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Early silvicultural intervention affects species dominance in efforts to restore pine-hardwood mixedwoods following stand-replacing disturbance

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ABSTRACT

Interest in replacing monocultures with species diverse stands has steadily grown. Mixedwoods (stands containing a balance of conifer and hardwood species) represent an alternative to monocultures and occur naturally through forest succession on most sites in eastern North America. In the central and southeastern United States, mixedwoods were generally dominated by pine and upland oak species. However, a combination of anthropogenic land use legacies has allowed fire-sensitive species to establish creating an opportunity for different mixedwood types to develop (e.g., pine-oak, pine-poplar, pine-gum). While any mixedwoods combination would increase tree species diversity relative to a monoculture, interest exists in whether silvicultural intervention can improve the performance of individual species to promote the development of different mixture types based on specific management objectives (e.g., wildlife habitat, timber quality, drought resistance). To address this question, we established an experiment examining the response of juvenile volunteer loblolly pine and six planted hardwood species (northern red oak, white oak, sweetgum, blackgum, yellow-poplar, and mockernut hickory to four silvicultural treatments (controlled release hardwood fertilization, coppicing, coppicing + broadcast fertilization, and planted control) in northern Mississippi, USA.

Four-years post-planting, our results demonstrate that all treatments produced loblolly pine-hardwood co-dominance; however, hardwood dominance varied among treatments. In the planted control, loblolly pine and sweetgum were the co-dominant species, and statistically outgrew all species except yellow-poplar. Mockernut hickory (+ 40%), yellow-poplar (+ 23%), and blackgum (+ 15%) seedling height increased in controlled release fertilization compared to the planted control; however, apart from northern red oak, seedling survival of all hardwood species was less than 50%. The controlled release hardwood fertilization treatment was co-dominated by loblolly pine, yellow-poplar, and sweetgum. Sprouting in the coppiced treatment (89%) statistically exceeded that in the coppiced + broadcast fertilization treatment (73%), but did not vary among species. In general, coppicing reduced sprout height and survival relative to seedlings in the planted control, and promoted loblolly pine, yellow poplar, and sweetgum co-dominance. Coppicing + broadcast fertilization consistently reduced sprout survival compared to the planted control. However, trends in seedling height were mixed, with northern red oak (+ 14%) showing the largest improvement, and volunteer loblolly pine the largest decline (- 34%). Moreover, coppicing + broadcast fertilization produced the most species diverse outcome featuring yellow-poplar, loblolly pine, sweetgum, and northern red oak in co-dominant growing positions. Collectively, these results indicate that sweetgum and loblolly pine are likely to be prominent species in contemporary mixedwoods regardless of treatment. However, more species-diverse mixtures may be promoted by coppicing and broadcast fertilizing early in stand development.

1. Introduction

Balancing productivity with a broad suite of desirable stand attributes is an emerging goal of forest management on public land. Promoting species diversity is one of the primary strategies for accomplishing this goal, as biodiversity has been linked to the provision of a broad suite of ecosystem services (Brockerhoff et al., 2017; Himes et al., 2020). Evidence supporting this strategy comes from several studies

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indicating that species diverse stands can be more productive, resistant to species specific pests and pathogens, and drought resistant compared to monocultures (Forrester and Bauhus, 2016; Jactel et al., 2017; Fichtner et al., 2020; Pretzsch, 2022; Clark et al., 2022). Consequently, interest in establishing and perpetuating species diverse stands has steadily grown (Paquette and Messier, 2010).

Mixedwoods contain a softwood and hardwood component where neither functional group exceeds 75–80% of the stand (Helms, 1998). In the central and southeastern United States, pine-hardwood mixtures are the primary mixedwood type (Kenefic et al., 2021). Pine-hardwood mixedwoods occur naturally through forest succession, but succeed to hardwood dominance without recurrent, intermediate severity disturbance (Goode, and et al., 2021, 2022). Prior to European settlement, mixtures in the region occurred as open woodlands featuring upland oaks (*Quercus* spp.), pine (*Pinus* spp.), and hickory (*Carya* spp.) (Hilgard, 1860; Peacock et al., 2008). Mixedwoods provided habitat for mast-dependent wildlife such as fox squirrel (*Sciurus niger*) (Loeb and Lennartz, 1989), and promoted surface fire through the input of flammable litter (Babl et al., 2020; Varner et al., 2021). However, over the past several decades, combined effects of anthropogenic activities including forest clearing for agriculture, subsequent agricultural abandonment, and decades of fire suppression have promoted fire-sensitive species encroachment, potentially altering patterns in mixedwoods assembly (Brewer et al., 2001).

One of the more impactful changes has been the widespread replacement of shortleaf pine (*Pinus echinata*) with loblolly pine (*P. taeda*) (Hanberry, 2021). Although both species are related and share several functional similarities (Willis et al. in review), loblolly pine possesses a more competitive suite of life history traits facilitating rapid colonization following disturbance (Lawson, 1990; Schultz, 1997). Indeed, loblolly pine has been shown to dominate abandoned agricultural fields and large harvest gaps potentially delaying the recruitment of hardwood species (Bormann, 1953; Mohler et al., 2021). Competitive advantages wrought from early site colonization can be mitigated by planting hardwood species immediately following disturbance. However, given the difference in early height growth potential between pine species, upland oaks are likely to be less compatible in mixture with loblolly pine than shortleaf pine (Granger and Buckley, 2021). Planting hardwood species better adapted to compete with loblolly pine may be a better option for accelerating mixedwood development. For example, yellow-poplar (*Liriodendron tulipifera*) and sweetgum (*Liquidambar styraciflua*) accrue height rapidly on favorable sites (Kormanik, 1990; Kota et al., 2007). Nevertheless, it is unclear whether planting alone will accelerate mixedwoods development or if additional treatments will be needed to increase hardwood competitiveness.

Coppicing advance regeneration is one option for reducing the relative competitive ability of loblolly pine. While not as well-adapted to top-kill as shortleaf pine (*P. echinata*), loblolly pine can sprout vigorously as a juvenile seedling (Mattoon, 1915; Little and Somes, 1960; Shelton and Cain, 2002; Lilly et al., 2012). Loblolly pine sapling survival is also higher following top-kill by clipping compared to prescribed burning (Will et al., 2013). However, sprouting capacity diminishes with age and can be strongly affected by seasonality (Campbell, 1985). For example, loblolly pine saplings top-killed in the winter or early spring survive better than those killed in the late fall or spring when coppiced at age three (Will et al., 2013). In contrast, most hardwood species sprout vigorously as seedlings from dormant buds located on the root collar or from the roots themselves (Del Tredici, 2001; Keyser, 2019). Coppicing may be particularly beneficial to upland oak and hickory due to their relatively high investment in belowground structures and root-stored non-structural carbohydrates (Kruger and Reich, 1997; Bond and Midgley, 2003; Knapp et al., 2021) and sweetgum due to its root sprouting capacity (Kormanik, 1990; Ficklin and Shelton, 2007). Indeed, Willis et al. (2021) reported that coppiced planted northern red oak (*Q. rubra*) seedlings improved their competitive position within northern hardwood harvest gaps. However, given the reduced sprouting potential of loblolly pine seedlings with age and low investment in non-structural carbohydrates (Pile et al., 2017), coppicing may have the unintended effect of promoting hardwood dominance rather than a balanced mixedwoods stand if treatment occurs outside the dormant season.

Another option for improving the relative competitiveness of planted hardwood seedlings is to apply a controlled release fertilizer at planting. Hardwood seedling performance is often stunted by nutrient or moisture stress post planting (Becker et al., 1987). Controlled release fertilizers can mitigate stress by supplying nutrients directly to the rhizosphere of hardwood seedlings for extended periods of time. Moreover, by minimizing leaching, controlled release fertilizers can help inadvertent fertilization of competing non-tree vegetation, which often presents an obstacle to seedling survival and growth without fertilization (Lorimer et al., 1994; Royo and Carson, 2006). Although more commonly applied to western conifers (Carlson and Preisig, 1981; Haase et al., 2006), controlled release fertilizers have been shown to accelerate early root collar, height, and nutrient uptake for a variety of planted hardwood species (Jacobs et al., 2005; Lesko and Jacobs, 2018; Redick et al., 2020). Nevertheless, it is currently unknown whether fertilized hardwood seedlings can remain competitive with unfertilized volunteer loblolly pine over time, or whether more intensive treatments will be required. One such option is to combine coppicing and broadcast fertilization. If successful, broadcast fertilization could enhance the competitive advantage of vigorous hardwood sprouts over the sprouts of loblolly pine.

Accelerating the development of mixedwoods stands is an emerging topic in the southeastern United States (Willis et al., 2019). Previous studies have examined site preparation options for establishing planted conifers on cut-over sites (Waldrop and Lloyd, 1989; Glover and Zutter, 1993; Clabo and Clatterbuck, 2015; Clabo and Clatterbuck 2020 a & b). However, a search of the literature has not revealed how mixedwoods development occurs in the absence of hardwood sprouts, or whether silvicultural intervention can promote development of specific mixedwood types (e.g., pine-oak, pine-gum, pine-poplar). To address these questions, we established an experiment examining the response of one-to-two-year-old volunteer loblolly pine and planted one year-old northern red oak, white oak (*Q. alba*), sweetgum, blackgum (*Nyssa sylvatica*), yellow-poplar, and mockernut hickory (*C. tomentosa*) to a planting only control, controlled release hardwood fertilization, coppicing, and coppicing + broadcast fertilization treatment in northern Mississippi, USA. Specifically, we predict that: (1) loblolly pine will dominate the planted only treatment; (2) fertilization will promote the codominance of yellow- poplar, sweetgum, and loblolly pine; and (3) coppicing alone and coppicing + fertilization will promote hardwood dominance over loblolly pine. The information gained from this study will improve our fundamental understanding of mixedwoods dynamics with loblolly pine, and the ability of silviculture to alter mixedwood type. Understanding these relationships has implications for mixedwoods management at regional and international scales, as loblolly pine is one of the most widely distributed conifer species in the world.

2. Methods

2.1. Study site

On December 23, 2015, an EF4 tornado damaged several locations throughout northern Mississippi. Among the impacted areas was an 18.2 ha stand in the Holly Springs National Forest near Walnut, Mississippi USA (34°56′57″ N 88°54′35″W) (Fig. 1). The stand was clearcut in the spring of 2016 and chemically treated with glyphosate (9.3 L ha^{-1} at 53.80%) and sulfometuron methyl (280.2 g ha^{-1}) in August 2017 for reforestation. Prior to clearcutting, the site was a closed canopy, mature stand dominated by a mixture of loblolly pine, shortleaf pine, white oak, post oak (*Q. stellata*), sweetgum, and mockernut hickory. Post-planting, the site was dominated by a mix of herbaceous and woody vegetation including: greenbriar (*Smilax* spp.), poison ivy (*Toxicodendron radicans*),

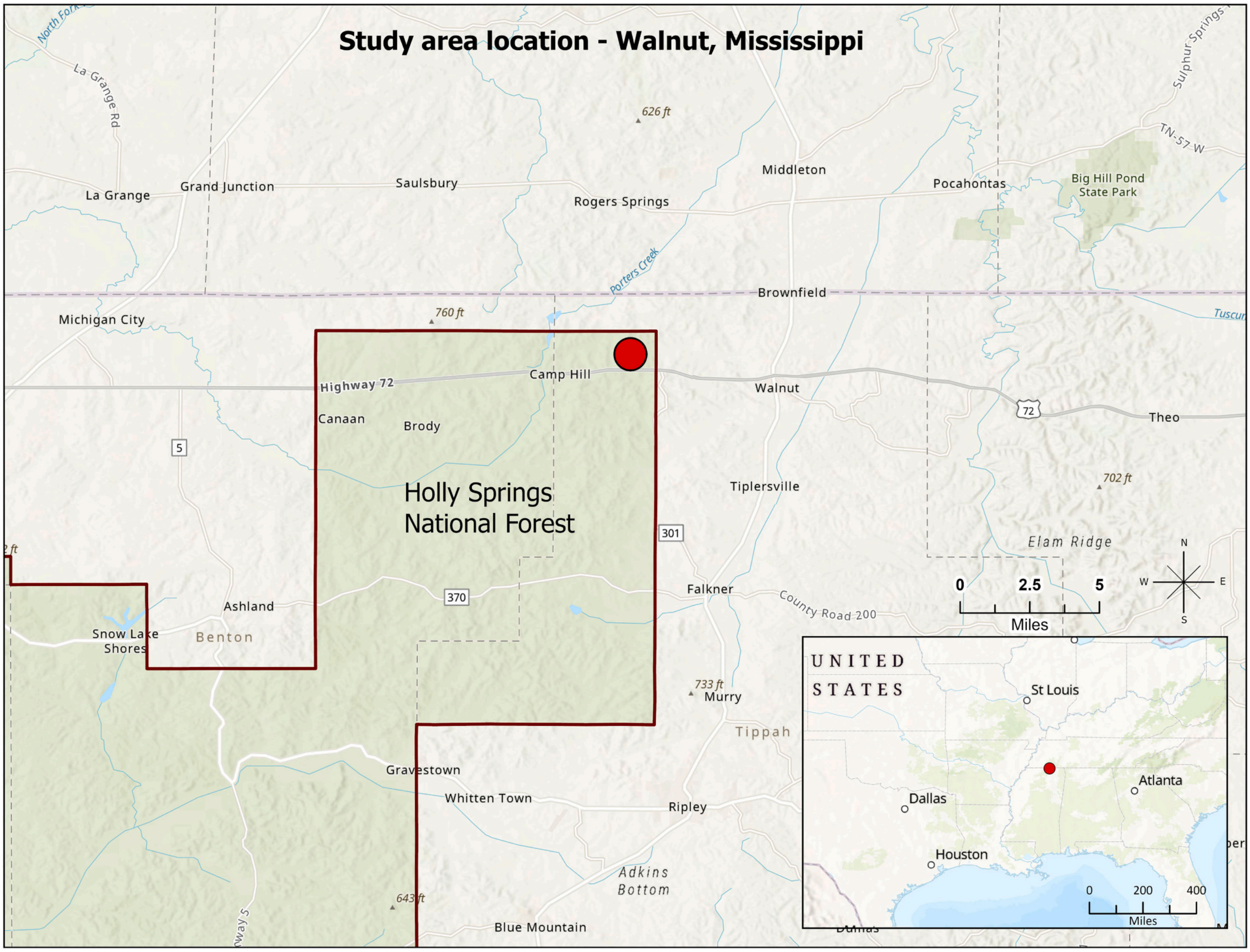

Fig. 1. Location of the study in the Holly Springs National Forest near Walnut, Mississippi USA. The location of the site represented in the map originated from a Google Maps shape file and is in the Geographic Coordinate System, WGS 1984 projection.

devil's walking stick (*Aralia spinosa*), little bluestem (Schizachyrium scoparium), Desodium spp, Panicum spp., Solidago spp., Rubus spp., saltbush (*Baccharis pilularis*), Japanese honeysuckle (*Lonicera japonica*), winged sumac (*Rhus copallinum*), and Sericea lespedeza (*Lespedeza cuneata*).

Climatic conditions near Walnut are humid tropical with the hottest temperatures occurring in July (22.2 - 32.7 °C) and the coldest in January (0.0 – 11.1 °C). Precipitation occurs almost exclusively in the form of rain averaging 1397 mm yr^{-1}. Soils are primarily of the Udorthents Lexington Complex (fine-silty, active, thermic Ultic Hapludalfs) featuring well-drained silty loams (Soil Survey Staff, 2023). Topographic conditions at the stand are varied and include ridge summits, east-southeast facing backslopes (5–10°), and toeslopes. Based on slope position and aspect, site index at a base age of 50 ranged from 21.3–22.9 m for loblolly pine, 19.8–21.3 m for northern red and white oak, 21.3 m for sweetgum, and 21.3–24.4 m for yellow-poplar (Smalley et al., 1991).

2.2. Experimental design

The experiment utilized a completely random design. In the winter of 2017–2018, 48 plots (10 *10 m) were established throughout the stand. Plots were located in areas where residual logging slash was minimal. Each plot was hand-planted with seven one-year old bare root northern red oak, white oak, blackgum, yellow-poplar, sweetgum, and mockernut hickory, respectively (n = 42). Seedlings were planted randomly approximately 1 m apart, to approximate natural regeneration dynamics, and tagged for identification. All seedlings were obtained from the Tennessee State Nursery in Pinson, TN USA. In addition to the planted seedlings, seven volunteer loblolly pine seedlings (1–2 years-old) were retained within each plot. Additional volunteer loblolly pine seedlings were pulled from the plots by hand. Volunteer loblolly pine seedlings were aged in the field based on their size and morphological characteristics (Williams, 1987). In addition, volunteer seedling age was confirmed by counting the rings on a subset of deceased seedlings. Two additional chemical control treatments were applied to each plot post-planting. In March 2018, plots were sprayed with sulfometuron methyl (140.1 g ha^{-1}) to control herbaceous competition. Subsequently, in December 2018, a cut stop stump treatment was applied to control non-tagged woody sprouts and volunteer seedlings (triclopyr-amine 31.8%). Prior to planting, each plot was randomly assigned one of four treatments: hardwood fertilization at time of planting, coppicing post planting, coppicing + post planting broadcast fertilization, and a planting only treatment (n = 12). While technically a silvicultural treatment, the purpose of the planting only control was to assess stand dynamics between volunteer loblolly pine and planted hardwood seedlings. Therefore, we considered this treatment a control. Controlled release fertilization was accomplished by placing one tablet (10-g $plant^{-1}$, 20 N-10 P-5 K) in the planting hole near the root tips of each planted seedling. Volunteer loblolly pine seedlings were not fertilized in this treatment. The coppiced and coppiced + post-planting fertilization treatments were implemented in May of 2019. We delayed these treatments by one growing season to allow for seedling establishment and to avoid confounding planting effects with treatment effects. In both treatments, all seedlings were coppiced approximately six cm above the root collar with hand shears. All species were fully foliated at the time of treatment. Coppiced plots receiving post planting fertilization were broadcast treated with a water soluble 20 N-20 P-20 K fertilizer at a rate of 44.8 kg ha^{-1} immediately following coppicing (Jokela and Long, 2000). The granular fertilizer required to treat each plot was pre-weighed in the lab, stored in Ziplock bags, and added to a rotary spreader in the field. The rotary spreader was set to the level recommended on the fertilizer label. Fertilizer was spread equally throughout the plot in a grid pattern.

2.3. Field measurements

Initial seedling height and root collar diameter measurements were obtained one month after planting. Root collar diameter was measured to the nearest millimeter with calipers, while height was measured at the terminal bud to the nearest centimeter with a height pole. Seedling survival was documented in the winter of 2018–2019 one-year after planting. Seedlings found alive during this check were included in this study (Appendix 1). All dead seedlings were excluded due to potential confounding issues with planting shock. Two plots were removed from the study due to poor initial seedling survival (< 20% survival) (Table 1). One growing season after coppice, we conducted a sprouting census for seedlings established in plots receiving a coppicing treatment. Seedling survival and height was again measured in the winter of 2021 to assess treatment effects on competitive dynamics.

2.4. Statistical methods

Seedling sprouting, growth, total height, and survival were analyzed with a two-way mixed-effects analysis of variance (ANOVA) in R (version 4.3.1) with the lme4 package (Bates et al., 2014). Analysis of sprouting was limited to the coppiced and coppiced + fertilization treatments. Seedlings that died in the coppicing treatments were excluded from the growth and total height analyses but included in the analysis of survival. All performance metrics were averaged at the plot level to avoid pseudoreplication. Fixed effects in the model included treatment and species nested within treatment. The lone random effect was treatment nested within plot. Significant effects were further explored with Tukey's adjusted multiple comparison tests within the emmeans package (Lenth et al., 2019). Differences among treatments or species within treatments were considered significant at $\alpha = 0.05$. Model assumptions of equal variance and normality were examined with quantile-quantile plots and plots of the residuals and met model assumptions.

3. Results

3.1. Survival

Treatment significantly affected seedling survivorship ($F = 5.167$, $P = 0.002$). Survival in the planted control significantly exceeded all other treatments (Table 2). No other statistical differences occurred among treatments (Table 2). Species survival also varied significantly within treatments ($F = 3.822$, $P < 0.001$). In the planted control, survival was generally high among species (63–96%). Volunteer loblolly pine and planted sweetgum survived at a significantly higher rate than northern red oak and mockernut hickory (Fig. 2). No other statistical differences in survival occurred among species (Fig. 2).

With the exception of northern red oak (+ 4%), all species survival declined in the controlled release hardwood fertilization compared to the planted control. Blackgum (- 60%) experienced the largest decline in survival, while unfertilized volunteer loblolly pine declined the least (-14%). Moreover, despite not being fertilized, volunteer loblolly pine had the highest survival in the controlled release fertilization treatment, statistically exceeding that of blackgum and mockernut hickory (Fig. 2).

Like the controlled release fertilization treatment, survival of all species in the coppiced treatment declined compared to the planted control except for northern red oak (+ 13%). White oak experienced the lowest decline in survival (−15%), while mockernut hickory (- 62%) declined the most. All species sprout survival statistically exceeded that of mockernut hickory in the coppiced treatment (Fig. 2).

Compared to the planted control, all species survival declined in the coppiced + broadcast fertilization treatment. Northern red oak (- 3%) had the smallest drop in survival, while sweetgum (- 37%) declined the most. However, no statistical differences were detected among species (Fig. 2).

3.2. Sprouting

Treatment significantly affected sprouting frequency, as seedlings within the coppiced treatment were 15% more likely to sprout than those within the coppiced + broadcast fertilization treatment (F =

Table 2
The main effects of treatment on seedling sprouting, height, and survival (± 1 SE).

Treatment	Sprouting (%)	Seedling (height (cm)	Survival (%)
Planted Control	N/A	125.4 ± 8.7[a]	81 ± 4[a]
Coppiced	88 ± 4[a]	102.0 ± 9.2[a]	65 ± 4[b]
Controlled Release Fertilization	N/A	128.0 ± 9.5[a]	52 ± 4[b]
Coppiced + Broadcast Fertilization	73 ± 4[b]	108.2 ± 8.9[a]	61 ± 4[b]

Table 1
Average (± 1 SE) seedling root collar diameter and height of black gum (BG), mockernut hickory (MH), northern red oak (NRO), sweetgum (SG), volunteer loblolly pine (LP), yellow poplar (YP), and white oak (WO) within each treatment one-month post-planting in 2018.

Initial metric	Treatment	BG	MH	NRO	SG	LP	YP	WO
Root collar diameter (mm)	Planted Control	5.4 (2.0)	5.3 (2.3)	6.3 (2.2)	5.9 (1.4)	5.2 (1.1)	8.4 (2.9)	6.0 (2.6)
	Coppiced	5.0 (1.7)	5.1 (1.5)	6.6 (1.9)	5.8 (1.7)	5.2 (1.6)	9.1 (2.6)	6.3 (2.3)
	Controlled Release Fertilization	5.3 (1.7)	5.2 (2.2)	6.4 (1.8)	5.2 (1.7)	5.3 (1.6)	8.4 (3.3)	6.4 (2.4)
	Coppiced + Broadcast Fertilization	5.2 (2.1)	4.1 (2.6)	6.8 (2.6)	6.2 (1.9)	5.2 (1.5)	10.3 (3.4)	6.5 (2.7)
Height (cm)	Planted Control	33.2 (15.2)	19.3 (8.6)	49.8 (19.3)	46.3 (14.2)	31.8 (8.4)	42.3 (20.1)	34.9 (17.2)
	Coppiced	32.4 (14.0)	19.5 (7.3)	45.8 (19.2)	44.1 (15.2)	33.5 (10.0)	41.5 (22.2)	34.7 (13.9)
	Controlled Release Fertilization	40.3 (15.7)	20.1 (8.6)	43.7 (15.6)	41.3 (11.9)	33.1 (11.2)	46.9 (20.4)	40.3 (12.8)
	Coppiced + Broadcast Fertilization	32.5 (10.6)	15.0 (4.3)	49.4 (17.8)	46.7 (16.7)	32.9 (10.2)	45.7 (20.8)	36.5 (13.0)

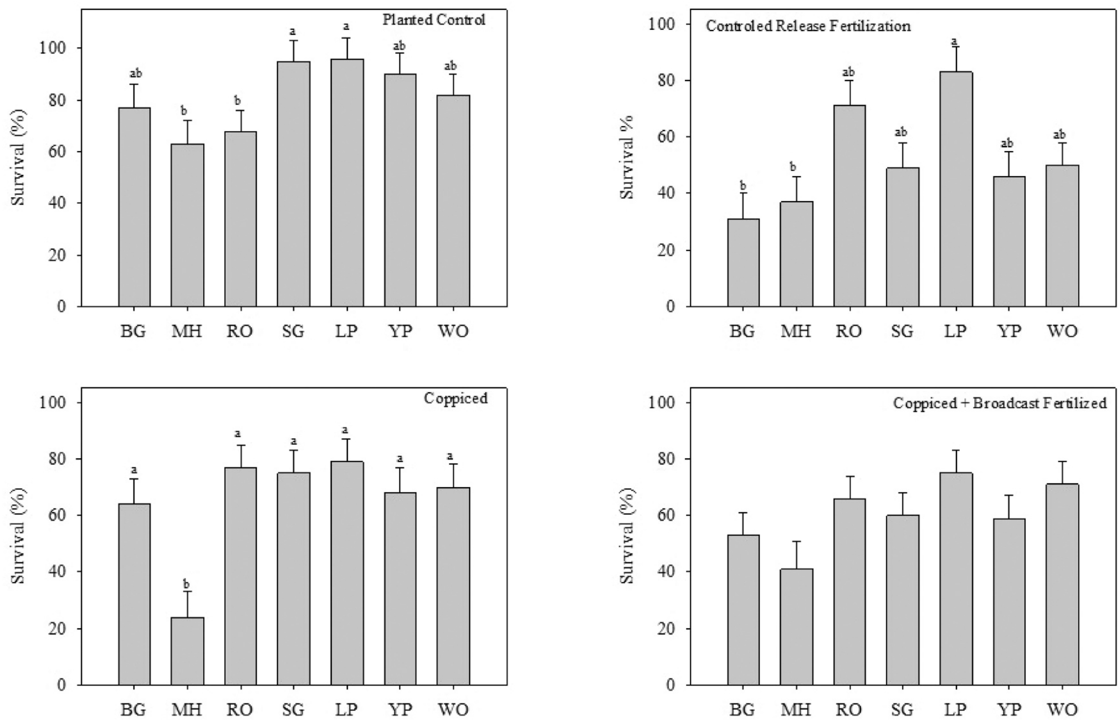

Fig. 2. The effects of treatment (± 1 SE) on black gum (BG), mockernut hickory (MH), northern red oak (NRO), sweetgum (SG), volunteer loblolly pine (LP), yellow poplar (YP), and white oak (WO) on seedling survival four-years since planting and three-years since coppicing.

4.025, P = 0.047) (Table 2). Blackgum sprouted at the highest rate (96% ± 8), while mockernut hickory was the least likely to sprout following coppicing (71% ± 8). Loblolly pine also sprouted vigorously in response to coppicing (92% ± 8). However, species effects were not statistically significant (F = 1.831, P = 0.051).

3.3. Height and competitive position

Seedling total height was highest in the fertilized treatment (128.0 cm ± 9.5) and lowest in the coppiced treatment (102.0 cm ± 9.2), but did not significantly differ (F = 0.233, P = 0.873) (Table 2). However, significant differences in total height were found among

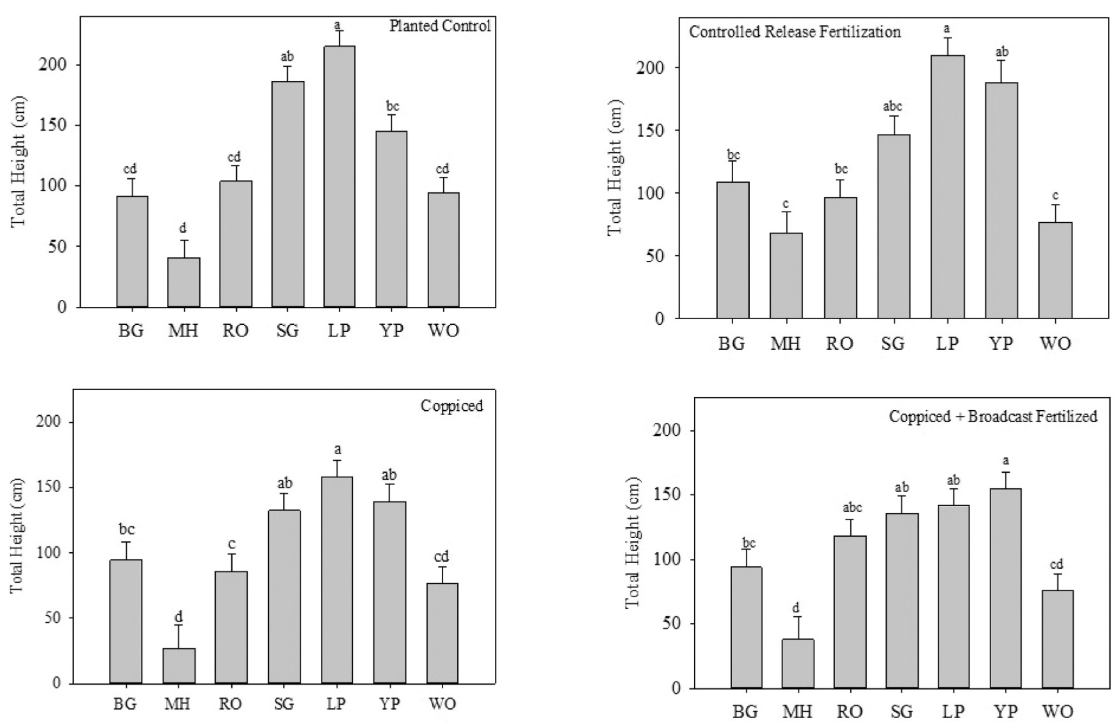

Fig. 3. The effects of treatment (± 1 SE) on black gum (BG), mockernut hickory (MH), northern red oak (NRO), sweetgum (SG), volunteer loblolly pine (LP), yellow poplar (YP), and white oak (WO) on seedling height four-years since planting and three-years since coppicing.

species within treatments (F = 18.344, P = < 0.001). In the planted control, volunteer loblolly pine seedlings were at least twice as tall (214.8 cm ± 12.6) as all other species except sweetgum and yellow-poplar, and significantly taller than all species except sweetgum (Fig. 3).

Controlled release hardwood fertilization produced mixed results. Mockernut hickory (+ 40%), yellow-poplar (+ 23%), and blackgum (+ 15%) seedling height increased following fertilization, while sweetgum (- 22%), white oak (−19%), and northern red oak (- 7%) were taller in the planted control. However, it should be recognized that part of this result can also be attributed to initial seedling size (Table 1). Although controlled release fertilization improved the performance of certain hardwood species, only yellow-poplar (187.6 cm ± 18.1) was statistically competitive with loblolly pine (209.7 cm ± 13.7) and sweetgum (146.8 cm ± 14.9) for growing position (Fig. 3).

Coppicing generally had a negative effect on seedling height, but produced a similar pattern of species competitive dynamics. Apart from blackgum (+ 3%), all species sprouts were shorter in the coppiced treatment compared to seedlings in the planted control. Mockernut hickory (−34%), sweetgum (- 29%), and volunteer loblolly pine (−27%) experienced the largest loss in height from coppicing. Despite the reduction in height, volunteer loblolly pine (157.7 cm ± 13.2), yellow-poplar (139.2 cm ± 13.7), and sweetgum (132.4 cm ± 13.2) sprouts were significantly taller than those of mockernut hickory (27.3 cm ± 18), white oak (76.2 cm ± 13.2), and northern red oak (85.8 cm ± 13.2) (Fig. 3).

Coppicing + broadcast fertilization produced a mixed response among species, but had the largest effect on competitive dynamics. Northern red oak (+ 14%), blackgum (+ 2%) and yellow-poplar (+ 7%) were modestly taller following the combination of treatments, while loblolly pine (−34%), sweetgum (−27%), white oak (- 20%), and mockernut hickory (- 7%) were taller in the planted control. In contrast to all other treatments, yellow-poplar (154.5 cm ± 13.5) was the tallest species and significantly exceeded blackgum, mockernut hickory, and white oak in total height (Fig. 3). Northern red oak (118.5 cm ± 12.6) also improved its relative growing position, as its total height was statistically indistinguishable from sweetgum, volunteer loblolly pine, and yellow-poplar (Fig. 3).

4. Discussion

4.1. Mixedwoods development without post-planting manipulation

Post-planting competitive dynamics in the control treatment were generally aligned with differences in species life history strategy. Partially consistent with our initial hypothesis, volunteer loblolly pine exceeded all other species except sweetgum in terms of height growth. This result is unsurprising considering the substantial height growth potential of loblolly pine on cutover sites (Jokela et al., 2004; Zhao et al., 2019). Although we did not foresee planted sweetgum height growth being competitive with volunteer loblolly pine sans silvicultural intervention, this result is unsurprising considering that sweetgum is also an early colonizer of disturbed sites and has been shown to respond to disturbance faster than slash pine (*P.elliottii*) (Kormanik, 1990; Pile et al., 2019); a species with a similar life history strategy to loblolly pine (Pile et al., 2017). Willis and Blazier (2022) also found that sweetgum height growth was statistically indistinguishable from loblolly pine across a range of planting densities after 23-years. We suspect that the proximity of hardwood competitors played a role in constraining loblolly pine height growth, as loblolly pine seedling development has been shown to be more sensitive to interspecific competition with hardwood species than intraspecific competition early after establishment (Glover and Zutter, 1993; Glover and Quicke, 1999).

Among the hardwood species falling behind sweetgum were the upland oaks. Both species experienced comparatively high mortality in at least one treatment and modest height growth across treatments. The relatively poor performance of oak could be related to the initial size of the planting stock, as oak seedlings featuring a large initial root collar diameter, shoot height, first order lateral density and root volume are generally the most competitive when outplanted (Kormanik et al., 1995; Dey and Parker, 1997; Clark et al., 2000; Jacobs et al., 2005). For comparison, the average initial height and root collar diameter of oak seedlings planted in this study were less than half the size of premium graded northern red oak planting stock, and smaller than standard size planting stock (Clark et al., 2015). Therefore, the root system of most oak seedlings was likely insufficient to support rapid height growth and escape competition with non-tree vegetation. Nevertheless, an early height advantage does not guarantee future sweetgum dominance over oak. Long-term results from a mixed-hardwood planting indicate that sweetgum reaches dominant canopy position early in stand development with cherry bark oak (*Q. pagoda*), but eventually cedes canopy position after two-decades (Lockhart et al., 2006). However, we are unaware of any evidence showing a similar competitive dynamic between sweetgum and northern red and white oak. Early growth deficits were also expected for blackgum and mockernut hickory given their conservative growth strategy. Nevertheless, both species can persist in subcanopy positions better than upland oak or yellow-poplar creating the opportunity for future release following disturbance (Abrams, 2007; Rentch et al., 2009; Knapp et al., 2021).

While limited to the group of species examined, and the edaphic conditions at our site, these results suggest that interplanting alone promotes the co-dominance of loblolly pine and sweetgum rather than a pine-upland oak mixture. It should also be recognized that the results from this treatment do not represent a true control; and therefore, should not be interpreted as what would occur via natural regeneration without silvicultural intervention. A loblolly pine-sweetgum mixedwood may be more effective than a monoculture in mitigating species-specific pests or pathogen risk (Jactel et al., 2017); however, it may provide lower-quality habitat for hard mast dependent species, compared to pine-oak mixedwoods (Lee et al., 2001; Perkins and Conner, 2004), and will be less productive than a loblolly pine monoculture (Glover and Quicke, 1999; Willis et al., 2022). Thus, the effectiveness of interplanting without silvicultural intervention ultimately depends on which management objectives are being prioritized.

4.2. Effects of controlled release hardwood fertilization

Consistent with our initial hypothesis, yellow-poplar, and sweetgum were the tallest hardwood species in the controlled release fertilization treatment; yet, neither species was taller than volunteer loblolly pine. Our nested experimental design prevented a statistical comparison of the interaction between species and treatment; however, a biological evaluation of this relationship revealed a mixed response to fertilization. Notably, yellow-poplar benefited from fertilization, which is consistent with previous reports (Jacobs et al., 2005; Schuler and Robison, 2006), while sweetgum height declined in fertilized plots conflicting with results from fertilization experiments in monocultures (Guo et al., 1998; Coyle et al., 2008). The negative response of sweetgum to fertilization was particularly surprising considering that planting occurred on a cutover site with a low-to-moderate site index value (Scott et al., 2004). While we did not assess soil nutrition directly, this latter point suggests that fertilization should have improved the growth and survival of all species. Nevertheless, apart from northern red oak, hardwood survival did not exceed 50% post-fertilization. Collectively, the high mortality rate and mixed response among species adds to existing uncertainty over the potential efficacy of early hardwood fertilization (Schuler and Robison, 2010).

We do not suspect that overfertilization was the cause of poor seedling survival, as a relatively low rate (10 g tablets) of fertilizer was applied at planting and we did not observe any evidence of fertilizer burn. Other common explanations for fertilization failure, such as competition from sprouts and herbivory are unlikely causes of seedling mortality in our study (Taylor et al., 2006; Berenguer et al., 2009;

Schuler and Robison, 2010; Frank et al., 2018; Lesko and Jacobs, 2018), as root sprouts were controlled within the plots and browse damage was minimal (John Willis, Personal Observation). While herbaceous vegetation was controlled during the first growing season, and mineral nutrition was directly applied, competition with non-tree vegetation likely contributed to the mixed growth response, as grass and shrub species often overtopped seedlings in subsequent growing seasons. We also suspect that a combination of planting shock and small initial seedling size contributed to seedlings not escaping the non-tree vegetation layer, as our seedlings were mostly < 50 cm tall with a root collar diameter < 10 cm at planting (Struve, 1990; Dierauf and Garner, 1996; Clark et al., 2000; McNabb and VanderSchaaf, 2005; Morrissey et al., 2010).

4.3. Effects of coppicing with and without fertilization

In contrast to our initial hypothesis, coppicing produced a competitive mixture similar to the fertilization treatment. The most interesting aspect of this result was not the vigorous sprouting response of the coppiced volunteer loblolly pine seedlings, but the subsequent competitiveness of its sprouts with and without broadcast fertilization considering the seedlings were coppiced in the spring. (Shelton and Cain, 2002; Lilly et al., 2012; Will et al., 2013). Our coppicing treatments were purposely conducted in the spring, when loblolly pine is more sensitive to top-kill given its low investment in non-structural carbohydrates (Will et al., 2013; Pile et al., 2017). For this reason, in addition to the strong sprouting potential and conservative growth strategy of many of the hardwood species planted in this study, we expected both coppicing treatments to accelerate hardwood dominance. While loblolly sprouts were shorter than loblolly pine saplings in the planted control, coppicing had little effect on the relative competitiveness of loblolly pine with hardwood sprouts.

Explaining this result based on the data collected is challenging. Seedling age at coppicing likely improved loblolly pine sprout performance, as sprout survival and vigor has been shown to be generally strong at age two (Lilly et al., 2012). We also cannot rule out the possibility that volunteer loblolly pine gained a rooting advantage due to its earlier establishment, which may have increased resource acquisition and subsequent carbohydrate production and storage. In contrast, bare-root hardwood seedlings may have experienced planting shock potentially limiting resource acquisition in the year between planting and coppicing (Struve, 1990). Thus, the difference in establishment history may explain why loblolly pine sprouts remained competitive with planted hardwoods three-years post coppicing. We suspect the sprouts of most hardwood species would have become dominant if the initial size of the hardwood planting stock was larger, the interval between planting and coppicing longer, containerized seedlings were planted instead of bareroot, or if the volunteer loblolly pine seedlings were coppiced at an older age (Dey and Parker, 1997; Wilson et al., 2007; Will et al., 2013).

We also cannot discount the possibility that at least a portion of the volunteer seedlings were shortleaf-loblolly pine hybrids, as both species were present in adjacent stands. However, a limited investigation of needle length and size were consistent with values reported for pure loblolly pine seedlings (Lilly et al., 2012). Further studies examining the physiological performance and underlying genetics of the volunteer loblolly pine seedlings will be required to further explain loblolly pine sprout performance.

Coppicing in combination with broadcast fertilization produced the greatest equality in species height among treatments, and the only treatment where the height of yellow-poplar sprouts biologically exceeded that of volunteer loblolly pine. Sweetgum and northern red oak were also among the most competitive species following the combination of treatments. From a hardwood perspective, this result is not surprising, as it corresponds with previous reports of sweetgum, yellow poplar, and northern red oak sprouting and post top-kill growth potential (Ficklin and Shelton, 2007; Keyser, 2019; Willis et al., 2021). While these early results are encouraging for promoting species diverse mixedwoods, the future development of both coppicing treatments remains uncertain, as we are unaware of any studies documenting sprout competition between loblolly pine and hardwood species originating from top-killed seedlings. Waldrop (1989, 1997) reported that planted loblolly pine can outcompete hardwood sprouts over time. Miller et al. (2003), also reported a decline in hardwood sprout basal area when competing against planted loblolly pine seedlings over the course of 15-years. In contrast, Willis and Blazer (2022) reported that loblolly pine experienced high levels of mortality when planted in mixture with sweetgum seedlings after 23-years. However, in that study, sweetgum seedlings were planted one-year prior to loblolly pine. Differences in site quality between studies further complicate projecting the future outcome of either coppicing treatment.

5. Conclusion

Anthropogenic land use legacies have altered the structure and species composition of forests in eastern North America (Foster et al., 2003; Dyer, 2010; Abella and Schetter, 2021). Fire-sensitive species (e.g., loblolly pine, blackgum, and sweetgum) are now prevalent across much of the region and are modifying ecological function (Alexander et al., 2021). One of the potential consequences of fire-sensitive species establishment is the cessation of recruitment of fire-adapted species such as oak (Palus et al., 2018). Changes in recruitment dynamics have implications for forest management, as tree species composition influences the type of stand attributes that develop over time.

In this study, we examined how mixedwoods development was affected by competition with fire-sensitive species on a cutover site; and if silvicultural intervention could influence species composition. After four-years, our results indicate that each treatment option created conditions promoting pine-hardwood co-dominance. Volunteer loblolly pine consistently occupied dominant or co-dominant growing position across treatments, but silvicultural intervention altered hardwood competitiveness producing differing patterns of species dominance. Planting without further treatment, controlled release fertilization of hardwoods at planting, and coppicing one-year post-planting promoted co-dominance between volunteer loblolly pine and sweetgum (planting only) or a mixture featuring sweetgum and yellow-poplar (controlled release fertilization or coppiced). In contrast, coppicing in combination with broadcast fertilization produced the most species diverse pattern of co-dominance, promoted yellow-poplar to dominant growing position, and increased the competitiveness of northern red oak.

While it is still early in stand development, important lessons can be taken from our results. First, loblolly pine sprouts can successfully compete with those deriving from small hardwood planting stock if seedlings are coppiced at a young age (1–2 years). This result is consistent with the findings of Lilly et al. (2012). Second, northern red oak required a combination of treatments to become competitive with encroaching, fire-sensitive species. This agrees with several studies indicating that reintroducing fire into degraded stands often promotes-fire sensitive species recruitment over upland oaks without additional silvicultural treatments (Arthur et al., 2012; Brose et al., 2013; Izbicki et al., 2020), but differs in that our study was conducted on a cutover site with minimal light limitation. Finally, sweetgum and loblolly pine are likely to occupy dominant-to-co-dominant growing positions within mixedwoods regardless of silvicultural intervention. Consequently, future studies should investigate how loblolly pine-sweetgum mixtures functionally compare to the previously dominant shortleaf pine-upland oak communities.

CRediT Authorship Contribution Statement

JL Willis: Conceptualization, Methodology, Formal analysis, Data curation Writing original draft, Writing review & editing, Visualization, Project administration, Funding acquisition. **AB Self**: Data curation, Writing review & editing, Funding acquisition.

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.

Data availability

Data will be made available on request.

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Appendix 1. – Initial number of plots and black gum (BG), mockernut hickory (MH), northern red oak (NRO), sweetgum (SG), volunteer loblolly pine (LP), yellow poplar (YP), and white oak (WO) seedlings within each treatment at the start of the experiment in 2019

Treatment	Plots	BG	MH	NRO	SG	LP	YP	WO
Planted	12	31	18	69	45	63	35	64
Coppiced	11	37	24	57	49	65	44	67
Controlled Release Fertilization	11	48	32	47	28	47	24	49
Coppiced + Broadcast Fertilization	12	39	13	79	43	64	41	60

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