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forest management

White Oak (*Quercus alba*) Response to Thinning and Prescribed Fire in Northcentral Alabama Mixed Pine–Hardwood Forests

Callie J. Schweitzer, Daniel C. Dey, and Yong Wang

Strong white oak sawtimber markets, partially attributed to the stave and cooperage industries, are encouraging forest managers to re-examine silvicultural practices for white oak (*Quercus alba*). We examined recruitment and retention of white oak in mixed oak–pine stands on the William B. Bankhead National Forest in northcentral Alabama. Stands were subjected to three thinning levels (residual basal areas of 75 ft²/ac, 50 ft²/ac, and no thinning) and three fire frequencies (dormant season burns of none, one, three fires) in a factorial design. Both thinning treatments reduced overstory white oak tree densities, and fire had no effect on densities. For all reproduction height classes, regardless of thinning treatment, three prescribed burns increased white oak densities; thinned and burned stands had larger white oak seedling sprouts than those thinned with no burn. However, white oak reproduction height was primarily less than 2 ft tall, and seedlings larger than 4 ft tall were reduced. Thinning with one fire resulted in the highest densities of large white oak reproduction (4 ft tall up to 1.5 in. dbh). Red maple reproduction was the dominant competitor in all treatments and is positioned to dominate the reproduction cohort without additional tending treatments.

Keywords: white oak, thinning, prescribed fire, Cumberland Plateau, red maple

Oak (*Quercus* spp.) represents approximately 11 percent of the total US tree population of trees 1 in. in diameter at breast height (dbh) and greater, and white oak (*Quercus alba* L.) is 19 percent of all oak biomass, the most of any oak species (Oswalt in press). The amount of time it takes for oaks to grow from sapling size to sawtimber may be as short as 50 years or as long as 75 years or more (Luppold in press). The value in sawtimber-sized trees is not only in commodity markets but also for biological legacy benefits (providing acorns for reproduction and wildlife, for example) (McShea et al. 2007). The White Oak Initiative is an innovative effort that is seeking to encourage the management of white oak, including engaging landowners and using cost-share programs to offset management expenditures (Chappell 2018). The recent surge in production of barrels for use in the spirit markets has expanded the reach of those interested in managing for white oak, although non-American entities have been interested in white oak barrels for some time (Rous and Alderson 1983, Chatonnet and Dubourdieu 1998).

Difficulties sustaining oak in upland mixed oak–hardwood forests have been well documented throughout the eastern United States (Loftis and McGee 1993, Spetich 2004, Clark and Schweitzer in press, Johnson et al. 2019), and fire suppression has been indicated as a key factor contributing regeneration failures (Adams and Rieske 2001, Abrams 2003, Dey and Hartman 2005, Nowacki and Abrams 2008). Despite still having considerable stocking of mature oaks, and abundant small regeneration, the bottleneck is related to successful recruitment of oak advance reproduction into the overstory. The challenge exists in timing prescribed fire to meet desired goals (Arthur et al. 2012, Dey and Schweitzer 2018), as increased scrutiny is being placed on the long-term impact of fire damage on residual tree quality and its need for developing desired reproduction (oaks) (Marschall et al. 2014, Wiedenbeck and Schuler 2014). Consequently, caution on the use of fire is still reported, as there is a lack of research on helping us to understand fire injury to hardwood trees and silvicultural methods to minimize damage (Schweitzer et al. 2018).

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Additional oak management goals also include restoration of oak woodlands and savannas that once were historically prominent throughout much of the eastern deciduous forests (Noss 2013, Dey et al. 2017). Before European settlement, fires burned frequently in this region and occurred primarily in the dormant season, i.e., from fall to spring (McEwan et al. 2007, Flatley et al. 2013, Aldrich et al. 2014). After half a century or more of fire suppression, forests have become two to three times more dense than in historic times (Hanberry et al. 2014), and in some cases, the original hardwood forests have been replaced by "off-site" pine plantations. Reducing stand density, often through overstory thinning, and reintroducing fire are needed to promote native ground flora development and oak regeneration in these fire-dependent mixed oak–hardwood–pine systems.

Using fire to manipulate the understory in hardwood systems, with a goal to enhance oak recruitment into larger size classes, has been reported with disparate results (McEwan et al. 2011, Hutchinson et al. 2012, Brose et al. 2013, Arthur et al. 2015). We have reported on the initial results of the reproduction and stand dynamics in a mixed pine–hardwood forest undergoing thinning and prescribed fire treatments to drive transition toward upland hardwoods (Schweitzer et al. 2008, Schweitzer and Wang 2013, Schweitzer et al. 2016). Restoration and management of mixedwood systems, such as these, involved the planned introduction of targeted disturbances, including an initial thinning to remove pine and favor residual hardwoods, and prescribed fire. The use of fire had the dual objective in that managers wanted to restore the process of fire to these systems and use fire to manipulate the species composition in the midstory and understory. In this paper, we examine the response of white oak reproduction and midstory recruitment to thinning, prescribed fire, or their combination, and infer white oak dynamics in a mixed pine–hardwood forest under restoration management. We also examine potential issues with timber quality following treatments.

Study Site and Methods

The study was located on the William B. Bankhead National Forest (BNF) in northcentral Alabama, in the Cumberland Plateau Section of the Appalachian Plateaus physiographical province (Fenneman 1938). The study stands are more specifically characterized by the Strongly Dissected Plateau subregion of the Southern Cumberland Plateau, within the Southern Appalachian Highlands (Smalley 1979). The geology is primarily Pennsylvania Pottsville formation, with quartzose sandstone and interstratified layers of shale, siltstone, and thin discontinuous coal (Szabo et al. 1988). Past land use included cultivation, with ridgetops cutover; then several iterations of planting to loblolly pine (*Pinus taeda* L.), in the 1930s to reclaim eroded agricultural land and during the 1960–1980s for economic production (USDA Forest Service 2004). These are plateau tabletop sites with unmanaged pine plantations that have progressed to mixed hardwood–pine stands. Base age 50 site indices for loblolly pine, red oaks (northern red oak [*Q. rubra* L.], black oak [*Q. velutina* Lam.], scarlet oak [*Q. coccinea* Munchh.], southern red oak [*Q. falcata* Michx.]), and white oaks (white oak [*Q. alba* L.], chestnut oak [*Q. prinus* L.]) are 75 ft, 65 ft, and 65 ft, respectively (Smalley 1979). Initial restoration management focused on moving these stands towards upland hardwood dominance (*Quercus–Carya*) using thinning and prescribed fire (USDA Forest Service 2004).

The BNF study was a randomized complete block design with a 3 × 3 factorial treatment arrangement. A total of 36 stands were included in the study with one treatment combination replication applied to an individual stand. Stand size ranged from 22 to 46 acres with merchantable tree (>5.6 in. dbh) pretreatment basal areas ranging from 122 to 132 ft^2 per acre. Pretreatment stand basal area was dominated by loblolly pine, which accounted for 87 percent of the basal area. Three levels of thinning (residual basal area of 75 ft^2 per acre for the light thin; 50 ft^2 per acre for the heavy thin; and a no thinning control) and three fire-return intervals (no fire; infrequent fire of one fire every nine years; and frequent fire of one fire every three years) were studied. We report here on a complete cycle of treatments, with data collected on all treatments at pretreatment (T0) and again once all three fires were completed for the frequent fire treatment (T3). Thus, there were seven growing seasons from treatment initiation, allowing for implementation of one fire for the infrequent fire treatment and three fires for the frequent fire treatment. Commercial thinning was conducted by marking from below the smaller trees or trees that appeared stressed, diseased, or damaged; canopy trees were also removed to meet target residual basal areas. Target canopy removal trees were 6–12-in. dbh pine and low-quality oaks. Equipment used to harvest trees included a Hydro-Ax 511 Ex wheel-mounted feller buncher and a Timbco 415-C crawler-mounted feller buncher, with a Fabtek 546 B forwarder with a loader bucket used to move felled trees to the landing site. Thinning treatments were completed prior to the initiation of the burning treatments (thinning was conducted from June to December).

Prescribed burning was conducted during the dormant season (January through March 2006–14) using backing fires and strip head fires to ensure that only surface fire occurred. Mean ambient temperatures and relative humidity were 48.3° F and 40 percent for the first burn; 50.2° F and 50 percent for the second burn; and

Management and Policy Implications

Changes in historic disturbance regimes due to the interplay of social, cultural, economic, and environmental factors are impacting the sustainability of oak-dominated eastern forests. Our failure to regenerate upland oaks over the past 30 years has reduced ingrowth of these valuable hardwood species, including one of the most valued, white oak. A surge in industry interest in white oak, driven by the cooperage and distilling industries' reliance on white oak for barrels, is spurring us to examine our ability to successfully apply prescriptions to regenerate white oak, and subsequent impacts on residual white oak stems. Although much work has been done examining silviculture prescriptions to regenerate upland oaks, we remain stymied in our ability to do so, and less information is available concerning residual stand quality following prescribed fire. Restoration efforts, including restoring fire to these systems, have contributed to the conundrum of applying the proper prescription, and using the appropriate tools, as matched to site and management goals, and a longer-term impact of fire on tree status. We must consider the efficacy of our efforts on the totality of the systems, as management applied today impacts not only residual stem status, but also the reproduction cohort and the regeneration process, a long-term endeavor that involves establishment and recruitment.

63° F and 45 percent for the third burn, within the prescribed fire parameters for the Bankhead Ranger District (pers. commun.: Kerry Clark, Fire Management Officer, USFS, 1070 Highway 33 N, Double Springs, AL 3553). We followed Iverson et al. (2004) methods for collecting basic fire temperature data, using six to eight HOBO data recorders connected to a temperature probe (HOBO U12 Series Datalogger and HOBO TCP6-12 Probe Thermocouple Sensor, Onset Computer Corporation, Cape Cod, MA), with the temperature probe extending from the soil up to approximately 10 in. above the ground. On average, the maximum temperature was 203.9° F (standard deviation, 145.1° F) for the first burn, 253.8° F (std 130.3° F) for the second burn, and 407.1° F (std 165.4° F) for the third burn.

Prior to treatment, five 0.2-ac vegetation sampling plots were established in each stand. Plots were distributed across each stand, with one centrally located and the other four positioned to capture the range of conditions within each stand. Woody vegetation was inventoried prior to any treatment (thin or burn), and following each burn; data presented here are pretreatment (T0) and following completion of the third burn (T3). In each 0.2-ac plot, all trees ≥1.6 in. dbh were tagged, identified to species, and measured for dbh to the nearest 0.1 in. We used these data to calculate an importance value for white oak and compared those metrics to other species in the stands. Relative importance values were calculated for each tree species by summing the relative density and relative dominance, based on basal area, and dividing by 2 (Cottam and Curtis 1956, Crow et al. 2002). Bole wounds on white oak trees >5.5 in. dbh were recorded for the frequent fire treatments and the control at T0, following the thinning, and following fire; if there was any evidence of char on the bole, it was noted and measured to the nearest 0.1 in. (Keyser et al. 2018). Tree seedlings were tallied by species and size class (≤1 ft; >1 to ≤2 ft; >2 to ≤3 ft; >3 to ≤4.5 ft; and 0–1.5 in. dbh) on one 0.01-ac plot within the 0.2-ac plot. All seedlings were recorded by species and height class. For each seedling, the number of sprouts was noted; data were compiled by seedling densities, clump densities (clump defined as having two or more sprouts) and sprouts per clump densities. Seedlings were those that had only one sprout; all others were identified as seedling sprouts. Basal areas and stem densities were calculated for each treatment.

We used an analysis of variance (ANOVA) by implementing PROCMIXED in SAS 9.4 (SAS Institute Inc. 2013), specifying a random effect (block) and a repeated statement (time) with the type of covariance matrix assigned unstructured using TYPE-UN option specified as stand (treatment). The effects were then assigned between-subject degrees of freedom to provide for better small-sample approximations to the sample distributions. We used the DDFM = KENWARDROGER option to perform the degrees of freedom calculations detailed by Kenward and Roger (1997). We used ANOVA to test for differences in stem densities by size classes for overstory, midstory, and understory data among treatments (between subject factor) for pretreatment and post-treatment samples (within subject factor). We analyzed all reproduction tallies together, and then by seedlings only and by seedling sprouts only, and by their change. All analyses were conducted at a significance level of $\alpha \leq 0.05$ followed by Tukey's multiple comparison test to detect pairwise differences.

Results

Treatment Impact on White Oak Overstory and Midstory Trees

The response of stand structure and composition to the thinning, and initial sequence of prescribed fire were detailed in Schweitzer et al. (2016). In review, stands had 131.2 ft² per acre of basal area with 290 stems per acre (SPA), on average, at the beginning of the study (for stems >5.5 in. dbh). Residual basal areas and SPA following the first growing season after initial treatment sequence, thinning and one burn for all thinning and burn treatments, thinning only, or one burn only, averaged 67.9 ft² per acre and 113 SPA for the light thinning and 49.9 ft² per acre and 85 SPA for the heavy thin. At T3, stem density was lowest in stands subjected to heavy thinning–frequent fire (84 SPA) ($F_{3, 25} = 28.52$, $P \leq .001$) and highest in the unthinned stands, regardless of burn treatment, with 266 SPA in the no-fire treatment, 277 SPA in the infrequent-fire treatment, and 333 SPA in the frequent-fire treatment.

Thinning did not impact white oak densities, but relative basal area, relative densities, and importance values for white oak increased (Table 1). Across all nine treatments, for trees >5.5 in. dbh, white oak had a mean basal area of 2.0 ft² per acre and 5 SPA. White oak ranked in the top five relative importance for all treatments except the heavy thinning–frequent fire. Importance values for white oak increased in all treatments at T3 (Table 1).

Table 1. White oak overstory stems >5.5 in. diameter at breast height BA (ft²/ac), RelBA (percent), densities (SPA), and RelSPA (percent) and IV[a] at T0 (pretreatment) and T3 (post seven growing seasons).

Treatment		T0	T3	T0	T3	T0	T3	T0	T3	T0	T3
Thin[b]	Fire[c]	BA	BA	RelBA	RelBA	SPA	SPA	RelSPA	RelSPA	IV	IV
None	None	0.8	1.2	0.6	0.8	2	3	1	1	0.7	0.9
None	Infrequent	1.7	2.2	1.4	1.5	6	7	2	2	1.8	1.9
None	Frequent	3.0	3.8	2.5	2.4	5	7	2	2	2.0	2.2
Light	None	2.7	2.7	2.0	3.3	6	6	2	5	2.0	4.2
Light	Infrequent	3.6	5.1	2.6	5.6	10	11	3	9	2.9	7.1
Light	Frequent	0.1	0.2	0.6	1.1	1	1	1	2	0.8	1.6
Heavy	None	2.7	3.6	2.0	5.2	6	7	2	7	2.0	6.1
Heavy	Infrequent	2.8	2.9	2.1	4.4	7	6	2	6	2.1	5.3
Heavy	Frequent	0.8	0.6	0.6	1.0	3	1	1	1	0.7	1.2

Note: BA, basal area; IV, importance value; RelBA, relative BA; RelSPA, relative stems per acre; SPA, stems per acre; T0, time 0; T3, time 3.
[a]Calculated by summing the relative density and relative dominance (based on BAs) and dividing by 2.
[b]Light thinning residual BAs 75 ft²/ac; heavy thinning residual BAs 50 ft²/ac.
[c]Infrequent is defined as one fire; frequent is defined as three fires.

We were able to follow bole damage on these larger trees and documented charring for 78 white oaks across six treatments, ranging in dbh from 5.7 to 24.4 in. Only 16 of these trees had lower bole wounds, and none were deemed recently incurred; no new wounds were found after thinning or fire. White oaks in the frequently burned treatment did show evidence of bole char; infrequent burn treatment trees were not assessed. For the no thinning–frequent fire treatment, the number of total white oak trees with charred bark was 5 after the first burn (34 percent), 17 after the second burn (74 percent), and 20 (87 percent) after the third burn. The char heights increased with each burn, from 16.4 (std 12.6) to 33.8 (std 25.4) to 45.9 (std 24.2) in. following each burn. The light thinning–frequent fire white oak trees also experienced an increase in the number of trees charred and in char heights; from 10 (83 percent) to 5 (42 percent) to 12 (100 percent) white oaks with char, and heights increased from 7.9 (std 4.8) to 8.2 (std 4.7) to 47.7 (std 20.5) in. following burns 1, 2, and 3. The only white oak mortality was found in the heavy thinning–frequent fire treatment where one 7.1 in. dbh tree, without evidence of wounding or charring, died after the second burn. White oak trees in this treatment were all charred after each fire, and the char heights were 39.0 (std 16.0), 24.3 (std 7.8), and 26.0 (std 21.3) in. after burns 1, 2, and 3, respectively.

Midstory stems between 1.6 and 5.5 in. dbh, including white oak, were impacted most by the treatments. There was no loss of white oak stems in the >5.5 in. dbh class after the thinning-only treatment. However, within each thinning treatment, some differences were found between pretreatment densities (T0) and those at T3 for midstory stems. In the no-thin treatments, there were no significant changes in midstory white oak stem densities (Figure 1). In the light thinning treatments, midstory white oak stems were significantly lower after one (P = .011) and three (P = .048) fires than the pretreatment densities (Figure 1). All heavy thinning treatments had a significant reduction in midstory white oak; without fire, the densities declined from 18 SPA to none (P = .029), with one fire they declined from 44 to 10 SPA (P = .028), and following three fires white oak midstory stems were reduced from 36 to 6 SPA (P = .014)(Figure 1). The change in stem densities was modified by both thinning and fire (interaction P = .033), with a greater negative change in stem densities under heavy thinning with frequent fire.

White Oak Reproduction Characteristics and Treatment Response

Oak reproduction for all size classes and origins (seedling sprouts and seedlings) at pretreatment averaged 16.1 percent of all reproduction. Seven oak species were tallied in the regeneration cohort, and 33 percent of all oak were white oak, 19 percent scarlet oak, 18 percent chestnut oak, 13 percent southern red oak, 11 percent black oak, 4 percent post oak (*Q. stellata* Wang.), and 2 percent northern red oak.

All disturbance treatments (thin or fire or combination) increased the densities of the reproduction. Across all treatments, total white oak reproduction tallies ranged from 220 to 655 SPA (Figure 2), with 56.5 to 90.4 percent of these less than 2 ft tall, and 7.2 to 31.8 percent in the 0–1.5-in. dbh class. Across all height classes and including seedlings and sprouts, no differences were found for total white oak reproduction densities among treatments at T0 $F_{(8, 108)}$ = 1.30, P = .249, or at T3, $F_{(8, 108)}$ = 1.51,

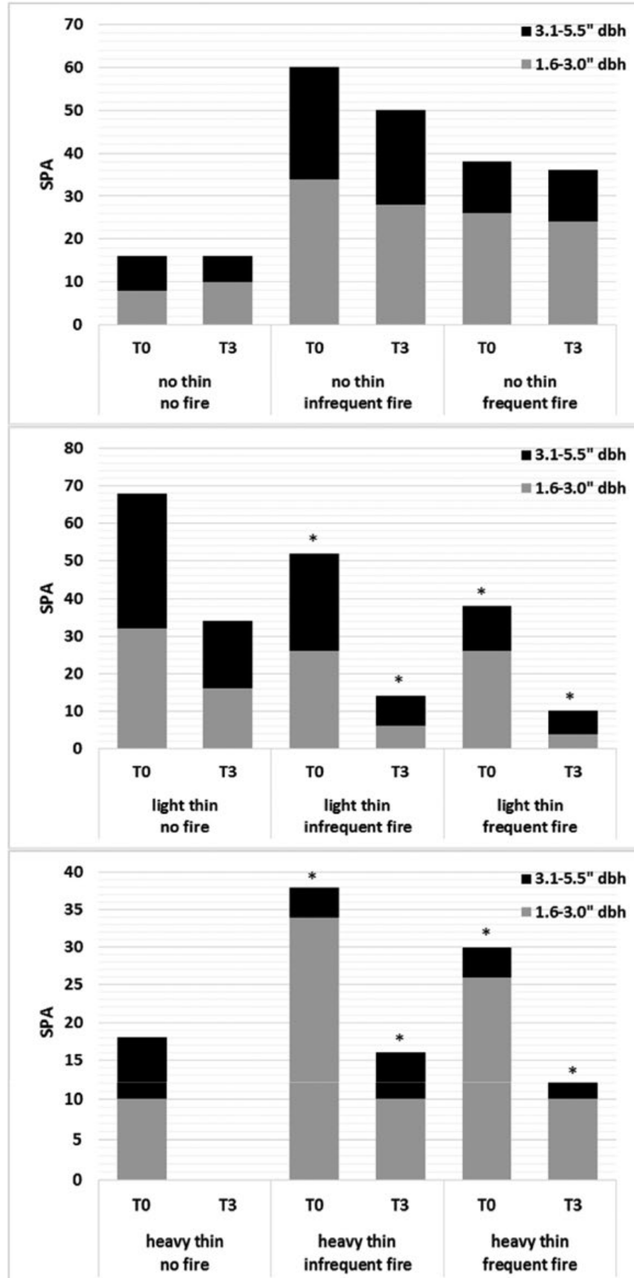

Figure 1. Midstory white oak stems per acre at pretreatment (T0) and following thinning (none, light thinning to 75 ft²/ac basal area, heavy thinning to 50 ft²/ac basal area) and prescribed fire (no fire, infrequent fire of one fire, frequent fire of three fires) and their combinations, at year 7 (T3). Bars are shaded to indicate two diameter classes, stems 1.6–3.0 in. dbh and stems 3.1–5.5 in. dbh. Significant differences at α < 0.05 for all stems 1.6–5.5 in. dbh between T0 and T3 within each thinning and fire treatment are indicated by "*."

P = .156. Within height classes at pretreatment, the only differences were found for the 2-ft class ($F_{8, 108}$ = 3.0, P = .004). This was due to a high number of pre-existing seedling-sprout clumps (100 per ac) and seedling sprouts in this height class (174 seedling sprouts per ac) in the treatment stands assigned to heavy thinning-frequent fire. The change in the densities of white oak reproduction was only different for the 0–1.5 in. dbh class, $F_{(8, 179)}$ = 7.98, P < .001, with the light thinning–no fire treatment having a greater change (increase)

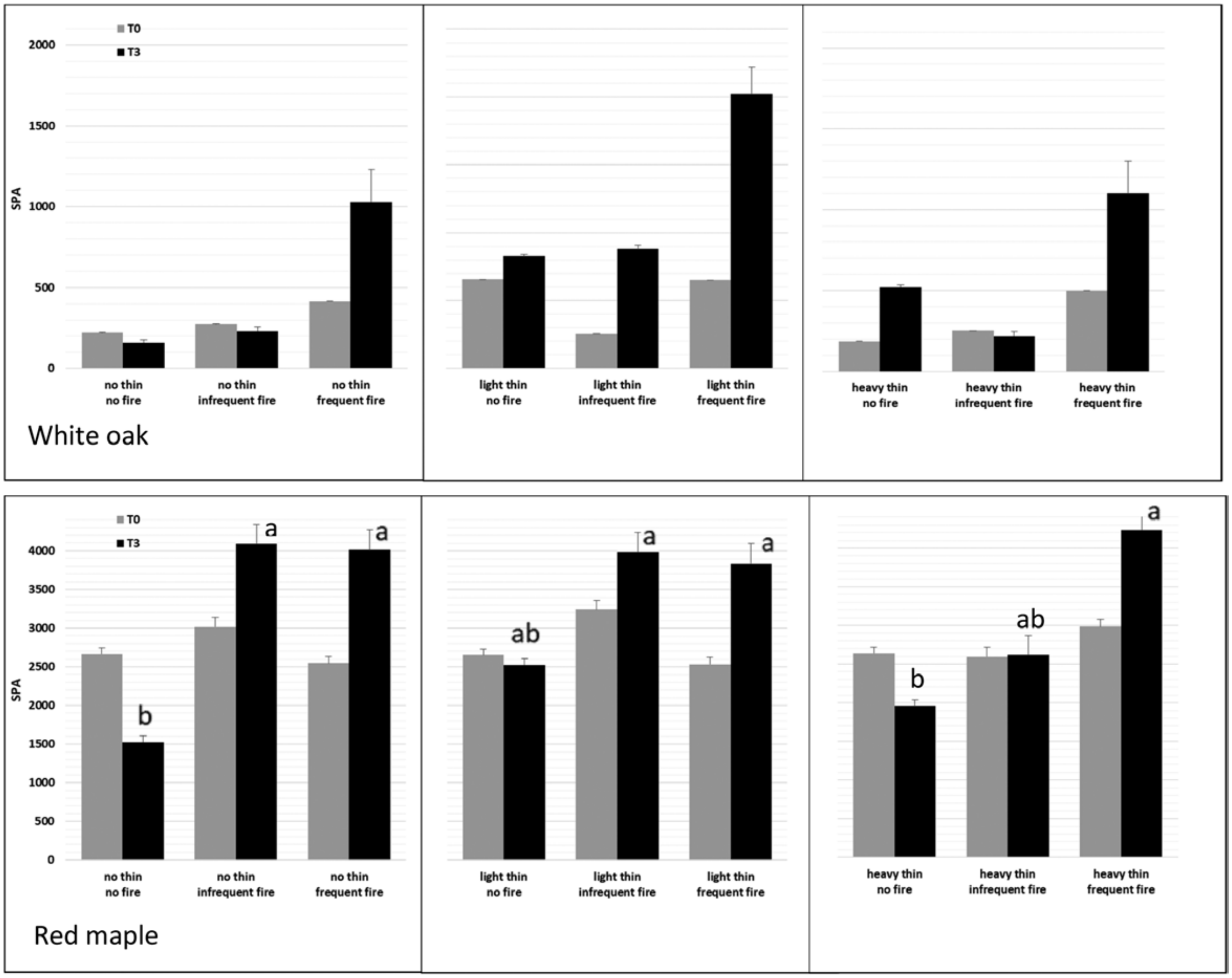

Figure 2. Stems per acre (SPA) of seedlings and seedling-sprout reproduction in all size classes from 1 ft tall up to 1.5 in. dbh for white oak (top panels) and red maple (bottom panels) at time 0 (T0 = pretreatment) and time 3 (T3 = post seven growing seasons). Letters indicate significant differences of T3 red maple reproduction among treatments at α < 0.05.

than all other treatments. Changes in red maple seedling and sprout tallies were significant for all height classes ($P < .001$), and total tallies decreased for the control, light thinning–no fire and heavy thinning–no fire treatments and increased for all other treatments (Figure 2).

The change in the number of white oak seedling-sprout clumps at T3 compared to T0 was an increase for all treatments, $F_{(8, 179)} = 2.00$; $P = .049$, with the largest increase in the light thinning–frequent fire treatment (an increase of +455 clumps per ac). On average, the change in white oak clumps was +129 per ac for the thinning treatments. Red maple sprouting clumps increased in all fire treatments, $F_{(8, 179)} = 4.72$; $P = .001$, with the heavy thinning–frequent fire treatment having a greater change than the no thinning–no fire and no thinning–infrequent fire treatments (increase from 210 to 734 clumps per ac). Across all thinning treatments, red maple clumps increased on average by +350 clumps per ac.

For white oak seedling-sprout numbers, the change over time was significantly different among treatments for the total stem counts and for the changes within stem-height classes. All treatments saw an increase in the total number of sprouts except the control. The light thinning–frequent fire treatment had a significantly greater change in total sprouts compared to all three no thinning treatments, the heavy thinning–no fire treatment, and the heavy thinning–infrequent fire treatment, $F_{(8, 179)} = 2.41$; $P = .017$ (Figure 3). The change in the number of seedling sprouts >1 ft tall to 2 ft tall was different for the light thinning–no fire (+455 per ac) and no thinning–no fire treatment (–10 per ac), $F_{(8, 179)} = 2.00$; $P = .049$. The change in sprouts in the largest size class (0–1.5 in. dbh class) was greatest for the light thinning–no fire treatment compared to all others, $F_{(8, 179)} = 5.71$; $P < .001$.

The changes in white oak seedlings by size class and by total counts were not different among treatments (Figure 3). There were, however, nominal differences as seedling densities increased for the no thinning–frequent fire, light thinning–infrequent fire, heavy thinning–no fire, and heavy thinning–frequent fire treatments, and decreased for all others. The change in red maple seedling densities was significant for all size classes, with the no thinning–infrequent fire, no thinning–frequent fire, light thinning–no fire, and heavy thinning–infrequent fire having a significantly greater change compared to all other treatments (see Schweitzer et al. 2016, Figures 2 and 3).

Discussion

Oak is a valuable resource to many industries and local and international economies, and for the sustainability of local communities

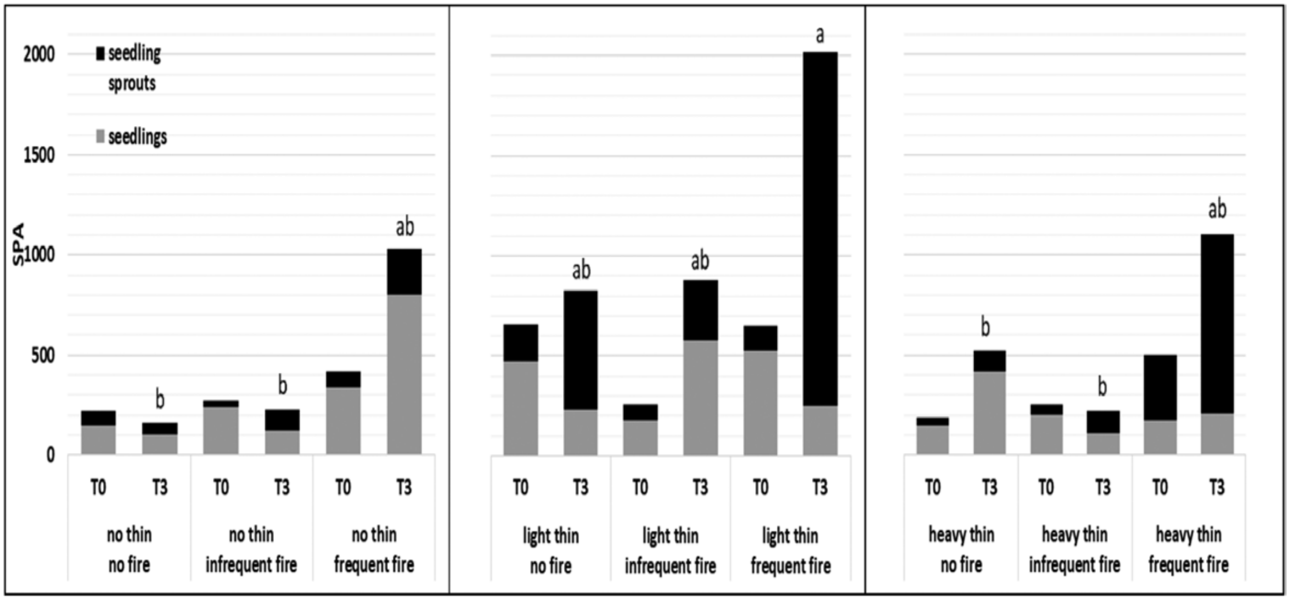

Figure 3. White oak stems per acre (SPA) of seedling sprouts and seedlings in all size classes from 1 ft tall up to 1.5 in. dbh at time 0 (T0 = pretreatment) and time 3 (T3 = post seven growing seasons). Letters indicate significant differences of T3 seedling sprouts among treatments at $\alpha < 0.05$.

(Clark and Schweitzer in press). Regeneration failures and loss of oak, including white oak, are occurring throughout eastern North America, and management strategies that include prescribed fire and thinning are being assessed as to their use in mitigating this decline. White oak remains a canopy-dominant species, and thinning accelerated its rise in importance in these mixed pine–oak stands. However, in our study, the removal of midstory white oaks with repeated fire is cause for concern; without this ascending layer, there will be a continued decline in the growing stock available as poletimber, as noted across the region by Luppold and Bumgardner (2018). The creation of midstory growing space, coupled with the removal of fire at this time, may allow for the white oak reproduction to recruit; this will only be possible if the competing red maple in the understory is arrested (Hutchinson et al. 2016).

Historically, fire and other land use practices promoted oak regeneration and dominance throughout North America. The use of fire in hardwood management raises concerns among managers over fire-caused mortality and injury that reduces timber volume, quality, and value. Past research on the effects of fire on oak forest dynamics as related to oak lumber quality focused primarily on wildfires, not prescribed fire (Hepting and Hedgcock 1935, Jemison 1946, Paulsell 1957, Carvell and Tryon 1961). Current studies have shown that the risk to tree value with prescribed fire may be offset by gains in oak-regeneration success and the production of other ecosystem goods and services (Stambaugh and Guyette 2008, Marschall et al. 2014, Wiedenbeck and Schuler 2014, Dey et al. 2017).

We used prescribed fire and overstory thinning in mixed loblolly pine–hardwood stands to increase resiliency by making stands more reflective of natural forest composition that result from historical disturbance regimes. The goal is to have resultant stands that more closely reflect natural forest composition and historical disturbance regimes. The use of prescribed fire and thinning mimics natural processes that resulted in oak dominance by favoring oak regeneration and its competitive ability over other vegetation (Abrams and Nowacki 1992, Kruger and Reich 1997). Scientists and managers aim to find the right sequences and combinations of repeated disturbances that reduce overstory density and affect competing vegetation in favor of oak. Although white oak can be more shade-tolerant than other oak species, without any disturbance white oak seedlings are decreasing in the study stands. Without fire, it has taken decades for the stands to shift in species composition, most consequentially toward higher densities of larger understory red maple. It will take more than one to three fires and 10 years to change conditions that would favor oak. Herbicide stem injection during initial thinning perhaps would be a more direct and effective method for removing the larger red maple in the understory. They, too, are prolific sprouters and can do well in the light environment of thinned stands.

We found little damage and slight mortality of the overstory oak (less than 10 percent mortality) in this study. Delayed mortality has been reported in hardwood stands subjected to fire, from 5 years following a single fire in West Virginia upland hardwoods (Wendel and Smith 1986), to continued increased mortality 30 years post summer fire in Connecticut mixed hardwoods (Ward and Stephens 1989) and 27 years post periodic burning on the Highland Rim in Tennessee (DeSelm et al. 1991). Of greater concern may be the impact these disturbances are having on tree quality. For all species, heavy thinning and frequent burning resulted in more trees with wounds (4.5 per acre) than the other treatments, but most wounds noted on white oak were not caused by the treatments under this study. Wounding and mortality were greatest for the most prevalent species, loblolly pine, and mortality in the control stands appeared to be related more to overstocking than in any of the treated stands. Fire-damaged oaks in Missouri were found to have butt-log defect in proportion to the size of the fire scar, the time since fire injury and as stem diameter decreased (Stambaugh and Guyette 2008). Others have found that value and volume loss associated with stands managed with prescribed fire are due to tree size changes and degrade and rot (Reeves and Stringer 2011, Marschall et al. 2014, Wiedenbeck and Schuler 2014).

Thinning these stands allowed white oak to assume a more important ranking in terms of density and basal area, as the calculated importance value doubled for white oak in all the thinned treatments. As there are no plans to harvest the overstory within the next 15 years, these white oak will continue to increase in size and should also continue to provide acorn crops. Similar to assessments done by Keyser et al. (2018), we noted low or no mortality of overstory white oak as related to char height. Concern over the high incidence of charring should be noted as a potential timber quality defect, especially if these trees are not removed within 15 years (Marschall et al. 2014). We do not know if the evidence of char on the outer bark of these trees is indicative of damage. However, whether char results in real or imagined degrade, timber buyers in the north Alabama area, for example, will scale logs lower if they have any evidence of fire, and some loggers have been known to cut off the lower bole of fire-scarred trees, leaving those portions at the landings (pers. commun.: Billy Rye, Forest Management Specialists, Inc., 4886 Chisholm Road, Florence, AL 35734 and Jim Jeter, retired Hardwood Specialist, Alabama Forestry Commission, 513 Madison Avenue, Montgomery, AL 36130).

Although the thinnings were not regeneration treatments, they affected oak-reproduction dynamics. Variable responses of oak reproduction to prescribed fire, thinning, and their combination may be attributed to the myriad of factors that impact reproduction responses to disturbances (McEwan et al. 2011, Hutchinson et al. 2012, Brose et al. 2013, Keyser et al. 2017). While site factors, including soil fertility and moisture, and past disturbance regimes are drivers in forest regeneration and species competitive interactions, the stands in this study had similar site characteristics, which facilitated assessing treatment effects on regeneration. Frequent fire reduces midstory white oak, whereas understory oak are top-killed by fire, but resprout and recover between fires before being top-killed again in the next fire (i.e., a seedling-sprout fire trap; Grady and Hoffman 2012). While frequent topkilling disturbance persists, seedlings and sprouts are unable to recruit and replace midstory oaks killed by successive fires, resulting in a "persistence niche" (Bond and Midgley 2001) within the "regeneration niche" (Grubb 1977). However, oak sprouts are able to build root mass in between fires if there is sufficient light, and larger root systems increase oak competitiveness and ability to recruit into the midstory during sufficiently long fire-free periods (Dillaway et al. 2007, Brose 2008). Informed management prescriptions should ensure advanced oak reproduction gains in competitive position with the use of fire and then remove fire to allow recruitment into the midstory.

Repeated prescribed burning is keeping the oaks and their most prolific competitor, red maple, in a shrub-like layer in the understory in a reproduction fire trap (Hutchinson et al. 2012, Schweitzer et al. 2016). Periodic fires during this study increased the density of all seedlings, with clumps of seedling sprouts, and larger seedling sprouts, increasing in all three thinning treatments. Under heavy thinning at time 3, without fire, the number of small sprouts (less than 1 ft tall) was low (25 SPA) and the number of seedlings high (255 SPA), whereas the response after three fires was fewer seedlings (20 SPA) and larger sprouts (275 SPA). For the largest white oak reproduction, stands that received frequent fire, regardless of thinning treatment, had the lowest densities of large white oak seedlings but the greatest densities of large red maple. Others have noted retarded height growth for white oak on multiple burn sites (Beck 1970, Arthur et al. 1998, Brose and VanLear 1998). Dey et al. (1996) reported that white oak stump sprouts had the lowest probability of surviving to age 5 compared to other upland oaks, and Brose (2008) found that white oak seedlings (from acorns) had the slowest growth for years compared to other oaks. White oak seedlings invest growth to roots, which may facilitate their enhanced ability to remain alive in the event of repeated disturbances such as repeated fires (Rebbeck et al. 2011). That oaks exhibit lower plasticity, both morphologically and physiologically, than shade-intolerant competitors (Kolb et al. 1990) may infer that the physiologic variation among white oak and red maple is sufficient, along the understory disturbance frequency gradient resulting from multiple fires, that one species is better suited to respond. Frequent disturbance, by thinning (Shifley 2004) or by fire (Abrams and Nowacki 1992), should benefit white oak over red maple. Perhaps the altered disturbance regime in these systems, which includes essentially no disturbance for over 40 years, along with the initial site conversion to pine, has resulted in species mixes and structures that are not positioned to respond to thinning and fire as in the past.

At this stage, removing fire from these systems will most likely benefit the red maple to the detriment of the white oak, and other oaks as well. An additional tending treatment, such as selectively treating the red maple with herbicide, will be required if the desired future condition of this stand is to be oak-dominated. Removing fire from these stands now, treating the competitive red maple in the understory, and removing the overstory in a timely manner are proposed as the most effective silviculture treatment to move these stands toward hardwood, and oak dominance. Harvesting sawlogs within this time frame should minimize degradation because of fire or other damage. Recruitment of the white oak into midstory and overstory positions would benefit from both tending and removal activities.

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