STEM DIAMETER DYNAMICS UNDER VARYING SHELTERWOOD TREATMENTS IN AN UPLAND HARDWOOD FOREST ON THE CUMBERLAND PLATEAU ESCARPMENT

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Abstract—Managing forests on the Cumberland Plateau escarpment for select desirable species can be particularly onerous due to the high diversity of dominant tree species. We implemented 5 treatments to alter species composition and structure in an effort to favor *Quercus* and maintain its dominance in the stands. Treatments were shelterwood prescriptions that in the first stage retained a percentage of the basal area (100, 75, 50, 25 and 0 percent retentions). After 9 growing seasons, the residual trees in all but the 0 percent retention treatment were removed. We installed permanent vegetation measurement plots and recorded species and diameter for all trees 1.5 inches dbh and greater in 2001 (pretreatment); 2002 (first growing season post stage one harvest); 2009 (8 years post stage one harvest), 2011 (first growing season post stage two harvest) and in 2014 (4 years post stage two harvest). None of the treatments increased *Quercus* stems. In the 0 percent retention, or clearcut, *Quercus* stems changed from 37 stems per acre (SPA), to 5 SPA immediately after harvest, to 24 SPA thirteen years post-harvest; while *Liriodendron tulipifera* stems increased from 16 SPA pretreatment to 523 SPA thirteen years later. In the 75 percent retention treatment (midstory herbicide in first stage; residual commercial harvest in final stage), for all species, SPA declined from 320 to 35; there were no *Quercus*, *Acer saccharum* or *L. tulipifera* stems found in 2014. The residual stems were *Carya ovalis*, *Fagus grandifolia*, *Fraxinus americana* and *Cercis canadensis*. Clearcutting and the 25 percent retention shelterwood showed the highest potential for recruiting *Quercus* into competitive size classes; additional intervention may be needed to control non-*Quercus* competitors.

INTRODUCTION

Cumberland Plateau forests, which includes those found in northeastern Alabama, are dominated by either *Quercus*-*Carya* upland types on the broad tabletops or intermediate mixed mesophytic and *Quercus*-*Carya* types on the side slopes, or escarpment (Braun 1950). These classifications result from local topographic and edaphic conditions, a consequence of geological uplifting and subsequent erosion. Over 30 canopy species can be found in the highly biodiverse forests of the Cumberland Plateau (Hinkle and others 1993). Myriad disturbances have influenced these forests and most stands are considered second or third growth (Hart and Grissino-Mayer 2008). Over 50 to 100 years, the result of these large-scale disturbances was a massive intrusion of oaks (*Quercus* spp.), yellow-poplar (*Liriodendron tulipifera* L.), ash (*Fraxinus* spp.), and other important species.

Today's upland hardwood forests in the Tennessee Valley of north Alabama and adjacent regions contain a mixture of species with wide ranges of shade tolerance and growth rates. Failure of *Quercus* to regenerate and recruit into smaller 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 and others 2008, Loftis 1990a, Loftis 1990b, Parker and Dey 2008, Schweitzer and Dey 2011). The disturbance intensity and regime needed to accomplish this remains unknown, as prescriptions need to be site-specific. High intensity disturbances such as clearcutting may result in a conversion of stands to *L. tulipifera* (Beck and Hooper 1986, Groninger and Long 2008, Jenkins and Parker 1998, Loftis 1990b). Intermediate-intensity density reductions via shelterwood prescriptions have been tested as a means to alter light to favor *Quercus* over non-*Quercus* species (Johnson and others 2002, Loftis 1990a, Sander 1972, Schlesinger and others 1993, Schweitzer and Dey 2011, Spetich and others 2002).

The analysis of stand structure following differing levels of disturbance allows us to quantify changes in the residual structure and composition. As clearcutting may often have adverse social impacts, the two-phase harvesting associated with shelterwood prescriptions may result in a less severe visual impact

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and greater social acceptance. What is unknown in upland hardwood forests on the escarpment of the Cumberland Plateau is the level of disturbance needed to regenerate desired species, and the changes in the residual stands as prescriptions are implemented. In this paper, we evaluate the changes in sapling-sized and larger stems over two-phases of variable-retention shelterwood treatments, and clearcutting. The efficacy of these prescriptions on the regeneration response will be presented in elsewhere. The management goal is to maintain a similar species composition as current by mimicking the disturbance regime that gave us the stands we have today. The challenge is recruiting desirable species into competitive positions by altering the disturbance intensity.

METHODS

Study sites were located at the southern end of the Mid-Cumberland Plateau in northeastern Jackson County, Alabama 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 with a mean temperature of 55°F, and mean precipitation of 59 inches (Smalley 1982).

We used a randomized complete block design with three replications of five treatments. Each site (block) comprised one replication of five treatments established along the slope contour. One replication, located on Miller Mountain (34° 58' 11" N, 86° 12' 21" W) had a southwestern aspect and a mean elevation of 1600 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 1496-feet elevation and the other at 1200-feet elevation. Treatments were randomly assigned to 10-acre areas within each replicated block because the land owner at the time of study implementation, Mead Corporation, mandated the maximum size of upland hardwood clearcuts at 10 acres. Dominant canopy tree taxa on both sites included *Quercus* that represented 46 percent of pretreatment basal area, including *Q. velutina* Lamarck, *Q. rubra* L., *Q. alba* L., *Q. montana* L. *Carya* species was 15 percent pretreatment basal area, *Acer saccharum* Marsh. was 13 percent pretreatment basal area and *L. tulipifera* was 9 percent pretreatment basal area. Common understory species included *Cornus florida* L., *Cercis canadensis* L., and *Oxydendrum arboretum* DC.

The treatments consisted of five levels of BA retention percentages: 0 (clearcut), 25, 50, 75, and 100 (untreated control; not harvested ≥ 40 years) (table 1). Shelterwood prescriptions were implemented in two phases. In the first phase, tree harvest for the 0, 25 and 50 percent retention treatments was accomplished by chain saw felling and grapple skidding, and done from fall 2001 through winter 2002. Trees in the 25 percent and 50 percent retention stands were retained on the basis of species [favoring oak, ash (*Fraxinus* spp.), and persimmon (*Diospyros virginiana*)], vigor class, and crown position. Trees were marked to be retained using guidelines outlined originally by Putnam and others (1960), and recently updated by Meadows and Skojac (2008). The 75 percent retention stands were treated using a herbicide (Arsenal®, active ingredient imazapyr) by means of tree injection technique in fall of 2001 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, prior to leaf fall. The goal was to minimize the creation of overstory canopy gaps while removing 25 percent of the basal area in the stand midstory. All injected trees were in lower canopy positions, reducing the creation of canopy gaps.

All 15 stands grew for eight years, prior to phase II, the final harvest in the fall of 2010. Merchantable trees (primarily those greater than 5.5 inches diameter at breast height, dbh) in the 25, 50, 75, and 100 percent retention stands were then removed through chainsaw felling and grapple skidding. The 0 percent retention treatment, clearcut in 2001, was not retreated. The second phase of treatment resulted in four forest cohorts: (1) nine-year old regenerating clearcut, (2) released regeneration with older non-merchantable residuals from the first phase harvest (25 and 50 percent retentions); this cohort differed due to phase I treatment, and included a well-established mid and understory in conjunction with scattered residual canopy trees, (3) released regeneration from the 75 percent retention, which lacked a well-developed midstory (mostly small-diameter sugar maple) and lacked scattered residuals and large sprouts, (4) new "clearcut", formerly the 100 percent retention which under phase I was not treated and under phase II had all overwood removed.

Prior to treatment, five measurement plots were systematically located in each treatment area. Plot

Table 1—Shelterwood retention study treatment descriptions and time frames for upland hardwood stands located in Jackson County, Alabama. Residual basal area targets were for merchantable stems, 5.6 inches dbh and greater

Treatment designation	History 2001	November 2001-December 2002 Phase I	2002 Data collection (growing seasons post Phase 1)	2009 Data collection (growing seasons post Phase 1)	2010 Phase II	2011 Data collection (growing seasons post Phase II)	2014 Data collection (growing seasons post Phase II)
Control	Pretreatment	No cut	1	8	All residual trees cut	1	4
75 percent retention	Pretreatment	Herbicide midstory	1	8	All residual trees cut	1	4
50 percent retention	Pretreatment	Cut to 40 ft^2/a basal area	1	8	All residual trees cut	1	4
25 percent retention	Pretreatment	Cut to 30 ft^2/a basal area	1	8	All residual trees cut	1	4
Clearcut	Pretreatment	Cut to 5 ft^2/a basal area	1	8	No additional cut	1	4

centers were permanently marked with a 24-inch piece of reinforcing steel, and GPS coordinates were recorded. At each plot center, a 0.025-acre plot was established and all trees 1.5 inches dbh and greater were monumented (distance and azimuth measured and recorded from plot center, each tree tagged with a numbered aluminum tag) and species and dbh recorded. Data were recorded in late summer of 2001, 2002, 2009, 2011, and 2014 (table 1). For this analysis, we combined all *Quercus* (*Q. alba*, *Q. veluntina*, *Q. montana*, *Q. rubra*, *Q. muehlenbergii* Englem.). We used an analysis of variance (ANOVA) by implementing PROC MIXED in the SAS 9.0 system (SAS Institute 2000) and 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 basal area and stems were assessed using Tukey's HSD test with significance set at α 0.05.

RESULTS AND DISCUSSION

Initially, stands contained 26 species and composition was typical for Cumberland Plateau escarpment forests. Pretreatment inventories showed that stands were fully stocked and had basal areas between 119.4 and 147.6 square feet per acre (ft^2/a) for all trees 1.5 inches and greater dbh, averaging 129.2 ft^2/a (table 2). Diameters ranged from 1.5 to 28.3 inches dbh. Trees with diameters greater than 20 inches dbh included *Q. alba*, *Q. rubra*, *Q. veluntina*, *Q. montana*, *L. tulipifera*, and *F. grandifolia*. Stem densities ranged from 291 to 347 stems per acre (SPA) (table 2). 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 (fig. 1). On average, 60.2 percent of the stems were between 1.5 and 5.5 inches dbh.

From 2001 through 2009, the control treatment accrued 24 additional SPA, and 14.4 ft^2/a of basal area (figs. 2 and 3). Ingrowth species were *F. grandifolia*, *Cercis canadensis* L., and *Magnolia acuminata* L. Control treatment basal area did not differ from that of the 75 percent retention treatment across phase I and phase II of the shelterwood treatments (table 2). In 2010, the control stands were essentially clearcut, resulting in 26.5 ft^2/a of residual basal area and 104 SPA. In 2014, four growing seasons post cut, the control stands had no stems greater than 15.5 inches, and 62.4 percent of the stems were 1.5-3.5 inches dbh (fig. 4). There were 37 SPA of *L. tulipifera* in the smallest diameter class, 13 SPA of *A. saccharum*, and no *Quercus*.

In the 75 percent retention treatment, the herbicide treatment targeted midstory trees and not overstory

Table 2—Stems per acre (SPA)(std) and basal area (BA ft^2/a)(std) for all species 1.5 inches dbh and greater, under five shelterwood retention treatments, over four time periods, for upland hardwood stands located in Jackson County, Alabama. Times are as follows: 2001, pretreatment; 2002, one-year post treatment; 2009, 8 growing seasons post treatment; 2011, one year post final harvest; 2014, four years post final harvest. Phases of treatments and descriptions are given in Table 1

	2001		2002		2009		2011		2014	
	SPA	BA	SPA	BA	SPA	BA	SPA	BA	SPA	BA
Control	291a (112)	126.6a (71.8)	280a (105)	126.6a (71.8)	315a (100)	141.0a (80.1)	104c (135)	26.5a (37.5)	141c (186)	27.1a (38.9)
75 percent retention	320a (138)	120.6a (77.4)	117b (78)	94.6ab (77.4)	88b (50)	101.6ab (70.3)	19c (40)	14.1a (44.4)	35c (77)	14.4a (44.5)
50 percent retention	347a (100)	147.6a (79.3)	112b (111)	53.3bc (79.1)	336a (369)	58.6bc (91.0)	555b (428)	46.4a (94.0)	632b (438)	52.1a (94.9)
25 percent retention	331a (112)	119.4a (53.4)	136b (118)	43.6c (53.6)	419a (218)	52.6bc (57.6)	532b (415)	27.2a (22.0)	600b (407)	32.0a (23.1)
Clearcut	331a (156)	131.8a (70.0)	88b (148)	19.6c (28.0)	427a (206)	20.6c (21.2)	1021a (435)	43.1a (19.4)	1208a (527)	54.5a (21.2)

Different letters within columns indicate significant difference among treatments at α 0.05

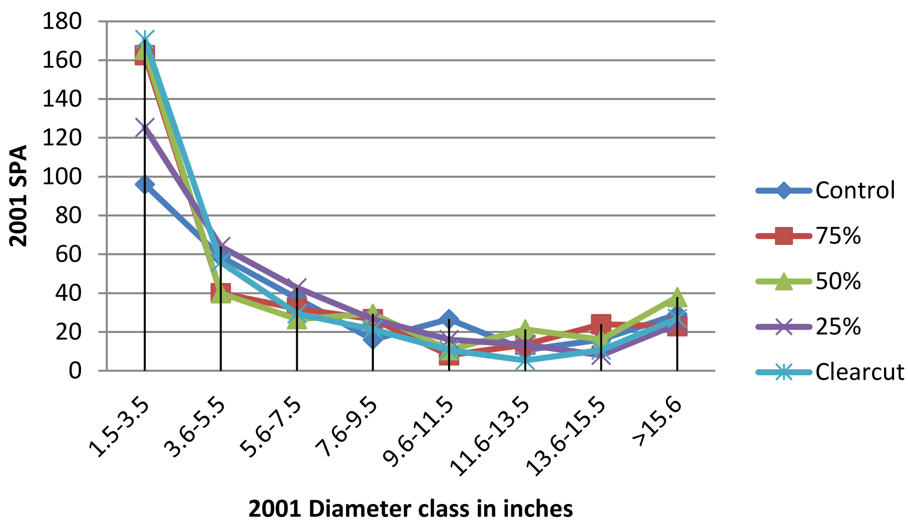

Figure 1—Pretreatment diameter distributions for all woody stems 1.5 inches dbh and greater in stands targeted for five silvicultural prescriptions on the Cumberland Plateau escarpment in Jackson County, AL. Phase I treatment assignments were Control (no treatment); 75 percent (shelterwood with initial midstory herbicide treatment to retain 75 percent of the basal area); 50 percent and 25 percent (shelterwood treatments with commercial harvests to retain 50 and 25 percent of the basal area); Clearcut (removal of all merchantable stems).

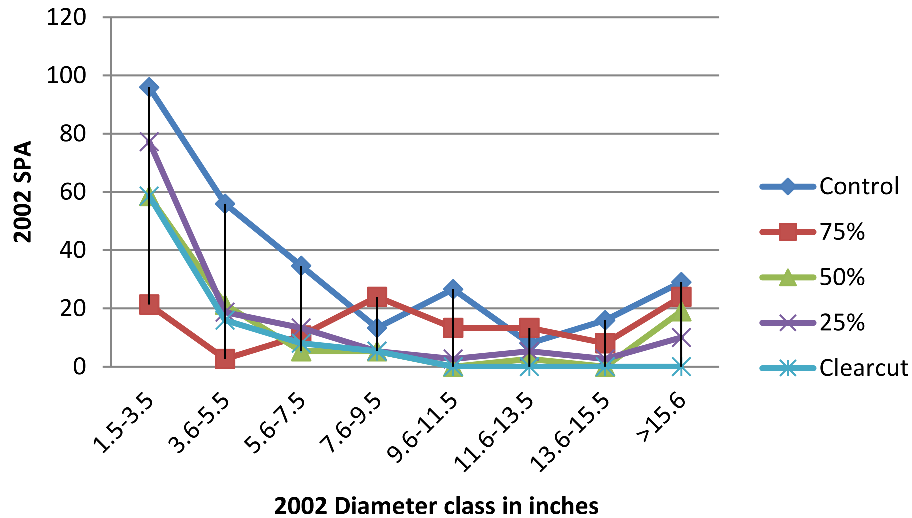

Figure 2—First-year diameter distributions following Phase I treatment for all woody stems 1.5 inches dbh and greater in stands under five silvicultural prescriptions on the Cumberland Plateau escarpment in Jackson County, AL. Phase I treatments were Control (no treatment); 75 percent (shelterwood with initial midstory herbicide treatment to retain 75 percent of the basal area); 50 percent and 25 percent (shelterwood treatments with commercial harvests to retain 50 and 25 percent of the basal area); Clearcut (removal of all merchantable stems).

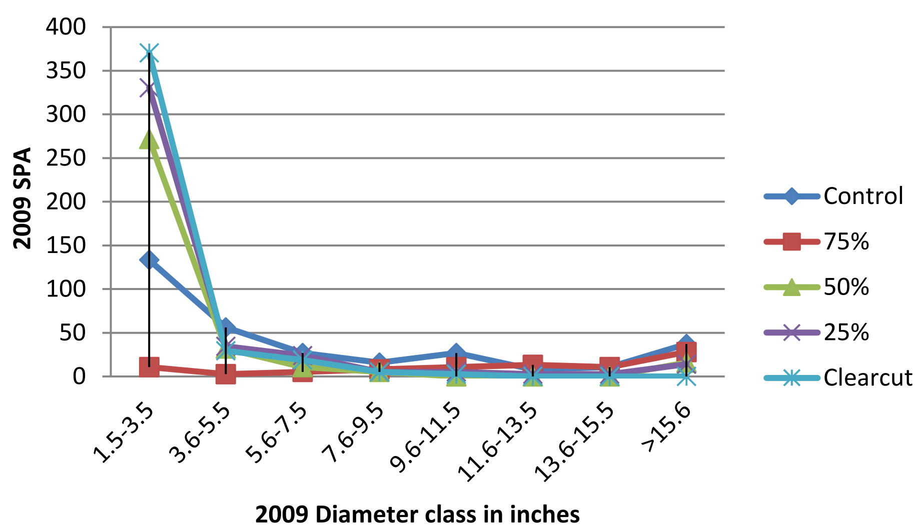

Figure 3—Eight-year diameter distributions following Phase I treatment for all woody stems 1.5 inches dbh and greater in stands under five silvicultural prescriptions on the Cumberland Plateau escarpment in Jackson County, AL. Phase I treatment assignments were Control (no treatment); 75 percent (shelterwood with initial midstory herbicide treatment to retain 75 percent of the basal area); 50 percent and 25 percent (shelterwood treatments with commercial harvests to retain 50 and 25 percent of the basal area); Clearcut (removal of all merchantable stems).

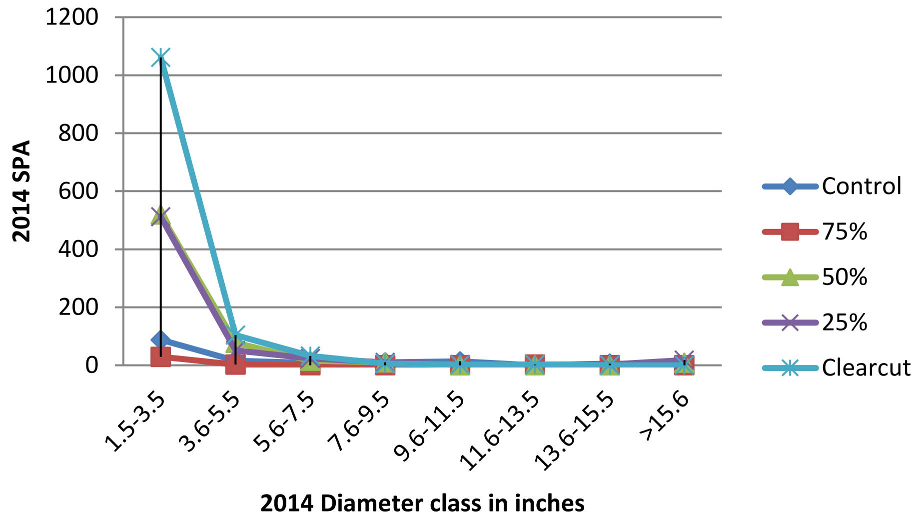

Figure 4—Four-year post final harvest (Phase II) diameter distributions for all woody stems 1.5 inches dbh and greater in stands under five silvicultural prescriptions on the Cumberland Plateau escarpment in Jackson County, AL. Phase I treatment assignments were Control (no treatment); 75 percent (shelterwood with initial midstory herbicide treatment to retain 75 percent of the basal area); 50 percent and 25 percent (shelterwood treatments with commercial harvests to retain 50 and 25 percent of the basal area); Clearcut (removal of all merchantable stems). Phase II removed all merchantable stems in the Control, 75 percent, 50 percent, and 25 percent retention treatments.

trees. We herbicided 202 SPA, ranging from 1.5 inches dbh up to 10.5 inches. The amount of basal area removed in this treatment was 19.4 ft^2/a, or 16.1 percent of the total. Initially, residual basal area differed from only the clearcut treatment, and stem densities only differed from that of the control treatment (table 2). Nine species were targeted in the herbicide treatment, with *A. rubrum* L. the primary species for removal (56 SPA treated), followed by *A. saccharum* (53 SPA treated) and *Nyssa sylvatica* Marsh. (40 SPA treated). Following the midstory removal, the diameter distribution curve changed, especially in comparison to the other treatments (fig. 2). There were 27 SPA of *Quercus* following the herbicide treatment, 13 SPA in the 7.5 to 19.5 inch diameter class, and 14 SPA greater than 19.5 inches dbh. There were also 13 SPA of *A. saccharum*, all less than 13.5 inches dbh, and 3 SPA of *L. tulipifera* in the 7.6 to 9.5 inch dbh classes. There were no stems of ingrowth recorded in the eight growing seasons post-herbicide. Prior to phase II, the final overstory removal harvest, these stands had 101.6 ft^2/a of basal area and 88 SPA, and after the harvest had 14.5 ft^2/a of basal area and 19 SPA (figs. 3 and 4). The residual stems were *Carya ovalis* Sarge., *F. grandifolia*, *Fraxinus americana* L. and *C. canadensis.* The *C. ovalis* was the largest diameter tallied at 11.5 inches dbh, while the other stems were all less than 4.0 inches dbh. These results were exactly the same four years after the final harvest (2014) as in 2011 (one year post harvest).

The 50 and 25 percent retention treatments reacted similarly to the initial and final harvest, and SPA and basal area did not differ over the course of study (table 2). When considering all stems 1.5 inches dbh and larger, the residual basal area for both these treatments was 36 percent of the pretreatment basal area. In the 50 percent retention treatment, stems were still distributed among the diameter classes, but there were no *Quercus* stems less than 15.5 inches dbh, and 11 SPA of *Quercus* between 15.6 and 19.5 inches dbh. Although total SPA continued to increase with time, *Quercus* SPA did not. In 2009, there were 91 SPA of ingrowth, and 37 of these were *L. tulipifera*. After the final harvest and four growing seasons, 520 SPA of the total 632 SPA were in the 1.5 to 3.5 inch diameter class, and 164 SPA of the 520 were *L. tulipifera*. There were over 100 SPA in the 3.6 to 9.5 diameter class, and 9 SPA of large canopy trees that were not removed (greater than 7.6 inches dbh). However, this is slightly misleading as we had one entire survey plot that was not harvested, and that plot accounted for all residual stems over 21.6 inches dbh, which were *Q. alba*, *Q. rubra* and *L. tulipifera*. The 25 percent retention treatment increased stem densities over time and those stems were also dominated by the smallest diameter class size, 512 SPA out of 600 at four years post final harvest. This treatment did result in the recruitment of 11 SPA of *Quercus* in the 1.5 to 5.5 inch dbh class; prior to treatment there were no *Quercus* less than 5.5 inches dbh (figs. 3 and 4).

Clearcutting resulted in the most dramatic change to diameter distributions, as well as increasing basal area by 34.9 ft^2/a following 13 growing seasons. Immediately after the harvest, there were no stems greater than 9.5 inches dbh, but eight years later there were 6 SPA greater than 9.5 inches dbh (fig. 2). The greatest number of ingrowth stems occurred in this treatment, with 227 new stems tallied eight growing seasons postharvest (fig. 3). These stems were dominated by *L. tulipifera*, *Robinia pseudoacacia* L., and *Prunus serotina* Ehrh. Clearcut stands had significantly greater SPA in 2014 (table 2) than the other four treatments in this study. Of the 1208 SPA, 1061 SPA were in the 1.5-3.5 inch dbh class, and 485 SPA of these were *L. tulipifera* (fig. 4). *Quercus* density changed from 38 SPA pretreatment, somewhat evenly distributed among diameter classes but with none in the smallest size class, to 24 SPA after 13 growing seasons, with 16 SPA in the 1.5 to 5.5 inch dbh class. *Liriodendron tulipifera* SPA changed from 16 SPA pretreatment, all under 9.5 inches dbh, to 522 SPA in this same size range. *A. saccharum* density in the 1.5 to 5.5 dbh class changed little, from 98 SPA pretreatment to 88 SPA 13 growing seasons after treatment.

Reducing stem density from below using herbicides has been reported to create conditions necessary for growth of small *Quercus* stems (Loftis 1990a). Loftis (1978) noted that this treatment also removes a source of sprout competition, which was obvious in our study. Four years after final overstory removal, the stands remained sparsely populated by woody stems. We did tally 9380 SPA of reproduction (1 foot tall up to 1.5 inches dbh), which was 9.8 percent *Quercus*, 10 percent *A. saccharum*, and 21 percent *L. tulipifera*, with over 32 percent of the stems greater than 4.5 feet tall and less than 1.5 inches dbh. While there is potential for these stands to regenerate to desirable woody species, the resultant stand structure four years after final harvest appears decimated and resembles a shrubby abandoned field. The interim visual appearance following phase II of the oak shelterwood may be perceived negatively and its initial structure and composition should be detailed to landowners. We found that the increase in light created by deadening the midstory was ephemeral, lasting only a few growing seasons prior to that space being occupied by *A. saccharum*. (Schweitzer and Dey 2011). In order for this low intensity shelterwood treatment to provide increased light over a longer time frame, we suggest deadening or removing a few dominant canopy trees during phase I to create gaps in the canopy. In these systems with both shade intolerant *L. tulipifera* and tolerant *A. saccharum*, the amount of light will need to be carefully controlled. Not enough light will stimulate *A. saccharum* in the understory, while too much light will stimulate *L. tulipifera*. We did note an increase in *L. tulipifera* in the understory after the initial treatment, but these newly emerged seedlings slowly faded out as the *A. saccharum* occupied the midstory space. The *L. tulipifera* positively responded to the final harvest and are quickly dominating, and the majority of stems will soon be in sapling sizes.

In these aggregating hardwood forests, the absence or low density of small stems of *Quercus* strongly suggests that these species will decline in importance in the next stand. The emergence of *Quercus* 25-30 years after stand initiation may occur, however, even if there are relatively few *Quercus* in subordinate positions early in stand development. This *Quercus* development could be stimulated by a targeted intermediate treatment to control *Quercus* competitors in the succeeding stands. In clearcut upland hardwood forests in southern Indiana, Morrissey and others (2008) found that *Quercus* persisted during the stem exclusion stage (21-35 years after harvesting) in association with *L. tulipifera*. If the shelterwood method is going to be successful in regenerating *Quercus*, established *Quercus* must be of competitive size, such as the 5 foot height given by Sander (1972). If we use 1.5 inches dbh as the acceptable cut-off size for competitive *Quercus*, which is reasonable on these higher productivity sites that have an abundance of early-successional and fast growing *L. tulipifera*, none of the shelterwoods tested in this study would meet a desired stocking goal for *Quercus*, regardless of the end density. In upland hardwood stands in North Carolina treated with two-phase shelterwood harvests, Loftis (1983) found 16 years after harvest oak seedling density increased, but tolerant hardwoods dominated. In our stands, we also have the threat of tolerant *A. saccharum* moving into larger and more competitive size classes. As with Groninger and Long (2008), we found that clearcutting was more effective for maintaining *Quercus* compared to any of the two-stage shelterwoods, but not without a concurrent stimulation of both *L. tulipifera* and *A. saccharum*. On a productive site in the southern Appalachians of North Carolina, Loftis (1978) reported that four years after clearcutting stands treated with a preharvest herbicide treatment resulted in the same number of desirable stems 0.5 inch dbh and greater as a complete clearcut with no pretreatment. Without post-clearcutting competition control, *Quercus* will most likely lose dominance in Cumberland Plateau escarpment forests.

CONCLUSIONS

In an attempt to mimic the perfect storm of disturbances that resulted in the forest composition we have today, we are testing various residual basal area retention shelterwoods to ascertain how a change in basal area, stem density, and subsequent light levels and competition, impact Cumberland Plateau stands. Although studies in similar areas have reported that the conditions created by the first phase of the shelterwoods were conducive to promoting desired species such as *Quercus*, few have followed stand structure and associated dynamics after the final harvest. We should use caution in interpreting results at any intermediary stage. In our study, desirable stems of *Quercus* have not recruited beyond the regeneration stratum. However, in terms of esthetics and wildlife habitat creation, these successive disturbances may appeal to some land owners.

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