OAK COMPETITIVE STATUS IN 27-YEAR-OLD GROUP OPENINGS IN A WEST GULF COASTAL PLAIN PINE-HARDWOOD FOREST

Colby E. Mohler, Mohammad M. Bataineh, Don C. Bragg, Robert L. Ficklin, Matthew H. Pelkki, and Matthew G. Olson

Abstract—Due to their high ecological and economic value, oaks (*Quercus* spp.) are a desirable species group for mixedwood management. However, little information exists on oak competitiveness at the local, neighborhood scale in harvest gaps beyond the first few growing seasons. The objective of this research is to determine if oak competitive status is related to neighborhood composition and gap size. A total of 156 oak stems at least 3.5 inches in diameter at breast height and their respective neighborhoods were sampled in nine experimental harvest gaps (ranging in size from 0.25 to 1.0 acre) on the Kisatchie National Forest. Using neighborhood species importance values, a cluster analysis identified five neighborhood types: pine (*Pinus* spp.), pine-sweetgum (*Liquidambar styraciflua*), pine-oak, mixed hardwood-pine, and oak. No significant effects of neighborhood type or gap size were detected for subject tree heights or competition index; however, gap size was a significant factor in explaining red oak (section *Lobatae*) live crown ratio, and neighborhood type was a significant factor in predicting live crown ratio of all oaks. Red oaks in smaller gaps had significantly higher live crown ratios when compared to those in medium or large gaps. Oaks in pine neighborhoods had significantly lower live crown ratios when compared to neighborhoods with a greater hardwood component. These results suggest that managers should consider implementing timber stand improvement earlier in gap development to release oaks from pine and other shade-intolerant competition if earlier canopy recruitment of oak is desired. Alternative research approaches may be required to fully evaluate oak competitive status in gap cohorts initiated by group selection, such as stem analysis of oak subjects and neighbors and including oaks of all size classes.

INTRODUCTION

Mixedwoods, defined as stands composed of hardwood and softwood species in which neither group comprises more than 70 to 80 percent of the total stand basal area (Cavard and others 2011, Kabrick and others 2015), are a covertype that can offer many ecological and societal benefits. For example, mixedwoods tend to have greater structural heterogeneity and biodiversity than either hardwood- or softwood-dominated stands, and this offers more niche space for a variety of wildlife (Hunter 1999, Kabrick and others 2015). Mixedwood stands may be more resilient to the impacts of climate change and associated factors, such as increased insect pest outbreaks, drought, and severe weather (Griess and Knoke 2011, Guldin 2011, Jactel and Brockerhoff 2007). Mixedwood forests could also help mitigate the impacts of climate change, as ecosystems with more species are more efficient in resource uptake due to different strategies (Kirby and Potvin 2007), suggesting a positive relationship between biodiversity and carbon sequestration (Bunker and others 2005, Caspersen and Pacala 2001). Forest carbon stocks may be enhanced by management promoting compatible species mixtures where productive early-successional and long-lived, late-successional species coexist (Caspersen and Pacala 2001). Managing for mixedwoods may also be an attractive option on small, nonindustrial private holdings and public lands as it offers many ecological and recreational benefits while still being economically viable (Perry and Waldrop 1995, Phillips and Abercrombie 1987, Trammell and others 2017).

Oaks (*Quercus* spp.) are a desired species group for mixedwood management in the West Gulf Coastal Plain due to their high ecological and economic values. An array of flora and fauna depend on oaks for habitat, food, and nutrient recycling (Dey 2014). Oak crown structure, mast production, and leaf litter provide favorable conditions for diverse herbaceous understories which enhance cover and food for important insects and

Author information: Colby E. Mohler, Graduate Research Assistant, University of Arkansas-Monticello, Monticello, AR 71655; Mohammad M. Bataineh, Associate Professor, University of Arkansas-Monticello, Monticello, AR 71655; Don C. Bragg, Project Leader, U.S. Department of Agriculture, Forest Service, Southern Research Station, Monticello, AR 71655; Robert L. Ficklin, Associate Dean of Academics, Professor, University of Arkansas-Monticello, Monticello, AR 71655; Matthew H. Pelkki, George H. Clippert Endowed Chair, Professor, University of Arkansas-Monticello, Monticello, AR 71655; and Matthew G. Olson, Assistant Professor, Stockton University, Galloway, NJ 08205.

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small mammals (Dey 2014, Fralish 2004, Phillips and Abercrombie 1987). Maintaining an oak component in mixed pine (*Pinus* spp.)-hardwood forests can help retain soil moisture and reduce soil erosion following heavy cutovers due to remaining oak root mats that provide suitable conditions for stand regeneration (Phillips and Abercrombie 1987). The hydraulic function of the deep root systems of oaks has also been shown to facilitate the survival of co-occurring species during drought conditions (Pretzsch and others 2013). Oaks are also an important timber-producing genus that contributes high commercial value to mixed stands and diversifies timber markets for landowners (Trammell and others 2017). For example, TimberMart-South reported fourth-quarter 2018 stumpage prices for oak sawtimber in southern Arkansas were an average of $378 per thousand board feet (Scribner), compared to pine sawtimber average prices at $183 per thousand board feet (TimberMart-South 2019). Although the production period for oak may be much longer than pine, the nontimber values of oak are often enough for landowners (Haymond 1988, Shelton and Murphy 1997). Some timber-oriented landowners may still reject the idea of retaining an oak component because of the risk of losing pine sawtimber growth. However, oak retention of 15 and 30 square feet per acre in southern Arkansas had no significant effect on total stand merchantable growth and the hardwoods even improved loblolly pine (*Pinus taeda*) stem quality by acting as trainers to the larger pines and contributed to the total merchantable volume growth in a 35-year-old natural stand (Shelton and Murphy 1997).

Understanding neighborhood-scale patterns and competitive status of mixed oaks and pines in the West Gulf Coastal Plain is essential to manipulating a stand for a desired future composition that satisfies landowner objectives. After all, trees in mixedwoods experience a wide range of interactions based on species (for example, inter- and intraspecific competition), successional status, neighboring tree size, and nutrient requirements and uptake strategies than found in monospecific stands (Zhao and others 2006). For example, in closed canopy forests, light is often the most common limiting factor (Hanson and Lorimer 2007, Oliver and Larson 1996, Trammel and others 2017), placing high importance on tree height relative to neighbors. Proximity of competitors also plays a major role in tree competitiveness, especially in high-stocked, even-aged stands where above- and belowground competition may be great (Coates and others 2009, Hanson and Lorimer 2007, Montgomery and others 2010, Wimberly and Bare 1996). In aboveground competition, close proximities restrict an individual's capacity for crown growth, both horizontally and vertically. A considerable amount of research has been conducted to relate live crown ratio (the ratio of crown length to total tree height) to tree vigor (Dyer and Burkhart 1987, Perry and Thill 2003, Rose and others 2012). In southern pine-hardwood stands, pines trade the development of dense crown for height growth to establish an early height advantage, while the slower growing oaks develop denser, laterally expanding crowns to collect sufficient sunlight through the pine upper canopy (Canham and others 2004, Oliver and Larson 1996).

Unfortunately, there is little information on the effects of interspecific competition from neighboring trees on oak competitive status in younger stands, especially in southern pine-hardwood forests. Therefore, the objective of this study is to investigate neighborhood-scale competitive status of oak species in harvest gaps 27 years after gap creation. Specifically, this research will determine if (1) oak competitiveness (explained by total and relative heights, live crown ratio, and percentage of oak subjects in upper canopy positions) is related to neighborhood composition and (2) if that relationship is affected by gap size.

METHODS

Original Study Design

The study site was a 120-acre, second-growth pine-hardwood stand in the Winn District of the Kisatchie National Forest in Grant Parish, LA. The site has an elevation of approximately 130 feet above sea level with 2 to 12 percent slope. The soil type is primarily Cadeville very fine sandy loam with minor components of Mayhew and Metcalf series (USDA NRCS 2017). This soil is moderately well drained with a site index of about 90 feet at a base age of 50 years for loblolly pine. Common pine species from this study were loblolly and shortleaf pine (*P. echinata*). Some common hardwood species were southern red oak (*Quercus falcata*), sweetgum (*Liquidambar styraciflua*), post oak (*Q. stellata*), red maple (*Acer rubrum*), white oak (*Q. alba*), hickory (*Carya* spp.), and blackgum (*Nyssa sylvatica*).

The original experiment (Cain and Shelton 2001) employed a randomized complete block design with three replications of a 3x3 factorial treatment combination with the gap as the experimental unit, yielding 27 experimental units (gaps). The blocks were approximately 40 acres and based on proximity to an intermittent drainage. Each block consisted of nine group openings of three sizes: three 0.25-acre gaps, three 0.625-acre gaps, and three 1-acre gaps. The three opening sizes were selected to create gaps with diameters being about 1.2, 2.0, and 2.5 times the height of the dominant pines on the gap edge (95 feet). Three site preparation methods were tested: chemical, mechanical, and untreated (control). Combinations of gap size and method of site preparation were randomly assigned to gap locations in each block and separated by at least 100 feet from the nearest opening. In October 1991, all merchantable pines and hardwoods were removed to create the harvest gaps. A thinning of only pine sawtimber was conducted in the area between the gaps (in other words, no pine pulpwood or hardwoods were removed) to a residual pine basal area of 75 square feet per acre. Hardwood basal area between gaps averaged 54 square feet per acre.

Current Study Design

We first updated our estimates of expanded gap size by mapping the gap perimeters using a Garmin® GPSMAP® 64s unit (table 1). Expanded gaps consist of the canopy gap plus the adjacent area extending to the bases of canopy trees surrounding the canopy gap (Runkle 1982). Data collection for the present study began in the summer of 2018 in the nine untreated (harvested, no site preparation) gaps. These were chosen because if a private landowner were to seek oak recruitment as part of a mixedwood cohort, they would not spray herbicides or bulldoze within harvest gaps to control hardwoods and promote pine establishment. Crews conducted an exhaustive search for all oak stems at least 3.5 inches in diameter at breast height (d.b.h.), which, hereafter, are called subject trees, in the expanded-gap area of untreated harvest gaps and marked their location with a Garmin® GPSMAP® 64s unit.

For each subject tree (n = 156), species, d.b.h., height (total height and crown base height), and Kraft crown class (dominant, codominant, intermediate, overtopped; Kraft 1884) were recorded, as well as whether the subject tree was of a sprout group. Next, the neighborhood of each subject tree was determined by selecting all trees with crowns immediately competing with the crown of the subject tree. Further, to be considered a neighbor, the top of the competing tree's crown must be equal to or taller than the subject tree's crown base. This implies that if the subject tree is already overtopping a neighbor, then its dominance over that neighbor has already been achieved and, therefore, the neighbor is not influencing the amount of crown space or light received. Hence, we assumed light is the most important limiting factor in this fairly productive site (Coates and others 2009, Hanson and Lorimer 2007, Montgomery and others 2010, Oliver and Larson 1996). Species, d.b.h., height (total height and crown base height), Kraft crown class, and distance from subject tree were also recorded for each neighbor. Heights and distances were measured using a Haglöf vertex IV hypsometer. D.b.h. was measured to the nearest 0.1 inch, and height and distance from subject tree to each neighbor were measured to the nearest 0.1 foot.

Analysis

A cluster analysis was conducted based on the importance values of competitors in each neighborhood to quantitatively determine the appropriate number of differing neighborhood types. Importance value was calculated as:

$$IV_i = \left(\frac{pBA_i + pTPA_i}{2} \right) \qquad (1)$$

where

IV = importance value for species i,
pBA_i = relative basal area (from 0 to 1) within each neighborhood, and
$pTPA_i$ = relative density (from 0 to 1) within each neighborhood.

Relative basal area and relative density were calculated by dividing a species group's basal area and density, respectively, by the sum of all species' basal area and density within each neighborhood. A hierarchical clustering procedure was performed using Euclidean Distance and Ward's Linkage Method. The resulting dendrogram was used to identify multiple clustering solutions based on pruning the longest stems, which yielded three alternatives of three, five, and seven clusters. Following Dufrêne and Legendre (1997), indicator species analysis was used to objectively select a cluster solution. This procedure selects the cluster solution that yields the lowest average p-value and highest number of significant p-values from the Monte Carlo test of significance of observed maximum indicator values. Based on this procedure, a five-cluster solution was selected. The indicator values from the indicator analysis were compared to the importance values of competitors within each respective cluster to reveal strong similarities between the indicator values and importance of species within each cluster. Neighborhood types were based on importance values.

Table 1—Kisatchie National Forest average gap metrics based on actual gap sizes measured in 2016 and 2017

Gap size	Gap area	Gap diameter	Canopy height	Diameter:Height
	acres	*feet*	*feet*	
Small	0.33	137	100	1.37
Medium	0.70	203	108	1.88
Large	1.15	259	108	2.40

Effects of neighborhood composition (neighborhood type) and gap size on the status (competition index, total height, relative height (the height of subject tree relative to the mean height of neighbors), and live crown ratio (the ratio of crown length to total tree height)) of red oaks (section *Lobatae*), white oaks (section *Quercus*), and all oaks combined were assessed (see table 2 for species in red and white oak groups). Unfortunately, this study lacked sufficient sample size and balance to rigorously test for interactions between gap size and neighborhood type; therefore, interpretations were based on observation of main effects. Hegyi's (1974) distance-dependent competition index was chosen as it has been shown to be an effective method for evaluating crowding in fully stocked, mixed-species stands (for example, Holmes and Reed 1991, Lorimer 1983, Wimberly and Bare 1996):

$$CI = \sum_{j=1}^{n} \frac{D_j / D_i}{DIST_{ij}} \qquad (2)$$

where

CI = competition index,
D_j = diameter of competitor tree *j,*
D_i = diameter of subject tree *i,*
$DIST_{ij}$ = distance between trees *i* and *j, and*
n = total number of competitors.

Table 2—Number of subject trees of each *Quercus* species and species group by gap size in the nine untreated gaps on the Kisatchie National Forest, Louisiana

	Gap size			
Species/group	Small	Medium	Large	Total
Q. alba	10	10	41	61
Q. stellata	1	7	2	10
White oak group	11	17	43	71
Q. falcata	0	1	1	2
Q. nigra	11	13	18	42
Q. pagoda	6	13	22	41
Red oak group	17	27	41	85

Competition index, gap size, and neighborhood type were used to explain effects on relative height and live crown ratio for all oaks combined and red oaks and white oaks separately. Generalized linear models were run in R 3.4.3 using a quasi-binomial distribution and an alpha level of 0.05. The three predictor variables were also used to explain effects on subject tree total heights using PROC GENMOD in SAS® 9.4 with a normal distribution, identity link, and an alpha of 0.05.

RESULTS

A total of 156 subject trees and corresponding neighborhoods were recorded (85 red oaks, 71 white oaks; table 2) with an average competitive influence zone radius of 12.8 feet. Neighborhood types were determined by the species importance values that make up the majority of the neighborhood (table 3). Composition of the five neighborhood types from cluster analysis were defined as: pine, pine-sweetgum,

Table 3—Importance values and indicator values of species groups within each neighborhood type

	Neighborhood type				
Species group	Pine	Pine-sweetgum	Pine-oak	Mixed hardwood-pine	Oak
Importance value					
Pine	0.83	0.54	0.46	0.18	0.01
Sweetgum	0.04	0.20	0.05	0.10	0.03
All oaks	0.05	0.09	0.34	0.27	0.76
Tolerant hardwoods	0.08	0.16	0.12	0.43	0.19
Other	<0.01	0.01	0.02	0.03	0.01
Indicator value					
Pine	0.42	0.26	0.23	0.07	0.00
Sweetgum	0.04	0.45	0.05	0.12	0.02
All oaks	0.01	0.07	0.40	0.40	0.92
Tolerant hardwoods	0.07	0.20	0.14	0.87	0.14
Other	<0.01	0.03	0.08	0.06	0.03

The all oaks species group consisted of sampled oaks in the red oak group and white oak group.

Tolerant hardwoods included red maple, blackgum, and American holly, and a mix of red oaks and white oaks.

pine-oak, mixed hardwood-pine, and oak. The mixed hardwood component comprised mainly shade-tolerant hardwoods, including red maple, blackgum, and American holly (*Ilex opaca*), and a mix of red oaks and white oaks.

The number of red oak and white oak subject trees were fairly consistent among each neighborhood type (table 4). Each species group had the most subjects located in pine-oak neighborhoods. Each species group had the fewest subjects located in pine and oak neighborhoods; however, red oaks had double the number of subjects in pine neighborhoods compared to white oaks. As for pine-sweetgum and mixed hardwood-pine neighborhoods, the two species groups had no more than a difference of two subjects (table 4). Of the 156 neighborhoods, most were classified as pine-oak while far fewer pine and oak neighborhoods were recorded (table 4).

Heights of red oak and white oak subjects were generally equal to or slightly lower than the mean heights of their neighborhoods (fig. 1). Height distributions show oaks, including subject trees, mainly occupied the middle range of height classes from 25 to 75 feet (fig. 1). However, in oak neighborhood types, oak subjects reached into the 85-foot height class. Pines tended to dominate larger size classes, especially in pine-dominated neighborhoods, whereas pines were scarcer in larger height classes in hardwood-dominated neighborhoods. Tolerant hardwoods were concentrated in lower height classes. Sweetgum tended to occupy similar height classes as oak subjects; however, the number of sweetgum stems usually greatly outnumbered subjects in respective classes. Stems in the greater-than-85-foot height classes were border trees located on gap edges in the mature forest, or matrix, surrounding the gaps. These trees were not of the gap cohort. Pine-dominated neighborhoods contained the most border trees greater than 85 feet tall (these were usually pines). Hardwood-dominated neighborhoods contained fewer border trees, and these were usually hardwoods.

Results from the generalized linear models testing the effects of competition index, gap size, and neighborhood type on the relative height of subject red oaks, white oaks, and all oaks combined found no significant effects. However, gap size was a significant predictor of red oak live crown ratio, and neighborhood type was a significant predictor of all-oak live crown ratio ($p < 0.05$; table 5). Red oak live crown ratios were significantly greater in small gaps compared to large and medium gaps, averaging 0.52 compared to 0.43 and 0.42, respectively. For all oaks combined, subject tree live crown ratios were significantly lower in pine neighborhoods when compared to those in pine-sweetgum. Oak subject live crown ratios in pine neighborhoods averaged 0.41 when compared to 0.50 in pine-sweetgum, 0.49 in pine-oak, and 0.52 in oak. Subject live crown ratios in oak neighborhoods were significantly greater than in mixed hardwood-pine neighborhoods, averaging 0.52 versus 0.45, respectively.

DISCUSSION

The neighborhood types determined from the cluster analysis reflect the relatively diverse tree species composition of this pine-hardwood forest. These neighborhood types also reflect local, within-gap variation, as pockets of different species mixtures are distributed among the gap depending on gap size and position within the gap. This compositional variability is typical of earlier stages of secondary succession in West Gulf Coastal Plain forests where early- and late-successional species coexist (in other words, initial floristics composition; Egler 1954). The fast-growing, shade-intolerant pines are the early-successional group that initially achieves dominance following intermediate to severe canopy disturbances (Runkle and Yetter 1987, Trammell and others 2017, Weber and others 2014). This pattern is evident in this study where pine makes up four of five neighborhood types and is dominant in three. As cohorts approach the stem exclusion stage, the dominant pines begin to relegate many of the hardwoods to subordinate positions. The oak and the sweetgum maintain similar height growth rates and compete in the

Table 4—Number of red oak and white oak subject trees within each neighborhood type

	Number of subject trees		
Neighborhood type	Red oak group	White oak group	All oak
Pine	12	6	18
Pine-sweetgum	16	18	34
Pine-oak	32	24	56
Mixed hardwood-pine	18	17	35
Oak	7	6	13
Total	85	71	156

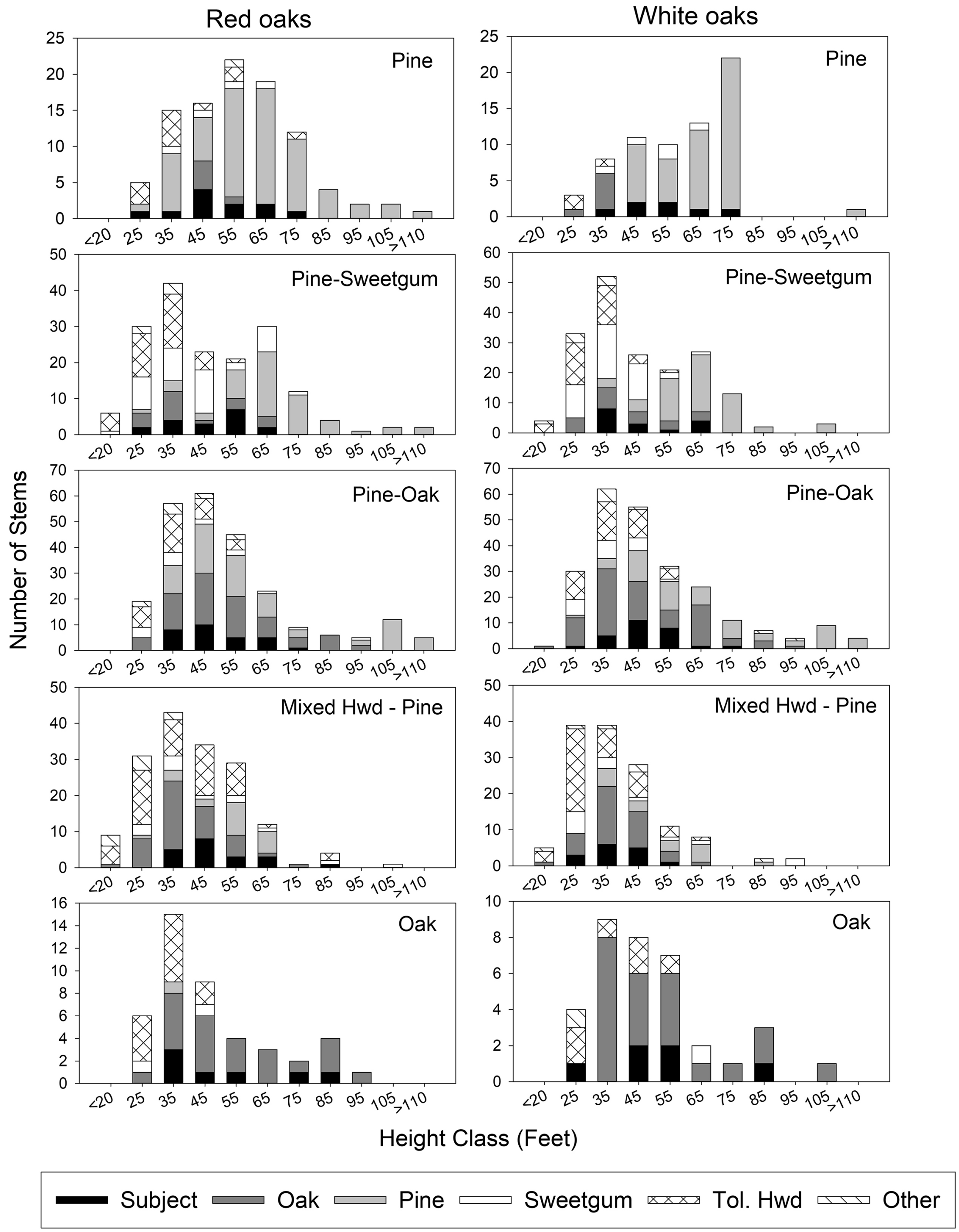

Figure 1—Number of stems in each height size class of subject trees relative to neighbors within each neighborhood type. Subject refers to subject oak trees and Tol. Hwd refers to the tolerant hardwood species group.

Table 5—*p*-values from the generalized linear models testing the effects of competition index, gap size, and neighborhood type on live crown ratio of red oaks, white oaks, and all oaks combined

Species group	Competition index	Gap size	Neighborhood type
Red oaks	0.528	0.020	0.266
White oaks	0.144	0.639	0.050
All oaks	0.138	0.124	0.012

lower canopy layers until eventually the hardier crowns of oak outcompete sweetgum (Clatterbuck and Hodges 1988, Oliver and Larson 1996). The most shade-tolerant hardwood species in Coastal Plain forests (blackgum, red maple, American beech [*Fagus grandifolia*], and American holly) are also the slowest growing, yet are capable of surviving beneath multiple canopy strata. However, oaks appear to be faring well in harvest gaps. Oaks are a major component in two of five neighborhood types and make up a considerable portion of the mixed-hardwood type. As these gap cohorts mature, many of the oaks will eventually attain upper canopy positions as the dominant pines senesce and begin to drop out of the overstory (Clatterbuck and Hodges 1988, Lloyd and Waldrop 1993, Weber and others 2014).

Oak subjects in pine neighborhoods had significantly lower live crown ratios than in pine-sweetgum, pine-oak, and oak neighborhoods. This may be attributed to the differences in crown characteristics that allow oaks and pines to coexist. The crowns of shade-intolerant pines allow for more light to penetrate through the upper canopy to the competing oaks (Canham and others 1994). Given that crown ratio is related to tree vigor (Dyer and Burkhart 1987), the greater live crown ratios in pine-sweetgum, pine-oak, and oak neighborhoods compared to pine neighborhoods from this study suggest that oak vigor is greatest in mixed-species neighborhoods rather than pure pine neighborhoods. Oak competitiveness may be increased with an increasing conspecific component, as evident in this study where the rates of increased live crown ratios relative to pure pine neighborhoods were greatest in oak neighborhoods, followed by pine-oak and pine-sweetgum, respectively. In addition, crown ratios in oak neighborhoods were significantly greater than in mixed hardwood-pine.

Live crown ratios of red oak subjects were greatest in small gaps when compared to medium and large gaps. This is likely due to the smaller openings favoring release of lower canopy oaks, rather than increasing light levels that favor establishment of pine. Larger group openings tend to reset successional trajectories and favor shade-intolerant species, while smaller openings are more likely to accelerate succession and favor shade-tolerant species (Prévost and Raymond 2012, Rantis and Johnson 1998, Trammell and others 2017). Harcombe and others (2002) found larger canopy disturbances promoted shade-intolerant species recruitment into the upper canopy and enriched the understory in shade-tolerant species. Shade-intolerant sapling density has also been noticed to increase with gap size (Perry and Waldrop 1995, Weber and others 2014) which could impose greater competition on oak stems. This study site in particular has seen this effect, where results of another investigation of this site show significant increases in pine and sweetgum density and basal area with increasing gap size. As opposed to white oaks, where no significant effects of gap size on live crown ratio were detected, red oak live crown ratio was largest in small gaps, suggesting red oaks benefited from the creation of smaller harvest openings. The percentage of upper canopy red oak subjects across the stand was greater when compared to the percentage of upper canopy white oaks in this study, further signifying greater competitiveness of red oaks versus white oaks at this stage of stand development.

In the Southern United States, making decisions at a neighborhood scale based on successional status of available species may aid in achieving desired stand conditions (Canham and others 2006, Coates and others 2003). Some studies have shown species of different shade tolerances have different effects on target trees (Zhao and others 2006); therefore, management that reduces direct competition from target species will have greater effects on achieving desired stand composition (Murphy and others 1993). Based on this study, managers in this region should consider timber stand improvement earlier in gap-cohort development if faster recruitment of oaks into larger size classes is desired (Murphy and Ehrenreich 1965). These entries should target neighboring dominant pine and competing sweetgum to allocate growing space to released oaks (Blair and Enghardt 1976). This may also benefit future oak mast production and increase oak basal area (Perry and Thill 2003, Rose and others 2012). Targeting larger pines could also provide timber-based revenue to the landowner, although this would require that the volume selected to cut meets the requirements for a timber sale; otherwise, this may not be a feasible option.

CONCLUSIONS

This study found a high diversity of neighborhood types within these earlier-successional group openings, supporting the initial relay floristics model, which states stands in the earlier stages of secondary-succession tend to accommodate early- and late-successional species. In addition, oak competitiveness may be increased with an increasing conspecific component within their neighborhoods given the higher live crown ratios of oak subjects in mixed-species neighborhoods compared to lower live crown ratios of oak subjects in pine-dominated neighborhoods. Subject trees in the red oak group were generally more competitive when compared to those in larger gaps, possibly due to lower light conditions initially suppressing pine dominance after gap creation, giving red oaks a competitive advantage. Managing southern mixedwoods may depend on making decisions at the neighborhood scale to achieve desired stand conditions. Nonetheless, this study provided an early framework for future experiments to examine longer term oak competitiveness in harvest gaps. For instance, additional studies could be conducted to better explain the effects of gap size and neighborhood competition on oak competitiveness. Future research may also include sampling oaks across a wider range of size classes to gain a better sense of oak's true competitiveness at the neighborhood scale.

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LITERATURE CITED

Blair, R.M.; Enghardt, H.G. 1976. Deer forage and overstory dynamics in a loblolly pine plantation. Journal of Range Management. 29(2): 104–108.

Bunker, D.E.; DeClerck, F.; Bradford, J.C. [and others]. 2005. Species loss and aboveground carbon storage in a tropical forest. Science. 310(5750): 1029–1031.

Cain, M.D.; Shelton, M.G. 2001. Effects of opening size and site preparation method on vegetation development after implementing group selection in a pine-hardwood stand. In: Reynolds, D.B, ed. Proceedings, 54th annual meeting of the Southern Weed Science Society. Champaign, IL: Southern Weed Science Society: 191–197.

Canham, C.D.; Finzi, A.C.; Pacala, S.W.; Burbank, D.H. 1994. Causes and consequences of resource heterogeneity in forests: interspecific variation in light transmission by canopy trees. Canadian Journal of Forest Research. 24(2): 337–349.

Canham, C.D.; LePage, P.T.; Coates, K.D. 2004. A neighborhood analysis of canopy tree competition: effects of shading versus crowding. Canadian Journal of Forest Research. 34(4): 778–787.

Canham, C.D.; Papaik, M.J.; Uriarte, M. [and others]. 2006. Neighborhood analyses of canopy tree competition along environmental gradients in New England forests. Ecological Applications. 16(2): 540–554.

Caspersen, J.P.; Pacala, S.W. 2001. Successional diversity and forest ecosystem function. Ecological Research. 16(5): 895–903.

Cavard, X.; Macdonald, S.E.; Bergeron, Y.; Chen, H.Y.H. 2011. Importance of mixedwoods for biodiversity conservation: evidence for understory plants, songbirds, soil fauna, and ectomycorrhizae in northern forests. Environmental Reviews. 19: 142–161.

Clatterbuck, W.K.; Hodges, J.D. 1988. Development of cherrybark oak and sweet gum in mixed, even-aged bottomland stands in central Mississippi, USA. Canadian Journal of Forest Research. 18(1): 12–18.

Coates, K.D.; Canham, C.D.; Beaudet, M. [and others]. 2003. Use of a spatially explicit individual-tree model (SORTIE/BC) to explore the implications of patchiness in structurally complex forests. Forest Ecology and Management. 186(1–3): 297–310.

Coates, K.D.; Canham, C.D.; LePage, P.T. 2009. Above- versus below-ground competitive effects and responses of a guild of temperate tree species. Journal of Ecology. 97(1): 118–130.

Dey, D.C. 2014. Sustaining oak forests in Eastern North America: regeneration and recruitment, the pillars of sustainability. Forest Science. 60(5): 926–942.

Dufrêne, M.; Legendre, P. 1997. Species assemblages and indicator species: the need for a flexible asymmetrical approach. Ecological Monographs. 67(3): 345–366.

Dyer, M.E.; Burkhart, H.E. 1987. Compatible crown ratio and crown height models. Canadian Journal of Forest Research. 17(6): 572–574.

Egler, F.E. 1954. Vegetation science concepts I. Initial floristic composition, a factor in old-field vegetation development with 2 figs. Vegetatio. 4(6): 412–417.

Fralish, J.S. 2004. The keystone role of oak and hickory in the central hardwood forest. In: Spetich, M.A., ed. Upland oak ecology symposium: history, current conditions, and sustainability. Gen. Tech. Rep. SRS-73. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station: 78–87.

Griess, V.C.; Knoke, T. 2011. Growth performance, windthrow, and insects: meta-analyses of parameters influencing performance of mixed-species stands in boreal and northern temperate biomes. Canadian Journal of Forest Research. 41(6): 1141–1159.

Guldin, J.M. 2011. Experience with the selection method in pine stands in the Southern United States, with implications for future application. Forestry. 84(5): 539–546.

Hanson, J.J.; Lorimer, C.G. 2007. Forest structure and light regimes following moderate wind storms: implications for multi-cohort management. Ecological Applications. 17(5): 1325–1340.

Harcombe, P.A.; Bill, C.J.; Fulton, M. [and others]. 2002. Stand dynamics over 18 years in a southern mixed hardwood forest, Texas, USA. Journal of Ecology. 90(6): 947–957.

Haymond, J.L. 1988. Adoption of silvicultural practices by opinion leaders who own nonindustrial private forestland. Southern Journal of Applied Forestry. 12(1): 20–23.

Hegyi, F. 1974. A simulation model for managing jack-pine stands. In: Fries, J., ed. Growth models for tree and stand simulation. Res. Note 30. Stockholm, Sweden: Royal College of Forestry: 74–90. In Swedish.

Holmes, M.J.; Reed, D.D. 1991. Competition indices for mixed species northern hardwoods. Forest Science. 37(5): 1338–1349.

Hunter, M.L., ed. 1999. Maintaining biodiversity in forest ecosystems. Cambridge, UK: Cambridge University Press. 698 p.

Jactel, H.; Brockerhoff, E.G. 2007. Tree diversity reduces herbivory by forest insects. Ecology Letters. 10(9): 835–848.

Kabrick, J.M.; Knapp, B.O.; Dey, D.C.; Larsen, D.R. 2015. Effect of initial seedling size, understory competition, and overstory density on the survival and growth of *Pinus echinata* seedlings underplanted in hardwood forests for restoration. New Forests. 46(5–6): 897–918.

Kirby, K.R.; Potvin, C. 2007. Variation in carbon storage among tree species: implications for the management of a small-scale carbon sink project. Forest Ecology and Management. 246(2–3): 208–221.

Kraft, G. 1884. Beiträge zur lehre von den durchforstungen, schlagstellungen und lichtungshieben. Hannover, Germany: Klindworth's Verlag. 147 p. In German.

Lloyd, F.T.; Waldrop, T.A. 1993. Relative growth of oaks and pines in natural mixtures on intermediate to xeric Piedmont sites. In: Loftis, D.L.; McGee, C.E., eds. Oak regeneration: serious problems, practical recommendations. Gen. Tech. Rep. SE-84. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southeastern Forest Experiment Station: 196–201.

Lorimer, C.G. 1983. Test of age-independent competition indices for individual trees in natural hardwood stands. Forest Ecology and Management. 6: 343–360.

Montgomery, R.A.; Reich, P.B.; Palik, B.J. 2010. Untangling positive and negative biotic interactions: views from above and below ground in a forest ecosystem. Ecology. 91(12): 3641–3655.

Murphy, A.; Ehrenreich, J.H. 1965. Effects of timber harvest and stand improvement on forage production. Journal of Wildlife Management. 29(4): 734–739.

Murphy, P.A.; Shelton, M.G.; Graney, D.L. 1993. Group selection—problems and possibilities and for the more shade-intolerant species. In: Gillespie, A.R.; Parker, G.R.; Pope, P.E.; Rink, G., eds. Proceedings of the 9th central hardwood forest conference. Gen. Tech. Rep. NC-161. St. Paul, MN: U.S. Department of Agriculture, Forest Service, North Central Forest Experiment Station: 229–247.

Oliver, C.D.; Larson, B.C. 1996. Forest stand dynamics. New York, NY: John Wiley & Sons, Inc. 544 p.

Perry, C.J.; Waldrop, T.A. 1995. Opening size and site preparation techniques affect regeneration success for uneven-aged pine-hardwood mixtures. In: Boyd, E.M., comp. Proceedings of the eighth biennial southern silvicultural research conference. Gen Tech. Rep. SRS-1. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station: 406–412.

Perry, R.W.; Thill, R.E. 2003. Initial effects of reproduction cutting treatments on residual hard mast production in the Ouachita Mountains. Southern Journal of Applied Forestry. 27(4): 253–258.

Phillips, D.R.; Abercrombie, J.A. 1987. Pine-hardwood mixtures—a new concept in regeneration. Southern Journal of Applied Forestry. 11(4): 192–197.

Pretzsch, H.; Schütze, G.; Uhl, E. 2013. Resistance of European tree species to drought stress in mixed versus pure forests: evidence of stress release by inter-specific facilitation. Plant Biology. 15(3): 483–495.

Prévost, M.; Raymond, P. 2012. Effect of gap size, aspect and slope on available light and soil temperature after patch-selection cutting in yellow birch–conifer stands, Quebec, Canada. Forest Ecology and Management. 274: 210–221.

Rantis, P.A.; Johnson, J.E. 1998. Natural regeneration in canopy gaps in pine, pine-hardwood, and hardwood forest stands in the Upper Coastal Plain. In: Waldrop, T.A., ed. Proceedings of the ninth biennial southern silvicultural research conference. Gen. Tech. Rep. SRS-20. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station: 349–353.

Rose, A.K.; Greenberg, C.H.; Fearer, T.M. 2012. Acorn production prediction models for five common oak species of the Eastern United States. Journal of Wildlife Management. 76(4): 750–758.

Runkle, J.R. 1982. Patterns of disturbance in some old-growth mesic forests of Eastern North America. Ecology. 63(5): 1553–1546.

Runkle, J.R.; Yetter, T.C. 1987. Treefalls revisited: gap dynamics in the Southern Appalachians. Ecology. 68(2): 417–424.

Shelton, M.G.; Murphy, P.A. 1997. Understory vegetation 3 years after implementing uneven-aged silviculture in a shortleaf pine-oak stand. Res. Pap. SO-296. New Orleans, LA: U.S. Department of Agriculture, Forest Service, Southern Forest Experiment Station. 20 p.

TimberMart-South. 2019. Arkansas timber price report. www.timbermart-south.com. [date accessed: January 15, 2019].

Trammell, B.W.; Hart, J.L.; Schweitzer, C.J. [and others]. 2017. Effects of intermediate-severity disturbance on composition and structure in mixed *Pinus*-hardwood stands. Forest Ecology and Management. 400: 110–122.

U.S. Department of Agriculture, Natural Resources Conservation Service [USDA NRCS]. 2017. Web soil survey. https://websoilsurvey.nrcs.usda.gov/app/WebSoilSurvey.aspx. [date accessed: May 2, 2019].

Weber, T.A.; Hart, J.L.; Schweitzer, C.J.; Dey, D.C. 2014. Influence of gap-scale disturbance on developmental and successional pathways in *Quercus-Pinus* stands. Forest Ecology and Management. 331: 60–70.

Wimberly, M.C.; Bare, B.B. 1996. Distance-dependent and distance-independent models of Douglas-fir and western hemlock basal area growth following silvicultural treatment. Forest Ecology and Management. 89(1–3): 1–11.

Zhao, D.; Borders, B.; Wilson, M.; Rathbun, S.L. 2006. Modeling neighborhood effects on the growth and survival of individual trees in a natural temperate species-rich forest. Ecological Modelling. 196(1–2): 90–102.