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Impacts of oak-focused silvicultural treatments on the regeneration layer nine years posttreatment in a productive mixed-oak southern Appalachian forest

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Abstract. Oaks (*Quercus* spp.) are foundational species in forests and woodlands in the eastern USA. An oak regeneration bottleneck has occurred throughout its range in recent decades, and refining silvicultural treatments to localized conditions has become a focus in addressing this problem. This study was developed to determine species regeneration dynamics among oak and oak competitors on productive sites in response to silvicultural treatments in oak-dominated southern Appalachian mountain forests. The treatments were: an oak shelterwood treatment (25–30% basal area [BA]) reduction through midstory removal with herbicides); a prescribed fire treatment (two, late-dormant season prescribed fires occurring over a 9-yr period); a shelterwood and burn treatment (one, late-dormant season prescribed fire 3–5 yr following 30–40% BA removal); and an unmanaged control. To determine treatment impacts on the regeneration layer, changes in relative and absolute importance values and stems ha^{-1} (germinants up to stems $\leq$ 4.9 cm diameter at breast height [DBH]) were calculated at the species group and individual species level 0 and 9 yr postinitial treatment. The greatest relative increases in importance values were 1,401% and 2,995% for the red oak group and yellow-poplar (*Liriodendron tulipifera*), respectively, in the shelterwood and burn (SWB). Changes in all species groups were predominantly influenced by the smallest size-class ($<$ 0.6 m tall), with the exception of northern red oak (*Q. rubra*) and yellow-poplar in the SWB. The SWB significantly reduced importance values of all shade-tolerant species groups and was the only treatment to decrease red maple (*Acer rubrum*) importance value and density over the study duration. The prescribed fire (RXF) treatment increased the red oak group importance value, while simultaneously decreasing yellow-poplar's importance value and increasing red maple's importance value. Changes in the red oak group in the SWB and the RXF were driven by northern red oak. Treatments did not significantly change the importance value of the white oak group. The SWB was the only treatment to significantly decrease overstory BA. The RXF and SWB treatments improved the competitive status of only some oak species, but modifications to these treatments might result in better control of yellow-poplar and red maple competition, further improving oak's competitive status. Although the SWB resulted in modest recruitment of northern red oak saplings, all treatments appear in need of additional follow-up vegetation control to further improve the competitiveness and recruitment of oak into large size-classes.

Keywords: importance value, oak regeneration, prescribed burn, shelterwood, stem density

Throughout the eastern USA, upland oak (*Quercus* spp.) forests are experiencing successional displacement, with increased presence of nonoak species and low oak recruitment (Abrams 1992, Nowacki and Abrams 2008) threatening the long-term persistence and spatial coverage of upland oak species. Oaks are foundational species in temperate forests (Dey *et al*. 2010, Brose *et al*. 2014, Hanberry and Nowacki 2016). Oaks drive disturbance regimes and are important for biodiversity support (Gribko *et al*. 2002, McShea and Healy 2002, Smith 2006). Oak leaf litter, bark, and canopy traits tend to promote fire and are commonly displaced by tree species that reduce this flammability (Babl *et al*. 2020, Alexander *et al*. 2021). This displacement threatens the supply of acorns, a keystone food resource for many wildlife species (Greenberg 2021). The current scope of the successional displacement of oak by more shade-tolerant species has been well-documented throughout oak's native range in the eastern USA (Beck and Hooper 1986, Aldrich *et al*. 2005, Moser *et al*. 2006, Fei *et al*. 2011, Dey 2014, Knott *et al*. 2019).

It is hypothesized that the upland oak regeneration bottleneck is due to altered historic distur-

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bance regimes, leading to current favorable conditions for the establishment and recruitment of nonoak species (Abrams 1992, Dey *et al*. 2010, McEwan *et al*. 2011, Dey 2014, Pederson *et al*. 2014, Hanberry *et al*. 2020b). In the absence of disturbance, reproduction of shade-tolerant, mesophytic species often grows faster and outcompetes oak in oak-dominated forests (Abrams *et al*. 1995, Nowacki and Abrams 2008, McEwan *et al*. 2011). Where density of shade-tolerant trees and shrubs has increased, canopy openness has diminished, and sufficient light levels for long-term oak reproduction survival are often not present (Parker and Dey 2008, Keyser *et al*. 2016, Hanberry *et al*. 2020a).

Often accelerating the displacement of oak is mismanagement. Mismanagement takes three primary forms: (1) overstory removals in the absence of advance reproduction of oak in the understory, (2) use of prescribed fire without any or only small advance reproduction present and (3) excessive or insufficient reductions in overstory cover without subsequent compositional control efforts. For upland oak species, newly germinated and small seedlings are not competitive with co-occurring species (Loftis 1990a). Additionally, although oak stump sprouts can grow quickly, the likelihood of an oak sprouting after top-kill decreases with increasing stem diameter and age (Johnson 1977, Keyser and Loftis 2015). Therefore, in these systems, advance reproduction (*i.e*., stems approximately 1.4 m tall) is the most important source of upland oak reproduction. This advance reproduction is often not present in adequate size to effectively compete with more numerous, competitive regeneration. Even with sufficient advance oak reproduction present, however, both excessive and insufficient reductions in overstory BA can still promote oak's competitors to the detriment of oak (Loftis 1990b). Relatively low light levels of 5% to 20% of full sunlight in the understory are sufficient to disfavor oak's shade-intolerant competitors and promote oak, but shade-tolerant competitors also can be favored under these conditions (Parker and Dey 2008). Likewise, if light levels increase too much, oak's competitive standing against shade-tolerant competitors will improve, but will also worsen against shade-intolerant competitors (Dey *et al*. 2010, Hackworth *et al*. 2020, Izbicki *et al*. 2020).

In the southern Appalachians, common oak competitors are shade-intolerant yellow-poplar (*Liriodendron tulipifera*) and shade-tolerant red maple (*Acer rubrum*). Yellow-poplar's rapid growth rate enables it to outcompete oak in the regeneration layer after severe, punctuated overstory disturbance (Beck and Hooper 1986, Swaim *et al*. 2016). Yellow-poplar is also a prolific seeder, and its seed remains viable in the soil for 4–7 yr (Burns and Honkala 1990, Clark and Boyce 1964). Overstory removals also expose mineral soil and improve microsite conditions for newly fallen yellow-poplar seed to establish (Swaim *et al*. 2016). Red maple possesses a plastic growth rate and is capable of responding positively to the full spectrum of postdisturbance light conditions (Beck and Hooper 1986, Abrams 1998). Red maple also vigorously resprouts following top-kill, enabling it to persist on many fire-treated sites (Arthur *et al*. 2015). Because of the responses of species such as yellow-poplar and red maple to overstory removals, preharvest or postharvest release treatments, such as burning, mechanical removal, or herbicides, are often needed to directly target these species.

The degree of competition from species associated with oak is modulated by site quality, and thus, overstory reductions and understory vegetation control efforts need to reflect these conditions to maintain compositional control of the stand. Competitive advance oak reproduction is more likely to be abundant in xeric (Johnson 1992) than more mesic forests (Dey *et al*. 2010). Generally, as sites become increasingly mesic, competition from nonoak species intensifies, requiring greater silvicultural intervention to maintain an oak component (Babl *et al*. 2020). In topographically diverse systems, site quality can vary within stands. Iverson *et al*. (2008) found the variation in canopy openness and topography across a stand can lead to a nonuniform response of oak regeneration and competing species. Site-specific and even substand (Puettmann *et al*. 2009) silvicultural interventions are, therefore, often necessary to maintain an oak component in eastern USA hardwood forests (Dey *et al*. 2010).

Many studies have been conducted over the last few decades to determine the effects of silvicultural treatments on oak regeneration and eventual recruitment into the overstory, with varying results (Loftis 1990b, Schuler and Miller 1995, Larsen and Johnson 1998, Hackworth *et al*. 2020). To date, little research has been conducted to inform guidelines for promoting oak regeneration in the southern Appalachians. For southern Appalachian oak forests, Loftis (1990b) recommended herbicides to remove midstory stems (*i.e.*, suppressed and intermediate canopy classes) of competitive species and increase understory light to promote the development of competitive northern red oak (*Q. rubra*) advance reproduction. Prescribed fire can also be a useful tool for exerting compositional control in upland oak systems. Upland oak species have several adaptations that serve as a competitive advantage over fire-intolerant, mesophytic species (Burns and Honkala 1990, Dey *et al*. 2010, Brose *et al*. 2013, Johnson *et al*. 2019). Oak species have hypogeal germination, which places the root collar beneath the soil, protecting it from fire damage when young (Burns and Honkala 1990). As seedlings, root growth is favored over stem growth, and young oaks are able to use carbohydrate reserves in the roots to resprout and grow rapidly after top-kill by fire (Brose and Van Lear 2004). Mature oak's thick bark protects the cambium from fire damage, and oak is able to compartmentalize wounds (Lorimer 1984, Smith and Sutherland 1999). Many of oak's mesophytic competitors do not possess these traits, increasing their susceptibility to fire mortality and damage (Arthur *et al*. 2012, Brose *et al*. 2013, Dey *et al*. 2014, Keyser *et al*. 2018). These contrasting, fire-related traits between oak and its competitors are thought to have contributed to a greater historical presence of oak. Single prescribed fires have had detrimental effects on upland oaks, however, and further refinement of its use across the topographically and compositionally diverse southern Appalachians is needed (Loftis 1990b).

Our goal was to compare the response of the regeneration layer, including oak and its common competitors, to four treatments in oak-dominated stands in the southern Appalachian Mountains. An operational-scale set of replicated silvicultural trials were established in western North Carolina in 2009 to test the effects of the following treatments in promoting oak regeneration: (1) untreated control, (2) oak shelterwood by midstory reduction, (3) prescribed fire, and (4) shelterwood and burn (*i.e.*, a "traditional" shelterwood). The regeneration layer, midstory, and overstory were inventoried pretreatment and 9 yr posttreatment. Site characteristics, including soil and physiographic data, were also collected for each treatment replication. These treatments were tested because they are commonly utilized to promote oak, but results are often variable, thus warranting further study. Specifically, we aimed to: (i) quantify the change in importance value (sum of relative dominance and relative density; defined in Materials and Methods) of the red oak group (*Quercus,* section *Lobatae*), the white oak group (*Quercus,* section *Quercus*) and oak competitors in response to the four different silvicultural treatments 9 yr posttreatment; (ii) quantify changes in stem density of oak at the species level, and changes among oak's major competitors across treatments and size classes; and (iii) determine the contribution of site-specific factors to the change in importance value of the red oak group, the white oak group, yellow-poplar, and red maple. We hypothesized that: (1) the faster growth and reduced shade tolerance among species found in the red oak group relative to the white oak group would increase importance value the most following the shelterwood and burn (SWB) treatment; (2) the relatively low disturbance severity and high seedling sprout potential of oak species and greater fire-sensitivity of small, mesophytic competitors would increase the relative density of oak species most in the prescribed fire (RXF) treatment; and (3) site-specific factors, such as greater BA reductions and lower site index, would be related to greater increases in oak importance values where oaks possess a competitive advantage over mesophytic species.

Materials and Methods. SITE DESCRIPTION. The study site was located on the Cold Mountain Game Lands (CMGL) in western North Carolina, which lie within the Southern Blue Ridge Mountains subsection of the broader Central Appalachian Broadleaf Forest–Coniferous Forest Province (Cleland *et al*. 2007). This site has steep, mountainous terrain (elevation: 980 m to 1,259 m ASL). Oak site index ranges between 15.5 m and 32.6 m at base age 50. Average rainfall is 1,060 mm yr^{-1}. The three primary soil series are Plott, Edneyville, and Chestnut. These typically are well-drained and deep to very deep. Average high and low temperatures in July and January are 28 °C and –4 °C, respectively. The CMGL are an upland mixed-oak forest. The midstory trees (stems with crowns beneath the overstory canopy layer) generally consist of blackgum (*Nyssa sylvatica*), red maple, sourwood (*Oxydendrum arboreum*), and silverbell (*Halesia tetraptera*). Common overstory trees (stems with crown that compose the overstory canopy layer) are sugar maple (*A.*

Table 1. Midstory (stems ≥ 5 cm and < 25 cm diameter at breast height [DBH]); overstory (stems ≥ 25 cm DBH); and total basal area pretreatment (m^2 ha^{-1}), posttreatment (m^2 ha^{-1}), and relative change in basal area (%) over the 9-yr period (least squares [LS] mean ± standard error) by treatment on sites in Cold Mountains Game Land, Haywood County, NC, USA. CON = control, SW = shelterwood, RXF = prescribed fire, and SWB = shelterwood and burn. Significant *P* values are in bold. Values that do not share a letter within a given canopy class category (*i.e.*, midstory, overstory, or total) are significantly different.

	Basal area m^2 ha^{-1}					
	Pretreatment	Treatment *P* value	9 yr posttreatment	Treatment *P* value	Relative change ± %	Treatment *P* value
Midstory						
CON	6.5 ± 0.2		5.1 ± 0.3a		−20.2 ± 8.6a	
SW	6.7 ± 1.5		1.6 ± 0.1b		−76.7 ± 8.2b	
RXF	7.7 ± 1.3		5.6 ± 0.5a		−27.0 ± 8.4a	
SWB	4.0 ± 1.1	0.36	0.6 ± 0.5b	< **0.001**	−84.3 ± 8.6b	< **0.001**
Overstory						
CON	26.6 ± 1.8		25.3 ± 3.0a		−4.6 ± 4.1a	
SW	29.5 ± 4.6		29.4 ± 4.8a		−0.4 ± 3.8a	
RXF	29.0 ± 4.4		28.6 ± 4.3a		−1.3 ± 3.9a	
SWB	31.6 ± 2.7	0.84	8.4 ± 3.1b	< **0.001**	−73.6 ± 3.8b	< **0.001**
Total						
CON	33.1 ± 3.0		32.1 ± 1.5a		−3.0 ± 4.1a	
SW	36.2 ± 2.8		32.2 ± 1.5a		−11.0 ± 3.9a	
RXF	36.6 ± 2.9		34.9 ± 1.5a		−4.6 ± 4.0a	
SWB	35.6 ± 2.9	0.77	6.3 ± 1.6b	< **0.001**	−82.3 ± 4.1b	< **0.001**

saccharum), black cherry (*Prunus serotina*), yellow-poplar, northern red oak, black oak (*Q. velutina*), chestnut oak (*Q. montana*), scarlet oak (*Q. coccinea*), white oak (*Q. alba*), hickory (*Carya* spp.), and red maple.

EXPERIMENTAL DESIGN. On the CMGL, 16 5-ha units were selected where upland oak was the predominant forest cover type. A completely randomized design was used to assign four treatments to the 16 units (4 replications per treatment). The following criteria had to be met for selected units: (1) stands within oak-forest types with a substantial component of oak in the canopy, (2) no known recent history (< 20 yr) of substantial disturbance, (3) minimal ericaceous shrub cover, (4) full stocking, and (5) composed of trees that were greater than 70 yr old. Across all units, average stem densities in the regeneration layer were 15,063 stems ha^{-1}. Pretreatment midstory (stems ≥ 5 cm and < 25 cm diameter at breast height [DBH]) and overstory (stems ≥ 25 cm DBH) BA are included in Table 1.

TREATMENTS. The study consisted of four treatments: (1) untreated control (CON), (2) oak shelterwood harvest (SW), (3) prescribed fire (RXF), and (4) shelterwood and burn (SWB) (Greenberg et al. 2016). The treatments SW, RXF, and SWB were selected because they are commonly utilized with the goal of maintaining and promoting oak regeneration in this region, but results are often inconsistent across sites. The SW was based on guidelines presented in Loftis (1990b): 25–30% BA removal without reducing the overstory. Garlon 3A (active ingredient: triclopyr 44.4%) was applied as a basal application to all nonoak and nonhickory (*Carya* spp.) trees between ≥ 0.5 cm and ≤ 25 cm DBH in September 2008, prior to leaf-fall, with the hack and squirt method. For the RXF treatment, each unit received two late dormant season prescribed burns. The first prescribed burns occurred in February 2009 for two of the RXF units and April 2010 for the remaining two RXF units. During these burns, relative humidity (RH) was between 20% and 40%, winds were between 2 kilometers per hour (kph) and 11 kph, and temperatures were between 15 °C and 27 °C. The second prescribed burns were conducted in April 2014 or March 2015. During these burns, RH was between 20% and 37%, winds were between 5 kph and 13 kph, and temperatures were between 12 °C and 23 °C. The SWB was based on guidelines presented in Brose et al. (1999). An establishment was conducted in 2009–10 to reduce stand BA by 40–50%. Oak and hickory species were retained, when possible, during the harvest. A dormant-season prescribed burn was conducted 3–5 yr after the initial overstory removal. Units in the SWB were harvested before the growing season in 2010 or 2011 and burned in March of 2015 or 2016. During these burns, RH was between 20% and 40%, winds were between 6 kph and 15 kph, and temperatures were between 7 °C and 16 °C. In general, all prescribed burns utilized a combination of backing and flaking strip lighting that incorporated short-strip head firing.

DATA COLLECTION. Six 0.05-ha overstory plots (12.6 m radius) were located within each 5-ha treatment unit. Plots were placed in a 3-m by 2-m array. Three of the six overstory plots were randomly selected for data collection. A midstory plot (5.6-m radius) was concentrically nested within the 0.05-ha overstory plots. Aspect and elevation were measured at each plot center. Additional topographic variables measured at each plot included landform index (LFI) (McNab 1993) and terrain shape index (TSI) (McNab 1989).

Prior to treatment, all live overstory trees (stems $\geq$ 25 cm diameter at breast height [1.37 m; DBH]) within each 0.05-ha plot and all midstory trees (stems $\geq$ 5 cm DBH and $<$ 25 cm DBH) within the concentrically nested 0.01-ha plot were stem-mapped and tagged, and species and DBH were recorded. Tree status (live or dead) was recorded nine growing seasons after the initial treatment was completed (*i.e.*, nine growing seasons after the collection of pretreatment data in CON, nine growing seasons after the first of two burns in RXF, nine growing seasons after the harvest in SWB, and nine growing seasons after the herbicide treatment in SW). Stem diameter of all tagged stems was recorded again in 2013, at which time new ingrowth into the midstory and overstory size classes were recorded.

To quantify treatment effects on tree species regeneration, two 0.004-ha (3.6-m radius) subplots were established within each 0.05-ha overstory plot. These subplots were 8 m and 45° and 225° from the plot center and permanently monumented. Species and size class were recorded for all stems in the regeneration layer prior to treatment and again nine growing seasons after the initial treatments. Size classes were: (1) $<$ 0.3 m tall, (2) $\geq$ 0.3 $<$ 0.6 m tall, (3) $\geq$ 0.6 $<$ 0.9 m tall, (4) $\geq$ 0.9 $<$ 1.2 m tall, (5) $\geq$ 1.2 m tall and $<$ 3.8 cm DBH, and (6) $\geq$ 3.8 $<$ 5 cm DBH. Stem diameter (DBH) was recorded to the nearest 0.1 cm for the largest two size classes. Species were assigned to one of 11 species groups: striped maple (*A. pensylvanica*); red maple; sugar maple; hickory; yellow-poplar; other midtolerant species; white ash (*Fraxinus americana*); the red oak group (*i.e.,* black oak, northern red oak, and scarlet oak); other shade-intolerant species; other shade-tolerant species; and the white oak group (*i.e.*, chestnut oak and white oak). Shade tolerance designations were informed by Hanberry (2019).

Regeneration was characterized in multiple ways. Not all stems in the regeneration plots were tall enough to possess a DBH (*i.e.*, $<$ 1.37 m in height). Evaluating "relative dominance" (defined later) required a metric which could be used to assess size evenly across all stem sizes. Therefore, absolute biomass (g) per stem was estimated using the aboveground biomass equation found in Williams and McClenahen (1984). For stems $<$ 1.37 m in height, we used the mean of measured basal diameters from a subset of stems in this study for each size class. The results were 0.3 cm for the $<$ 0.3 m height class, 0.6 cm for the $\geq$ 0.3 $<$ 0.6 m height class, 0.9 cm for the $\geq$ 0.9 $<$ 1.2 m height class, and 1.2 cm for stems $>$1.2 m and $<$1.37 m in height. These mean basal diameters were used to calculate biomass for stems without a DBH. Absolute density was the number of stems of a given species group per 0.004-ha regeneration subplot (referred to as stem density or stems ha^{-1}). Relative biomass (*i.e.*, relative dominance) was the total biomass (g) of a given species group divided by total biomass (g) of all species groups on the 0.004-ha regeneration plot, then multiplied by 100. Relative density was the total stems per 0.004 ha of a given species group divided by the total stems on that 0.004-ha regeneration plot, then multiplied by 100. Importance value was calculated as the sum of relative dominance and relative density, with a maximum potential value of 200. Analysis of importance values facilitates the evaluation of stem size and abundance of a given species in relation to the other associated species and is, thus, a useful metric in evaluating the competitiveness of a species (*e.g.*, Fei *et al.* 2011).

Stems ha^{-1} was calculated for yellow-poplar, red maple, and hickory, and at the species level for all oaks (white, black, chestnut, northern red, and scarlet) at year 0 and again 9 yr postinitial treatment. The six original size classes as defined above were combined into three size classes for ease in interpretation and used to analyze stem densities by species group. They were defined as: small seedlings ($<$ 0.6 m tall), large seedlings ($\geq$

0.6 $<$ 1.2 m tall), or saplings ($\geq$ 1.2 m tall and $<$ 5.0 cm DBH). Absolute changes by size class and total stems 0 yr to 9 yr posttreatment were recorded.

STATISTICAL ANALYSES. Mixed-effects analyses of variance (ANOVAs) were used to test the effects of treatments on structural differences among treatments pre- and posttreatment. The following response variables were tested: (1) pretreatment midstory BA (m^2 ha^{-1}), (2) midstory BA (m^2 ha^{-1}) 9 yr posttreatment, (3) relative change in midstory BA (%) over the 9-yr period, (4) pretreatment overstory BA (m^2 ha^{-1}), (5) overstory BA (m^2 ha^{-1}) 9 yr posttreatment, (6) relative change in overstory BA (%) 9 yr posttreatment, (7) total BA pretreatment (m^2 ha^{-1}), (8) total BA 9 yr posttreatment (m^2 ha^{-1}), and (9) relative change in BA (%) over the 9-yr period. Treatment was included as a fixed effect and plot nested within unit was a random effect. For posttreatment values, pretreatment values were included as a covariate (ANCOVA). Posthoc tests were conducted using Tukey's HSD to test differences among treatments.

To analyze effects of treatments on changes in species-level importance value and stem density, we used mixed effects ANOVAs. For regeneration layer importance value analyses, treatment, species group, and the interaction between treatment and species group were included as fixed effects, and regeneration plot nested within unit was included as a random effect. For stem density, treatment, species, and the interaction between treatment and species were included as fixed effects, and regeneration plot was included as a random effect. ANOVAs were conducted in the following order: (1) posttreatment absolute change in importance value, (2) posttreatment relative change in importance value, (3) posttreatment absolute change in total stems ha^{-1}, (4) posttreatment absolute change in stems ha^{-1} of small seedlings, (5) posttreatment absolute change in stems ha^{-1} of large seedlings, and (6) posttreatment absolute change in stems ha^{-1} of saplings. Tests of absolute change in importance value and absolute change in stems ha^{-1} included pretreatment importance value and pretreatment stems ha^{-1}, respectively, as covariates (ANCOVA). Posthoc tests were conducted using Tukey's HSD to test differences among treatments within species groups. All analyses were performed using JMP® 15.2.1 (SAS 2020). The alpha value was 0.05.

Results. STRUCTURAL CHANGES AMONG TREATMENTS. Pretreatment midstory, overstory, and total BA did not differ by treatment (midstory: $F = 1.11$, $P = 0.36$; overstory: $F = 0.27$, $P = 0.84$; total: $F = 0.38$, $P = 0.77$; Table 1), whereas absolute posttreatment BA and relative changes among treatments did vary within strata and in total (absolute: midstory: $F = 10.35$, $P < 0.001$; overstory: $F = 84.41$, $P < 0.001$; total: $F = 63.05$, $P < 0.001$; relative change: midstory: $F = 17.86$, $P < 0.001$; overstory: 119.26, $P < 0.001$; total: $F = 77.67$, $P < 0.001$; Table 1). Midstory BA was significantly reduced in the SW and SWB but only the SWB resulted in a significant reduction in overstory BA (Table 1).

COMPOSITIONAL CHANGES AMONG TREATMENTS. All analyses revealed significant interactions between treatment and species group or species: (A) treatment × species group; absolute change in importance value ($F = 5.98$, $P < 0.001$), relative change in importance value ($F = 5.78$, $P < 0.001$); (B) treatment × species; absolute change in total stem density ($F = 5.23$, $P < 0.001$), absolute change in density of small seedlings ($F = 3.89$, $P < 0.001$), absolute change in large seedlings ($F = 2.68$, $P < 0.001$), and absolute change in saplings ($F = 7.25$, $P < 0.001$). In all ANOVAs evaluating change in stem density by size-class, the covariate of pretreatment density of stems per size-class and species was significant and included in the models ($P < 0.05$).

Red Oak Group. The absolute change in importance value for the red oak group increased significantly in the SWB (16.0 ± 4.6) and RXF (13.4 ± 4.6) compared with the SW (–1.7 ± 4.5) (Table 2). Relative change in importance value increased significantly in the SWB (1,392.6% ± 290.4) compared to the CON (63.1% ± 298.2) and SW (525.2% ± 294.4) (Table 3). Absolute changes were statistically similar between the CON, RXF, and SWB. Relative changes were statistically similar between the CON, SW, and RXF.

The total density of northern red oak in the SWB (2,308.2 ± 509.5 stems ha^{-1}) increased more than in the RXF (480.9 stems ha^{-1} ± 515.4) and the SW (–150.36 stems ha^{-1} ± 508.5) (Table 4). Total stem density was four times greater in the SWB than the RXF. Differences in scarlet oak stem density were not significant among treatments. Black oak experienced little change across all treatments.

Table 2. Absolute change in importance value (least squares [LS] mean ± standard error) by species group; striped maple (ACPE), red maple (ACRU), sugar maple (ACSA), other shade-tolerant species (ST), hickory (CARYA), red oak group (RO), white oak group (WO), other midtolerant groups (MT), white ash (FRAM), yellow-poplar (LITU), and other shade-intolerant species (SI); and treatment, control, shelterwood, prescribed fire, and shelterwood and burn on sites in Cold Mountain Game Land, Haywood County, NC, USA. Tukey's HSD differences are within species group and are noted by letter distinctions. Values that do not share a letter within a species are significantly different.

Species group	Control	Shelterwood	Prescribed fire	Shelterwood and burn
ACPE	−4.37 ± 3.92a	−0.22 ± 3.70a	−0.46 ± 3.80a	−19.40 ± 3.65b
ACRU	9.73 ± 3.88a	5.71 ± 3.89a	3.73 ± 3.91ab	−7.86 ± 3.82b
ACSA	−5.21 ± 3.51ab	−1.86 ± 3.38a	−3.24 ± 3.45a	−17.22 ± 3.52b
ST	−2.81 ± 3.74	−2.87 ± 3.66	−1.89 ± 3.71	−8.11 ± 3.80
CARYA	−2.73 ± 2.65	−0.39 ± 2.61	1.29 ± 2.60	−2.48 ± 2.57
RO	9.58 ± 4.70ab	−1.67 ± 4.49b	13.43 ± 4.58a	15.99 ± 4.58a
WO	−4.17 ± 1.55	−0.18 ± 1.46	−2.55 ± 1.48	−3.98 ± 1.48
MT	1.25 ± 2.59	1.43 ± 2.46	1.37 ± 2.51	0.28 ± 2.43
FRAM	−2.43 ± 3.70ab	4.45 ± 3.58a	−11.54 ± 3.73b	−12.35 ± 3.87b
LITU	3.99 ± 5.05b	4.65 ± 4.95b	1.10 ± 4.92b	32.87 ± 4.94a
SI	−8.68 ± 4.66b	−9.50 ± 4.54b	−2.77 ± 4.56b	20.23 ± 4.53a

Changes in the density of the red oak group were driven primarily by increases in the abundance of small seedlings (< 0.6 m tall; Table 4), with northern red oak increasing the most dramatically of the red oak group. Northern red oak's stem density significantly differed among treatments in the small seedlings and saplings size classes (Table 4). Increases in density of small northern red oak seedlings in the SWB (1,841.1 stems ha^{-1} ± 467) were significantly greater than in the SW (–209.1 stems ha^{-1} ± 468.0). The SW was the only treatment to experience decreases in the density of small northern red oak seedlings. The density of northern red oak saplings in the SWB (221.2 stems ha^{-1} ± 49.8) was significantly greater than in all other treatments. The resulting total stem densities 9 yr posttreatment were greatest for northern red oak in the SWB.

White Oak Group. Neither absolute nor relative changes in importance value differed significantly among treatments (Tables 2 and 3). The increase in total stem density of chestnut oak was significantly greater in the RXF treatment (274.9 stems ha^{-1} ± 191.1) than in the CON (–540.2 stems ha^{-1} ± 201.1), although increases were modest at 275 stems ha^{-1}. The total change in total density of white oak stem density did not differ significantly among treatments (Table 4).

Significant changes in total chestnut oak stem density were largely driven by small seedlings

Table 3. Relative change (%) in importance value (least squares [LS] mean ± standard error) by species group: striped maple (ACPE), red maple (ACRU), sugar maple (ACSA), other shade-tolerant species (ST), hickory (CARYA), red oak group (RO), white oak group (WO), other midtolerant groups (MT), white ash (FRAM), yellow-poplar (LITU), and other shade-intolerant species (SI); and treatment, control, shelterwood, prescribed fire, and shelterwood and burn on sites in Cold Mountain Game Land, Haywood County, NC, USA. Tukey's HSD differences are within species group and are noted by letter distinctions. Values that do not share a letter within a species are significantly different.

Species group	Control	Shelterwood	Prescribed fire	Shelterwood and burn
ACPE	5.50 ± 88.31	210.31 ± 88.31	14.41 ± 88.31	−44.14 ± 88.31
ACRU	124.76 ± 95.04	333.79 ± 93.10	80.18 ± 93.77	195.10 ± 92.41
ACSA	42.29 ± 50.87	45.11 ± 50.87	74.23 ± 50.87	−41.34 ± 50.87
ST	0.05 ± 52.41	21.72 ± 52.41	53.56 ± 52.41	142.09 ± 52.41
CARYA	64.30 ± 55.01	10.04 ± 55.04	25.86 ± 55.04	131.64 ± 55.04
RO	63.07 ± 298.24b	32.09 ± 292.45b	524.24 ± 294.38ab	1,392.60 ± 290.40a
WO	−13.99 ± 50.26	99.26 ± 49.51	12.94 ± 49.68	55.34 ± 49.28
MT	157.65 ± 128.52	40.91 ± 125.06	4.53 ± 126.32	255.89 ± 123.81
FRAM	6.12 ± 39.00	91.63 ± 38.57	−38.62 ± 38.65	5.03 ± 38.45
LITU	255.41 ± 465.03b	591.97 ± 465.03b	93.28 ± 465.03b	2,952.00 ± 465.03a
SI	−25.34 ± 76.11b	11.90 ± 76.11b	5.71 ± 76.11b	370.95 ± 76.11a

Table 4. Absolute change in stem density from pretreatment to 9 yr posttreatment of small seedlings (stems $\text{ha}^{-1} < 0.6$ m tall), large seedlings (stems $\text{ha}^{-1} \geq 0.6 < 1.2$ m tall), and saplings (stems $\text{ha}^{-1} \geq 1.2$ m and < 5 cm diameter at breast height [DBH]) (least squares [LS] mean ± standard error) by species: red maple (ACRU), hickory (CARYA), yellow-poplar (LITU), white oak (QUAL), scarlet oak (QUCO), chestnut oak (QUPR), northern red oak (QURU), and black oak (QUVE); and treatment, control, shelterwood, prescribed fire, and shelterwood and burn on sites in Cold Mountain Game Land, Haywood County, NC, USA. LS means are reported with standard error in parentheses. Values that do not share a letter within a species and a given size-class are significantly different.

Species and density	Control	Shelterwood	Prescribed fire	Shelterwood and burn
ACRU				
Small seedlings	760.29 ± 420.40ab	399.21 ± 424.30ab	1,349.05 ± 437.04a	−498.13 ± 423.13b
Large seedlings	165.47 ± 71.20	15.51 ± 71.65	60.11 ± 71.20	50.57 ± 71.46
Saplings	43.86 ± 66.61	213.56 ± 656.92	43.89 ± 65.72	240.36 ± 66.18
Total	1,041.77 ± 439.83	717.60 ± 442.02	1,257.38 ± 451.78	−172.99 ± 443.35
CARYA				
Small seedlings	−86.33 ± 201.82ab	85.71 ± 194.43ab	515.79 ± 197.90a	−283.25 ± 192.79b
Large seedlings	22.17 ± 32.27	75.35 ± 32.12	−1.34 ± 32.37	70.49 ± 32.12
Saplings	0.00 ± 37.39b	41.67 ± 37.39b	31.25 ± 37.33b	187.50 ± 37.47a
Total	−5.72 ± 202.14	174.95 ± 199.68	480.56 ± 202.87	−3.95 ± 200.07
LITU				
Small seedlings	78.27 ± 205.18b	474.94 ± 205.88b	109.52 ± 205.18b	1,347.69 ± 204.62a
Large seedlings	42.14 ± 83.94b	26.42 ± 84.10b	−33.43 ± 83.78b	402.37 ± 83.83a
Saplings	33.60 ± 166.35b	9.10 ± 158.41b	16.22 ± 159.30b	995.82 ± 157.36a
Total	97.81 ± 378.40b	557.33 ± 376.40b	78.11 ± 373.15b	2,756.33 ± 373.97a
QUAL				
Small seedlings	−25.26 ± 137.87	−56.99 ± 133.73	95.04 ± 142.92	100.40 ± 132.84
Large seedlings	−0.32 ± 10.660	21.51 ± 10.70	−0.22 ± 10.60	−0.22 ± 10.56
Saplings	−1.85 ± 6.98	−1.22 ± 6.67	−0.98 ± 6.76	3.15 ± 6.54
Total	−36.53 ± 138.41	−51.85 ± 134.65	106.63 ± 143.69	105.53 ± 134.09
QUCO				
Small seedlings	768.50 ± 294.88	233.59 ± 297.57	982.38 ± 315.79	98.86 ± 299.54
Large seedlings	24.19 ± 16.37	−7.59 ± 15.74	36.96 ± 15.92	−3.40 ± 15.49
Saplings	0.00 ± 7.37	10.42 ± 7.37	10.42 ± 7.37	0.00 ± 7.37
Total	791.20 ± 303.76	233.56 ± 306.37	1,029.56 ± 325.46	101.93 ± 308.64
QUPR				
Small seedlings	−536.90 ± 181.84b	1.24 ± 171.12ab	246.74 ± 172.22a	−135.43 ± 176.35ab
Large seedlings	90.90 ± 60.40	158.18 ± 60.95	11.37 ± 60.38	−10.45 ± 60.78
Saplings	−11.65 ± 8.33	−4.16 ± 8.26	−3.95 ± 8.24	−11.83 ± 8.11
Total	−540.23 ± 201.14b	130.07 ± 190.09ab	274.88 ± 191.14a	−70.36 ± 196.00ab
QURU				
Small seedlings	621.24 ± 488.84ab	−209.14 ± 467.99b	564.38 ± 474.77ab	1,841.14 ± 467.37a
Large seedlings	7.71 ± 82.31	44.60 ± 80.40	−69.38 ± 80.75	200.97 ± 80.59
Saplings	20.00 ± 49.66b	9.59 ± 49.66b	−11.25 ± 49.66b	221.24 ± 49.84a
Total	606.63 ± 530.44ab	−150.36 ± 508.48b	480.93 ± 515.36b	2,308.16 ± 509.52a
QUVE				
Small seedlings	−97.01 ± 110.06	−78.55 ± 108.40	97.85 ± 108.57	−74.05 ± 110.11
Large seedlings	−7.77 ± 17.44	27.15 ± 16.85	15.36 ± 17.14	7.78 ± 16.73
Saplings	−2.60 ± 5.30	−2.60 ± 5.24	7.81 ± 5.24	−2.60 ± 5.24
Total	−114.68 ± 115.27	−66.27 ± 113.86	138.90 ± 113.88	−62.95 ± 116.58

(Table 4). Changes in chestnut oak small seedling densities among treatments were greatest in the RXF (246.7 stems ha^{-1} ± 172.2), which were significantly greater than in the CON (–536.9 stems ha^{-1} ± 181.84). The density of white oak seedlings, regardless of size, did not differ by treatment.

Hickory. For hickory species**,** absolute and relative change in importance value did not differ among treatments (Tables 2 and 3). Change in total stem density did not differ among treatments, but changes were significant for small seedlings and saplings (Table 4). The change in density of small hickory seedlings was greater in the RXF (515.8 stems ha^{-1} ± 197.9) than in the SWB (–283.3 stems ha^{-1} ± 192.8). Increases in hickory sapling density were greater in the SWB (187.5 stems ha^{-1} ± 37.5) than in all other treatments, however (Table 4).

Major Non-Oak Competitors: Red Maple and Yellow-Poplar. Nine yr posttreatment, the absolute change in the importance value of red maple differed significantly among treatments, while relative values did not (Tables 2 and 3). Red maple absolute change in importance value decreased significantly in the SWB (–7.9 ± 3.8) compared to the CON (9.73 ± 3.9), and the SWB was the only treatment to reduce the importance value of red maple 9 yr later.

Changes in total stems ha^{-1} of red maple did not significantly differ by treatment. Changes in small red maple seedling densities did differ by treatment, however (Table 4). Small red maple stems ha^{-1} decreased in the SWB (–498.1 stems ha^{-1} ± 423.1) which differed significantly from the increases in RXF (1,349.1 stems ha^{-1} ± 437.0).

Both absolute and relative changes in importance value of yellow-poplar differed among treatments (Tables 2 and 3). Absolute increases in importance value of yellow-poplar in the SWB (32.9 ± 4.9) were significantly greater than in all other treatments, and were approximately 30 times greater than in the RXF treatment (1.1 ± 4.9). The RXF treatment had the smallest increase in absolute and relative changes in importance value of yellow-poplar. Additionally, relative change in yellow-poplar was greatest in the SWB (2,952.0% ± 465.0) and was significantly greater than in the CON (255.4% ± 465.0), SW (592.0% ± 465.0), and RXF (93.3% ± 465.0).

The increase in total stems ha^{-1} of yellow-poplar in the SWB (2,756.3 stems ha^{-1} ± 374.0) was significantly greater than in all other treatments, while the increase was statistically similar among the SW (557.3 stems ha^{-1} ± 376.4), the RXF (78.1 stems ha^{-1} ± 373.2), and the CON (97.8 stems ha^{-1} ± 378.4). Small seedlings, large seedlings, and saplings of yellow-poplar experienced changes in stem density that significantly differed among treatments (Table 4). The increase in density of yellow-poplar small seedlings, large seedlings, and saplings was significantly greater in the SWB (1,347.7 stems ha^{-1} ± 204.6, 402.4 stems ha^{-1} ± 83.8, 995.8 stems ha^{-1} ± 157.4, respectively) than in all other treatments.

Other Competing Species Groups. Shade-intolerant species generally responded more positively to the SWB whereas shade-tolerant species responded more positively to the CON and RXF. Absolute change in importance value was significantly different among treatments for striped maple, sugar maple, white ash, and the other shade-intolerant species group (Table 2). The decrease in importance value of striped maple in the SWB (–19.4 ± 3.7) was greater than in all other treatments. The decrease in importance value of sugar maple in the SWB (–17.2 ± 3.5) was greater than in the RXF (–3.2 ± 3.5) and the SW (–1.9 ± 3.4). The importance value increase of white ash was significantly greater in the SW (4.5 ± 3.6) than in the RXF (–11.5 ± 3.7) and SWB (–12.4 ± 3.9). Additionally, all other shade-intolerant species' importance values decreased across all treatments except the SWB, which experienced significant increases in shade-intolerant species importance values (20.2 ± 4.5). The shade-intolerant species group also experienced a significant change in relative importance value among treatments (Table 3). The relative change in importance value of the shade-intolerant species group was greater in the SWB (371.0% ± 76.1) than in all other treatments.

Discussion. Overall, the treatments elicited different responses among species groups. Among sapling-sized oak species, only northern red oak in the SWB increased in stems ha^{-1} over the 9-yr period, indicating low overall recruitment of oak species among treatments. Generally, the RXF improved small seedling stem density of the majority of oak species, but only significantly so for chestnut oak. Shade-tolerant species' importance value and stem density tended to decline under the SWB, whereas those of shade-intolerant species tended to increase (except for white ash, which declined). The SW treatment generally caused no change or reductions in the presence of oaks. In all, the RXF and the SWB improved the competitive standing of oak but, as the results suggest, the RXF did not reduce overstory BA sufficiently for oak recruitment, and the relatively high disturbance severity of the SWB invigorated yellow-poplar. In both of these modestly successful treatments, additional follow-up treatments will be necessary to control competing species and recruit more oak into large size classes.

The SWB was the only treatment to increase the number of sapling-sized oaks. The only oak species to increase in density in the sapling size class, however, was northern red oak. Although absolute increases in importance value of the red oak group (*i.e.*, northern red oak, black oak, and scarlet oak) were similar between the RXF and SWB treatments, the SWB resulted in greater increases of relative change in importance value. Additionally, the SWB was the only treatment to decrease the importance value of red maple and the "other" shade-tolerant species group. The absolute changes in importance value were the most negative under the SWB for striped and sugar maple. On the other hand, yellow-poplar and the "other" shade-intolerant species group responded positively to the SWB treatment; the importance value of yellow-poplar increased two times more than that of the red oak group, and sapling-sized yellow-poplar increased nearly five times that of sapling-sized northern red oak. Oakman *et al.* (2019) similarly found increases in both oak and yellow-poplar in response to a combination of mechanical removal and fire. Likewise, Dey *et al.* (2009) also found yellow-poplar to limit red oak success in response to treatments with overstory removal. Similar to the results of our study, Brose *et al.* (1999) found yellow-poplar competition inhibited oak growth following a shelterwood and burn. Their results suggested, however, that the season of burn interacts with burn intensity to favor either oak species or yellow-poplar. In low-intensity, dormant season burns, yellow-poplar had greater density and stocking than oak. Conversely, in medium- to high-intensity burns during the growing season, yellow-poplar was scarce, and free-to-grow oaks were abundant. In contrast, Keyser *et al.* (2019) found no compositional differences in the regeneration layer between dormant and growing season burns in a xeric, southern Appalachian oak forest. In our study, dormant season burns reflected the realities of operational prescribed fire practices, where growing season burning is rarely possible. Despite the documented reduced efficacy of dormant season burns relative to growing season burns in increasing the competitiveness of oak species (Brose *et al.* 1999), some oak species increased in number and size in response to our SWB that included a late, dormant-season burn. Height growth and recruitment into the midstory can be slow for oaks (Redmond *et al.* 2012). Hackworth *et al.* (2020), however, found black oaks and white oaks to grow nearly 1 m in height following shelterwood establishment cuttings over a similar 9-year period. Like our study, however, competitors still minimized the number of free-to-grow oak stems in the understory. This suggests that follow-up treatments in our SWB, such as herbicide or prescribed fire, will be needed to reduce yellow-poplar in order for oak to successfully recruit into large size-classes. If managing for oak where mature, seed-bearing yellow-poplar are or have been present recently, addressing yellow-poplar in a timely manner will be important. The control of yellow-poplar 7 yr or more before overstory manipulations are made might deplete the seed bank and reduce yellow-poplar's presence postharvest.

Similar to northern red oak, sapling-sized hickory stem density increased more in the SWB than other treatments, but increases in small seedling hickory density were greatest in the RXF. Hickory is a common associate of oak, and, like oak, is fire-adapted (Eyre 1980, Fralish 2004) and is currently experiencing similar regeneration problems (Pierce *et al.* 2006, Lefland *et al.* 2018). Some traits of hickory species are distinct from oak, including greater resource allocation to root growth; higher shade tolerance; consistent, rather than erratic, mast production and recruitment; and less flammable and smaller leaf litter (Babl *et al.* 2020, McDaniel *et al.* 2021, Pile Knapp *et al.* 2021). Therefore, attempting to maintain both an oak and a hickory component might require balanced consideration for these co-occurring species with disparate ecologies.

The small seedling density of chestnut oak and hickory species increased in the RXF, but red maple also experienced an increase in seedling density in the RXF. The density of small seedling chestnut oaks increased in RXF compared to CON, but the change in large seedlings and saplings over the 9-yr posttreatment period was negative. Likewise, RXF increased the small seedling density of hickory species but failed to recruit hickory saplings. The density of yellow-poplar increased by an average of 78.1 stems ha^{-1} in the RXF, but it increased approximately 35 times this amount, on average, in the SWB. Conversely, RXF caused less of a reduction in striped and sugar maple than SWB. Barnes and Van Lear (1998) similarly found burning alone benefited oak over yellow-poplar. They found three winter burns over a 3-yr period reduced yellow-poplar 71% and improved oak root-to-shoot ratios. In our study, RXF had lower absolute increases in red maple importance value than the CON and SW, but these differences were not significant. In a study on the impacts of single and repeated fires on oak and its competitors, Alexander *et al*. (2008) found both single and repeated spring prescribed fires, especially at higher burn temperatures, reduced survival of small red maple seedlings. However, despite the ability of fire to control small red maple, in the long term, even frequent fires were unable to control competition from shade-tolerant species, including red maple (Keyser *et al*. 2017). The treatment resulted in a greater density of oaks, but reduced competitiveness. Additionally, single- and consecutive-season experimental fire treatments on 2- and 3-yr-old seedlings have resulted in taller resprouts of yellow-poplar and red maple than red and white oaks (Green *et al*. 2010, Arthur *et al*. 2015, Keyser *et al*. 2019, Schweitzer *et al*. 2019). This result suggests that generalizations about the competitive advantages fire-tolerant species are thought to possess over fire-intolerant species do not always hold true. Fire might provide promise for improving the red oak group's competitive status on these sites while minimizing competition from oak's two major competitors, red maple and yellow-poplar (Keyser *et al*. 2012, Izbicki *et al*. 2020, Dems *et al*. 2021). Pairing a more frequent prescribed fire regime such as this with a shelterwood might prove to dramatically improve oak regeneration (Hutchinson *et al*. 2005, 2012).

The red and the white oak groups responded differently to the treatments. Although the red oak group responded positively to RXF and SWB, the white oak group, overall, did not respond positively to any of the treatments. This is similar to the results of Albrecht and McCarthy (2006), who compared the effects of prescribed fire, thinning, and their combination. In our study and theirs, species in the white oak group decreased across all treatments, including the CON, but species in the red oak group responded positively to some treatments. During the 5-yr window leading up to and immediately following treatment installation (2006–10), acorn production among the white oak group in the Cold Mountain area of Haywood County was considered "good" to "fair" in 2006 and 2007, "poor" in 2008 and 2009, and "good" again in 2010 (Jones 2006; Olfenbuttel 2007, 2008, 2009, 2010). The red oak group's acorn production over this time was deemed "poor" during all years except 2008, when production was "good" (Jones 2006; Olfenbuttel 2007, 2008, 2009, 2010). We would have expected the success of the red oak group to be partially explained by a documented, sustained increase of acorn production relative to the white oak group, leading up to the treatment period, but no strong evidence of this was documented in the records.

Interestingly, chestnut oak small seedling densities did increase under RXF, and it was the only oak species responding positively to fire. This supports the results of Royse *et al*. (2010) who found increased survival of chestnut oak on burned sites, regardless of fire frequency.

Our results suggest the white oak group might be more sensitive to extremes in disturbance severity. Brose (2011) found small increases in light (from 4% to 14%) greatly improved white and chestnut oak survival. Additionally, Brose (2008) found that northern red oak was more responsive to increases in light levels, whereas white and chestnut oak maximum growth occurred at midrange light levels. Rebbeck *et al*. (2011) similarly found that the greatest white oak diameter increases in the regeneration layer occurred at 18% full sunlight compared with 6% and 25%. Evaluation of BA change showed the SW was the only treatment to significantly reduce midstory BA, while having minimal impact on the overstory. The SWB created the greatest decreases in total BA and the CON experienced the least change in BA. Absolute importance of the white oak group decreased the least in the SW treatment, and substantially in CON, RXF, and SWB. This suggests white oak might have a narrow window for regeneration success that was not achieved in this study.

Oak seedlings that are able to grow under the low light conditions common in closed canopy forests will have a better competitive advantage when understory light is increased. In our study, northern red oak density increased the CON treatments, while white oak density decreased. This is similar to results in Brose (2011), where survival of northern red oak was greater than white, chestnut, and black oaks in uncut stands. Additionally, Dillaway *et al*. (2007) found older white oak seedlings growing under closed canopies had lower root nonstructural carbohydrates than younger seedlings, suggesting a decreased ability to grow beneath the canopy as well as respond to increases in resource (*i.e*., light) availability. In our study, white oak growing in a suppressed position might not have possessed the ability to respond to the increased light. In long-unburned stands, the red oak group might potentially be in a better competitive position than the white oak group prior to disturbance due to its ability to improve its status under limited light levels, regardless of treatment. Additional and/or more varied release treatments, such as targeted control of competing vegetation control, additional prescribed burns, and incrementally increasing BA reductions might be needed if specific management goals are to include white oak.

For the remaining species, treatment responses were largely based on shade tolerance and their interaction with treatment. In the SWB, shade-tolerant species groups decreased the most, whereas shade-intolerant species groups increased the most. We can infer that this treatment caused the most overall changes in the light environment based on measured BA reductions and shade-intolerant species proliferation. The SWB caused the greatest reductions in overall BA (–82.3%), whereas the CON experienced the least (–3.0%). Reductions in BA in the SWB were driven by overstory and midstory reductions, while the RXF and SW saw minimal overstory reductions. All midtolerant species groups, except the red oak group, responded negatively to the SWB. The CON, SW, and RXF resulted in less changes in importance value across all shade tolerance levels, although the RXF did show some evidence of promoting the red oak group, while minimizing increases in red maple and yellow-poplar relative to the SW and CON.

Conclusions. Although we observed decreased importance values and densities among some competing species in the treatments that were evaluated in this study, additional or repeated treatments will be needed to ensure oaks successfully transition into the midstory and, eventually, the overstory. Yellow-poplar and red maple competition are consistently associated with low oak regeneration success regionally and in all treatments tested in this study. Improving the status of regeneration layer oak amid competition is a long-term and intensive process. Fire alone or in combination with a shelterwood harvest appeared to benefit oak in the regeneration layer at the expense of many competitors. Oak species responded differently to treatments, and improving the competitive status of white oak could be more difficult than other oak species. Modification of the SW, RXF, or SWB could have yielded different, and potentially better, results for both the red oak and white oak group. Slight increases in BA reductions in the SW might have resulted in an improved response of the white oak group. Given that our treatments consisted of either a single prescribed burn or two prescribed burns, we have not yet emulated the fire regime consistent with these forests. Additional treatments such as prescribed fires or herbicide applications in the RXF and SWB postharvest might have improved the outcome for oak.

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