MIDSTORY SHELTERWOOD TO PROMOTE NATURAL *QUERCUS* REPRODUCTION ON THE MID-CUMBERLAND PLATEAU, ALABAMA: STATUS 4 YEARS AFTER FINAL HARVEST

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Abstract.—In 2001, we initiated a study in Jackson County, AL, to examine shelterwood prescriptions in mixed mesophytic upland hardwood forests located on the escarpment of the mid-Cumberland Plateau. We were particularly interested in testing a shelterwood method that was successfully applied in other upland hardwood systems to recruit *Quercus* into competitive size classes. In the midstory herbicide shelterwood (MSW) we used an herbicide to inject more than 380 stems per acre (SPA) in three stands; average diameter of killed trees was 3.5 inches diameter at breast height (d.b.h.). After 8 growing seasons, all merchantable trees were removed in a commercial harvest. Control stands were left untreated for 8 years and then underwent the same final harvest. Before treatment, densities of trees ≥1.5 inches d.b.h. were 320 SPA for all species and included 27 SPA of *Quercus* spp., 67 SPA of *Acer saccharum* Marsh., and 3 SPA of *Liriodendron tulipifera* L. The MSW reduced the total SPA to 117. *Quercus* and *L. tulipifera* SPA were unchanged compared to pretreatment densities, and *A. saccharum* was reduced to 13 SPA. The MSW also increased the amount of full sun reaching the seedling layer for 3 years compared to the control. After the final harvest, there were only 19 SPA in the MSW, with no stems of *Quercus*, *A. saccharum*, or *L. tulipifera*. Control stands after final harvest had 104 SPA, with no stems of *Quercus*. The reproduction cohort in both control and MSW treatments shifted from 5 percent of stems in the smallest size class to 56 percent in the largest size class 4 years after the final harvest. Large *Quercus* seedling stems increased by 33 percent in the MSW and by 9 percent in the control. Survival and growth of tagged *Quercus* seedlings did not differ at any time between treatments. Competitor species of *L. tulipifera*, *A. saccharum*, *Fraxinus* spp., *Viburnum* spp., and *Cercis canadensis* L. may need additional treatment to maintain *Quercus* in these stands.

INTRODUCTION

Contemporary upland hardwood forests in the Tennessee Valley of northern Alabama and adjacent regions contain a mixture of species with wide ranges of shade tolerance and growth rates. Failure of *Quercus* to germinate and recruit into sapling size classes and the concurrent shift in dominance by mesophytic species remains a concern here as in other eastern forests (Nowacki and Abrams 2008). Manipulating light levels by reducing overstory and/or midstory stem densities is commonly recommended to promote oak over its competitors (Brose et al. 2008; Loftis 1990a, 1990b; Parker and Dey 2008; Schweitzer and Dey 2011). The disturbance severity and regime needed to accomplish this remain unknown because prescriptions need to be site-specific. High-severity disturbances such as clearcutting may result in a conversion of stands to *Liriodendron tulipifera* L. (Beck and Hooper 1986, Groninger and Long 2008, Jenkins and Parker 1998, Loftis 1990b). Intermediate-severity density reductions via shelterwood prescriptions have been tested as a means to alter light to favor *Quercus* over non-*Quercus* species

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(Johnson et al. 2009, Loftis 1990a, Sander 1979, Schlesinger et al. 1993, Schweitzer and Dey 2011, Spetich et al. 2002).

For decades those interested in forest management that facilitates the maintenance of *Quercus* in eastern hardwood forests have tried a variety of silviculture treatments. An initial promising prescription reported by Loftis (1990a) was a two-stage shelterwood in which the first stage involved removing the midstory, commonly implemented via herbicide injection of midstory stems. The premise behind this treatment was that it would create light levels on the forest floor that would enhance the growth and competitive position of small *Quercus* advance reproduction, while keeping competitive species that require higher light levels in check. Often the primary competitors are shade-intolerant species such as *L. tulipifera* and mid-tolerant species such as *Acer rubrum* L. On mesic side slopes, or the escarpment of the mid-Cumberland Plateau, *Quercus* reproduction competes with shade-intolerant species and with shade-tolerant *A. saccharum* Marsh. Positive results of this two-stage shelterwood were predicated on an assessment of the competitive position and density of *Quercus* reproduction following the midstory treatment (Craig et al. 2014, Janzen and Hodges 1987, Lockhart et al. 2000, Loftis 1990a, Miller et al. 2004, Parrott et al. 2012). No studies have reported on the results obtained from treatments applied at a stand level, or on results after phase II, which is a complete removal of the overstory.

We initiated a study in mature upland hardwood forests to evaluate the effectiveness of the midstory herbicide shelterwood prescription to promote the development of advanced *Quercus* reproduction. Our primary objective was to evaluate the longer-term efficacy of a two-phase shelterwood (herbicide midstory followed by overstory removal) applied at the stand level by monitoring stand regeneration and development after both phases. We compared the species composition and stand structure responses to control stands that were left untreated when phase I of the shelterwood treatment was implemented but were clearcut concurrent with removing the overstory in the shelterwood treatment. A secondary objective included characterizing the light environment at the seedling stratum under the two regeneration treatments.

METHODS

Study Site Description

This study was conducted in mature upland hardwood forested sites located at the southern end of the mid-Cumberland Plateau in northeastern Jackson County, AL, within the Cumberland Plateau section of the Appalachian Plateaus physiographic province (Fenneman 1938). The area was classed into the Cliff section of the Cumberland Plateau in the Mixed Mesophytic Forest region by Braun (1950) and the Eastern Broadleaf Forest (Oceanic) province and Northern Cumberland Plateau section by Bailey (1995). The area is characterized by steep slopes dissecting the plateau surface and draining to the Tennessee River. Soils are shallow to deep, stony and gravelly loam or clay, well drained, and formed in colluvium from those on the plateau top (Smalley 1982). Climate of the region is temperate with mild winters and moderately hot summers; mean annual temperature is 55 °F and mean annual precipitation is 59 inches (Smalley 1982).

We used a randomized complete block design with three replications of two treatments. Each site (block) comprised one replication of each treatment established along the slope contour. One replication located on Miller Mountain (34°58'11"N, 86°12'2"W), had a southwestern aspect and a mean elevation of 1,600 feet. Two replications located at Jack Gap (34°56'30"N, 86° 04'00"W), had northern aspects. One Jack Gap replication was located at an elevation of 1,496 feet and the other at an elevation of 1,200 feet. Treatments were randomly assigned to 10-acre areas within each replicated block. Dominant canopy tree taxa on both sites included *Quercus* that represented 46 percent of pretreatment basal area (BA; square feet per acre), including *Q. velutina* Lam., *Q. rubra* L., *Q. alba* L., and *Q. montana* L. *Carya* species were 15 percent of pretreatment BA, *A. saccharum* was 13 percent, and *L. tulipifera* was 9 percent. Common understory species included *Cornus florida* L., *Cercis canadensis* L., and *Oxydendrum arboretum* DC.

The midstory-herbicide shelterwood prescription (MSW) was implemented in two phases. Our goal was to retain 75 percent of the BA by removing midstory stems. In 2001, the stands were treated using an herbicide (Arsenal®, active ingredient imazapyr) by means of the tree injection technique to deaden the midstory. Rates of application were within the range recommended by the manufacturer. Watered solutions were made in the laboratory and then trees received application via waist-level hatchet wounds using a small, handheld sprayer. One incision was made per 3 inches of diameter, and each incision received approximately 0.15 fluid ounce of solution. Herbicide treatments were completed in autumn 2001, before leaf fall. The goal was to minimize the creation of overstory canopy gaps while removing 25 percent of the BA in the stand midstory. All injected trees were in lower canopy positions, reducing the creation of canopy gaps. Control stands received no phase I treatment.

Phase II was implemented in 2010 after 8 growing seasons. Phase II was the release or final harvest. Merchantable trees, primarily those ≥5.5 inches diameter at breast height (d.b.h.) in both treatments, were removed through chainsaw felling and grapple skidding.

Prior to treatment, five measurement plots were systematically located in each treatment area. Plot centers were permanently marked with a 24-inch piece of reinforcing steel, and GPS coordinates for plot centers were recorded. At each plot center, a 0.025-acre plot was established and all trees 1.5 inches d.b.h. and greater were monumented (distance and azimuth measured and recorded from plot center; each tree was tagged with a numbered aluminum tag and species and d.b.h. were recorded). Concentrically located in each of these plots was one 0.01-acre plot used to record the reproduction. Two additional reproduction plots were randomly located within each stand for a total of seven reproduction plots. At each reproduction plot, all woody stems were counted by species and by 1-foot height classes up to 4 feet tall, and then from 4 feet tall up to 1.5 inches d.b.h. A subsample of stems (6-10) across all species encountered on each plot was selected and stems were tagged and monumented. Digital calipers were used to measure each seedling's ground line diameter (g.l.d.) to the nearest 0.01 inch, and a calibrated measuring pole was used to measure height corresponding to the tallest shoot to the nearest 0.1 foot. Data were recorded in late summer of 2001, 2002, 2003, 2004, 2005, 2006, 2009, 2011, and 2014.

To determine how much of full sunlight was penetrating the canopy and reaching the seedling layer through the residual stand structure, we measured photosynthetically active radiation (μmol $m^{-2}s^{-1}$) in the understory and compared those values to measurements taken simultaneously in full sunlight. We used two AccuPar Linear Par Ceptometers, Model PAR-80 (Decagon Devices Inc., Pullman, WA). Measurements with one ceptometer were taken at 4.5 feet above the forest floor at each plot center and along transects equally dissecting each plot. Measurements with the second ceptometer were taken in completely open conditions adjacent to each stand. By matching two simultaneous readings, we could take into account some variation caused by changes in cloud cover. Before analysis, the square root of the percentage of full sunlight data was arcsine transformed to meet normality and homogeneity assumptions.

For this analysis, we combined all *Quercus* (*Q. alba*, *Q. veluntina*, *Q. montana*, *Q. rubra*, and *Q. muehlenbergii* Englem.). We used an analysis of variance by implementing PROC MIXED in the SAS 8.01 system (SAS Institute 2000). We specified a random effect (block) and a repeated statement (time) with the type of covariance matrix assigned unstructured by TYPE = UN option specified as stand (treat). Differences in stems per acre and BA and stems were assessed using Tukey's honest significant difference test with significance set at $\alpha \leq 0.05$.

Table 1.—Stems per acre (SPA) (standard deviation) and basal area (BA; square feet per acre) (standard deviation) for all species 1.5 inches diameter at breast height and greater, for a midstory shelterwood treatment (MSW) and a control, over five time periods, for upland hardwood stands located in Jackson County, AL. Times are as follows: 2001, pretreatment; 2002, 1-year post-treatment; 2009, 8 growing seasons post-treatment; 2011, 1 year after final harvest; 2014, 4 years after final harvest.

	2001		2002		2009		2011		2014	
Treatment	SPA	BA	SPA	BA	SPA	BA	SPA	BA	SPA	BA
Control	291 (112)	126.6 (71.8)	280 a (105)	126.6 (71.8)	315 a (100)	141.0 (80.1)	104 (135)	26.5 (37.5)	141 (186)	27.1 (38.9)
MSW	320 (138)	120.6 (77.4)	117 b (78)	94.6 (77.4)	88 b (50)	101.6 (70.3)	19 (40)	14.1 (44.4)	35 (77)	14.4 (44.5)

Different letters within columns indicate significant difference between treatments at α ≤ 0.05.

RESULTS

Overstory Canopy Composition and Structure

Stands initially contained 17 species common to both treatments, and composition was typical for Cumberland Plateau escarpment forests. Pretreatment inventories showed that stands were fully stocked and had BAs of 119.4-147.6 square feet per acre for all trees ≥ 1.5 inches d.b.h., averaging 129.2 square feet per acre (Table 1). Diameters were 1.5-28.3 inches d.b.h. Trees with diameters greater than 20 inches d.b.h. included *Q. alba*, *Q. rubra*, *Q. veluntina*, *Q. montana*, *L. tulipifera*, and *Fagus grandifolia* Ehrh. Stem densities were 291-320 stems per acre (SPA) (Table 1). Across all stands, stem densities were dominated by *A. saccharum* (30.7 percent), *Quercus* (11.1 percent), and *L. tulipifera* (4.6 percent). Distribution of stems by diameter class for all stands resembled a typical inverse J-shaped curve. On average, 60.2 percent of the stems were 1.5-5.5 inches d.b.h.

From 2001 through 2009, the control treatment accrued 24 additional SPA and 14.4 square feet per acre of BA on average. Ingrowth species were *F. grandifolia*, *C. canadensis*, and *Magnolia acuminata* L. Control treatment BA did not differ from that of the MSW treatment across phase I and phase II of the shelterwood treatments (Table 1). In 2010, the control stands were clearcut, resulting in 26.5 square feet per acre of residual BA and 104 SPA. In 2014, 4 growing seasons postcut, the control stands had no stems ≥ 15.5 inches, and 62.4 percent of the stems were 1.5–3.5 inches d.b.h. There were 37 SPA of *L. tulipifera* in the smallest diameter class, 13 SPA of *A. saccharum* in the smallest diameter class, 13 SPA in the 3.6- to 5.5-inch diameter class, and no stems of *Quercus*. In 2014, 17 species were tallied in the control, and the species lost compared to the pretreatment richness included *Nyssa sylvatica* M., *Robinia pseudoacacia* L., *Q. montana*, *C. florida*, *O. arboretum*, and *Q. alba*.

In the MSW treatment, the herbicide treatment targeted midstory and not overstory trees. We applied herbicide to 202 SPA of ≥1.5-10.5 inches d.b.h. BA removed in this treatment was 19.4 square feet per acre, or 16.1 percent of the total. Initially, residual BA did not differ from the control (P = 0.39), but stem densities differed from that of the control treatment (P < 0.001), and this difference was sustained through 2009 (Table 1). Nine species were targeted in the herbicide treatment. *A. rubrum* L. was the primary species for removal (56 SPA treated), followed by *A. saccharum* (53 SPA treated) and *N. sylvatica* (40 SPA treated). Following the midstory removal, the diameter distribution curve changed. There were 27 SPA of *Quercus* after the herbicide treatment, 13 SPA in the 7.5- to 19.5-inch diameter classes, and 14 SPA ≥19.5 inches d.b.h. There were also 13 SPA of *A. saccharum*, all ≤13.5 inches d.b.h., and 3 SPA of *L. tulipifera* in the

7.6- to 9.5-inch d.b.h. classes. No stems of ingrowth were recorded in the 8 growing seasons postherbicide. Before phase II—the final overstory removal harvest—these stands had 101.6 square feet per acre of BA and 88 SPA. After the harvest the stands had 14.5 square feet per acre of BA and 19 SPA. The species of residual stems after the final harvest were *Carya ovalis* Sarge., *F. grandifolia*, *Fraxinus americana* L., *C. canadensis*, *Prunus serotina* Ehrh., and *R. pseudoacacia.* The *C. ovalis* was the largest diameter tallied at 11.5 inches d.b.h.; the other stems were all ≤4.0 inches d.b.h. Only *C. canadensis* and *F. americana* were tallied more than once across all plots, and were the majority of the residual stems (8 SPA and 16 SPA, respectively). Results 4 years after the final harvest (2014) were similar to results 1 year after the final harvest (2011).

Understory Light Levels

We examined the percentage of full sunlight reaching the seedling layer for the control and MSW using values collected in August of each year. In 2004 (P = 0.0333), 2005 (P = 0.02), and 2006 (P = 0.012), greater light was transmitted in the MSW treatments compared to the controls (Table 2). The percentage of full sunlight penetrating the MSW canopy was twice that or greater than the control from 2002 through 2006. The range of full sunlight peaked immediately after the herbicide treatment, at 16.5 percent, and it remained around 8.5 percent over the next 7 years. For the control, the greatest light was recorded in 2002 at 8 percent and averaged half that amount, 4 percent, in the following years. After the final harvest, two to four times the light was received in both treatments, but this amount diminished with subsequent growing seasons.

Table 2.—Percentage of full sunlight reaching the seedling layer under a midstory shelterwood treatment (MSW) and a control over eight time periods. The MSW treatment was implemented in 2001; both treatments had complete overstory removal in 2010.

Treatment	Year	Percent full sunlight
Control	2002	8.0
MSW		16.5
Control	2003	5.9
MSW		10.3
Control	2004	3.0 a
MSW		6.3 b
Control	2005	3.6 a
MSW		8.5 b
Control	2006	2.5 a
MSW		9.3 b
Control	2009	5.2
MSW		8.3
Control	2011	57.7
MSW		79.8
Control	2014	44.0
MSW		57.3

Different letters within columns indicate significant difference between treatments at $\alpha \leq 0.05$.

Reproduction Composition and Structure

The reproduction cohort had 30 species common to the control and MSW. Control stands had 8,648 SPA and MSW stands had 9,819 SPA (Table 3). Most stems were ≤1 foot tall (61 percent of control stems and 72 percent of MSW stems), and we found significantly more small stems in the MSW compared to the control before treatment (P = 0.0203). In 2002, the first growing season post-treatment, these small stem densities did not differ between treatments. In 2003 (P = 0.0134), 2004 (P = 0 0.0022), and 2005 (P = 0.0193), the ≤1 foot tall stem densities were again greater in the MSW than in the control. No other differences between size classes were found. In 2006 and 2009, stem densities of seedlings >1 to ≤2 feet tall (P = 0.003) and >2 to ≤3 feet tall (P = 0.00164) were greater in the MSW than in the control, and in 2009 stems >3 to ≤4 feet tall were greater in the MSW than in the control (P = 0.0115). Total stem densities for all reproduction were also greater in the MSW than in the control in 2006 (P = 0.0049) and 2009 (P = 0032). Immediately after the final harvest, SPA of the MSW for stems >2 to ≤3 feet tall (P = 0.0329) and >3 to ≤4 feet tall (P = 0.0268) were greater than those in the control. In 2014, no differences in stem densities between treatments were found. Total stem densities for both treatments were similar to those found when the study began, with 9,329 SPA in the control and 9,386 in the MSW. A major difference, however, was that most of the stems were in the largest size class for both treatments (53 percent of the control and 59 percent of the MSW).

Table 3.—Seedling stems per acre (SPA) for all species, by five size classes and total seedling densities, for a midstory shelterwood treatment (MSW) and a control, over nine time periods, for upland hardwood stands located in Jackson County, AL. Times are as follows: 2001, pretreatment; 2002 through 2009, midstory herbicide post-treatment; 2011, 1 year after final harvest; 2014, 4 years after final harvest.

		Seedling size class					
Treatment	Year	≤1 foot	>1 foot to ≤2 feet	>2 feet to ≤3 feet	>3 feet to ≤4 feet	>4 feet to ≤1.5inches d.b.h.	Total
Control	2001	5,281 b	1,476	548	214	548	8,648
MSW		7,038 a	1,162	333	281	400	9,819
Control	2002	4,414	1,305	343	181	581	6,824
MSW		5,519	1,376	319	295	238	7,748
Control	2003	5,110 b	2,081	776	305	700	8,971
MSW		7,529 a	1,738	667	305	390	10,629
Control	2004	4,371 b	1,576	519	281	652	7,400
MSW		6,862 a	1,643	476	229	381	9,590
Control	2005	5,419 b	1,776	648	381	848	9,071
MSW		7,548 a	2,571	929	429	600	12,076
Control	2006	4,538	1,143 b	533 b	262	881	7,357 b
MSW		6,319	1,943 a	967 a	443	729	10,400 a
Control	2009	6,286	2,457 b	829 b	400 b	995	10,967 b
MSW		6,290	4,824 a	1,800 a	910 a	1,424	15,248 a
Control	2011	6,090	3,890	1,210 b	548 b	1,371	13,110
MSW		4,543	4,633	2,029 a	1,033 a	1,952	14,190
Control	2014	1,548	1,238	924	681	4,938	9,329
MSW		257	1,181	1,262	1,119	5,567	9,386

Different letters within columns indicate significant difference between treatments at $\alpha \leq 0.05$.

Before treatment, the MSW stands had more *Quercus* stems in the smallest height class than the control (P = 0.0269) (Table 4). One to five years post-treatment, this difference was not detected. In 2009, ≤1 foot tall *Quercus* stems were once again greater in the MSW than in the control (P = 0.0047). We did not detect a statistical difference in stem density in the other height classes in 2009 but noted that in the MSW, *Quercus* stems increased by 404 SPA in the >1 to ≤2 foot height class and stems in the other height classes increased from none before treatment to 62, 10, and 5 for the >2 to ≤3 foot tall, >3 to ≤4 foot tall, and >4 foot to ≤1.5 inch d.b.h. classes, respectively (Table 4). Immediately after the final harvest, the MSW had greater SPA in the >1 to ≤ 2 foot height class (P = 0.0352), and in 2014 there were more *Quercus* stems in the >3 to ≤4 foot (P = 0.0042) and >4 foot to ≤1.5 inch d.b.h. classes (P = 0.0211) compared to the control. Four years after the final harvest, total *Quercus* densities were 949 in the control and 914 in the MSW; 55 percent of these stems were in the smallest height class for the control and fewer than 5 percent for the MSW. Thirty-three percent of total *Quercus* stems in the MSW were in the largest size class, which represented a change from none before treatment to 300 SPA following 4 growing seasons after the final harvest.

Table 4.—Seedling stems per acre (SPA) for *Quercus,* by five size classes and total seedling densities, for a midstory shelterwood treatment (MSW) and a control, over 9 time periods, for upland hardwood stands located in Jackson County, AL. Times are as follows: 2001, pretreatment; 2002 through 2009 midstory herbicide post-treatment; 2011, 1 year after final harvest; 2014, 4 years after final harvest.

		Seedling size class					
Treatment	Year	≤1 foot	>1 foot to ≤2 feet	>2 feet to ≤3 feet	>3 feet to ≤4 feet	>4 feet to ≤1.5 inches d.b.h.	Total
Control	2001	776 b	129	14	5	14	938
MSW		1,524 a	29	0	0	0	1,552
Control	2002	557	105	19 a	0	14	695
MSW		1,086	24	0 b	0	0	1,110
Control	2003	490	129	14	0	10	643
MSW		1,095	71	0	0	0	1,167
Control	2004	486	124	24	0	14	648
MSW		995	76	24	10	0	1,105
Control	2005	748	81	29	5	14	876
MSW		986	90	10	0	5	1,090
Control	2006	595	76	14	0	10	695
MSW		748	86	19	0	0	852
Control	2009	752 b	114	29	5	5	905 b
MSW		1,143 a	433	62	10	5	1,652 a
Control	2011	795	143 b	25	14	33	1,010
MSW		395	348 a	105	52	14	914
Control	2014	519	229	90	24 b	86 b	948
MSW		48	233	205	129 a	300 a	914

Different letters within columns indicate significant difference between treatments at α ≤ 0.05.

In 2014, *L. tulipifera* was ranked first in the frequency of occurrence in both control and MSW plots and had the greatest number of SPA in the largest seedling size class; 995 SPA were in the MSW and 1,776 in the control. Before treatment, there were five SPA *L. tulipifera* in the control (all in the largest size class) and 64 SPA in the MSW (50 SPA ≤1 foot tall, and 9 SPA >1 to ≤2 feet tall). In 2003, 2004, 2005, 2006, and 2009, *L. tulipifera* total densities ($P < 0.001$) and ≤1 foot tall densities ($P < 0.001$) were greater in the MSW compared to the control; these stems were predominantly ≤1 feet tall. In 2009, we did not tally any *L. tulipifera* in the control. In 2009, we tallied 500 SPA of *L. tulipifera* in the MSW, with a gradient of stems across the seedling size classes—42 percent in the ≤1 foot tall size class, 37 percent were >1 to ≤2 feet tall, 12 percent were >2 to ≤3 feet tall, and 9 percent were taller than ≥3 feet to ≤1.5 inches d.b.h. In 2014, we found no differences for *L. tulipifera* tallies between treatments. In the control, 75 percent of the total 2,376 SPA of *L. tulipifera* were in the largest seedling size class, and in the MSW, 50 percent of the 1,986 SPA were in the largest size class. *Fraxinus americana* also ranked high as a frequent competitor and had high densities in the largest seedling size class compared to other species. In 2009, we observed more *F. americana* SPA in the MSW (961 SPA) compared to the control (371) ($P = 0.0228$). In 2014, the difference in *F. americana* stem densities did not differ between treatments, but 61 percent of the 625 SPA were in the largest seedling size class in the MSW, with 43 percent of the 250 SPA in the same size class for the control. *Acer saccharum* seedlings also ranked high in plot frequency and SPA. Before treatment, there were no differences for *A. saccharum* seedling densities between the control and MSW. One year after treatment (P = 0.0366), and in 2006 (P = 0.0473) and 2009 (P = 0.0135), there were higher densities of *A. saccharum* seedlings in the >1 to ≤2 foot size class for the MSW compared to the control. The number of seedlings in the MSW increased from 1,886 SPA pretreatment to 3,314 SPA 8 growing seasons post-treatment. In 2009, there were greater densities of *A. saccharum* seedlings in the >2 to ≤3 foot tall (P = 0.0099) and >3 to ≤4 foot size class (P = 0.0196) for MSW compared to the control. In 2011, only the MSW >2 to ≤3 foot height class still had greater SPA compared to the control (P = 0.0052). There were 943 total SPA of *A. saccharum* in the MSW in 2014; 38 percent of these were in the largest seedling size class.

We tagged 183 seedlings in the control and 166 seedlings in the MSW. Tagged seedlings represented 27 species in the control and 18 species in the MSW and included *Quercus* spp., *F. americana*, *A. saccharum*, *Carya* spp., and *P. serotina*. For all species, initial height and g.l.d. did not differ between the control and the MSW (P = 0.2527). Average height was 2.1 feet and average g.l.d. was 0.26 inch. In 2002, 88 percent of the MSW seedlings and control seedlings survived; stems of species that died were dispersed across all species. Control tagged seedling height (2.1 feet) (P = 0.0072) and diameter (0.28 inch) (P = 0.0322) were greater compared to MSW seedling height (1.2 feet) and diameter (0.20 inch). In 2009, 52.5 percent of the control seedlings and 62.7 percent of the MSW seedlings were alive. No differences in heights and diameters between treatments were found in 2009, although seedlings did grow, and control seedlings averaged 3.1 feet tall with 0.50 inch g.l.d., and MSW seedlings averaged 2.8 feet tall and had 0.43 inch g.l.d. In 2014 following the overstory harvest, 26.8 percent of the control seedlings were alive compared to 34.9 percent in the MSW treatment.

We tagged 66 *Quercus* seedlings in the MSW and 67 in the control. Survival after treatment was 85 percent in the control and 93 percent in the MSW. Survival after 8 growing seasons was 31 and 60 percent for the control and MSW, respectively, and after final harvest survival was 21 (control) and 29 (MSW) percent. There were no differences between treatments at any given time for tagged *Quercus* height and diameter. Control *Quercus* seedlings grew in height from 1.1 to 2.2 feet during the study, and MSW seedlings grew from 1.0 feet to 4.5 feet. In addition, g.l.d. increased for control (0.15 inch to 0.39 inch) and MSW (0.11 inch to 0.64 inch) seedlings.

DISCUSSION

Removing the midstory decreased density of stems 1.5 inches and greater compared to the control. The density of overstory and midstory *Quercus* stems did not change during phase I in the MSW and in the control over 8 growing seasons. After phase II—the final harvest—no residual *Quercus* stems were ≥1.5 inches d.b.h. in either treatment. Four years after the final harvest, the species composition of larger stems in the MSW is scant; only two species, *C. canadensis* and *F. americana*, provide any structure for stems greater than 1.5 inches.

Light availability in studies of midstory removal at phase I have been reported at 10-20 percent of full sun (Craig et al. 2014, Dey et al. 2012, Lhotka and Loewenstein 2009, Lorimer et al. 1994, Miller et al. 2004, Motsinger et al. 2010, Parrott et al. 2012, Schweitzer and Dey 2011). Deadening of the midstory provided an ephemeral increase in the amount of full sunlight reaching the seedling stratum (Lockhart et al. 2000, Miller et al. 2004, Schweitzer and Dey 2011). The highest light penetration was recorded in the first growing season post-treatment, and a diminishing percentage was recorded through 2009. Light availability in the MSW was only within a 10 to 20 percent range for 2 years post-treatment, although it was always higher than that measured in the control. In a central Appalachian hardwood stand in West Virginia, Miller et al. (2004) found slight reductions in light levels in their midstory removal treatment after 3 growing seasons and attributed this to the expansion of overstory trees into gaps created by the treatments. They expected, however, enhanced light under the most severe midstory treatment to continue for 10 to 12 years after treatment. On two studies on the northern Cumberland Plateau in Kentucky, Parrott et al. (2012) and Craig et al. (2014) removed midstory trees and reduced BA by 20 percent, which resulted in 14-18 percent of full light reaching the forest floor after 7 years.

On our mid-Cumberland Plateau escarpment study sites, we found increases in non-*Quercus* seedlings associated with increased light and growing space created by midstory removal. Our midstory herbicide treatment did not target stems ≤1.5 inches d.b.h. Our stands contained 400 SPA of seedlings >4 feet tall to ≤1.5 inches d.b.h. in 2001, and by 2009 this had increased to 1,425 SPA. *A. saccharum* stem density in the largest seedling size class increased from 110 SPA to 190 SPA, *L. tulipifera* from 0 SPA to 33 SPA, and *F. americana* from 4 SPA to 29 SPA. Forty percent of the occupancy of this stratum's growing space (taller than 4 feet to the midstory canopy) comprised shade-tolerant small-stature trees of *Viburnum* spp. and *C. canadensis* (571 SPA in 2009). Parrott et al. (2012) also reported that non-*Quercus* competitive species such as *A. rubrum* benefited from the midstory removal. Lhotka and Loewenstein (2009) implemented a midstory herbicide treatment in conjunction with the treatment of understory vegetation <4.5 feet tall, and they suggested that the small gain in *Quercus* height growth under the more severe treatment did not warrant the costs associated with treating the understory. This study did not consider the ground-layer understory vegetation in the treatment. On these sites, treating these ground-layer woody stems with herbicide may be prudent to prevent them from occupying the subsequent midstory growing space and decreasing the light created when the midstory dies.

Phase I of this shelterwood prescription was designed to develop and maintain *Quercus* species so that a critical density of competitive seedlings is present before the overstory is removed. Many have reported that a stocking goal should be 400 SPA of *Quercus* that are ≥4.5 feet tall (Janzen and Hodges 1987, Johnson et al. 2009, Lockhart et al. 2000, Sander 1979). Although we did not meet this minimum stocking level, we did have an increase from 0 to 300 SPA in the largest *Quercus* seedling size class in the MSW. In addition, we measured a 3.5-foot height growth and a 0.5 inch g.l.d. increase over the 8 growing seasons in the MSW treatment, compared to 1.1 feet height growth and 0.2 g.l.d. growth for *Quercus* in the control. Understory light levels of 20-50 percent full sunlight have been reported to promote *Quercus* growth (Ashton and Berlyn 1994, Gottschalk 1994, Hodges and Gardiner 1993, Rebbeck et al. 2012), although several studies have reported positive *Quercus* growth under a range of 3 to 18 percent full sunlight (Craig et al. 2014, Lhotka and Loewenstein 2009, Motsinger et al. 2010).

Four years after the final harvest, the MSW stands are devoid of vertical structure and appear shrubby, in contrast to the control stands, which had greater stump sprouting and higher diversity of woody stems. Landowners who are interested in pursuing such treatments to enhance or maintain *Quercus* in their stands should note the appearance of the MSW at this stage. The reproduction cohort continues to respond, and the MSW stands will continue to succeed toward a mixed upland hardwood forest, although the species composition may differ from that of the previous stand. The results of this study, which represent composition and structure dynamics at a stand level after the final harvest, indicated that although *Quercus* seedlings increased in densities and height, competing species also responded favorably to the MSW. An additional tending treatment to release competitive *Quercus* may be necessary to maintain its stocking in these stands.

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