objectives and structural or compositional conditions. Site preparation is commonly used in conjunction with timber production of other southern pines, and our results show that intensive site preparation resulted in the greatest growth and survival of longleaf pine. However, management objectives for longleaf pine are often different within the context of ecosystem restoration. Consequently, maintaining or enhancing other attributes, such as ground flora communities, appropriate fire regimes, and soil properties, are also targeted during restoration. The natural community of our study area has been described as longleaf pine wet savanna (Frost, 2001), which has relatively open forest structure and low stand density. Our study shows that planting approximately 1,050 trees/ha with no site preparation results in approximately 125 longleaf pine trees/ha at year 15. Although the trees were small (mean height = 1.2 m), the resulting stand may meet some objectives of savanna restoration if the trees continue to grow and survive to maturity. Although the stand development phase would be prolonged, slow tree growth could be considered beneficial because slower growth is correlated with increased longevity (Black et al., 2008). An alternative restoration scenario could be optimizing longleaf pine stand density and growth rates to minimize time required to satisfy red-cockaded woodpecker (Leuconotopicus borealis) habitat guidelines (Shaw and Long, 2007). In this scenario, site preparation may be useful to improve the establishment and long-term growth of planted seedlings on hydric sites.

Site preparation treatments are applied to address site-specific challenges, and the effectiveness of the treatments used in our study would be expected to vary across the wide range of site types on which longleaf pine is managed. On mesic and xeric sites, soil manipulation treatments are likely unnecessary because these site types lack the high water table that inhibits seedling growth and survival on hydric sites (Fox et al., 2007), although bedding has been shown to increase growth, but not survival, of longleaf pine seedlings on well-drained sites (Loveless et al., 1989). In contrast, herbicide is commonly used for site preparation on mesic and xeric sites because of longleaf pine’s intolerance to competition (Brockway et al., 2006). Our findings support previous studies and suggest that herbicide site preparation improves longleaf pine seedling growth regardless of site type (Addington et al., 2012; Boyer, 1988; Loveless et al., 1989).

Although longleaf pine would have naturally regenerated on hydric flatwoods sites under a regime of frequent fire (Frost, 2001; Peet, 2006), loss of overstory longleaf pine and legacies of infrequent fire have disrupted ecosystem processes and created barriers to restoration success. Feedbacks among longleaf pine dominance, fuel characteristics, and frequent fire contribute to ecosystem function. The disruption of these feedbacks presents a potential ecological threshold for longleaf pine restoration because conditions suitable for regeneration success are limited within current, pre-restoration community states (Martin and Kirkman, 2009; Suding and Hobbs, 2009). Site preparation, as an example of intensive intervention during restoration, may be necessary to promote longleaf pine establishment and overcome the threshold between the current and desired community states. Once longleaf pine is successfully established, the desired community state may be maintained by re-establishing ecosystem function through less intense management (e.g., frequent prescribed fire) (Martin and Kirkman, 2009). Thus, site preparation treatments for longleaf pine restoration must (1) result in adequate longleaf pine regeneration to develop a future stand of desired structure and composition and (2) sustain a frequent fire regime that is continuous in both time and space (Mitchell et al., 2009) to maintain ecosystem function. An evaluation of the study treatments’ impacts on the ecology of fire and fuels is beyond the scope of this study; however, our study does demonstrate that site preparation significantly improves establishment and growth of longleaf pine on hydric sites. We also found that survival of planted seedlings is still possible without site preparation, although this approach results in high mortality and slow growth.

Longleaf pine ecosystem restoration seeks to not only establish an overstory of longleaf pine but also maintain or improve the ground layer plant community (Walker and Silletti, 2006). Previous studies have documented reductions in native understory plants following site preparation, which raises concerns about using such treatments for restoration (Knapp et al., 2008; Litt et al., 2001; Pritchett, 1979; Schultz and Wilhite, 1974). For example, mechanical treatments reduce wiregrass populations, with slow recovery following disruption of the soil (Clewell, 1989). Deleterious impacts would be expected to be most severe in remnant, high-quality sites. However, the impact of site preparation may be less of a concern for restoration scenarios in which the understory community has already been degraded by past land use or management activity. Our future work will address these issues by exploring long-term understory responses to site preparation within these plantations.

CRediT authorship contribution statement

Connor D. Crouch: Conceptualization, Formal analysis, Investigation, Writing - original draft, Writing - review & editing. Benjamin O. Knapp: Conceptualization, Methodology, Writing - review & editing, Project administration, Supervision, Funding acquisition. Susan A. Cohen: Conceptualization, Writing - review & editing, Project administration. Michael C. Stambaugh: Methodology, Writing - review & editing. Joan L. Walker: Conceptualization, Methodology, Writing - review & editing. G. Geoff Wang: Conceptualization, Methodology, Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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