STATUS OF PLANTED OAK MONOCULTURES ON A COASTAL PLAIN MINOR BOTTOM IN THE FIFTH DECADE AFTER ESTABLISHMENT

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Abstract—In the mid-1970s, four oak (*Quercus* spp.) species adapted to bottomland sites, cherrybark oak (*Q. pagoda*), Nuttall oak (*Q. texana*), swamp chestnut oak (*Q. michauxii*), and water oak (*Q. nigra*), were planted in monocultures at several spacings to evaluate species and spacing effects on stand dynamics. The present investigation extends this study out to the fifth decade by comparing the oak monocultures planted at the two widest spacings (8 by 8 feet and 12 by 12 feet). A thinning in March 1996 provided an opportunity to assess potential effects of a single tending treatment. Results suggest that the original species and spacing treatments continue to influence development at individual-tree and stand levels. Red oak species were larger than swamp chestnut oak, while trees at the wider spacing (12 by 12 feet) were larger than trees established at the narrower spacing (8 by 8 feet). The effect of spacing on stems per acre was not statistically significant, but stand-level basal area was greater at the wider spacing. Both live-crown ratio and survival since 1996 were greater in stands that were treated with a one-time thinning. This study reinforces how decisions made at the time of stand establishment and early stand tending can have lasting effects on the development of planted bottomland oak stands.

INTRODUCTION

Although short-term studies of forests under active management can provide meaningful insights that help inform management decisions, the longevity of tree species and the multi-decadal nature of stand dynamics require a longer-term perspective to fully evaluate consequences of interventions in managed forests. Longitudinal investigations based on designed silviculture experiments can be particularly valuable to enriching our understanding of managed forests since they offer opportunities to address long-term impacts of deliberate manipulations of a stand within a statistically rigorous framework.

In the mid-1970s, the Forest Service, U.S. Department of Agriculture initiated a hardwood plantation experiment on a minor bottom in southeast Arkansas owned at that time by Georgia-Pacific Corporation. The experiment was installed to evaluate effects of species and spacing on the dynamics of planted hardwood monocultures. As part of this study, four oak (*Quercus* spp.) species were planted: three types of red oak (cherrybark oak (*Q. pagoda*), Nuttall oak (*Q. texana*), and water oak (*Q. nigra*)) and one white oak (swamp chestnut oak (*Q. michauxii*)). The present investigation compared these four species planted at the two widest spacings in the fifth decade after stand establishment. Approximately half of the planted oaks were treated with a precommercial thinning. Therefore, the potential effect of this one-time thinning was also assessed. The objective of this investigation was to evaluate long-term effects of species, spacing, and thinning on oak plantation development at the individual-tree and stand levels.

METHODS

The 75-acre study site is located on what is now Weyerhaeuser Company property in Drew County, Arkansas, on a terrace adjacent to a minor stream bottom in the Western Gulf Coastal Plain. The poorly drained Amy Series (a fine-silty loam) is the dominant soil at this site. Prior to initiating the study, the site supported a mixed hardwood-pine (*Pinus* spp.) stand that was harvested, cleared, root raked, and disked in the fall of 1975 (Carlson and Goelz 1998).

The original study consisted of a factorial of eight hardwood species planted at five spacings with treatment combinations replicated four times in a randomized complete block design (see Carlson and Goelz (1998) for details). The site was planted in May

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Citation for proceedings: Bragg, Don C.; Koerth, Nancy E.; Holley, A. Gordon, eds. 2020. Proceedings of the 20th Biennial Southern Silvicultural Research Conference. e–Gen. Tech. Rep. SRS–253. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station. 338 p.

1976. The present investigation considered only the cherrybark, Nuttall, swamp chestnut, and water oak plantings established at the two widest spacings: 8 by 8 feet (hereafter, “narrow”) and 12 by 12 feet (hereafter, “wide”). Deployment of these spacings on a per acre basis scaled up to 680 and 302 trees, respectively. Each experimental unit consisted of a block of 169 trees (13 rows by 13 columns). This design established stands of 0.25 acres at the narrow spacing and 0.56 acres at the wide spacing.

Following stand establishment, the study site was treated mechanically to control competing vegetation. Mechanical release was done by mowing between rows for the first 14 years. A precommercial thinning was applied in March 1996 to a subset of the stands. Stands were free thinned to either B-level stocking or to 50 percent stocking based on Goelz (1995), whichever was higher, by targeting volunteers and poorly formed planted trees. The intensity of thinning was variable among stands due to differences in the abundance of volunteers. For example, the reduction in basal area per acre (BA) from thinning ranged from 13 to 63 percent. The thinning treated 1 to 3 replicates of the oak species-spacing combinations. Thus, the thinning produced an unbalanced experimental design with only 1 or 2 replicates for most of the 16 three-way treatment combinations.

In the summer of 2017, all 32 stands of the oak species planted at narrow and wide spacings (4 species x 2 spacings x 4 replications) were revisited for sampling. Each sample was a nested-plot array consisting of a single, 0.10-acre plot (hereafter, “large plot”) established at the center of each plantation to capture trees at least 3.5 inches in diameter at breast height (d.b.h.) and a single, 0.05-acre plot (hereafter, “small plot”) centered within each large plot to capture trees 0.5 to 3.4 inches d.b.h. Species, d.b.h., total height, height to crown base, and condition were recorded for each sampled tree. Grade of the first 16-foot log was determined following the assessment by Rast and others (1973) for all planted trees greater than 10 inches d.b.h.

Analysis of variance (ANOVA) was used to assess the effects of species, spacing, and thinning on planted tree and stand attributes. Tree responses included mean d.b.h., mean height, and mean live crown ratio (LCR) of planted trees. Responses of planted trees at the population level consisted of mean BA, mean number of trees per acre (hence, stem density), two estimates of survival, and log grade of the first log. Planted-tree survival was calculated based on the stem density of live trees recorded in 2017 expressed as a percentage of 1) initial planting density for unthinned stands only (IPD) and 2) the immediate post-thinning density in 1996 (PTD). Several estimates of the number of grade-quality first logs (those receiving a grade of 1, 2, or 3) were estimated and analyzed including, mean density of grade 1 and 2 first logs per acre (sum of grades 1 and 2), mean density of grade 3 first logs per acre, and mean density of graded first logs (sum of grades 1, 2, and 3) expressed as both an absolute density (number of graded first logs per acre) and relative density (percent of total planted trees per acre). The mean BA of all trees (planted + volunteer) was used for assessing stand-level response as well as the mean BA of volunteer pine, hardwood, and both individually. Because the thinning created an unbalanced experimental design with low replication for most three-way treatment combinations, only the main effects and two-way interactions of species, spacing, and thinning were considered. Significance of ANOVA models was assessed at an alpha level of 0.05 and treatment means were compared using Tukey’s HSD. All analysis was performed in SAS 9.4.

RESULTS

Tree Attributes

ANOVA detected significant main effects of species and spacing on mean d.b.h. ($p = 0.049$ and 0.015, respectively) and mean height ($p = 0.001$ and 0.034, respectively) (table 1). Mean separation comparing d.b.h. among species and spacings revealed cherrybark oak was larger in diameter than swamp chestnut oak and trees planted on a 12- by 12-foot spacing were larger in diameter than trees on a narrow spacing. Comparisons of species based on height revealed cherrybark oak was taller than swamp chestnut oak and Nuttall oak, and water oak was taller than swamp chestnut oak. Mean separation of spacings based on height found trees planted on a wide spacing were taller than trees on a narrow spacing. An effect of thinning on mean LCR was detected ($p = 0.022$). Trees in thinned stands had larger LCR than those in unthinned stands. No significant interactions were detected.

Stand and Population Attributes

Species had a significant effect on both the BA ($p = 0.018$) and stem density ($p = 0.021$) of planted oaks (table 2). Cherrybark oak and water oak had significantly greater BA than Nuttall oak. For stem density, there were significantly fewer stems of Nuttall oak than swamp chestnut oak. There was no effect of spacing on stem density but spacing did affect BA ($p = 0.013$). Basal area of planted oak was greater at the wide spacing than the narrow spacing. An effect of thinning on stem density was detected ($p = 0.021$) and mean separation revealed a higher density of stems in unthinned than thinned stands. Spacing was a significant factor in ANOVA models of long-term survival in unthinned stands (IPD; $p = 0.002$), but species was not ($p = 0.058$). IPD was greater at the wide spacing (55.1 ± 2.9 percent) than the narrow spacing (27.8 ± 3.2 percent). Spacing ($p = 0.023$) and thinning ($p = 0.012$) had an effect on post-thinning

Table 1—Least squares means and standard errors of tree-level attributes (d.b.h., height, and LCR) for main effects of species, spacing, and thinning in a 41-year-old bottomland hardwood plantation experiment in southeast Arkansas

Attribute	Oak species		Spacing		Thinning	
			inches			
d.b.h.	Cherrybark	12.0 ± 0.6 a	Narrow	9.8 ± 0.4 b	Unthinned	10.0 ± 0.5
	Nuttall	10.7 ± 0.6 ab	Wide	11.4 ± 0.4 a	Thinned	11.1 ± 0.4
	Swamp chestnut	9.3 ± 0.6 b				
	Water	10.3 ± 0.6 ab				
			feet			
Height	Cherrybark	86.3 ± 2.6 a	Narrow	71.5 ± 3.3 b	Unthinned	72.9 ± 2.1
	Nuttall	73.4 ± 4.3 bc	Wide	79.2 ± 2.5 a	Thinned	77.4 ± 1.7
	Swamp chestnut	64.1 ± 3.9 c				
	Water	77.6 ± 2.2 ab				
			percent			
LCR	Cherrybark	49.5 ± 1.9	Narrow	48.0 ± 1.3	Unthinned	47.9 ± 1.3 b
	Nuttall	50.1 ± 1.9	Wide	51.5 ± 1.4	Thinned	52.2 ± 1.3 a
	Swamp chestnut	49.3 ± 1.9				
	Water	51.5 ± 1.9				

d.b.h. = diameter at breast height, LCR = live crown ratio, narrow = 8- by 8-foot spacing, wide = 12- by 12-foot spacing.

Tukey's HSD results are included comparing attribute means within a column. Means followed by the same letter were not significantly different at 0.05 level.

Table 2—Least squares means and standard errors of population-level attributes (BA, density, and PTD) for main effects of species, spacing, and thinning in a 41-year-old bottomland hardwood plantation experiment in southeast Arkansas

Attribute	Oak species		Spacing		Thinning	
			square feet per acre			
BA	Cherrybark	111.3 ± 8.2 a	Narrow	84.5 ± 5.6 b	Unthinned	100.3 ± 6.3
	Nuttall	74.5 ± 7.6 b	Wide	107.2 ± 5.8 a	Thinned	91.1 ± 5.0
	Swamp chestnut	90.8 ± 8.2 ab				
	Water	106.9 ± 8.2 a				
			stems per acre			
Density	Cherrybark	136 ± 15 ab	Narrow	165 ± 10	Unthinned	177 ± 12 a
	Nuttall	121 ± 14 b	Wide	144 ± 11	Thinned	133 ± 10 b
	Swamp chestnut	182 ± 15 a				
	Water	180 ± 15 ab				
			percent			
PTD	Cherrybark	70.5 ± 6.7	Narrow	61.9 ± 4.6 b	Unthinned	60.8 ± 5.1 b
	Nuttall	67.7 ± 6.3	Wide	78.6 ± 4.8 a	Thinned	79.6 ± 4.1 a
	Swamp chestnut	72.7 ± 6.8				
	Water	70.0 ± 6.8				

BA = basal area, PTD = post-thinning density in 1996.

Tukey's HSD results are included comparing attribute means within a column. Means followed by the same letter were not significantly different at 0.05 level.

survival (PTD). PTD was greater in the wide spacing than the narrow spacing and in thinned stands than unthinned stands. Species was a significant factor in the ANOVA model for volunteer pine basal area (p = 0.026) (table 3). Pine basal area was higher in Nuttall oak and swamp chestnut oak stands than planted stands of cherrybark oak and water oak. No effects were detected in ANOVA models for volunteer hardwood basal area, total volunteer basal area, or total stand-level basal area (planted plus volunteer). No significant interactions were detected.

Log Grade Assessment

Species was the only significant factor in the ANOVA models for relative (p = 0.002) and absolute (p = 0.003) density of graded first logs (sum of grades 1, 2, and 3). Mean separation revealed that both the relative density and absolute density of graded first logs were higher for cherrybark oak (table 4) than Nuttall oak, swamp chestnut oak, and water oak. No differences in relative density or absolute density of graded first logs were found among Nuttall oak, swamp chestnut oak, and water oak. Only species had an effect (p < 0.001) on the absolute density of grade 1 and grade 2 first logs (sum of grades 1 and 2). Cherrybark oak stands supported a higher absolute density of grade 1 and 2 first logs than Nuttall oak, swamp chestnut oak, and water oak. No differences in absolute density of grade 1 and grade 2 first logs were detected among the Nuttall oak, swamp chestnut oak, and water oak. None of the factors tested had an effect on the absolute density of grade 3 first logs. No significant interactions were detected.

DISCUSSION

Treatments implemented as part of the original experiment continue to explain differences among the planted oak monocultures. A salient finding of earlier reports was that swamp chestnut oak stems were generally smaller than stems of planted red oak species (Kennedy and others 1988). Our study observed a similar difference in tree size between oak species groups. The smaller size of swamp chestnut oak compared to the red oaks, particularly cherrybark oak and water oak, is consistent with growth differences between species of the red oak and white oak sections under open canopy conditions observed in upland oak ecosystems. In

Table 3—Least squares means and standard errors of basal area (square feet per acre) for volunteer trees and total stand basal area (planted + volunteer) sorted by stands planted to the four oak species in a 41-year-old bottomland hardwood plantation experiment in southeast Arkansas

	Volunteer basal area			
Oak species	Pine	Hardwood	Total	Stand basal area
Cherrybark	3.6 ± 2.7 b	26.1 ± 6.2	29.6 ± 10.8	141.9 ± 11.0
Nuttall	23.1 ± 5.1 a	35.1 ± 5.7	58.2 ± 14.0	138.3 ± 10.1
Swamp chestnut	22.3 ± 7.2 a	22.8 ± 6.2	45.2 ± 13.3	153.4 ± 11.0
Water	2.1 ± 2.1 b	17.6 ± 6.2	19.8 ± 8.3	126.7 ± 11.0

Tukey's HSD results are included comparing means within a column. Means followed by the same letter were not significantly different at 0.05 level.

Table 4—Least squares means and standard errors of absolute (stems per acre) and relative (percent of live planted trees) densities of graded first logs (grades 1+2+3), density of grades 1+2 first logs (stems per acre), and density of grade 3 first logs (stems per acre) sorted by the four planted oak species in a 41-year-old bottomland hardwood plantation experiment in southeast Arkansas

	Graded first logs			
Oak species	Absolute density	Relative density	Grades 1+2	Grade 3
Cherrybark	72 ± 7 a	53 ± 5 a	25 ± 6 a	47 ± 7
Nuttall	36 ± 6 b	30 ± 5 b	1 ± 1 b	35 ± 7
Swamp chestnut	35 ± 7 b	18 ± 5 b	2 ± 2 b	33 ± 7
Water	43 ± 7 b	23 ± 5 b	4 ± 2 b	38 ± 7

Tukey's HSD results are included comparing means within a column. Means followed by the same letter were not significantly different at 0.05 level.

the Missouri Ozarks, red oak saplings have a height growth advantage over white oak saplings at residual overstory densities less than 22 square feet per acre (Vickers and others 2014). The red oak species included in this study are shade intolerant (Meadows and Stanturf 1997) and capable of rapid growth in high light environments (Filer 1990, Krinard 1990, Vozzo 1990). Swamp chestnut oak, on the other hand, is moderately shade intolerant (Meadows and Stanturf 1997) with a moderate growth rate (Edwards 1990). Slower growth of swamp chestnut oak may be a trade-off for higher shade tolerance. There was also a high BA of volunteer loblolly pine (*Pinus taeda*) recorded in swamp chestnut oak stands. Furthermore, swamp chestnut oak was often in subordinate crown classes beneath the pine. The slower growth of swamp chestnut oak may have predisposed these stands to overtopping by volunteer pine, which may have exacerbated size differences with the red oaks.

Hydrology varied considerably across the 75-acre study area and the effect of species on planted tree BA and density (stems per acre) may have reflected interspecific differences in adaptability to bottomland landforms. Cherrybark oak and water oak are adapted to a wide range of soils (Krinard 1990, Vozzo 1990). These species were among the top performing in terms of tree-level growth and stand production at stand age 20 years (Carlson and Goelz 1998) and out to the fifth decade among the four oaks. Nuttall oak, however, had low BA and density compared to the other species. This species is often associated with wetter bottomland landforms (Filer 1990) and, of the oak species considered, is the least adaptable from a habitat perspective. Early reports noted high variability of Nuttall oak survival across the study site (Carlson and Goelz 1998, Kennedy and others 1988). Variability in Nuttall oak survival and poor performance at the population level may be linked to soil heterogeneity across the study area, yet also may be associated with high volunteer pine BA and interspecific competition.

Species had an effect on densities of graded first-logs, but spacing or thinning did not. This effect was attributable to cherrybark oak stands outproducing the other species, especially in yielding higher-valued grade 1 and 2 butt logs. Differences in butt-log grade among species was largely due to species-specific variation in stem quality and size. For example, the greater number of defects in both Nuttall oak and water oak contributed to lower densities of butt logs receiving a grade of 3 or better, while the smaller size of swamp chestnut oak stems limited the number of first logs that could receive a grade. Defects on Nuttall oak were mainly surficial bumps from occluded branch stubs and likely would be more correctable as tree size increases. In the case of water oak, however, many stems exhibited heavy decay originating from large dead branches and would be less likely to improve with time. Spacing did not affect log grade in this study. Quality growth has been linked to stand density, spacing, and the timing of crown closure (Sonderman 1985). The relatively low crown base heights in 10- to 20-year-old bottomland red oak plantations planted on a 12- by 12-foot spacing was likely due to delayed crown closure (Stoll and Frey 2016). It is possible that a spacing effect was detectable at a younger stand age when stems were smaller, but that it diminished as diameter growth dampened the visual impact of stem defects.

Although competition control was performed for over a decade post-establishment, this effort focused on treating the area between rows, while leaving competition within rows largely unchecked. By stand age 20 years, the BA of volunteers in oak stands ranged from 4 to 42 percent of total BA (planted plus volunteer), which is comparable to the 16 to 42 percent observed in 2017. The report on 20-year results alluded to potential negative effects of volunteer ingrowth on planted tree survival (Carlson and Goelz 1998). Our results suggest that volunteer encroachment, especially loblolly pine, may have contributed to the poor performance of swamp chestnut oak and Nuttall oak. Similar to findings at stand age 20 years, total BA in 2017 did not vary among the planted oaks despite significant variation in planted tree and volunteer BA. Carlson and Goelz (1998) speculated that similarity in total BA across treatments could be a reflection of stands growing at the site's carrying capacity. These authors also predicted that total BA would vary among species in the future due to the impacts of autecological differences in the planted species on stand dynamics. This prediction is consistent with the transitioning of an even-aged stand from the stem exclusion stage to the understory reinitiation stage of development (Oliver and Larson 1996). Results out to stand age 41 years indicate this prediction has not played out. Given time, density-independent factors, such as longevity, may still affect structural development in a species-specific manner.

Spacing effects on tree-level attributes noted in earlier reports have also persisted. The influence of initial spacing can be explained by stand dynamics concepts relating spacing and stand density to growing space allocation, tree growth, and self-thinning. All things being equal, crown closure will happen earlier in stands planted at a narrower spacing, leaving each tree with less space in the developing canopy, which, in turn, limits growth by restricting crown and leaf area development (Oliver and Larson 1996). Earlier onset of crown closure likely explains the smaller average stem diameter in stands at the 8- by 8-foot spacing compared to the 12- by 12-foot spacing. Larger stem diameter in the wider spacing may not be just a legacy effect of rapid early growth. A separate analysis based on this study found that individual-tree growth over the last 20 years was positively associated with spacing, suggesting that growth differences between these spacings have persisted. Higher survival at the wider spacing was likely linked to greater canopy space allocation and lower competitive stress at the individual-tree level. The higher rate of self-thinning in stands planted at the narrower spacing eliminated initial differences in population density. This difference in self-thinning also helps explain the higher BA in stands planted at the wider spacing, which, by age 41 years, supported planted populations of comparable density to the narrower spacing, but with a larger average stem diameter. Trees were also significantly taller in stands established at a 12- by 12-foot spacing. This result is interesting since height is generally assumed to be relatively independent of stem density (Oliver and Larson 1996). Considering initial density of the 8- by 8-foot spacing was over twice that of the 12- by 12-foot spacing (680 versus 302 stems per acre), it is plausible the height disparity observed between spacings is associated with density-dependent factors, including competitive pressure.

The precommercial thinning over 20 years ago explained variability in tree and population-level attributes of oak monocultures detected at stand age 41 years. Tree-level growth enhancement after thinning is largely the result of providing residual trees with access to additional canopy space for crown expansion and leaf area development (Oliver and Larson 1996). In this study, live crowns, but not stem diameters, were larger in thinned stands. Although not a significant factor in the model for tree diameter, the p-value for thinning was still relatively low ($p = 0.075$), suggesting a possible weak association in the third decade post-thinning. Another analysis of this study found that thinning enhanced tree-level basal area increment in the first decade after thinning but not the following decade. Thinned stands also had higher post-thinning survival than unthinned stands. Improved survival in thinned stands was likely related to enhanced tree vigor, as evidenced by a larger LCR, as well as the thinning's effectiveness in removing trees likely to succumb to mortality.

CONCLUSIONS

Research on the dynamics of older oak plantations, such as this study, enriches our understanding of managed oak ecosystems. This study reinforces how silvicultural actions can have long-term consequences on stand development at the individual-tree and stand levels. When growing bottomland oak plantations, stand establishment options, including what species to plant and at what spacing, should consider landowner objectives, site characteristics, and establishment costs. For example, if timber production is an objective on similar sites, then planting cherrybark oak at either spacing could meet management objectives. However, planting at the wider 12- by 12-foot spacing would cut the number of seedlings by more than half and reduce the cost of stand establishment. It is worth stating that this study assessed tree grade based on standing timber and, therefore, these results may not apply to effects of spacing on lumber grade. Early vegetation management to control competition both between and within rows is also likely warranted on similar sites. An early thinning could also benefit similar planted oak stands, especially where undesirable volunteer encroachment is severe. Finally, similar oak stands would likely benefit from a second thinning to enhance tree growth and improve stand quality that may also generate revenue.

ACKNOWLEDGMENTS

We thank Weyerhaeuser Company for access to the study site and the Center for Bottomland Hardwoods Research of the U.S. Department of Agriculture, Forest Service, Southern Research Station for providing older data and historical information on this study. We thank the 2017 field crew for their dedication to collecting quality data. Finally, we thank Dr. Benjamin Knapp and Dr. Brent Frey for reviewing an earlier draft. This work was supported by the U.S. Department of Agriculture, National Institute of Food and Agriculture, McIntire-Stennis Project (Accession #: 1010629).

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