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Forest structure, composition, and tree diversity response to a gradient of regeneration harvests in the mid-Cumberland Plateau escarpment region, USA

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Upland hardwood stands on mesic, escarpment-oriented sites on the Cumberland Plateau region of northeastern Alabama provide a myriad management opportunities. Stands are primarily managed for *Quercus*, but the high species diversity allows for management that targets multiple species. Stand composition is unique in that dominant species include shade tolerant species such as *Acer saccharum*, intermediate tolerant *Quercus* spp. and *Carya* spp., and intolerant *Liriodendron tulipifera*. Three replications of five levels of disturbance were created to assess species compositional changes; disturbances included three levels of harvest intensity, a mid-story herbicide treatment, and a control. After eight growing seasons, there were no discernable differences in species richness, diversity or evenness. Importance values based on relative basal area and relative density also changed little, except for clearcuts where *L. tulipifera* greatly increased. An initial gradient in basal area, canopy cover, and light created by harvesting or thinning dissipated following five growing seasons. Options exist for future stand management, including promoting two-aged or uneven-aged systems. Maintenance of *Quercus* will require additional tending.

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1. Introduction

Quercus L. ranks among the most important tree taxa in the northern hemisphere with about 600 species (Mabberley, 2008). Though dominant in mixed species forest throughout their wide distribution, there are reports of regeneration failures worldwide and sustaining or increasing levels of *Quercus* stocking is problematic (Watt, 1919; Thadami and Ashton, 1995; Li and Ma, 2003; Götmark et al., 2005; Pulido and Díaz, 2005; Zavaleta et al., 2007). In the eastern United States, *Quercus*-dominated forests are being successionally replaced often by more shade tolerant species such as *Acer rubrum* L. that are dominating the regeneration and forest understories due to changes in land use and disturbance regimes (Abrams, 1992, 1998, 2003; Nowacki and Abrams, 2008). In the Cumberland and Allegheny Plateau Regions, the lack of fire and other practices that result in high forest density are favoring the development of under- and midstories dominated by shade tolerant species that are recruiting into the overstory and replacing *Quercus* (Arthur et al., 1998; Hutchinson et al., 2005; Blankenship and Arthur, 2006; Alexander et al., 2008). Because of the ecological and economic value of *Quercus* is substantial, forest succession to non-*Quercus* species is of great conservation concern. But today, despite our best efforts to sustain *Quercus* in forests of the eastern United States through silvicultural regeneration methods, oak regeneration failures are still too common (Johnson et al., 2009).

For thousands of years, both anthropogenic and natural disturbances have influenced forests of this region (Delcourt and Delcourt, 1997, 1998), and the role of fire in human land use practices favored *Quercus* distribution and dominance. A review of anthropogenic land use and subsequent changes in the area has been provided by Hart and Grissino-Mayer (2008). In the 20th century, forests were impacted by drastic changes in land use primarily through forest conversion to agriculture, industrial logging and the introduction of invasive insects and diseases. *Quercus* and the diversity other tree species characteristic of Cumberland Plateau forests regenerated during this period of frequent disturbances and grew to become today's modern forests following the cessation of burning, changes in timber harvesting and agricultural abandonment. Now, forests are being regenerated under a new regime of forest disturbances and land uses that are less frequent, lower intensity and affecting smaller areas. For example, in a forest undisturbed by logging for over 80 years, Hart and Grissino-Mayer (2008) found only one exogenous disturbance that impacted the entire stand. Under conditions such as these, a midstory of shade tolerant species develops in the forest, and they often dominate regeneration following a more major disturbance. The net result is that forest diversity declines and there is less *Quercus*.

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On the Cumberland Plateau, the *Quercus–Carya* forest type dominates forests of northeastern Alabama. In Jackson County, located in the northeastern corner of the state, 79% of the 182,655 ha of timberland were classified as *Quercus–Carya* (Hartsell and Brown, 2002). These forested systems have faced similar stresses as other southern Appalachian plateau hardwood systems, including a mixed history of indiscriminant logging, fire, and sporadic, severe weather events. Over the past 50 to 100 years, the result of these widespread disturbances was a massive intrusion of *Quercus* species, *Liriodendron tulipifera* L., *Fraxinus americana* L., and other important hardwood species. Today's upland hardwood forests in the Tennessee Valley of the Cumberland Plateau and adjacent regions contain a mixture of species with wide ranges of shade tolerance and growth potential. Our research now focuses on how to manage the resulting stand structures and species compositions to meet current utilization goals and achieve our desired future conditions, which include sustaining *Quercus* in diverse hardwood forests.

Cumberland Plateau forests 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 escarpments. These classifications result from local topographic and edaphic conditions, a consequence of geological uplifting and subsequent weathering and erosion. Over 30 canopy species can be found in the highly biodiverse forests of the Cumberland Plateau (Hinkle et al., 1993). Myriad disturbances have influenced these forests and most stands are considered second or third growth (Hart and Grissino-Mayer, 2008). On the more xeric tabletop surface, forest management targeting *Quercus* timber production and regeneration is often successfully and efficiently accomplished by clearcutting when *Quercus* regeneration potential is adequate (Roach and Gingrich, 1968; Beck, 1988; Sander, 1977; Johnson et al., 2009). Competition with *Quercus* on these sites of lower productivity (site index <20 m *Quercus rubra* base age 50 years) is less and the more drought-tolerant *Quercus* has a competitive advantage over mesic, drought sensitive species. Thus, there is increased probability of *Quercus* dominance after a regeneration disturbance from both overstory *Quercus* stump sprouting and the accumulation of adequate numbers of large *Quercus* advance reproduction. However, on the more productive mesic side-slopes, regenerating *Quercus* is complicated by site factors that promote intense competition from a wide variety of species such as *L. tulipifera*, *Acer rubrum* and *Acer saccharum* Marsh. representing a diverse range of life history and ecological characteristics (Loftis, 1990; Johnson et al., 2009).

Disturbance intensity is a main determinant of species richness in many ecosystems, and this interacts with site productivity (Huston, 1979; Kondoh, 2001). Diversity often is increased with increasing disturbance intensity on most sites with average or better productivity. What is unclear at this time is how the gradient of forest disturbance represented by the various regeneration methods, i.e., single-tree selection to clearcutting, affects tree diversity and regeneration on the Cumberland Plateau escarpment. Stand structure analysis following differing levels of managed disturbances allows us to quantify residual compositional changes due to a range of increasing levels of disturbance when forests are regenerated. More specifically, what is unknown in upland hardwood forests on the escarpment of the Cumberland Plateau is what level of managed disturbance is needed to regenerate desired species such as *Quercus*, where the goal is not merely to maximize species diversity. Common management goals in the region are to restore native forests and woodlands, promote *Quercus* dominated ecosystems, conserve native species diversity and maintain current species mixtures where they are diverse by emulating natural disturbance regimes, which historically have included combinations of single-tree gaps to stand replacement events depending on the timeframe considered (USDA Forest Service, 2004a,b). An important distinction is that forest managers want some certainty in the outcome in terms of forest structure and composition when they apply silvicultural methods to achieve forest plan goals. The challenge then is to recruit desirable species into competitive positions and create desired future conditions by altering one highly influential and manageable variable, i.e., disturbance intensity (Loftis, 1990).

Quercus species are desirable, and a considerable body of work has been published detailing *Quercus* ecology and silviculture (Johnson et al., 2009). Various scientists have advocated the use of selection (Loewenstein et al., 2000; in xeric *Quercus* forests), shelterwood, and clearcut regeneration methods (Roach and Gingrich, 1968; Sander, 1977; Loftis, 1990; Johnson et al., 2009) to sustain *Quercus* dominated forests depending on the site quality, region and competing species. But failures to regenerate *Quercus* by these various methods also are commonly reported in the literature (see review by Johnson et al., 2009). The decision to forgo silvicultural intervention in mature *Quercus* dominated forests is usually followed by successional replacement of *Quercus* by shade tolerant species as stands become old growth (Johnson et al., 2009). Less information is available on forest response and regeneration to varying disturbance intensity on the escarpment of the Cumberland Plateau. Although we are aware that species patterns associated with successional stage is most likely confounded by historical or stochastic phenomena, our interest is in the resulting forest structure and composition along the disturbance gradient created by application of the traditional regeneration methods. Specific study objectives were to: (1) quantitatively describe species composition and structural attributes under five disturbance regimes that vary in level of intensity, (2) evaluate differences and changes in canopy cover and understory light levels following eight growing seasons after application of five disturbance levels, and (3) compare structural complexity and species richness following five disturbance intensities.

2. Methods

2.1. Site description

The study sites are located in Jackson County, northeastern 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 et al. (1994). 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 13 °C, and mean precipitation of 149 cm (Smalley, 1982). We conducted our study at two separate sites. One site was located on a south, southwest-facing slope of Miller Mountain (34°58′11″ N, 86°12′21″ W). The second site was located on a north-facing slope at Jack Gap (34°56′30″ N, 86°04′00″ W). Dominant canopy tree taxa on both sites included *Quercus*, including *Quercus velutina* Lamarck, *Q. rubra* L., *Quercus alba* L., *Quercus prinus* L., 46% of pretreatment basal area; *Carya* species, 15% pretreatment basal area; *A. saccharum*, 13% pretreatment basal area; and *L. tulipifera*, 9% pretreatment basal area. Common understory species included *Cornus florida* L., *Cercis canadensis* L., and *Oxydendrum arboreum* DC.

2.2. Study design

The study design was a randomized complete block, with three replications of five treatments. Each site (block) comprised one replication of five treatments established along the slope contour. Forests in this area were established following heavy cutting 80–100 years prior, and are considered even-aged. One replication, located on Miller Mountain, had a southwestern aspect and a mean elevation of 488 m. Two replications, located at Jack Gap, both had northern aspects. One Jack Gap replication was located at 456 m elevation and the other at 366-m elevation. Treatments were randomly assigned to 4.0-ha areas within each replicated block. The treatments constituted five levels of overstory basal area retention: (1) 100% retention, untreated control (control) (2) first treatment of 75% retention shelterwood (75SW) (3) first harvest of a 50% retention shelterwood (50SW) (4) first harvest of a 25% retention shelterwood (25SW) and (5) 0% retention, a commercial clearcut (clearcut). The commercial clearcut removed all merchantable trees, which included all species having diameter at breast height (dbh, *ca.* 1.4 m above the surface) approximately 14 cm and greater. For the 50SW and 25SW, trees were marked to be retained using guidelines outlined originally by Putnam et al. (1960), and recently updated by Meadows and Skojac (2008). Residual trees were chosen on the basis of species, favoring *Quercus*, *F. americana* and *Diospyros virginiana* L.; and class, favoring preferred and reserve growing stock. All leave trees had dominant or codominant crown positions and exhibited high vigor. Additional residual trees were retained to meet residual basal area goals; these trees were primarily *Carya*, *A. saccharum* and *L. tulipifera*. Trees were harvested by conventional methods of chainsaw felling and grapple skidding along pre-designated trails. Trees were harvested from fall 2001 through winter 2002.

For the 75SW treatment, an herbicide (Arsenal®, active ingredient imazapyr, BASF Corporation, Florham Park, NJ) was used 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 7.5 cm of diameter and each incision received approximately 4.4 fluid ml of solution. Herbicide treatments were completed in fall 2001, prior to leaf fall. The goal was to minimize the creation of overstory canopy gaps while removing 25% of the basal area in the stand midstory. All injected trees were in lower canopy positions, reducing the creation of canopy gaps.

2.3. Field methods

Prior to treatment, five measurement plots were systematically located in each treatment area. Plot centers were permanently marked with a 60-cm piece of reinforcing steel, and geographic coordinate pairs were recorded using a handheld GPS receiver. At each plot center, a 0.08-ha plot was established, and all trees 14.2 cm 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. An additional 0.01-ha plot, located concentrically, was established and all trees 3.8 cm dbh and greater were measured and monumented as previously noted.

In mid- to late-summer 2002, 2003, 2004, 2005, 2006 and 2009, all measurement plots were revisited. A hand-held spherical densitometer was used to measure canopy cover at one vertical level, 1.4 m above the forest floor surface, with measurements taken at plot center and at 3.7 m in each cardinal direction from plot center. An AccuPAR Linear Par Ceptometer, Model PAR-80 (Decagon Devices Inc., Pullman, WA), was used to measure photosynthetically active radiation at each plot center and along transects equally dissecting each plot at 1.4 m above the forest floor. Over 60 readings were obtained across the entire 4-ha treated stand at each sampling period. Another ceptometer was placed in full sun conditions during data collection, allowing for the determination of the amount of light transmittance under each treatment condition as compared to full sunlight levels. By matching two simultaneous readings, we could take into account some variation due to changes in cloud cover. Prior to analysis, the square root of the percentage data was arc sine transformed to meet normality and homogeneity assumptions.

Shannon–Weaver's index of diversity (H') (Shannon and Weaver, 1949) and Pielou's evenness index (J') (Pielou, 1966) were computed for trees 3.8 cm and greater. Basal area for woody stems was used for diversity estimates, as basal area is a better reflection than density of the degree to which each species occupies a site (McMinn, 1992). Diversity was calculated following $H' = \sum p_i \ln p_i$ where p_i is the proportion of total basal area of species *i*. Species evenness was calculated as $J' = H'/H'_{max}$, where H'_{max} is the maximum level of diversity possible within a given population. The Shannon–Weaver diversity index has been commonly applied to assess species composition in Appalachian and similar forested systems (McCarthy and Bailey, 1996; Elliott et al., 1997; McMinn, 1992; Brashears et al., 2004; Hart et al., 2008). A relative importance value was calculated for each tree species by summing the relative density and relative dominance (based on basal area) and dividing by two (Cottam and Curtis, 1956; Crow et al., 2002).

2.4. Data analysis

Vegetation was analyzed by standard descriptors of density, basal area, importance, richness, the Shannon diversity index (H'), and evenness (J) (Cottam and Curtis, 1956; Ludwig and Reynolds, 1988). Normality and homogeneity of variances were examined using graphical analysis, and transformations were not necessary. Two-way factorial analysis of variance (ANOVA) was used to test the treatment and year effects while controlling the block effect. Tukey's Honestly Significant Difference (HSD) tests were used for mean separation (SAS, 2000). When an interaction occurred between year and treatment, we analyzed year separately using analysis of variance (ANOVA) with treatment and block as main factors. We used one-way ANOVA to evaluate the stand-level differences in diversity, evenness and richness for preharvest and the 2009 postharvest data. We used Pearson correlations and linear regression to examine relationships among stand basal area and stems per hectare and light (light reduction for August) and canopy cover. We reported means and standard errors. Statistical tests were declared significant when the probability of Type I error was smaller than $\alpha \leqslant 0.05$.

3. Results

3.1. Overstory tree conditions

Residual canopy data were assessed using the 0.08-ha plot which represented harvestable tree diameters for this project. Stands initially contained 35 species and composition was typical for Cumberland Plateau escarpment forests. Pretreatment inventories showed that stands were fully stocked and contained between 23.2 and 26.6 $m^2 ha^{-1}$ basal area for overstory trees (trees $\geqslant$14.2 cm dbh), averaging 25.2 $m^2 ha^{-1}$ (Table 1). Diameters ranged from 4.2 to 90.9 cm. The dominant species based on percent of total basal area were *Q. alba* (17%), *Carya* spp. (16.1%), *Q. prinus* (14.3%), *A. saccharum* (13.8%), *Q. rubra* (11.6%) and *L. tulipifera* (10.4%). *Carya* species included *C. glabra* Sweet, *C. ovalis* Sarge., *C. ovata* K. Koch., and *C. tomentosa* Nutt. *Carya ovalis* accounted for 50.5% of the total *Carya* basal area, and 9.6% of total stand basal area. Other *Quercus* species in the canopy layer included *Q. velutina* (2.8%), *Q. muehlenbergii* Englem., (1.5%) and *Q. coccinea* Muench. (0.7%).

Table 1
Pre and posttreatment basal area ± SE (BA m^2/ha) and shelterwood retention goals for stands in Jackson County, Alabama.

Treatment	Pre treatment BA	Target BA retention	Residual BA retention	Actual% retained
Control	23.2 (1.5)a	23.2	23.1 (1.5)a	99.4
75% Retention	26.7 (1.9)a	20.0	26.3 (1.4)a	98.5
50% Retention	25.8 (3.8)a	12.9	10.1 (4.1)b	39.0
25% Retention	24.2 (1.9)a	5.5	8.1 (3.3)bc	34.0
Clearcut	26.0 (1.9)a	0.0	1.4 (1.8)c	5.2
p-Value	0.5722		0.0001	
$F_{4,2}$	0.98		37.31	

Columns with different letters are significantly different at the 0.05 level.

Following treatment application, three different basal areas resulted (Table 1). For the control and 75SW, basal area remained relatively unchanged from pretreatment values. The herbicide treatment targeted the midstory trees, and few overstory trees were treated. On average, 93 stems ha^{-1} were treated with herbicide, with a median diameter of 9.7 cm and a range from 3.3 to 45.0 cm. The clearcut resulted in the lowest residual basal area, 1.4 m^2 ha^{-1}, and was significantly different from all other treatments except the 25SW ($F_{4,2}$ = 37.31, P = 0.0001). The 50SW left 10.1 m^2 ha^{-1}, which was significantly different from all other treatments except the 25SW. The 25SW had a residual basal area of 8.5 m^2 ha^{-1}, and this was only significantly different than the control and 75SW. A gradient of residual basal areas was created, and the percent reduction goals are given in Table 1.

The herbicide treatment targeted midstory, not overstory trees, and those trees had diameters that were below the threshold used for the overstory data. If we consider data from the 0.01-ha plot, which included all trees 3.8 cm dbh and greater, the amount of basal area removed in this treatment was 7.6 m^2 ha^{-1}, or 27% of the total (total basal area = 27.7 m^2 ha^{-1} including small diameter stems). Eleven species were targeted in the herbicide treatment, with *A. rubrum* the primary target having 25 stems ha^{-1} treated, followed by *A. saccharum* (21 stems ha^{-1}) and *Nyssa sylvatica* Marsh. (17 stems ha^{-1}).

Because the combination of year and treatment varied with respect to the residual basal areas, the univariate effects were tested separately. The gradient of basal area of residual overstory trees created by the various treatments varied only slightly over time (Table 2), and after eight growing seasons were nearly the same as in the first posttreatment year. Treatment effects among years showed that for the clearcut, 25SW and 50SW, residual basal area was immediately significantly different from pretreatment levels and this difference was maintained even after eight growing seasons. Control and 75SW gradually increased basal area, with a linear change rate over time. Diameter growth of the residual overstory trees eight years after harvesting ranged between 9.4 cm in clearcut stands to 16.5 cm in the 50SW. *L. tulipifera* had the greatest diameter growth in all treatments among all species, increasing 9.2 cm in the clearcut, 3.0 cm in the 50SW, 3.6 cm in the 75SW and 25SW, and 7.6 cm in the control. *Quercus* diameter growth was minimal for the control stands, averaging only 2.0 cm for *Q. alba*, with no diameter change for *Q. prinus* or *Q. rubra*. It was greatest in the 50SW treatment (10.2 cm), followed by the 25SW (7.1 cm), 75SW (6.4 cm) and the clearcut (5.1 cm).

3.2. Stand structure and composition

After eight growing seasons, the species composition for all stems 3.8 cm dbh and greater did not change appreciatively for the control and 75SW stands. *Quercus* (*Q. prinus, Q. alba and Q. rubra*) relative basal area (species basal area as a percent of total basal area) remained at approximately 40% in control stands, and other dominant species did not change. For the 75SW, relative *Quercus* basal area increased from 40.5% to 48.9%, gaining 1.6 m^2 ha^{-1} overall. Clearcutting influenced composition, with *Quercus* being reduced from 40% to 11% relative basal area (11.0 to 0.7 m^2 ha^{-1}) following harvest (Table 3). However, in these stands, *A. saccharum*, *L. tulipifera*, *Magnolia acuminata* L., and *Fagus grandifolia* Ehrh. relative basal area increased. The residual stands in the 50SW had an increased relative basal area for *Quercus* from 23.7 to 32.0%, while the relative basal area of *L. tulipifera* doubled, and *Carya* and *A. saccharum* declined. The 25SW also had reduced *Carya* basal area, and basal area for *L. tulipifera* remained unchanged, while that of *Quercus* slightly increased.

Eleven trees ha^{-1} died naturally over the 5-year study period in the control stands. These trees averaged 2.5 m^2 ha^{-1} and 18.3 cm dbh, and consisted of *A. saccharum*, *L. tulipifera*, *A. rubrum*, *Robinia pseudoacacia* L., and *Ulmus rubra* Muhl. In the 75SW, three trees ha^{-1} died of natural causes, including *N. sylvatica*, *C. ovalis*, and *Q. alba*; their average basal area was only 0.6 m^2 ha^{-1}, with an average diameter of 17.8 cm. Two residual trees ha^{-1} died in both the 50SW and 25SW. These were small-diameter trees, 11.1 cm and 13.2 cm dbh, respectively, and accounted for 0.2 m^2 ha^{-1}.

3.3. Forest composition

By examining data collected from plots that included all stems 3.8 cm dbh and greater, we can better quantify species composition and structure within the stands. Twenty-six species were

Table 2
Treatment basal area ± SE (BA m^2/h) comparison within each year, including 2001 pretreatment values and following over eight growing seasons, for stands in Jackson County, Alabama.

Treatment	2001	2002	2003	2004	2005	2006	2009
Control	23.2 (1.5)a	23.1 (1.5)a	23.8 (1.6)a	24.3 (1.4)a	24.8 (1.7)a	25.4 (1.6)a	25.2 (2.5)a
75% Retention	26.7 (1.9)a	23.1 (1.4)a	23.8 (1.3)a	24.3 (1.7)a	24.8 (1.6)a	25.1 (1.7)a	24.6 (2.4)a
50% Retention	25.8 (3.8)a	10.0 (4.1)b	10.1 (3.9)b	10.7 (4.2)b	11.2 (4.2)b	11.1 (4.1)b	11.0 (4.2)b
25% Retention	24.2 (1.9)a	8.5 (3.3)bc	8.0 (2.9)bc	8.7 (2.8)b	8.9 (2.8)b	8.9 (3.1)bc	8.7 (3.4)bc
Clearcut	26.0 (1.9)a	1.2 (1.8)c	1.3 (1.9)c	2.5 (2.7)b	2.5 (2.8)b	1.7 (2.3)c	1.8 (2.3)c
$F_{4,2}$	0.98	37.31	45.46	34.28	33.79	41.61	33.13
p-Value	0.5722	0.0001	0.0001	0.0001	0.0001	0.0001	0.0006

Columns with different letters are significantly different at the 0.05 level.

Table 3
Percent of total basal area by species (3.8 cm and larger) following, three harvest intensities, for years one, five and eight posttreatment.

	Clearcut			50% Retention			25% Retention		
	2001-pre treatment	2006-post treatment	2009-post treatment	2001-pre treatment	2006-post treatment	2009-post treatment	2001-pre treatment	2006-post treatment	2009-post treatment
Acer saccharum	9.9	29.7	22.3	15.4	7.3	9.7	28.4	35.0	32.1
Carya spp.	13.8	0.0	0.4	24.7	10.4	9.5	14.6	0.1	0.2
Liriodendron tulipifera	2.4	11.6	14.7	10.0	21.2	20.9	3.0	1.7	3.3
Quercus alba	15.6	10.0	8.1	12.7	22.7	21.8	5.9	6.9	6.6
Quercus prinus	24.0	0.4	1.1	9.5	11.0	10.2	14.3	14.7	14.4
Quercus rubra	0.2	2.7	2.1	1.5	0.0	0.0	14.2	21.2	19.4

Table 4
Pretreatment overstory and midstory species basal area (m^2/ha), stems per hectare (SPH), and Importance Value (IV) for all stems 3.8 cm dbh and greater for each treatment (n = 3 stands per treatment).

Species	Control			75% Retention			50% Retention			25% Retention			Clearcut		
	BA	SPH	IV	BA	SPH	IV	BA	SPH	IV	BA	SPH	IV	BA	SPH	IV
Acer rubrum L.	0.5	13	6.7	1.8	25	13.1	0.3	2	1.3	0.6	8	4.0	0.4	6	3.2
Acer saccharum Marsh.	6.8	40	30.1	2.5	27	15.4	5.0	52	26.6	7.5	40	29.1	2.7	44	21.4
Aesculus sylvatica Bartr.	0.0	0	0.0	0.0	0	0.0	0.4	3	1.8	0.0	0	0.0	0.0	0	0.0
Carya glabra Sweet	0.6	1	1.5	0.1	1	0.7	0.0	0	0.0	0.0	0	0.0	0.1	1	0.7
Carya ovalis Sarge.	0.2	0	0.5	4.8	14	14.7	2.1	5	5.2	2.4	4	6.2	1.1	3	3.2
Carya ovata K. Koch.	1.1	5	4.3	0.1	1	0.7	5.9	11	13.0	1.4	3	3.9	2.5	8	7.4
Cercis canadensis L.	0.0	0	0.0	0.0	0	0.0	0.0	2	0.8	0.0	1	0.5	0.2	6	2.8
Cornus florida L.	0.1	2	1.1	0.0	1	0.4	0.0	2	0.8	0.0	3	1.3	0.1	4	1.8
Fagus grandifolia Ehrh.	0.0	1	0.5	1.8	10	7.2	0.1	1	0.6	0.1	6	2.6	5.1	8	12.0
Fraxinus americana L.	1.1	5	4.4	1.1	6	4.5	1.4	8	5.3	0.3	8	3.8	0.4	12	5.2
Liriodendron tulipifera L.	4.9	11	13.7	0.2	1	0.8	3.2	6	7.3	0.8	4	3.1	0.7	6	3.6
Magnolia acuminata L.	0.3	2	1.6	0.0	0	0.0	0.1	5	2.1	0.0	1	0.5	0.1	1	0.6
Nyssa sylvatica Marsh.	0.2	3	1.7	1.9	21	11.6	2.6	8	7.1	0.9	3	3.0	0.5	5	2.9
Ostrya virginiana K. Koch.	0.0	0	0.0	0.0	1	0.5	0.0	3	1.2	0.0	1	0.5	0.0	0	0.0
Oxydendrum arboreum DC	0.1	1	0.7	0.4	6	3.4	0.6	6	3.3	0.5	5	2.9	0.2	3	1.5
Quercus alba L.	6.8	11	24.7	6.7	8	15.7	4.1	5	8.3	1.6	3	4.2	4.3	6	10.2
Quercus prinus L.	2.1	3	5.2	1.5	1	3.4	3.1	2	5.5	3.8	5	9.2	6.6	6	14.4
Quercus muehlenbergii Englem.	0.0	0	0.0	0.0	0	0.0	1.6	2	3.2	0.6	3	2.3	0.0	0	0.0
Quercus rubra L.	1.7	3	4.5	2.4	2	5.4	0.5	1	1.2	3.7	4	8.7	0.1	1	0.5
Quercus velutina Lamarck	0.0	0	0.0	0.0	0	0.0	0.9	1	1.8	0.7	1	1.7	1.7	2	3.9
Rhamnus caroliniana Walt.	0.0	0	0.0	0.0	1	0.5	0.0	2	0.8	0.0	2	0.9	0.0	0	0.0
Robinia pseudoacacia L.	0.3	2	1.4	0.6	2	2.0	0.0	0	0.0	0.1	3	1.5	0.2	1	0.8
Sassafras albidum (Nutt.) Nees.	0.3	2	1.4	0.0	0	0.0	0.2	1	0.7	0.4	6	3.2	0.2	3	1.6
Tilia glabra Vent.	0.0	0	0.0	0.0	0	0.0	0.0	1	0.4	0.0	1	0.4	0.0	2	0.9
Ulmus alata Michx.	0.0	0	0.0	0.0	0	0.0	0.0	0	0.0	0.5	3	2.2	0.0	1	0.4
Ulmus rubra Muhl.	0.5	5	3.3	0.0	0	0.0	0.2	3	1.5	0.2	10	4.0	0.1	2	1.0
Total	27.6	113	100.0	26.2	128	100.0	32.3	137	100.0	26.4	134	100.0	27.5	135	100.0

identified on these plots across all study stands. Stands were dominated by *A. saccharum*, which ranked first or second in importance (IV) for all treatments prior to manipulation (Table 4). The five most important species in control stands (72.8 total IV) represented a range of shade tolerances, including shade tolerant *A. saccharum*, intermediate tolerant *A. rubrum*, *Q. alba* and *Q. prinus*, and intolerant *L. tulipifera* (Table 5). Relative density of these species combined was 69.1 and relative basal area was 76.7. After five growing seasons of only minor natural disturbances, control stand composition did not change with the exception of *C. canadensis*, which was present but not large enough to tally pretreatment. After eight growing seasons, a few *Ostrya virginiana* K. Koch. were tallied in the understory. There were no differences in H', H'_{max}, J' or richness between pretreatment and 8-year posttreatment values (Table 6).

The 75SW were also dominated by *A. saccharum* (IV = 15.4) and *Q. alba* (IV = 15.7) prior to treatment, followed by *C. ovalis*, *A. rubrum*, and *N. sylvatica* (Table 5). Stems per hectare decreased from 128 to 38 to 55 following treatment and five ($F_{1,4} = 64.15$, $P = 0.0013$) and eight growing seasons ($F_{1,5} = 47.41$, $P = 0.0024$). Posttreatment composition reflected treatment targeted species, as *A. saccharum* IV was reduced to 9.7 in 2006 and then increased to 11.4 in 2009, and *A. rubrum* was below 2 in 2006 and increased to 4.7 in 2009. *A. rubrum* stem density changed from 27 stems ha^{-1} to 1 stem ha^{-1} in 2006 to 4 stems ha^{-1} in 2009, as *A. rubrum* saplings were targeted midstory species herbicided in this treatment. *A. rubrum* between 3.8 to 12.7 cm dbh were reduced from 15 to 0 stems ha^{-1}, and *A. rubrum* between 12.7 to 38.1 cm dbh were reduced from 10 to 0 stems ha^{-1}. Both *F. americana* and *Q. rubra*, desirable species that were not treated, increased their relative dominance as *A. saccharum* and *A. rubrum* were killed. Relative density and basal area did not change for *F. americana* or *Q. rubra* posttreatment. Species richness decreased from 17 to 13 from 2001 to 2006, ($F_{1,4} = 8.47$, $P = 0.047$), with the loss of midstory occupants *O. virginiana*, *C. florida*, *O. arboreum*, and *C. ovata*, but increased to 15 in 2009 with the addition of *O. virginiana* and *O. arboreum*. Diversity and evenness did not differ from pretreatment values following eight growing seasons (Table 6).

The 50SW had 23 species prior to treatment and 21 after 5 years posttreatment (2006) and 24 species after eight years (2009). Diversity, evenness and richness eight growing seasons posttreatment did not differ from pretreatment. The dominant species pretreatment were *A. saccharum* (IV = 26.6), *C. ovata* (IV = 13.0), *Q. alba* (IV = 8.3), *L. tulipifera* (IV = 7.3) and *N. sylvatica* (IV = 7.1)

Table 5
Importance values (IV), relative density (RD) and relative basal area (RBA) for highest ranked species by treatment, for pretreatment (2001), 5-years posttreatment (2006) and 8-years posttreatment vegetation 3.8 cm and greater.

	Pretreatment				5-years Posttreatment				8-years Posttreatment			
	Species	IV	RD	RBA	Species	IV	RD	RBA	Species	IV	RD	RBA
Control	*Acer saccharum*	30.1	35.5	24.7	*Acer saccharum*	25.9	33.5	18.3	*Acer saccharum*	26.9	32.2	21.6
	Quercus alba	17.1	9.6	24.7	*Quercus alba*	18.0	9.1	26.9	*Quercus alba*	16.1	8.1	24.1
	Liriodendron tulipifera	13.7	9.6	17.9	*Liriodendron tulipifera*	13.3	7.3	19.4	*Liriodendron tulipifera*	13.0	8.1	18.0
	Acer rubrum	6.7	11.5	1.9	*Acer rubrum*	6.4	10.9	2.0	*Carya ovalis*	5.3	4.0	6.6
	Quercus prinus	5.2	2.9	7.5	*Quercus prinus*	5.6	2.7	8.5	*Fagus grandifolia*	4.2	8.1	0.4
Control	Totals	72.8	69.1	76.7	Totals	69.2	63.5	75.1	Totals	65.5	60.5	70.7
75% retention	*Quercus prinus*	15.7	5.9	25.4	*White oak*	23.3	16.2	30.4	*Quercus alba*	22.1	14.0	30.2
	Acer saccharum	15.4	21.0	9.7	*Carya ovalis*	20.1	21.6	18.6	*Carya ovalis*	19.8	20.0	19.6
	Carya ovalis	14.7	10.9	18.5	*Acer saccharum*	9.7	10.8	8.5	*Acer saccharum*	11.4	14.0	8.8
	Acer rubrum	13.1	19.3	6.9	*Fraxinus americana*	9.2	13.5	4.9	*Nyssa sylvatica*	7.5	10.0	5.0
	Nyssa sylvatica	11.6	16.0	7.3	*Quercus rubra*	8.4	5.4	11.5	*Fraxinus americana*	7.2	10.0	4.3
75% retention	Totals	70.5	73.1	67.8	Totals	70.7	67.5	73.9	Totals	68.0	68.0	67.9
50% retention	*Acer saccharum*	26.6	37.8	15.4	*Liriodendron tulipifera*	27.8	34.4	21.2	*Liriodendron tulipifera*	28.9	37.0	20.9
	Carya ovata	13.0	7.9	18.2	*Acer saccharum*	15.3	23.3	7.3	*Acer saccharum*	14.7	19.7	9.7
	Quercus alba	8.3	3.9	12.7	*Quercus alba*	12.5	2.2	22.7	*Quercus alba*	11.7	1.6	21.8
	Liriodendron tulipifera	7.3	4.7	10.0	*Nyssa sylvatica*	7.5	3.3	11.7	*Nyssa sylvatica*	6.6	2.4	10.7
	Nyssa sylvatica	7.1	6.3	8.0	*Quercus prinus*	6.0	1.1	11.0	*Quercus prinus*	5.5	0.8	10.2
50% retention	Totals	62.3	60.6	64.3	Totals	69.1	64.3	73.9	Totals	67.4	61.5	73.3
25% retention	*Acer saccharum*	29.1	29.8	28.4	*Acer saccharum*	26.1	17.2	35.0	*Acer saccharum*	22.6	13.1	32.1
	Quercus prinus	9.2	4.0	14.3	*Quercus rubra*	11.4	1.7	21.2	*Quercus rubra*	10.3	1.2	19.4
	Quercus rubra	8.7	3.2	14.2	*Quercus prinus*	8.7	2.6	14.7	*Liriodendron tulipifera*	9.7	16.2	3.3
	Carya ovalis	6.2	3.2	9.2	*Ulmus rubra*	8.1	12.9	3.3	*Quercus prinus*	8.8	3.1	14.4
	Quercus alba	4.2	2.4	5.9	*Liriodendron tulipifera*	6.9	12.1	1.7	*Fraxinus americana*	6.8	10.6	2.9
25% retention	Totals	57.4	42.6	72.0	Totals	61.2	46.5	75.9	Totals	58.2	44.2	72.1
Clearcut	*Acer saccharum*	21.4	9.9	9.9	*Acer saccharum*	24.9	20.0	29.7	*Liriodendron tulipifera*	18.5	22.2	14.7
	Quercus prinus	14.4	24.0	24.0	*Fraxinus americana*	14.1	13.3	14.8	*Acer saccharum*	17.6	13.0	22.3
	Fagus grandifolia	12.0	18.5	18.5	*Liriodendron tulipifera*	13.1	14.7	11.6	*Fraxinus americana*	11.6	9.9	13.3
	Quercus alba	10.2	15.6	15.6	*Acer rubrum*	7.8	12.0	3.6	*Acer rubrum*	6.2	7.4	5.0
	Carya ovata	7.4	9.2	9.2	*Fagus grandifolia*	6.3	8.0	4.5	*Prunus serotina*	5.8	7.4	4.2
Clearcut	Totals	65.4	77.2	77.2	Totals	66.2	68.0	64.2	Totals	59.7	59.9	59.5

Table 6
Shannon–Weaver's index of diversity (H') (Shannon and Weaver, 1949) and Pielou's evenness index (J') (Pielou, 1966) for trees 4.1 cm and greater. H'_{max} is the maximum level of diversity possible within a given population, and richness is the total number of species 3.8 cm and greater, for pre (2001) 5 years post (2006) and eight years post (2009) treatment for stands subjected to a gradient of disturbances.

	Treatment Time	H'	H'_{max}	J'	Richness
Control	2001	2.29	2.89	0.79	18
	2006	2.16	2.94	0.73	19
	2009	2.16	3.00	0.72	20
75% Retention	2001	2.22	2.83	0.78	17
	2006	2.07	2.56	0.81	13
	2009	2.10	2.71	0.77	15
50% Retention	2001	2.44	3.14	0.78	23
	2006	2.09	3.04	0.69	21
	2009	2.24	3.18	0.70	24
25% Retention	2001	2.27	3.18	0.72	24
	2006	2.06	3.18	0.64	24
	2009	2.21	3.18	0.70	24
Clearcut	2001	2.26	3.09	0.73	22
	2006	2.31	2.99	0.77	20
	2009	2.55	3.18	0.80	24

(Table 5). Five and eight growing seasons after cutting, *L. tulipifera*, *A. saccharum*, *Q. alba* and *N. sylvatica* retained their dominance, with *C. ovata* being replaced by *Q. prinus* (Table 5). The number of *L. tulipifera* stems ha^{-1} increased from 6 to 34 to 51, and relative density from 5% to 34% to 37%. Basal area of *L. tulipifera* declined slightly, from 3.2 m^2 ha^{-1} to 2.5 m^2 ha^{-1} to 2.8 m^2 ha^{-1}, as large *L. tulipifera* were removed during harvest. Five species were lost 5-years posttreatment, including *Q. muehlenbergii* and *Q. rubra*, *A. rubrum*, *Aesculus sylvatica* Bartr., and *Rhamnus caroliniana* Walt.; both *A. sylvatica* and *Q. rubra* were tallied in 2009. Three new species were noted 5-years posttreatment, *Prunus serotina* Ehrh. and *Ulmus alata* Michx., and the invasive species *Paulownia tomentosa* (Thunb.) Sieb & Zucc. ex Steud., with the addition of *Crataegus* spp. and *C. occidentalis*. There were no differences in diversity, evenness or richness from 2001 to 2009 (Table 6).

The 25SW were dominated by *A. saccharum* (IV = 29.1), *Q. prinus* (IV = 9.2), *Q. rubra* (IV = 8.7), *C. ovalis* (IV = 6.2) and *Q. alba* (IV = 4.2). Posttreatment, *A. saccharum*, *Q. rubra*, and *Q. prinus* all remained ranked in the top 5 dominance category, with *L. tulipifera* and *U. rubra* replacing *Q. alba* and *C. ovalis* in 2006, and *F. americana* replacing *U. rubra* in 2009. Harvesting resulted in the initial loss of *Q. coccinea*, *Q. muehlenbergii*, and *C. ovalis*, and the gain of *P. serotina*, *Carpinus caroliniana* Walt., and the invasive species *P. tomentosa*. Following eight growing seasons, *D. virginiana* was added and *C. caroliniana* was lost. Species richness remained at 24. The number of *L. tulipifera* stems increased from 4.5 to 15 to 28 stems ha^{-1}, although basal area decreased. The diameter distribution of *L. tulipifera* shifted from three stems ha^{-1} in the 12.7–38.1 cm class and 1 stem ha^{-1} in the less than 12.7 cm class, to zero posttreatment in the 12.7–38.1 cm class and 15 stems ha^{-1} in the smallest diameter class. These *L. tulipifera* stems had a median dbh of 3.4 cm. Overall species diversity, evenness and richness did not differ among pretreatment and 8-year posttreatment stand composition.

Clearcut stands were dominated by *A. saccharum* (IV = 21.4), *Q. prinus* (IV = 14.4), *F. grandifolia* (IV = 12.0), *Q. alba* (IV = 10.2), and *C. ovata* (IV = 7.4). The harvest was commercially-driven, and stems approximately 15 cm dbh and greater were removed; remaining stems were not felled, which is the common commercial practice. *A. saccharum*, *L. tulipifera*, and *F. grandifolia* were ranked 1, 3 and 5 in dominance posttreatment 2006, with *F. americana* and *A. ru-*

brum; 2009 IV rankings were similar, with *P. serotina* replacing *F. grandifolia* as fifth ranked in importance. Species richness changed from 22 to 20 to 24, with 6 species lost 5-years after treatment, including *Q. coccinea*, *C. florida*, *C. glabra*, *C. ovalis*, *C. ovata*, and *O. arboreum*. Four new species tallied 5-years posttreatment included *P. serotina*, *O. virginiana*, and *Aralia spinosa* L., and the invasive species *P. tomentosa*. Following eight growing seasons, *C. glabra* and *C. ovalis* were present, along with *Rhus copallina* L. Evenness and diversity increased 8-years posttreatment compared to pretreament (Table 6).

3.4. Changes in canopy cover and below canopy light environment

There was a significant treatment by year interaction for canopy cover ($P = 0.0065$). Prior to treatment, the mature hardwood canopy cover was nearly 100% for all stands (Table 7). Immediately following treatment, canopy cover fell into three distinct groups ($F_{4,2} = 19.26$, $P = 0.0004$), full canopy for the control and 75SW, 75% cover for the 50SW and 25SW stands, and 31% cover for the clearcut. By the fifth growing season, there were no significant differences among treatment canopy cover ($F_{4,2} = 2.23$, $P = 0.1556$), with cover ranging from 84% in the 50SW to 96% in the control.

The percent reduction in photosynthetically active radiation compared to full light conditions, was assessed. Monthly data were collected in 2004, 2005, 2006 and 2009. In 2004, following three growing seasons posttreatment, three light regimes emerged for the average yearly light reduction ($F_{4,2} = 1087.03$, $P = 0.0001$), with control and 75SW receiving significantly less light (reduced by 74% and 64%, respectively) compared to the 50SW and 25SW treatments (both reduced 44%). Clearcut treatments received the most light, with only a 40% reduction across the first three years. By 2006, this trend had changed, with control stands having significantly less light (66% reduced) compared to the 50SW (55% reduced) and the clearcut (45% reduced). Light reduction for the 75SW was similar to both the 25SW and 50SW, and the 25SW retention treatment was similar to the clearcut. In 2009, light was reduced ($F_{4,2} = 186.35$, $P = 0.0001$) most for control (77.5%), followed by the 75SW (72.1%), 50SW (69.2%), and clearcut (69%) and 25SW (64%). During the peak of the growing season, August, light reduction was greatest in control stands; clearcuts received the most light following five growing seasons (Table 8). After eight growing seasons, there were no significant differences in the amount of light penetrating the canopies among all treatments.

Within each year, cover and August percent light reduction were strongly correlated. In 2003, the correlation coefficient was $r = 0.95$, with a $P = 0.0001$. The correlation for 2001 and 2006 were the same, with $r = 0.65$ and $P = 0.0085$. Total basal area was also strongly correlated with both the cover and light reduction, significant during years one through five postharvest. Stems ha^{-1} were not correlated to either cover or light reduction.

4. Discussion

4.1. Forest response to regeneration methods

Initial stand conditions in this study were characterized by species rich, mature, fully-stocked stands dominated by *A. saccharum*, *Quercus* species, *A. rubrum*, and *L. tulipifera*. A midstory of shade tolerant species was present and contributed toward the moderate to low light levels in the understory, where full sunlight was reduced by 92% or more. Over the course of this study (8 years) in the no treatment control plots, changes in species composition, stand structure, and species dominance rankings were insignificant. *Quercus* still comprised about 40% of the total basal area, due largely to its dominance in the overstory, but mid- and understories were dominated by shade tolerant species, and there was a definite absence of large *Quercus* advance reproduction, as existing *Quercus* in the understory were small in size (<60 cm in height). The future success of *Quercus* regeneration appears to be low when assessing the potential contributions from stump sprouts and advance reproduction, and given the presence of *L. tulipifera* and well-developed, large advance reproduction of shade tolerant species (according to Johnson et al., 2009; Loftis, 1990).

Table 7
Treatment percent canopy cover ± SE comparison within each year, and following over eight growing seasons, for stands in Jackson County, Alabama. Pretreatment (2001) Canopy cover was estimated at 100% for all stands.

Treatment	2002	2003	2004	2005	2006	2009
Control	99.7 (0.3)a	96.8 (3.2)a	98.8 (2.3)a	96.2 (2.9)a	95.8 (1.9)a	97.5 (1.3)a
75% Retention	98.3(2.2)a	94.6 (4.1)a	96.2 (3.4)a	92.3 (4.4)ab	91.9 (2.5)a	93.4 (3.7)a
50% Retention	74.9 (11.9)a	44.7 (14.2)b	71.9 (19.1)ab	87.8 (11.0)ab	83.7 (9.8)a	93.3 (7.0)a
25% Retention	76.0 (14.3)a	48.0 (16.3)b	65.1 (21.9)ab	82.0 (14.1)ab	85.2 (6.6)a	95.4 (4.1)a
Clearcut	31.0 (28.6)b	5.4 (9.8)c	47.6 (29.6)b	80.4 (16.6)b	84.2 (19.0)a	92.0 (11.5)a
$F_{4,2}$	0.0004	<0.0001	0.0039	0.0228	0.1556	0.4503
p-Value	19.26	86.23	9.5	2.23	2.23	1.02

Columns with different letters are significantly different at the 0.05 level.

Table 8
Treatment percent light reduction, compared to full light conditions, for August, ±SE comparison within each year, and following over eight growing seasons, for stands in Jackson County, Alabama. No pretreatment (2001) light data were collected.

Treatment	2002	2003	2004	2005	2006	2009
Control	92.0 (10.3)a	94.1 (5.2)a	97.0 (4.9)a	96.4 (6.8)a	97.5 (1.6)a	94.8 (8.6)a
75% Retention	83.5 (14.0)ab	89.7 (10.5)a	93.7 (7.3)ab	91.5 (11.8)a	90.7 (4.1)a	91.7 (13.8)a
50% Retention	63.8 (35.5)ab	63.1 (23.6)b	73.3 (20.8)c	81.5 (22.5)ab	82.1 (9.6)ab	93.7 (10.1)a
25% Retention	68.9 (26.7)ab	53.4 (25.3)b	74.8 (19.2)bc	85.5 (16.5)a	66.7 (22.3)b	85.6 (14.7)a
Clearcut	29.9 (29.5)b	32.8 (23.8)c	41.0 (23.8)d	63.4 (27.6)b	67.5 (18.3)b	90.5 (11.3)a
$F_{4,2}$	0.0452	<0.0001	<0.0001	0.0071	0.001	0.2013
p-Value	4.00	37.17	32.33	7.87	14.43	1.92

Columns with different letters are significantly different at the 0.05 level.

Although the disturbance history in these stands is unknown, we may be able to make general inferences from work done by Hart and Grissino-Mayer (2008) in an upland *Quercus*–*Carya* forest on the Cumberland Plateau in Tennessee. The stand had originated after logging in the 1920s during a period when frequent disturbances were common on the Cumberland Plateau including fires, woods grazing, fuelwood cutting, conversion to agriculture, and other forest uses. However, since stand initiation, it had not been managed. Over that time, they found only one stand-wide disturbance event based on tree-ring analysis, and they described the disturbance regime as asynchronous with a high number of small-scale release events indicating that gap-phase dynamics drove forest development. Under this regime of disturbances, these *Quercus*–*Carya* forests are seen to be succeeding to *Acer*–*Fagus* dominance. We speculate that such was the likely disturbance history and forest development in our study stands prior to initiating our study. The stands have been on a successional trajectory away from a dominance of *Quercus* in species rich mixed forests to a composition dominated by more shade tolerant species with perhaps less diversity in tree species, under a regime of small-scale natural forest disturbances. In the absence of fire, mesophytic species are coming to dominance and forests are being transformed in ways that make it harder for them to be burned without silvicultural intervention. Such a process in eastern hardwood forests has been termed 'mesophication' by Nowacki and Abrams (2008). It leads to the successional replacement of *Quercus* by shade tolerant species without management and it describes a common process operating in eastern *Quercus*-mixed hardwood forests (Lorimer, 1993; Spetich and Parker, 1998; Abrams, 2005; Aldrich et al., 2005).

Low light levels in the understory of eastern hardwood forests are often limiting to the growth and accumulation of large *Quercus* advance reproduction, which is important to sustaining *Quercus* through regeneration and future stand development (Johnson et al., 2009). Crow (1992) and Loftis (1988) observed a negative exponential decline in separate populations of *Q. rubra* that established in the understory of heavily-shaded mature mesic hardwood forests in Wisconsin and North Carolina, respectively; with less than 10% of either cohort surviving 10 years after germination. A common condition in fully-stocked unmanaged hardwood forests in eastern North American is either an absence of *Quercus* advance reproduction, or numerous small seedlings (<10 mm in basal diameter) despite the presence of large seedbearing adults in the overstory, such was the situation in our study stands. Also common is the dominance of shade tolerant species in the understory, and succession, without active management, is toward dominance by *Acer* species and other silvically similar species (Jenkins and Parker, 1998). Hart and Grissino-Mayer (2008) predicted that under a disturbance regime characterized by asynchronous and abundant small-scale disturbances that *Quercus*–*Carya* forests on the Cumberland Plateau will shift to dominance by *Acer*–*Fagus* over time. And in fact, Hart and Grissino-Mayer (2009) reported that the dominant disturbance in secondary forests on the Cumberland Plateau was small single-tree gaps that were promoting the recruitment of *A. saccharum* and *A. rubrum* into the overstory.

The shelterwood method has been long recommended as a way to promote the development of *Quercus* advance reproduction (Sander, 1979; Hannah, 1987). But the shelterwood method is a highly flexible approach relative to the frequency and intensity of removal of the mid- and overstory, and design details for regeneration prescriptions are lacking for many forest regions. A single, intense shelterwood harvest increases available light to *Quercus* advance reproduction most dramatically but can also invigorate competing vegetation and encourage development of species such as *L. tulipifera* over *Quercus* (Loftis, 1983). Leaving high density shelterwoods may not increase light much above the levels found in uncut stands, and hence only promote further development of shade tolerant species in the understory. For example, Sander (1979) found that stand stocking has to be reduced by 60% or more to substantially increase light at the forest floor to 30 to 50% of full sunlight in Central Hardwood *Quercus*–*Carya* forests. The purpose of this study was to evaluate a gradient of shelterwood harvest treatments that were intended to promote *Quercus* reproduction development, and thus, improve *Quercus* regeneration competitiveness, while maintaining tree diversity in the Cumberland Plateau.

Loftis (1990) advocated the removal of the midstory and maintaining an intact high overstory canopy to promote the growth of large oak reproduction while limiting the competition from aggressive shade intolerant species like *L. tulipifera* on high quality mesic sites. In forests of the southern Appalachian Mountains or Blue Ridge that were similar to ours in many ways, Loftis (1990) showed that by reducing the competition in the midstory, small advanced *Quercus* reproduction were able to respond to the increased growing space and remain competitive following overstory removal. The 75SW treatment was specifically modeled after his design.

In the 75W treatment, overall stand basal area was similar to the control treatment, species composition and dominance had changed little from pretreatment conditions, and canopy cover and available light were similar to untreated stands after eight years. Although *A. rubrum* ($\geqslant$3.8 cm dbh) was temporarily eliminated from the stands following herbicide treatment, canopy cover remained high and above 90% for the duration of this study. Light in the understory of the 75SW treatment increased by 8% of full sunlight on average over the control treatment (average light = 8%) (Table 8), but any benefits of increased light at the forest floor due to reductions in stand density with midstory removal were transitory, with only 6% of full sunlight reaching the forest floor three years after the 75SW treatment. Others have found similar increases in light within a meter of the forest floor when the midstory has been removed in hydric bottomlands (Motsinger et al., 2010), and mesic hardwood forests (Lorimer et al., 1994; Miller et al., 2004). The high levels of canopy cover and low light levels in this study were most likely due to the growth of *A. saccharum* advance reproduction after midstory removal. Although not measured, there was an appreciable increase in the lateral spread of the *A. saccharum* in the understory three years posttreatment. These *A. saccharum* fully occupied the growing space from 1.4 to 6 m in the understory. The importance values for *Q. alba* increased only slightly after eight years due largely to reductions in density of competitors resulting from herbicide treatment of the midstory, not from actual gains in development of *Quercus* reproduction.

Removal of the midstory layer in the 75SW treatment did not significantly improve the regeneration potential of *Quercus* over its competitors after eight years from treatment. We found that *A. saccharum* reproduction (<3.8 cm dbh) was prevalent by the end of the study in the 75SW treatment. Based on regeneration tallies we found that density of *A. saccharum* increased 516 stems ha^{-1} from 2001 to 2009 for trees greater than 0.3 m in height but less than 3.8 cm dbh. Concurrently, *Quercus* seedlings in the same stratum increased only by 275 stems ha^{-1}, and the majority of these stems were small (<0.6 m tall) with low regeneration potential (Loftis, 1990; Johnson et al., 2009). *Quercus* seedlings greater than 3.8 cm dbh increased minimally by 4 stems ha^{-1}. The expected benefit of the 75SW to *Quercus* in our study may have been less than what Loftis (1990) observed in the Appalachian Mountains, because of the prevalence of *A. saccharum* on the Cumberland Plateau. Others have found that by reducing or eliminating the midstory vegetation, established *Quercus* reproduction responded by growing into more competitive positions (Janzen and Hodges, 1987; Lockhart et al., 2000; Stringer, 2005). In southwestern Wisconsin mesic and dry-mesic *Quercus*–*Acer* forests, Lorimer et al. (1994) found that removal of the tall (>1.5 m) woody midstory trees significantly improved the survival and height growth of planted and natural *Q. rubra* and *Q. alba* reproduction. Similarly, Motsinger et al. (2010) were able to improve survival and growth in *Q. palustris* Muenchh. advance reproduction in bottomland forests in southeast Missouri by killing the midstory trees by herbicide injection. Changes in light and growing space conditions had some impact on the seedling cohort, but it remains to be seen, following the overwood harvest, if the disturbance was significant enough to place *Quercus* in a competitive position.

L. tulipifera increased significantly in density and importance eight years after removing half of the stand basal area in the 50SW treatment. After harvest, a low density of *L. tulipifera* in the shelterwood (2 stems ha^{-1} > 20 cm dbh; 2.8 m^2 ha^{-1}) provided sufficient seed for abundant reproduction that set the stage for this tremendous increase in dominance as new seedlings grew into saplings in the increased light. Although these small stems only contributed 0.7 m^2 ha^{-1} of basal area, they played a significant role in the threefold increase in *L. tulipifera* IV due to the high stem density in the smallest diameter class. If *L. tulipifera* is in the stand or nearby, it is highly likely that abundant seed is present in the forest floor ready to germinate with vigor following a regeneration disturbance because it is a prolific seed producer, large crops are produced almost annually, and seed can retain its viability in the forest floor for four to seven years (Beck, 1990). In addition to increasing competition from *L. tulipifera* reproduction, shade tolerant *A. saccharum* maintained its initially high IV in the 50SW treatment, contributing to the intensity of competition with *Quercus*. Three years following the 50SW treatment, we measured crown cover at 75% under the shelterwood and this permitted 56% of full sunlight to reach the forest floor, which promoted the growth of shade intolerant species. This was slightly more light than Parker and Dey (2008) reported for a similar intensity of shelterwood harvest in Ontario *Quercus–Acer* forests where they achieved 25% of full sunlight at the ground after removing 55% of stand basal area leaving a shelterwood of 16 m^2 ha^{-1} and 80% crown cover. Some differences in light measurements among studies may be influenced by the height of light measurement and subtle differences in ground flora structure.

L. tulipifera increased substantially in importance after harvesting in the 25SW treatment while maintaining itself in terms of relative density. This resulted from a flush of vigorous reproduction that was able to replace the complete removal of all merchantable *L. tulipifera* with abundant regeneration and ingrowth into the sapling class, where trees averaged 4.8 cm dbh. Concurrently, *A. saccharum* maintained its prominence and dominance in the stand representing one-third of the relative basal area with only a slight decrease in IV over time. *Quercus alba* dropped out of the top five species in IV despite having a constant relative density after eight years. *Quercus rubra* and *Q. prinus* held their position in IV while maintaining or increasing slightly their relative density. At this level of harvest disturbance, *F. americana* rose in IV to be included in the top five prominent species. The shelterwood averaging 8 m^2 ha^{-1} and 76% crown cover reduced available light in the understory by 69% after harvest, similar to the 50SW treatment. Parker and Dey (2008) measured light that averaged 41% of full sunlight under an Ontario shelterwood where residual stand density was 5 m^2 ha^{-1} and crown cover was 49%.

A. saccharum and *L. tulipifera* increased three to five times, respectively, in relative density over pretreatment levels eight years after clearcutting. *A. saccharum* decreased only slightly in IV, while *L. tulipifera*, *F. americana*, *A. rubrum*, and *P. serotina* were now dominant species after eight years. The reproduction is increasingly being dominated by the less shade tolerant species. *Prunus serotina* in the Cumberland Plateau region are not vigorous growing quality trees and we do not expect them to remain dominant in these forests over time. The most light reaching the regeneration layer occurred after clearcutting where there was only a 30% reduction in light at 1.4 m above the ground under 30% crown cover and 1.4 m^2 ha^{-1}. *Quercus* on-the-other-hand have dropped significantly in importance and dominance, and are being suppressed by their competitors. Under clearcut harvesting, these stands will most likely lose *Quercus* dominance and will tend towards *L. tulipifera* and *Acer* dominated forests. Clearcutting seldom results in successful *Quercus* regeneration without competition control on all but the most xeric sites (Johnson et al., 2009), especially in the range of *L. tulipifera* and in the presence of abundant large shade tolerant advance reproduction. It is well established that in stands where both *Quercus* and *L. tulipifera* co-exist, *Quercus* are usually overtopped by *L. tulipifera* within 10 years post-disturbance (Loftis, 1983; Beck and Hooper, 1986; Dey et al., 2009). For instance, Weigel and Johnson (2000) observed that *L. tulipifera* completely dominated *Q. rubra* reproduction within 6 years of the shelterwood removal on good quality sites in southern Indiana. Likewise, both Jenkins and Parker (1998) and Weigel and Parker (1997) recorded *L. tulipifera* dominance of the reproduction in southern Indiana *Quercus–Carya* stands harvested by group selection or clearcutting. When trying to regenerate oak by the shelterwood method in the presence of *L. tulipifera*, Weigel and Johnson (2000) recommend follow-up control of competing vegetation within about 5 years after final overstory removal.

After eight years there was no significant difference in percent crown cover (range 92% to 98%) or percent light reduction (range 86% to 95%) among all the treatments, indicating that benefits to *Quercus* regeneration from these regeneration harvests were ephemeral and short-lived, and additional disturbances are needed to continue to control competition and provide *Quercus* with sufficient growing space. Brose et al. (1999, 2006) and Brose and Van Lear (1998), for example, have found that prescribed burning after shelterwood harvesting can promote *Quercus* reproduction over its less fire resistant competitors including *L. tulipifera* and *Acer* species. The shelterwood is applied to promote the growth of *Quercus* advance reproduction, and for a time *Quercus* does benefit from the increase in light and release. But as the competition begins to suppress the *Quercus* then prescribed fire is applied when the *Quercus* reproduction are sufficiently large to recover vigorously by sprouting after burning. Additional fires may be needed every three to 5 years until the *Quercus* is free-to-grow and has high probability of maintaining dominance on its own. There is still much uncertainty in how best to combine shelterwood cutting with prescribed burning to minimize the loss of *Quercus* to fire-caused mortality.

The accumulation of abundant large shade tolerant *A. saccharum* in the understory, along with the known potential of *L. tulipifera* new seedling establishment and rapid growth after overstory removal, makes entirely uncertain the success of *Quercus* regeneration no matter what silviculture disturbance was used in this study. One of the goals of the shelterwood harvests and herbicide treatment was to create favorable conditions for the recruitment of *Quercus*. *Quercus* remained a top-ranked species in terms of relative importance in the 25SW and 50SW because *Quercus* was a preferred leave tree. How species respond to the final removal harvest will be of interest, and will ultimately influence the composition of the resulting new stand.

4.2. Tree diversity response to regeneration method

Disturbance may increase species richness, primarily due to compensatory mortality and intermediate levels of changes in light and growing space (Connell, 1978; Huston, 1979). As related to calculated importance values, woody plants in this study had no discernable response pattern to partial harvesting or intermediate levels of disturbance. The physical factors related to canopy disturbance (light intensity and canopy cover) were ephemerally affected by overstory tree harvesting. This allowed for a rapid mixture of both shade and light patches, facilitating the coexistence of both shade tolerant (*A. saccharum*) and intolerant (*L. tulipifera*) species. Shelterwood harvest that resulted in a patchy distribution of residual trees did not alter the stochasticity of interspecific competition. Each harvest disturbance of 4-ha resulted in a maintenance or slight increase in species richness, and had no detectable change in diversity or evenness at this scale. It appears that in these highly productive stands, tree diversity is promoted by more intense disturbances (Huston, 1979). Richness was similar for all three harvested treatments following eight growing seasons, and all were greater than the control. Belote et al. (2008) found that intense tree harvesting increased richness of both native and non-native species in *Quercus*-dominated forested sites in the southern Appalachians of West Virginia. Jenkins and Parker (1998) evaluated the long-term effects of harvest intensity, i.e., single-tree selection, large group selection opening, or clearcut, on species richness and diversity of woody species *Quercus–Acer* and *Fagus–Acer* forests in southern Indiana. They reported that overstory species richness and diversity were significantly reduced by small-scale disturbances typical of single-tree selection because shifts in species to *A. saccharum* dominance were accelerated by the regeneration method. Clearcuts and large group openings had more early and mid-successional species growing with the *Acer* species and *F. grandifolia*. Similar findings of increasing diversity with increasing harvest disturbance intensity and size have been reported in the southern Appalachians by Wender (2000). Only two nonnative species invaded the harvested sites in this study, and their density was low, i.e., 1 stem ha^{-1}. Stands in this study were not biologically resistant to colonization by new species, as several new species were noted post-harvest. High resident species diversity may have contributed to only small changes in species richness post-harvest.

4.3. Future management direction

An assessment of regeneration eight years after harvesting indicates that stands of diverse and desirable species are regenerating in the clearcuts and shelterwoods in fulfillment of many of the management goals. One exception is the large reduction in the amount of *Quercus* in these stands, regardless of harvest intensity. One of the few management options in the clearcuts is to use crop tree release on individual *Quercus* trees to bring them into a position of dominance (Miller et al., 2008). In the shelterwood stands, shade from reserve trees will influence the development of new reproduction (Tworkoski et al., 1986; Gottschalk, 1994; Dey and Parker, 1997; Miller et al., 2006). In mesic, escarpment stands of the Cumberland Plateau, rapid establishment and growth of subcanopy species may be of a greater initial influence than that of the residual trees. The changes in light and canopy cover were measured at a level commensurate with subcanopy positions (at dbh). The complete occupancy of the midstory canopy by trees $\geqslant$3.8 cm dbh will most likely have the greatest contribution to future stocking in the stands harvested by the shelterwood method. *Quercus* in the subcanopy of the 25SW and 50SW may ascend into the overstory in sufficient numbers to meet management goals, but this will require additional disturbances of moderate and greater intensity. Rentch et al. (2009) found that increased disturbance intensity favored lower-canopy *Quercus* that then ascended into upper canopy positions.

The shelterwood treatments in this study were initiated as a first step to regenerating these diverse stands. None of the treatments evaluated in this study can be relied on to regenerate *Quercus* and sustain its stocking at current levels. Fox et al. (2007) have observed similar lack of successful *Quercus* regeneration response to various regeneration methods including clearcut, shelterwood, group selection and leave-tree in the Appalachians of Virginia and West Virginia. They attributed failure in *Quercus* regeneration to, in part, a lack of adequate *Quercus* advance reproduction, and noted that loss of *Quercus* was greatest on the more productive sites. In this study, as shelterwood harvest intensity increased above the 75SW level, light levels increased in the regeneration layer. Both *A. saccharum* and *Quercus* experience increases in net photosynthesis and growth with increasing available light as occurred in the 75SW treatment to the point that *A. saccharum* is light saturated (Parker and Dey, 2008). Increases in light above that point, as occurred in the 50SW and 25 SW, benefit *Quercus* reproduction more so than *A. saccharum*. However, continued increases in light above 50% of full sunlight promote the growth of the shade intolerant *L. tulipifera* over the *Quercus*. An optimal balance in shelterwood density that benefits *Quercus* while not overly invigorating either well-established shade tolerant reproduction, or newly germinating shade intolerant species may be mythical, or too hard to achieve strictly by regeneration harvesting. It may be more practical to provide to *Quercus* reproduction light in the range of 30 to 50% of full sunlight by the use of the shelterwood method and plan for post-harvest control of competing vegetation.

If one is willing to set aside the goal to sustain *Quercus* in these Cumberland Plateau forests, then several management options exist at this stage of stand development eight years after the regeneration treatments. A final shelterwood removal would likely result in a diverse stand of desirable species, albeit with less *Quercus* stocking. The probability of *Quercus* would be greatest in the 25SW and 50SW treated stands. Or, all or a portion of the remaining shelterwood could be retained longer to create two-aged stands. Management then can continue as two-aged stands, or an additional harvest could be implemented, retaining a portion of the overstory and contributing to the establishment of a new cohort. At this point, these stands would then be effectively considered an uneven-aged system and managed accordingly Helms, 1998). Retention of moderately dense overstories, or transition to uneven-aged management would promote dominance of the more shade tolerant species. Even-aged management would create the most diverse forests with greater representation of the shade intolerant species.

If, however, sustaining *Quercus* is desired, then additional tending treatment(s) that release competitive *Quercus* in the understory would be required to permit its recruitment into the overstory. Without further silvicultural intervention, the likelihood of these stands regenerating to *Quercus* is low, as competition by *L. tulipifera* and *A. saccharum* is intense. Miller et al. (2008) suggests that *Quercus* stocking and dominance can be improved by crop tree thinning around individual *Quercus* trees when done early in stand development, before the larger *Quercus* reproduction is suppressed. This may need to be repeated to maintain dominance of the *Quercus*, thus monitoring is essential to determine the need and timing of additional thinnings. In the 75SW, an adjustment to the initial treatment is recommended. Since our prescription in the 75SW only treated stems $\geqslant$3 cm dbh, this left an abundance of smaller *A. saccharum* that responded positively to the increased light and growing space created when the midstory was deadened. A second herbicide release is needed to maintain the existing *Quercus* in the subcanopy. Because of the aggressive nature of *L. tulipifera* on these sites, an additional release treatment following overwood removal may be required to promote *Quercus*.

There is evidence that fire has long been important in the rise of *Quercus* to its current level of dominance and distribution on the Cumberland Plateau and throughout eastern North America based on fire history and dendrochronological analyses of historical disturbances and stand dynamics (Delcourt and Delcourt, 1998; Guyette et al., 2002; McEwan et al., 2007; Hart and Grissino-Mayer, 2008, 2009; Dey et al., 2011). It is natural then that there is an increasing use of fire to sustain *Quercus* ecosystems given the many adaptations of *Quercus* to fire, its historic relationship with fire, and the presumed benefit to *Quercus* over its competitors conferred to it by fire (Abrams, 1992; Dey, 2002a, b).

Prescribed fire today is often applied as low intensity fires in the dormant season. Such fires are effective in eliminating stems in the midstory that are <10 cm dbh and a significant portion of those in the 10 to 20 cm dbh size class, but they seldom cause mortality in the overstory (Waldrop et al., 1992; Barnes and Van Lear, 1998; Hutchinson et al., 2005; Dey and Hartman, 2005; Blankenship and Arthur, 2006). Many of these stems resprout after the fire kills the shoots leading to an increase in the density of stems in the seedling size class. Under high overstory basal area, these sprouts exhibit slow height growth (Signell et al., 2005; Dey and Hartman, 2005). However, shoot and height growth of sprouts increases as overstory density decreases. Increases in understory light following shelterwood harvesting are ephemeral, due in large part to the flush of sprout growth after harvesting and burning. Thus, additional prescribed burns may be required in three to 5 years to maintain *Quercus* dominance (Chiang et al., 2005; Alexander et al., 2008).

Most changes in forest structure resulting from low intensity fire occur after the first prescribed burn, additional fires cause minor changes in stand structure (Arthur et al., 1998; Dey and Hartman, 2005). Repeated prescribed burns have been shown to favor the development of *Quercus* advance reproduction over that of *Acer* species or *L. tulipifera*, however, any fire conducted when *Quercus* seedlings are small in stature causes high mortality and results in a loss of regeneration potential for *Quercus* in the stand (Hutchinson et al., 2005; Signell et al., 2005; Brose et al., 2006; Alexander et al., 2008). *Quercus* dominance in the understory over *Acer* species and *L. tulipifera* increases as season of burn changes from dormant to growing season, and fire intensity increases from low to high (Brose, 2010), and when reductions in overstory density by thinning or shelterwood harvests are combined with multiple prescribed burns (Brose and Van Lear, 1998; Albrecht and McCarthy, 2006; Brose et al., 2006; Iverson et al., 2008). Low intensity fires alone often create stand structures similar to the 75SW treatment where the midstory was eliminated by herbicide application. A singular but important difference here is that effective herbicide application completely kills the tree and there is no persistence in the stand through sprouting, and no subsequent increase in seedling density of undesirable competitors. A further benefit of herbicide use to reduce the dominance of competing reproduction and increase light to *Quercus* in the understory is that it avoids the risk of fire damage to desirable growing stock intended for future timber harvest.

To create forest structure similar to the 50SW or the 25SW treatments requires much more intense fires capable of killing large diameter overstory trees. Fire used to thin the overstory may not be as desirable as doing so with a timber harvest or mechanical/chemical thinning because fire kills indiscriminately trees in the overstory, thus, there is less control over distribution of residual trees, and it fails to recover forest products and value. Hot fires are more likely to scar desirable trees, and if wounded trees remain in the stand for decades before harvest, the probability of volume and value loss to wood decay is great (Hesterberg, 1957; Ohman, 1970). To minimize damage to merchantable timber, fire should be used as a silvicultural tool only to the point of securing free-to-grow *Quercus* in numbers sufficient to achieve desired stocking targets. Then, fire should be withheld from the stand until needed again to prepare for regeneration at the end of the rotation. Other factors that complicate the use of prescribed burning on private lands are the issue of landowner liability, and lack of expertise and resources to conduct burns.

5. Conclusion

Tree dynamics in silviculturally disturbed stands on productive Cumberland Plateau sites are complicated due to the complex species mixture that contains numerous commercially valuable but silvically different species. The differential response of these species to the gradient of disturbances was manifested across our study. Although no discernable changes were noted for species richness, evenness or diversity, we observed the rapid capture of the growing space by a range of shade tolerant species, *Acer rubrum*, and *A. saccharum*. As vegetation on these sites reacts quickly to disturbance, we also noted an ephemeral effect of increased light to benefit *Quercus* reproduction growth. Maintenance of the *Quercus* dominance in these stands is threatened without additional treatment to ensure competitive replacement. Future work will examine the resultant regeneration cohort following the final harvest and will help us better predict the extent of need to more intensively manage for selected species.

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