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RESEARCH ARTICLE

HARDWOOD-PINE MIXEDWOODS STAND DYNAMICS FOLLOWING THINNING AND PRESCRIBED BURNING

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ABSTRACT

Restoration of hardwood-pine (*Pinus* L.) mixedwoods is an important management goal in many pine plantations in the southern Cumberland Plateau in north-central Alabama, USA. Pine plantations have been relatively unmanaged since initiation, and thus include a diversity of hardwoods developing in the understory. These unmanaged pine plantations have become increasingly vulnerable to insects, and management activities were initiated to facilitate transition towards hardwood-pine mixedwoods. We evaluated a combination of thinning and prescribed fire prescriptions in a randomized complete block design with a 3 × 3 factorial treatment arrangement and four replications of each treatment. Treatments were combinations of thinning to three residual basal areas (no thin, light thin to 17.2 m^2 ha^{-1}, heavy thin to 11.5 m^2 ha^{-1}) and three prescribed burn applications (no burn, one burn to be repeated every 9 years, three burns repeated every 3 years). Burning without thinning altered stand structure by reducing overstory stem density by 15 %, whereas thinning without burn-

RESUMEN

La restauración de bosques mixtos de especies de maderas duras y pinos (*Pinus* L.) es un objetivo de manejo importante en muchas plantaciones de pino en el sur del Cumberland Plateau en el centro-norte de Alabama, EEUU. Las plantaciones de pino han estado relativamente sin manejar desde su inicio, e incluyen así una diversidad de especies de maderas duras que se desarrollan en su sotobosque. Estas plantaciones de pino sin manejo se han ido convirtiendo progresivamente en más vulnerables a insectos, por lo que fueron iniciadas actividades de manejo tendientes a facilitar la transición hacia bosques mixtos de maderas duras y pinos. Nosotros evaluamos una combinación de raleo y quemas prescriptas en un diseño en bloques completos al azar con un arreglo factorial de tratamientos de 3 × 3 y cuatro repeticiones por tratamiento. Los tratamientos fueron combinaciones de raleo que representaban tres áreas basales residuales (sin raleo, raleo leve de 17,2 m^2 ha^{-1}, raleo fuerte de 11,5 m^2 ha^{-1}) y tres aplicaciones de quemas prescriptas (sin quema, una quema repetida cada 9 años, y tres quemas repetidas cada 3 años). Las quemas sin el raleo alteraron la estructura del rodal mediante la reducción de la densidad de los fustes del dosel superior en un 15 %, mientras que el raleo sin la quema reduing reduced density by 70% and burning coupled with thinning resulted in reduced overstory trees by 72%. Frequent fire had the greatest impact on midstory structure and regeneration. Midstory stem density was reduced by 90% following thinning and burning. Oaks (*Quercus* L.) and red maple (*Acer rubrum* L.) were the most common understory species after thinning only, burning only, and thinning combined with burning. There were more oak and red maple seedling sprouts following frequent burning. Currently, >75% of red maple sprouts dominate the regeneration, compared to only 40% of the oaks. Although the treatments have accelerated the transition toward hardwood-pine mixedwoods, the fate of oak and which hardwood species will be dominant in the future remains uncertain.

jo la densidad del rodal en un 70%, y la quema junto con el raleo resultó en una reducción de árboles del dosel superior del 72%. El fuego frecuente tuvo el mayor impacto en el estrato medio de la estructura y en la regeneración del rodal. La densidad de fustes del estrato medio fue reducida en un 90% luego del raleo y la quema. Los robles (*Quercus* L.) y los arces rojos (*Acer rubrum* L.) fueron las especies más comunes en el estrato inferior después del tratamiento sólo de raleo, sólo de la quema y del raleo combinado con la quema. Más brotes de plántulas de robles y arces rojos se produjeron después de las quemas frecuentes. Actualmente, >75% de los brotes de arces rojos dominan la regeneración, comparados con solo el 40% de los robles. A pesar de que los tratamientos han acelerado la transición hacia un bosque mixto de especies de maderas duras y pinos, el porvenir como dominantes tanto de los robles como de las especies de madera dura permanece incierto.

Keywords: Alabama, Cumberland Plateau, oaks, prescribed fire, red maple, regeneration, saplings, sprouts, thinning, William B. Bankhead National Forest

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INTRODUCTION

Forests on the Cumberland Plateau in southeastern USA contain an amalgamation of species with a range of shade tolerances, regeneration mechanisms, and competitive capabilities (Hinkle *et al.* 1993). Variation in site characteristics such as elevation, soil moisture, and fertility levels create environmental gradients that add to the region's diversity in natural communities (Hinkle *et al.* 1993, Clatterbuck *et al.* 2006). Forest diversity has also been influenced by the history of land use and shifting complex major disturbances. Lands were cleared for agriculture in the 1800s, heavy timber cutting and wildfires were prominent in the early 1900s, and the demise of the American chestnut (*Castanea dentata* [Marsh.] Borkh.) occurred in the 1930s (Hart and Grissino-Mayer 2008). Beginning in the 1950s, native forests were converted to pine (*Pinus* spp. L.) plantations over large areas of the Cumberland Plateau, but many stands were left unmanaged and hardwoods reestablished among the pines, resulting in mixedwoods. Recent infestations of southern pine beetle (*Dendroctonus frontalis* Zimm.) that caused widespread decline and mortality in southern yellow pines illuminated the negative consequences of simplifying forest composition and structure across the landscape. Hence, goals and objectives to restore the currently pine-dominated forests to more closely resemble their historical composition and structure, which would diversify the forests of the Cumberland Plateau, were adopted by natural resource agencies (e.g., USDA Forest Service 2003). The potential for restoring native forests after decades of conversion to pine plantations, however, is currently unknown.

The southern Cumberland Plateau is classified as a transitional region between the *Quercus-Pinus* Forest Region to the south and the Mixed Mesophytic Forest Region to the north (Braun 1950). Species composition on a given site depends on topography (Zhang *et al.* 1999) and soil-water availability (Hinkle 1989). Ridgetop sites in this region are classified as *Quercus-Pinus*, mid-slope sites are classified as *Quercus* L., and mixed mesophytic communities occur in protected areas such as shaded coves and riparian zones (Zhang *et al.* 1999). Hinkle *et al.* (1993) identified over 30 potential canopy tree species on the Cumberland Plateau, exemplifying the high species richness characteristic of this region. Zhang *et al.* (1999) classified 14 ecological communities in the Sipsey Wilderness Area within the William B. Bankhead National Forest and found that *Quercus* was the most abundant genus and occurred in the majority of the delineated community types. Ridges and upper slope positions are often dominated by loblolly pine (*Pinus taeda* L.) and Virginia pine (*P. virginiana* Mill.), mixed with upland hardwoods. Over a distance of less than 100 m along a topographic gradient, stands may transition to support a stronger component of hardwood species (Zhang *et al.* 1999, Parker and Hart 2014). Middle and lower slope positions are characterized by mesic hardwood stands that include strong components of oak (white oak [*Quercus alba* L.], black oak [*Q. velutina* Lam.], and chestnut oak [*Q. montana* L.]), American beech (*Fagus grandifolia* Ehrh.), yellow-poplar (*Liriodendron tulipifera* L.), and bigleaf magnolia (*Magnolia macrophylla* Michx.) (Hardin and Lewis 1980, Zhang *et al.* 1999, Martin *et al.* 2009, Richards and Hart 2011, Parker and Hart 2014). This area is at the southern limit of the distribution of many hardwood species characteristic of the temperate eastern deciduous forest.

Natural disturbances on the Cumberland Plateau have included wildfires that are usually surface fires of mixed severity, diseases, insects, wind, drought, and ice that result in a range of gap sizes from single-tree to larger-scale openings (Hart *et al.* 2012). These disturbances can be classified into two groups: disturbances from below or from above, depending on which portion of the size distribution is most directly impacted (Smith *et al.* 1997). For instance, fire is generally considered a disturbance from below in the southeastern US, and its greatest effect is on seedlings, which occur within the flaming zone, and saplings, whose bark is insufficient to resist cambial death from fire. Disturbances from above (e.g., high winds), on the other hand, tend to remove the overstory and release existing regeneration from competition for sunlight. Over decades, cumulative disturbances of varying intensity, frequency, seasonality, extent, and severity defined the disturbance regime, and this in turn directs succession and future forest composition.

Silvicultural prescriptions are designed to mimic natural disturbance regimes via an array of treatments that favor regeneration and dominance of desired species, and consider initial stand conditions, site factors and the ecology of desired species. Desired species, such as the upland oaks, are preferred for their economics (timber value) and ecology (wildlife habitat value). Most tree species are adapted to a particular type of disturbance regime; for example, upland oaks are adapted to relatively frequent and mixed-severity fire regimes, while maples (less desired in these systems) can rise to dominance in disturbance regimes that result in small canopy gaps in the absence of fire (Nowacki and Abrams 2008, McEwan *et al.* 2011). Developing silvicultural prescriptions that mimic natural disturbance regimes in highly diverse forests is challenging because the preferred disturbance regime is species-dependent, and there is broad amplitude in the ecology of competing species. We lack knowledge of how different combinations of silvicultural practices to guide forest regeneration and succession affect future forest composition and productivity when combinations of the two types of disturbances (from above or below) are applied in unmanaged southern pine plantations to restore hardwood-pine mixedwoods.

The southern Cumberland Plateau and other areas of northern Alabama are dominated by oak-hickory forest types except where pines were planted for commercial purposes. A common situation in pine plantations is to have hardwoods dominant in midstory and understory canopies because overstory composition is a strong determinant of the overall plant community in this area (Zhang *et al.* 1999). Manipulating the overstory can strongly influence the character and development of the understory vegetation (Oswald and Green 1999). Thus, a major challenge in forest restoration is to direct natural stand development as the pine overstory is removed to achieve a hardwood forest with desired composition that meets management objectives. We designed several combinations of silvicultural treatments including various intensities of overstory removal by harvesting and various frequencies of prescribed burning to restore more diverse native species forests in current southern pine plantations. The unique aspect of this study is the addition of fire to timber harvesting as a secondary disturbance type to represent disturbances that affect midstory and understory structure. Fire is also used because of its perceived benefits in promoting oak regeneration and dominance (Brose and Van Lear 1998, Hutchinson *et al.* 2005, Alexander *et al.* 2008, Arthur *et al.* 2012, Hutchinson *et al.* 2012). Although little work has documented regeneration responses in mixed pine-hardwood forests managed to succeed towards hardwoods, it has been noted that competition from red maple, sassafras (*Sassafras albidum* [Nutt.] Nees.), black gum (*Nyssa sylvatica* Marsh.) and yellow-poplar is high following prescribed fire, despite the fact that prescribed burning was intended to favor oaks (Hutchinson *et al.* 2005, Albrecht and McCarthy 2006, Blankenship and Arthur 2006, Iverson *et al.* 2008). These species are abundant and often dominant in pine understories. Dormant season fires implemented with the intent to differentially impact hardwood species, such as favoring regenerating oak over red maple, may be creating a bottleneck in stand development by slowing tree recruitment into large size classes.

Sprouting of understory trees is a mode of persistence and recruitment. Persistence happens under disturbance regimes in which severity and frequency are such that they do not cause mortality or release. The resulting bank of understory sprouts may eventually recruit into larger size classes (e.g., sapling, pole, overstory) in response to release from the overstory, or they may remain trapped in the understory seedling layer by disturbances such as fire that causes death of the shoot but not the roots and protected dormant vegetative buds. We tested the impact of this "fire trap'" (Grady and Hoffmann 2012), or top-killing of trees, by examining oak and red maple sprouting dynamics following thinning and one, two, and three prescribed burns in mixed pine-hardwood forest on the William B. Bankhead National Forest, Alabama, USA. Recent reviews have illustrated the conundrum of fire in upland hardwood forests on the resulting forest structure and composition (Brose 2010, McEwan *et al.* 2011, Arthur *et al.* 2012, Brose *et al.* 2013, Guyette *et al.* 2014, Nowacki and Abrams 2015), but few studies have been conducted in stands transitioning from pine plantations to mixed upland hardwood forests. We examined how specific forest management practices, those mimicking natural disturbances from above and below, influenced stand composition and structure. We were particularly interested in how sprouting versus seedling recruitment determines species composition, with emphasis on oak recruitment and red maple competition.

METHODS

Study Area

This study was conducted on the northern third of the William B. Bankhead National Forest in Lawrence County, Alabama, USA. The 72 875 ha Bankhead National Forest lies within the Cumberland Plateau section of the Appalachian Plateaus physiographic province (Fenneman 1938) and within the Southwestern Appalachian (level III) ecoregion (Griffith *et al.* 2001). This area is described by Smalley (1979) as the Strongly Dissected Plateau subregion of the Southern Cumberland Plateau. The geology is mainly composed of the Pennsylvania Pottsville formation, which consists of a gray conglomerate, fine- to coarse-grained sandstone, and is known to contain limestone, siltstone, and shale, as well as anthracite and bituminous coal (Szabo *et al.* 1988). Soils are Typic Hapludults, consisting of moderately deep, well-drained soils weathered from sandstone with a thin strata of siltstone or shale (USDA Soil Conservation Service 1959). The broad undulating uplands in this subregion are dominated by Hartsells, Linker, Nectar, Wynnville, Albertville, and Enders soil series, and site indices (height in meters at age 50 yr) for loblolly pine and white oaks are 23 m and 20 m, respectively. Stands are on gently sloping, undulating plateau tabletops to moderately steep side slopes and ridgetops with slopes ranging from 0 % to 30 %. Elevation averages 265 m and ranges from 218 m to 316 m.

The regional climate is humid mesothermal characterized by short, mild winters and long, hot summers (Thornthwaite 1948). Average annual precipitation is approximately 145 cm yr^{-1} with monthly means of 13 cm and 11 cm for January and July, respectively (PRISM Climate Group 2013), and average annual temperature is 16ºC (January mean: 5 °C, July mean: 26 °C). The frost-free period is approximately 220 days from late March to early November (Smalley 1979).

Study Design

Treatment stands were located on upland sites currently supporting 20 yr to 50 yr old loblolly pine plantations with a pronounced hardwood component in the understory. Stands were largely unmanaged since establishment. Criteria for stand selection were based on species composition, stand size, and stand age. Stands averaged 15 ha in area with a range of 8.9 ha to 55 ha and had high tree densities (>800 stems ha^{-1} for trees ≥10.3 cm dbh). Favored hardwood species included a variety of oak and hickory (*Carya* spp. Nutt.). Prior to the initiation of any treatments, the overstory was dominated by loblolly pine (29 % of total stem density) and Virginia pine (19 % of total stem density).

The management strategies examined incorporated an adaptive approach of modest implementation changes related to the most current Bankhead National Forest Forest Health and Restoration Project (USDA Forest Service 2003). The Project specified two primary management strategies: thinning (with a target residual basal area of 11.5 m^2 ha^{-1} to 17.2 m^2 ha^{-1}) and prescribed burning (with a target return interval of 3 yr to 9 yr). Thinning targeted merchantable stems (≥15 cm dbh) of all species. We applied a randomized complete block 3 × 3 factorial experimental design with three thinning intensities, three fire frequencies, and their combinations. All treatments were replicated four times across the landscape. The three levels of thinning included no thin, light thin to a residual basal area of 17.2 m^2 ha^{-1}, and a heavy thin to a residual basal area of 11.5 m^2 ha^{-1}. The prescribed burning included three return frequencies: no burn, infrequent burn once every 9 yr, and frequent burn once every 3 yr. For this study, one cycle of burning was completed, resulting in stands that were burned once (infrequent burn) and three times (frequent burn). All thinning was completed in the growing season prior to the initial burn. Treatment details, abbreviations, and a treatment schedule are given in Tables 1 and 2.

All fires were conducted during the dormant season of January, February, or March of each year. Immediately prior to each fire, we installed 6 to 8 HOBO data recorders (HOBO U12 Series Datalogger, Onset Computer Corporation, Cape Cod, Massachusetts, USA) connected to a temperature probe (HOBO TCP6-K12 Probe Thermocouple Sensor, Onset Computer Corporation, Cape Cod, Massachusetts, USA) at each vegetation sampling plot (30 to 48 probes per stand). Installation followed Iverson *et al.* (2004), with the probes extending from the soil upward to 25 cm above the ground. Of the 48 fires in this study, we were only able to obtain fire data for 32 fires, and only for the frequently burned treatments. Ignitions used hand strip firing at approximately 8 m intervals plus aerial ignition for six fires; all others were ignited by hand strip firing. All study burns were included as part of a larger target burn area on the Bank-

Table 1. Treatment abbreviations and descriptions for the thinning and prescribed burning study, William B. Bankhead National Forest, Alabama, USA. Thinning treatments are represented by 0, light, or heavy; prescribed fire frequencies are represented by 0Rx, 1Rx, or 3Rx.

Treatment abbreviation	Thinning target basal area (m^2 ha^{-1})	Fire return interval (yr)	Burns to date (*n*)
0/0Rx	No thin	0	0
0/1Rx	No thin	9	1
0/3Rx	No thin	3	3
Light/0Rx	17.2	0	0
Light/1Rx	17.2	9	1
Light/3Rx	17.2	3	3
Heavy/0Rx	11.5	0	0
Heavy/1Rx	11.5	9	1
Heavy/3Rx	11.5	3	3

Table 2. Schedule for thinning and prescribed burn treatments, William B. Bankhead National Forest, Alabama, USA. Each block contained 9 treatments as detailed in Table 1.

Block	Pre-treatment data collection time 0 (T0)	Thin	Burn 1 for frequent (3Rx) and infrequent (1Rx) treatments time 1 (T1)	Burn 2 for frequent (3Rx) treatments time 2 (T2)	Burn 3 for frequent (3Rx) treatments time 3 (T3)
Block 1	2004	2005	2006	2009	2012
Block 2	2005	2006	2007	2010	2013
Block 3	2005	2006	2007	2010	2013
Block 4	2006	2007	2008	2011	2014

head National Forest, and burn areas ranged from 61 ha to 1200 ha. Absolute maximum temperatures measured at 25 cm above ground surface ranged from 43.1 °C (27 Jan 2007) to 301.9 °C (16 Mar 2013). On average, the maximum temperature was 95.5 °C (SD 62.8 °C) for the first burn, 123.2 °C (SD 54.6 °C) for the second burn, and 208.4 °C (SD 74.1 °C) for the third burn.

Sampling

Prior to treatment, five 0.01 ha vegetation sampling plots (5.6 m radius circular plots) were established in each stand. These plots were distributed across each stand, with one centrally located and the other four positioned to capture the range of conditions within each stand by essentially arranging them in four cardinal directions from the center plot and equal distance from the center plot and stand boundary. Woody vegetation was inventoried prior to treatment (thin or burn, hereafter time = 0), and then following treatments. The next sampling period followed the thinning and first burn (hereafter time = 1, one growing season after pre-treatment), the next sampling period followed the second burn (hereafter time = 2, four growing seasons after pre-treatment), and the final sampling period followed the third burn (hereafter time = 3, seven growing seasons after pre-treatment). In each 0.01 ha plot, all trees ≥3.8 cm at dbh were tagged, identified to species, and measured for dbh. Importance values were calculated for each species by summing the relative density and relative dominance (based on basal area) and dividing by two, and then ranked. Tree seedlings (≤3.8 cm dbh) were tallied on a 0.004 ha plot within the 0.01 ha plot by 30.5 cm height size classes (starting with stems 0 cm to 30.5 cm) up to 3.8 cm dbh. If the seedling had more than one stem, it was considered a sprout; for each of these, the number of sprouts in each genet was counted; data were compiled by seedling densities, sprout densities (number of stems per genet), and total tallies (seedlings and sprouts combined). Basal areas for stems ≥3.8 cm dbh and stem densities for overstory trees (≥10.3 cm dbh), midstory trees (5.3 cm to 10.2 cm dbh), saplings (3.8 cm to 5.2 cm dbh), and seedlings were calculated for each treatment.

Data Analysis

Correlation analysis revealed that the relationship among dependent variables was not consistent among measurement periods. Therefore, the errors were not assumed to be uncorrelated, yet those correlations were unstructured. The observations were not independent due to the repeated measures on each, which necessitated fitting the means with covariances. In this case, we used an analysis of variance (ANOVA) by implementing PROC MIXED in SAS 9.0 (SAS Institute, Cary, North Carolina, USA), specifying a random effect (block) and a repeated statement (time) with the type of covariance matrix assigned unstructured by TYPE=UN option specified as stand (treat). The effects were then assigned the between-subject degrees of freedom to provide for better small-sample approximations to the sample distributions. We used DDFM=KENWARDROGER option to perform the degrees of freedom calculations detailed by Kenward and Roger (1997). According to Kenward and Roger (1997), this degrees of freedom approximation involves inflating the estimated variance-covariance matrix of the fixed and random effects so that the Type I error for testing the hypothesis is controlled at the desired rate (e.g., $\alpha < 0.05$). Least-square means of the treatment combinations were specified with LSMEANS and differences between least-squares means were tested using Tukey's multiple comparison test. Convergence criteria were met for each ANOVA.

We used ANOVA to test for differences in overstory basal areas and densities, seedling densities, and sprout densities among pre- and post-treatment samples (within subject factor) and among the treatments (between subject factor) and their interactions. All analyses were conducted at a significance level of $\alpha \leq 0.05$ followed by Tukey's multiple comparison test to detect pair-wise differences.

RESULTS

Overstory, Midstory, and Saplings Species Composition and Structure

Prior to treatment across all 36 stands, tree species richness (stems ≥3.5 cm dbh) ranged from 19 to 26 species. Stands were overwhelmingly dominated by loblolly and Virginia pines. Loblolly pine was the most important species for all nine treatments at initiation of the study, and this species retained that status throughout the study. Virginia pine was ranked second or third for all stands at time 0 and retained that ranking for the control treatments, but fell out of the ten most important species in the light thin and heavy thin, across all burning treatments. Other important species in the overstory and midstory at time 0 and then at time 3 included red maple, yellow-poplar, black cherry, white oak, chestnut oak, black oak, flowering dogwood (*Cornus florida* L.), and bigleaf magnolia.

Thinning immediately reduced stem density and basal area, and burn impacts were most pronounced after three burns. There were significant interactions between time and treatment for basal area ($F_{24, 42} = 10.56$, $P \leq 0.001$) and tree density ($F_{24, 42} = 7.42$, $P \leq 0.001$). For all thinned treatments, basal area and stem densities for all species were lower at times 1, 2, and 3 compared to time 0 ($F_{3, 25} = 158.18$, $P \leq 0.001$), and there were no differences, within each thinned treatment, between values at times 1, 2, and 3 (Tables 3 and 4). Residual basal areas at time 1 averaged 18.3 m^2 ha^{-1} for the light thin and 14.0 m^2 ha^{-1} for the heavy thin; these values included 2.7 m^2 ha^{-1} and 2.5 m^2 ha^{-1} of midstory non-merchantable stems between 3.8 cm and 14 cm dbh. Both thinning treatments similarly reduced stem densities at times 1 and 2 compared to the no thin treatment (time 1: $F_{3, 25} = 49.08$, $P < 0.001$; time 2: $F_{3, 25} = 53.12$, $P \leq 0.001$), and there was no ef-

Table 3. Basal area (m^2 ha^{-1}) for all stems 3.8 cm dbh and greater under three thinning (0 = no thinning, light = residual basal area 17.2 m^2 ha^{-1}, and heavy = residual basal area 11.5 m^2 ha^{-1}) and three prescribed burning regimes (0Rx = no fire, 1Rx = 1 fire in 7 years, 3Rx = 3 fires in 7 years) on the William B. Bankhead National Forest, Alabama, USA. Time 0 reflects pre-treatment, Time 1 is post thin and post first burn, Time 2 is post second burn, Time 3 is post third burn. Different letters within a column indicate significant difference at $\alpha < 0.05$.

	Time 0		**Time1**		**Time 2**		**Time 3**	
Treatment	**m^2 ha^{-1}**	**SE**	**m^2 ha^{-1}**	**SE**	**m^2 ha^{-1}**	**SE**	**m^2 ha^{-1}**	**SE**
0/0Rx	32.9b	7.5	34.3a	7.8	36.8a	9.5	35.4a	6.9
0/1Rx	37.2ab	11.0	37.9a	11.8	38.9a	12.0	38.8a	13.1
0/3Rx	36.7ab	9.7	38.8a	9.6	40.9a	9.8	41.0a	11.2
Light/0Rx	38.5ab	10.0	20.5b	7.2	23.2b	7.7	25.6b	8.4
Light/1Rx	43.2a	12.2	18.2bc	10.1	20.2bc	10.5	20.9bc	9.3
Light/3Rx	37.2ab	9.2	16.4bc	7.0	18.6bc	7.9	19.6bc	8.4
Heavy/0Rx	39.1ab	10.3	12.5c	5.5	14.3c	6.9	16.4c	7.7
Heavy/1Rx	39.0ab	7.0	14.6c	7.6	16.3c	8.3	18.4c	9.4
Heavy/3Rx	37.7ab	11.5	14.9bc	5.1	17.3bc	5.1	17.7c	7.1

Table 4. Stem densities ha^{-1} for all stems ≥3.8 cm dbh under three thinning (0 = no thinning, light = residual basal area 17.2 m^2 ha^{-1}, and heavy = residual basal area 11.5 m^2 ha^{-1}) and three prescribed burning regimes (0Rx = no fire, 1Rx = 1 fire in 7 yr, 3Rx = 3 fires in 7 yr) on the William B. Bankhead National Forest, Alabama, USA. Time 0 reflects pre-treatment, Time 1 is post thin and post first burn, Time 2 is post second burn, Time 3 is post third burn. Different letters within a column indicate significant difference at $\alpha < 0.05$.

	Time 0		**Time1**		**Time 2**		**Time 3**	
Treatment	**ha^{-1}**	**SE**	**ha^{-1}**	**SE**	**ha^{-1}**	**SE**	**ha^{-1}**	**SE**
0/0Rx	1754bc	672	1814b	704	1809b	586	1705ab	514
0/1Rx	2199ab	467	2130a	482	1868b	361	1527b	314
0/3Rx	2412b	754	2372a	736	2179a	736	1918a	761
Light/0Rx	1542c	702	593c	373	652c	329	865c	339
Light/1Rx	2209ab	954	751c	600	583c	440	766cd	408
Light/3Rx	2036ab	465	588c	363	608c	319	558de	311
Heavy/0Rx	1888bc	712	400c	225	484c	264	722c	363
Heavy/1Rx	1977abc	605	583c	541	514c	442	914c	544
Heavy/3Rx	1754bc	494	445c	225	405c	230	415e	255

fect from burning until time 3. At time 3, stem density was lowest in stands that received either a light thin or heavy thin and frequent prescribed fire (time 3: $F_{3,\,25} = 28.52$, $P \leq 0.001$). With no thinning, after one or three burns, stem densities did not differ from those of the unthinned, unburned stands.

Densities of trees in the largest size class (≥10.3 cm dbh) were reduced for the light thin and heavy thin treatments compared to the control; prescribed fire had no impact on these densities as the no thin stands had greater densities at times 1, 2, and 3 compared to the light thin or heavy thin treatments (time 1: $F_{3,\,25} = 40.03$, $P =< 0.001$; time 2: $F_{3,\,25} = 40.30$, $P < 0.001$; time 3: $F_{3,\,25} = 40.47$, $P < 0.001$; Table 5). For red maple, thin treatment, burning, and time did not change large stem densities (among times: $F_{3,\,25} = 4.40$, $P = 0.013$; among treatments: $F_{8,\,25} = 1.16$, $P = 0.361$; Figure 1). For oaks, there were no significant differences among treatments, but oak stem densities did decline among times within treatments ($F_{3,\,26} = 10.38$, $P \leq 0.001$; Figure 1). This change followed the thinning treatments, in which oak stems were reduced. Prescribed fire had no impact on large oak stem densities.

Midstory stem densities (5.3 cm to 10.2 cm dbh) were affected by both treatment and time (treatment: $F_{8,\,27} = 8.94$, $P \leq 0.001$; time: $F_{3,\,25} = 44.23$, $P \leq 0.001$; treatment*time interaction: $F_{24,\,42} = 2.94$, $P \leq 0.001$; Table 5). For all species, stem densities at times 1, 2, and 3 were reduced for the thin, and the thin and burn treatments, compared to the no thin, and the no thin and burn treatments. For each treatment, midstory densities were greater at time 0 compared to times 1, 2, and 3. Red maple midstory densities differed among time and treatment (treatment*time: $F_{24,\,42} = 3.00$, $P \leq 0.001$). Red maple midstory densities were reduced under all treatments except the control, in which midstory red maple stems increased by 109 ha^{-1} over 7 years (Figure 1). Both light and heavy thinning impacted red maple stems, resulting in a 54 ha^{-1} and 119 ha^{-1} decline for both, respectively, over 7 years, resulting in a final density for light thin at 74 ha^{-1} and heavy thin at 69 ha^{-1}. Under both light thin and heavy thin, the addition of fires re-

Table 5. Stem density ha^{-1} for stems of all species by three size classes for all trees ≥3.8 cm dbh under three thinning (0 = no thinning, light = residual basal area 17.2 $\text{m}^2\ \text{ha}^{-1}$, and heavy = residual basal area 11.5 $\text{m}^2\ \text{ha}^{-1}$) and three prescribed burning regimes (0Rx = no fire, 1Rx = 1 fire in 7 yr, 3Rx = 3 fires in 7 yr) on the William B. Bankhead National Forest, Alabama, USA. Time 0 reflects pre-treatment, Time 1 is post thin and post first burn, Time 2 is post second burn, Time 3 is post third burn.

Treatment	Dbh size class (cm)	Time 0	Time 1	Time 2	Time 3	T3 to T0 change (%)
0/0Rx	3.8 to 5.2	336	257	173	128	–61.8
	5.3 to 10.2	524	504	405	311	–40.6
	≥10.3	865	865	830	776	–10.3
0/1Rx	3.8 to 5.2	351	292	193	89	–74.6
	5.3 to 10.2	781	751	603	410	–47.5
	≥10.3	1043	988	914	840	–19.3
0/3Rx	3.8 to 5.2	405	336	232	143	–64.6
	5.3 to 10.2	791	751	642	489	–38.1
	≥10.3	1181	1161	1102	1058	–10.5
Light/0Rx	3.8 to 5.2	217	74	40	15	–93.2
	5.3 to 10.2	430	143	99	79	–81.6
	≥10.3	885	346	336	326	–63.1
Light/1Rx	3.8 to 5.2	331	84	40	20	–94.0
	5.3 to 10.2	776	237	99	40	–94.9
	≥10.3	1053	361	331	301	–71.4
Light/3Rx	3.8 to 5.2	400	69	49	35	–91.4
	5.3 to 10.2	667	193	133	94	–85.9
	≥10.3	959	311	301	292	–69.6
Heavy/0Rx	3.8 to 5.2	247	35	15	10	–96.0
	5.3 to 10.2	593	104	59	49	–91.7
	≥10.3	1043	247	237	237	–77.3
Heavy/1Rx	3.8 to 5.2	272	89	5	0	–100.0
	5.3 to 10.2	682	213	133	99	–85.5
	≥10.3	998	242	232	222	–77.7
Heavy/3Rx	3.8 to 5.2	262	44	20	15	–94.3
	5.3 to 10.2	514	104	44	35	–93.3
	≥10.3	964	287	282	262	–72.8

duced red maple: one fire reduced midstory red maple on average 185 ha^{-1}, while three fires reduced densities by 101 ha^{-1} (Figure 1). Under the most intense disturbance regime (heavy thin with three prescribed fires), midstory red maple was reduced from 109 ha^{-1} to only 5 ha^{-1}. Midstory oak declined in all treatments over time (treatment*time: $F_{24,\,44} = 1.53$, $P = 0.11$; time: $F_{3,\,26} = 16.42$, $P \leq 0.001$). Under the light thin and heavy thin combined with three burns treatments, midstory oak were reduced by 74 % and 87 % (197 ha^{-1} and 104 ha^{-1}), similar to the reduction of 83 % and 73 % (173 ha^{-1} and 98 ha^{-1}) in the Light/1Rx and Heavy/1Rx treatments. Residual midstory oaks averaged 36 ha^{-1} for the thin-burn treatment at year seven, while midstory red maple averaged 26 ha^{-1} under the same treatment.

Saplings (3.8 cm to 5.2 cm dbh) were also impacted by the treatments and time (treatment*time: $F_{24,\,42} = 1.75$, $P = 0.05$; Table 5). At times 1 and 2, no thin treatments had higher stem densities than light thin or heavy thin, across all burn treatments. At time 3, sapling

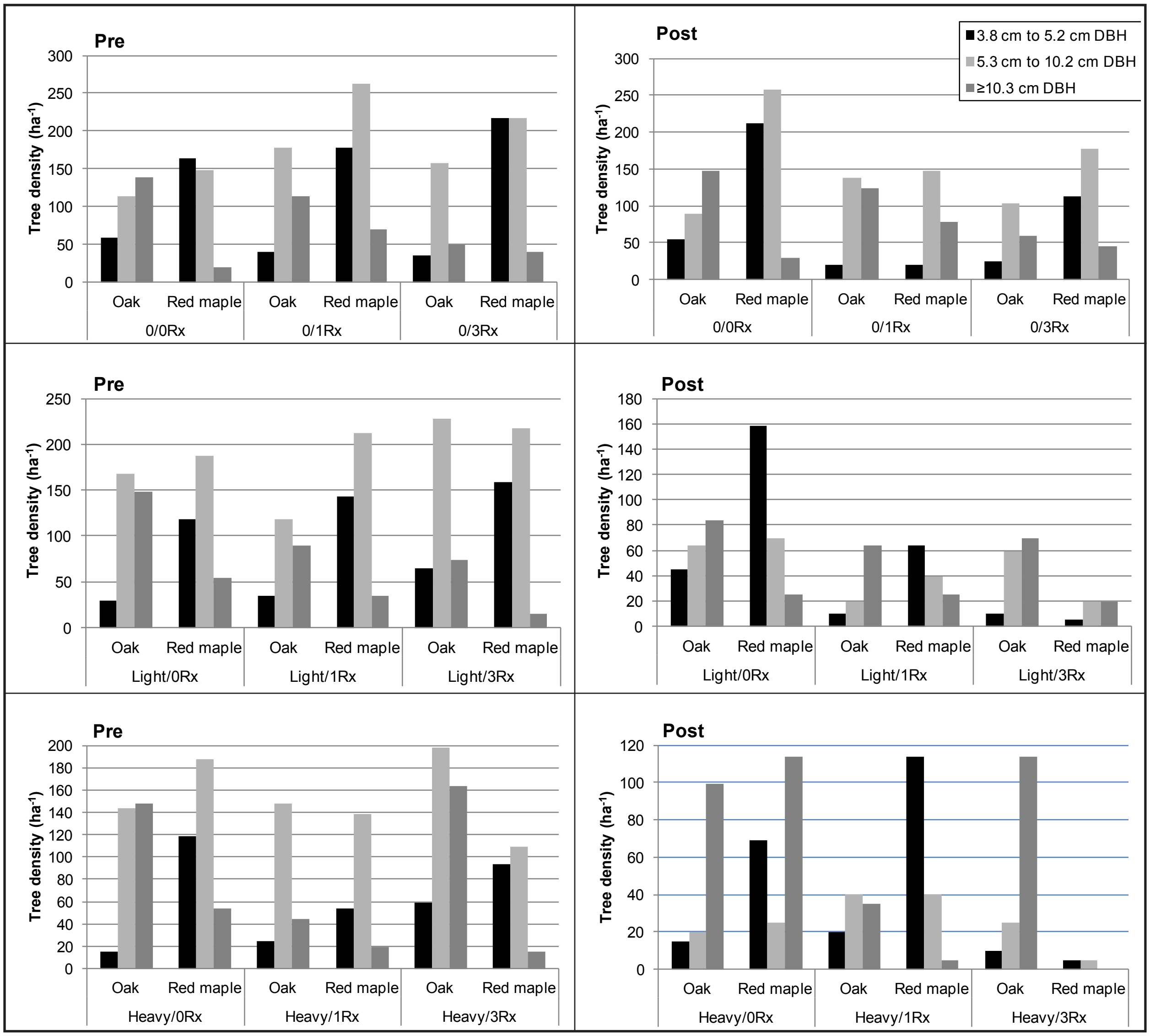

Figure 1. Red maple and oak species stem density ha-1 in three diameter size classes, for pre-treatment (Pre) and post-treatment (Post) distributions (post treatment is 7 growing seasons after treatment), by thinning (0 = no thin, light = thin residual goal of 17.2 m^2 ha^{-1}, heavy = thin residual goal of 11.5 m^2 ha^{-1}) and burning (0Rx = no fire, 1Rx = infrequent burn of one fire in nine years, 3Rx = frequent fire of three fires in nine years) on the William B. Bankhead National Forest, Alabama, USA.

stem densities followed the same pattern, except the light thin and three burn treatment was not different than the no thin no burn treatment. Red maple saplings were reduced after thinning and burning compared to no thin and no thin with burning ($F_{8, 22}$ = 3.80, P =0.006; Figure 1). After seven years and additional burns for the frequently burned treatments, red maple densities in the control differed from all other treatments except the Heavy/0Rx treatment. The Light/3Rx and Heavy/3Rx treatments saw a reduction of red maple saplings to 5 ha^{-1} (reductions of 153 ha^{-1} and 89 ha^{-1}, respectively), differing from the Heavy/0Rx (residual 39 ha^{-1}, 33 % increase) and Heavy/1Rx (residual 114 ha^{-1}, an increase of 111 % ha^{-1}), and the 0/0Rx treatment (residual 213 ha^{-1}, increase of 31 %) and three burns (residual 114 ha^{-1}, 48 % decrease) (Table 5). Oak saplings did not have a treatment by time interaction ($F_{24,\ 44}$ = 1.11, P =0.3712; Figure 1). Oak saplings increased only in the Light/0Rx treatment (from 30 ha^{-1} to 44 ha^{-1}). In the light and heavy thinning with frequent burns treatments, oak saplings were reduced by 54 ha^{-1} and 49 ha^{-1}, to a residual of 10 ha^{-1} for each thin treatment.

Regeneration Cohort

Prior to treatment, regeneration (≤3.8 cm dbh) originating from seed and sprout origin was comprised of 45 woody species. The majority of these stems were oaks and red maple, with a range of 47 % to 65 % of the regeneration tallied, respectively. Other prominent species included black gum (8 %), *Vaccinium* spp. L. (7 %), hickories (6 %), and maple-leaf viburnum (*Viburnum acerifolium* L.; 5 %). The seven oak species tallied in the pre-treatment regeneration cohort were combined for this analysis. Total oak regeneration included white oak (33 %), scarlet oak (*Q. coccinea* Muench.; 19 %), chestnut oak (18 %), southern red oak (*Q. falcata* Michx.; 13 %), black oak (11 %), post oak (*Q. stellata* Wang.; 4 %), and northern red oak (*Q. rubra* L.; 2 %). To facilitate reporting of these data, we detailed treatment and time responses by each thin treatment (none, light, heavy), by all species, all oaks, and red maple, the primary competitive species to oak.

In the no thin treatments, seedling and sprout tallies combined differed at time 2 (post second fire for the frequently burned treatment; treatment*time: $F_{24,\ 98}$ = 2.69, $P \leq 0.001$; time: $F_{3,\ 56}$ = 42.26, $P \leq 0.001$) for all species, with the no burn treatment having the lowest total densities (19 904 ha^{-1}), followed by one burn (57 341 ha^{-1}) then two burns (37 992 ha^{-1}). There were more seedlings in the one burn only compared to the no burn or two burns, but more sprouts in the two burns. After the third burn, seedling and sprout tallies combined were highest in the three burn treatment (33 594 ha^{-1}), with the next highest in the one burn (23 784 ha^{-1}) and the third highest in the no burn (13 949 ha^{-1}). Both seedling densities ($F_{8,\ 108}$ = 3.03, P =0.004) and sprout densities ($F_{8,\ 27}$ = 10.26, $P \leq 0.001$) were greatest in the three burn no thin treatment. Oak regeneration did not differ among these burn regimes after one or two burns, for all regeneration sources (seedlings, sprouts, all tallies). After the third burn, total oak stem, seedling, and sprout tallies combined did not differ, but there were more oak sprouts (2916 ha^{-1}) under the frequent burn compared to one burn (778 ha^{-1}) and no burns (1137 ha^{-1}; $F_{8,\ 108}$ = 26.48, $P \leq$ 0.001; Figure 2). In the no thin frequent burn treatment, 94 % of the oak sprouts were less than 61 cm tall. Red maple seedling and sprout tallies combined and seedlings did not differ compared to pre-burn densities following one burn, but the number of red maple sprouts increased following the initial burn (4176 ha^{-1}) compared to the densities pre-burn (717 ha^{-1}; $F_{3,\ 43}$ = 28.09, $P \leq 0.001$; Figure 2). After the third burn, red maple seedling and sprout tallies combined (9909 ha^{-1}) did not differ from those after one burn (10 107 ha^{-1}), but both differed from the no burn treatment (3768 ha^{-1}). At time 3, the density of red maple sprouts was greatest at 5436 sprouts ha^{-1}in the frequent burn compared to 2113 sprouts ha^{-1} after one burn and only 593 sprouts ha^{-1} with no burns. Eighty-three percent of red maple in the no thin frequent burn treatment was greater than 61 cm tall.

Light thinning alone did not change seedling and sprout stem densities combined, but densities increased after one burn in the light thin stands (time 3) to 25 477 ha^{-1} compared to 15 444 ha^{-1} at time 0 and after three burns, 30 728 ha^{-1} at time 3 compared to 16 964 ha^{-1} at time 0 ($F_{8,\ 108}$ = 5.44, $P \leq 0.001$). Total sprouts were higher in the frequently burned treatment (19 657 ha^{-1}) compared to no burn (7042 ha^{-1}) and one burn (9316 ha^{-1}; $F_{8,\ 27}$ = 10.36, $P \leq$ 0.001). In the light thin treatment, oak seed-

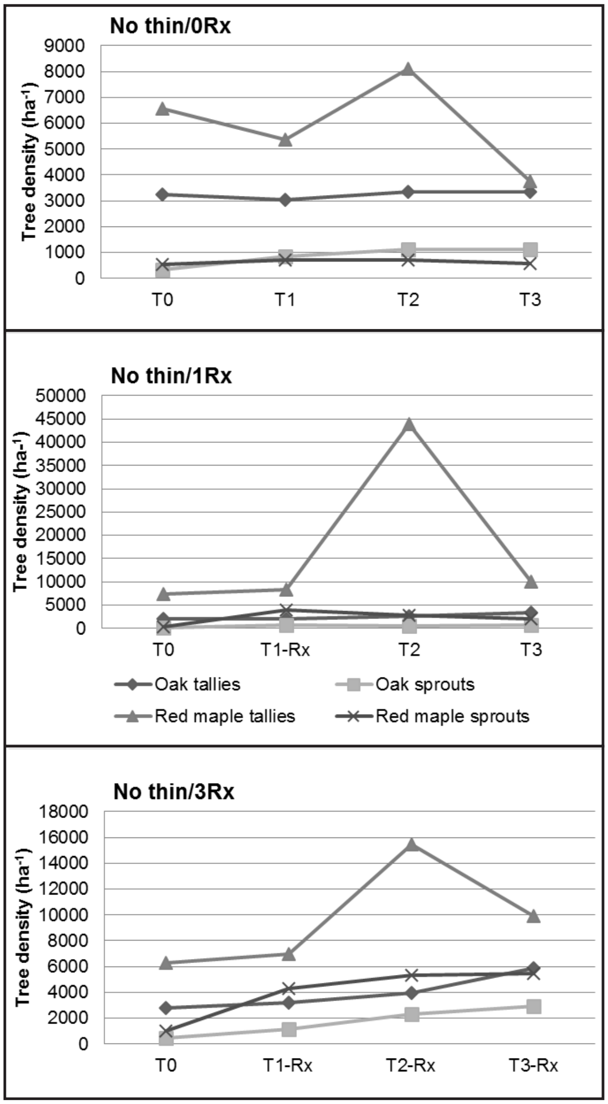

Figure 2. Red maple and oak species regeneration stem density ha^{-1} for all stems up to 3.8 cm diameter at breast height under no thinning prescriptions at four times (T0 = pre-treatment; T1 = one growing season post treatment, burn or no treatment; T2 = four growing seasons post T0; T3= seven growing seasons post T0) on the William B. Bankhead National Forest, Alabama, USA. Prescribed fire indicated by Rx next to time.

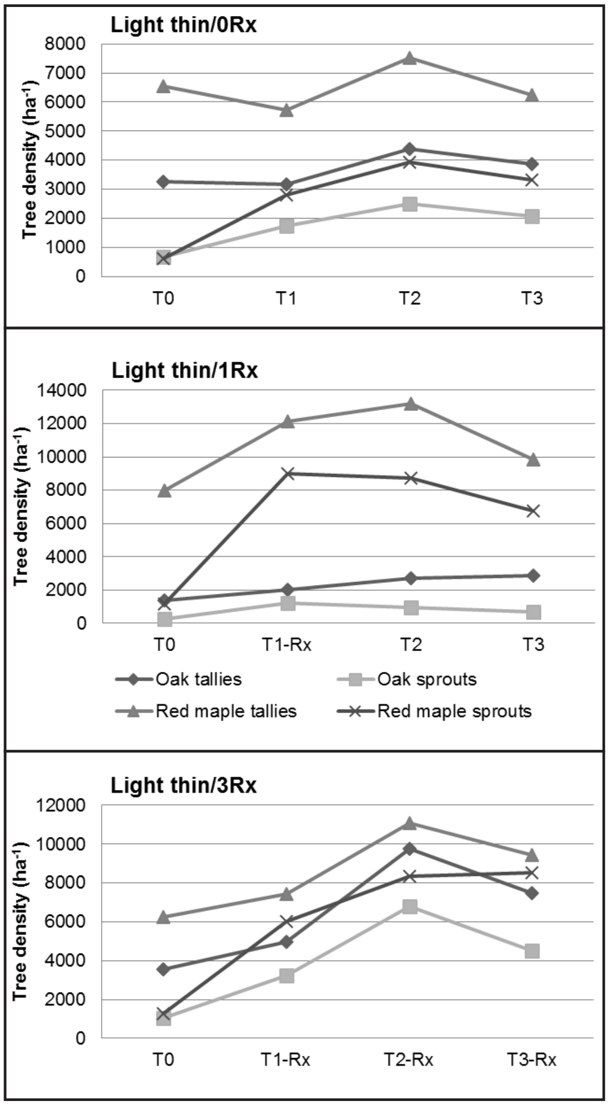

Figure 3. Red maple and oak species regeneration stem density ha^{-1} for all stems up to 3.8 cm diameter at breast height under light thinning prescriptions (thin residual goal of 17.2 m^2 ha^{-1}) at four times (T0 = pre-treatment; T1 = one year post treatment, thin, burn, thin and burn; T2 = four growing seasons post T0; T3 = seven growing seasons post T0) on the William B. Bankhead National Forest, Alabama, USA. Prescribed fire indicated by Rx next to time.

ling and sprout tallies combined and seedlings did not differ within treatment over time, or at any given time among the three burn regimes (Figure 3). After the third burn, there were more total sprouts in the frequently burned treatment (4497 ha^{-1}) and no burn (2063 ha^{-1}) compared to the one burn (704 ha^{-1}; $F_{8,\,108}$ = 26.48, $P \leq 0.001$). Oak sprouts in the no burn and infrequent burn treatments were larger, with 70% and 67% in the largest size class; for the frequently burned oak sprouts, the majority (73 %) was less than 61 cm tall. Red maple seedling and sprout tallies combined did not change among times within each light thin treatment. At time 3, red maple seedling and sprout tallies combined and seedlings did not differ among burn regimes, and there were more red maple sprouts in the infrequent (6758 ha^{-1}) and frequent burns (5813 ha^{-1}) compared to the light thin no burn (3324 ha^{-1}; $F_{8,\,27}$ = 3.83, P =0.004; Figure 3). Red maple sprouts in the no and infrequent burns primarily occurred in the largest size class, 94 % and 97 %, respectively; 70 % of the red maple sprouts in the light thin and frequent burn treatment was greater than 91.4 cm tall.

Under heavy thinning, only the frequently burned treatment had a significant time response at each time, with more total seedling and sprout tallies combined after two (46 295 ha^{-1}) and three burns (39 314 ha^{-1}) compared to those after one burn (28 565 ha^{-1}) and pre-treatment (20 114 ha^{-1}; $F_{3,\,56}$ = 42.26, $P \leq 0.001$). At times 1, 2, and 3, sprouts were greater with multiple frequent burns compared to one or no burns ($F_{3,\,25}$ = 118.53, $P \leq 0.001$). For example, at time 3, the frequently burned treatments had 26 033 ha^{-1} seedlings and sprouts compared to 5399 ha^{-1} for the other two burn frequency treatments. Oak seedling and sprout tallies combined and seedlings did not change across time within a given burn treatment; the number of sprouts were greater at time 3 (6746 ha^{-1}) compared to pre-treatment (2731 ha^{-1}; $F_{3,\,25}$ = 20.49, $P \leq 0.001$; Figure 4). Oak seedling and sprout tallies combined ($F_{8,\,108}$ = 10.24, $P \leq 0.001$) and sprouts ($F_{8,\,108}$ = 26.48, $P \leq 0.001$) were greatest for the frequently burned treatment at all four times compared to no burn and one burn. However, in the heavy thin frequently burned treatment, 73 % of the oak sprouts were less than 61 cm tall, and only 2 % were in the largest, most competitive size class. Red maple seedling and sprout tallies combined did not differ over time within a burn treatment under heavy thinning. After three burns, there were more red maple seedling and sprouts tallies combined (10 453 ha^{-1}) ($F_{8,\,108}$ = 2.42, P =0.019) and sprouts (9538 ha^{-1}; $F_{8,\,27}$ = 3.83, P =0.004; Figure 4) compared to one and no burn, and 35 % of these were in the largest size class.

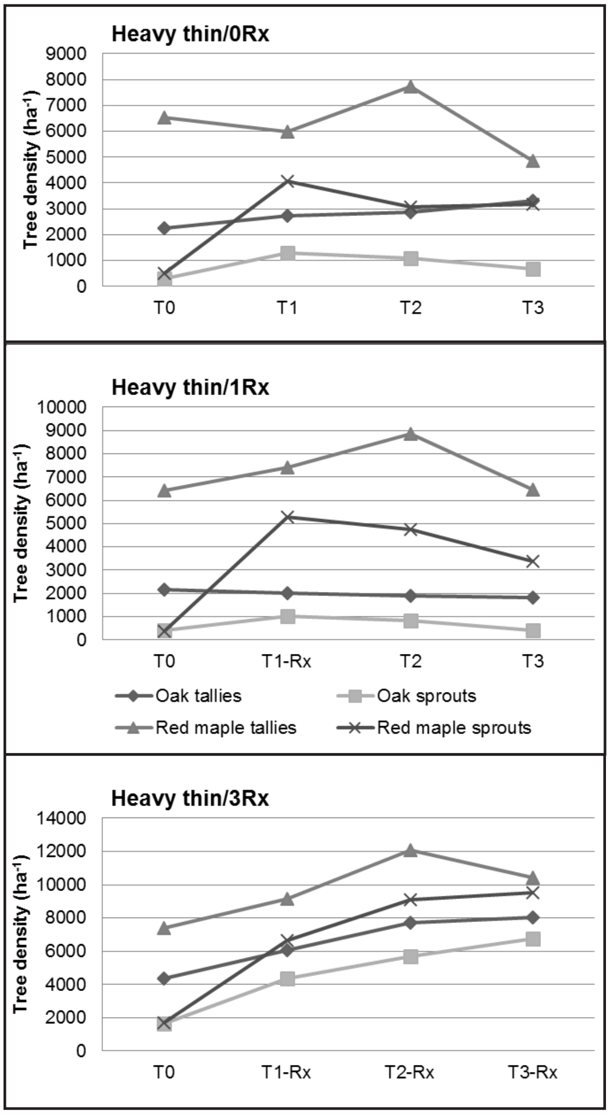

Figure 4. Red maple and oak species regeneration stem density ha^{-1} for all stems up to 3.8 cm diameter at breast height under heavy thinning prescriptions (thin residual goal of 11.5 m^2 ha^{-1}) at four times (T0 = pre-treatment; T1 = one year post treatment, thin, burn, thin and burn; T2 = four growing seasons post T0; T3 = seven growing seasons post T0) on the William B. Bankhead National Forest, Alabama, USA. Prescribed fire indicated by Rx next to time.

DISCUSSION

Combinations of practices are needed that collectively reduce the density of overstory pines to release understory hardwoods and encourage their recruitment into the canopy while controlling the less desirable hardwood species (red maple in these stands) so that succession is toward the desired future composition. The most expedient way to achieve the overall goal of moving these pine plantations toward a mixed native hardwood-pine forest might be to release the dominant midstory and understory hardwoods by harvesting the overstory pines. This treatment, however, would promote the less desirable hardwood species such as red maple because they are the most abundant and dominant species in the understory. In the study stands, the process of converting these loblolly pine-dominated stands commenced with either the light or heavy thinning treatment. In any of the burn and thin treatments, basal area and stem density were reduced, and these effects were maintained or enhanced with time or additional burns. Residual basal area was highest in the no thin, intermediate in the light thin, and lowest in the heavy thin treatments. The heavy thin and frequently burned treatments had the lowest stem densities.

For overstory trees, stem densities declined for all species in all treatments over time, indicating the overstocked status of these stands (Gingrich 1967). Decreases in density in control stands resulted from self-thinning and in other treatments from mechanical thinning. Similar to other research in southern Ohio (Hutchinson *et al*. 2012), we observed a 10% natural overstory mortality rate per decade in the control stands, and after one and three burns, stem density declined by 19% and 11%, respectively. Thinning alone and in combination with burning decreased large stem densities; large red maple stems were eliminated after the heavy thin and three burns, leaving no residual large red maple. In contrast, others have reported that single fires have no effect on large-diameter stems, such as overstory oaks (Thomas-Van Gundy *et al*. 2015), but multiple fires can eventually cause a reduction in saplings (Waldrop *et al.* 2008, Arthur *et al.* 2015). Repeated prescribed fires are necessary to target fire-sensitive species in the overstory.

Sapling density response to prescribed fire varied across studies, and was dependent on geography and species. In 14 studies examined in a meta-analysis of studies of prescribed fire and its effects on sustaining oak forests, Brose *et al.* (2013) found that post-burn sapling densities of all species (<10 cm dbh) declined by 88%; overstory trees decreased by 15%. In specific studies, red maple sapling dominance continued on sites burned four times in eight years (Arthur *et al.* 2015), and under thinning, burning, and thinning with burning, red maple sapling density increased more than oak density (Waldrop *et al.* 2008). Our treatments caused a decline in both oak and red maple saplings. Stands on the Bankhead National Forest that were not thinned but were burned three times in seven years had a 33% decline in sapling red maple stem density. Residual red maple sapling stem density was lowest after either light or heavy thinning and three burns, and declined following each burn. Red maple is initially a prolific sprouter after a single cutting or after fire that removes the parent stem (Albrecht and McCarthy 2006, Blankenship and Arthur 2006). Its moderate shade tolerance enables red maple capable of rapid height growth in thinned stands where light levels can range from 15% to 50% of full sun (Schweitzer and Dey 2015). After thinning and one burn, red maple saplings initially declined, but then increased over time. Fire-induced mortality among saplings has been widely reported, but in this study, red maple attrition was inefficient after one burn, and red maple reproduction was both numerous (high densities) and competitive (largest size class) following burning. Although it has been recommended that the burning associated with basal area and stem density reduction be implemented three to five years postharvest to facilitate oak root system growth (Brose and Van Lear 1998, Brose *et al.* 1999, Albrecht and McCarthy 2006, Brose 2010), we found that initiating the fire soon after harvest, and burning multiple times, led to a decline in red maple sapling density. Yellow-poplar is also a common oak competitor in eastern hardwood forests, but on our site its seed germination and competition were not driving factors in oak regeneration or stand regeneration. In similar hardwood systems, multiple fires have resulted in reductions in red maple density (Hutchinson *et al.* 2005, Blankenship and Arthur 2006, Fan *et al.* 2012, Hutchinson *et al.* 2012).

The cumulative impacts of the most intense disturbance were evident in the regeneration cohort. At time 3, the heavy thin with frequent fire treatment stands had greater regeneration than all other treatments except the no thin with frequent burning. The tallest regeneration stems (seedlings and sprouts combined) under this treatment were only slightly reduced in density after the thin and three burns treatment. This is in contrast to Hutchinson *et al.* (2012), who found a 95% reduction in stems in this size class over 13 years, during which stands had been burned three to five times. After one and two burns, without thinning in oak-pine forests on the Cumberland Plateau, Kentucky, Arthur *et al.* (1998) reported an increase in stems >50 cm tall to <2 cm dbh. Conditions created under frequent disturbance facilitate an increase in regenerating stems, but dominant stems may not be the most desirable species.

Prior to the heavy thin and frequent burn treatment, regeneration was dominated by seedlings, not sprouts. Post-heavy thin and frequent burning, the majority of the total regeneration tally were sprouts; Brose (2010) also found that dominant stems after burning were of sprout origin, noting seedling-origin dominant stems as being rare. Unfortunately, only 2% of all oak sprouts were in the largest size class after treatment, in contrast to Brose (2010) who reported that 71% to 89% of hickory and oak regeneration came from sprouts and that these oaks were co-dominating with hickory 11 years after a shelterwood with one burn in central Virginia. This trend of sprout-origin dominance in the regeneration cohort was apparent in the light thin with frequent burning treatment in which the majority of the oak and red maple regeneration was from sprouts, with more red maple in the largest size classes. Burning alone, without thinning, also increased the percentage of the regeneration in sprouts.

Without thinning, oak and red maple seedlings are caught in a fire trap (Grady and Hoffmann 2012). In our study, 80% to 90% of seedlings remained less than 30 cm tall after one or three fires. Although fire behavior was not assessed as an objective in this study, the fire temperatures we obtained were within the ranges reported by others for dormant season burns in eastern deciduous forests (Franklin *et al.* 1997, Iverson *et al.* 2004, Phillips and Waldrop 2008), but may have been insufficient to cause mortality of shade-casting overstory trees. Without thinning, available light is too low to support rapid rates of height growth for either oaks or red maple, and frequent fire in the short term sets back shoot development. Burns that reduce post-fire seedling emergence of red maple have been documented (Glasgow and Matlack 2007), and Brose (2010) noted that seedling-origin dominant stems were only found in controls, not in any of the burn treatments. With thinning, oak seedlings that were burned also appeared to be caught in a fire trap, with fewer stems tallied in the largest size classes. There was no clear pattern for red maple seedlings under thinning and fire, as distribution among height classes was somewhat even. In these systems, juvenile sprouting must be considered part of the recruitment strategy. Without thinning, red maple sprouts were not trapped in the smaller size classes following one fire, a trend found elsewhere (Arthur *et al.* 1998, Albrecht and McCarthy 2006). With three fires, red maple sprouts were maintained as smaller stems. Under thinning, oak and maple sprouts responded favorably to one fire, with over 60% of the sprouts in the largest size class for oak and over 90% for maple; with three fires, oak sprouts did not recruit into larger sizes. The key to developing large oak advance reproduction is to have sufficient light in the understory and time between fires to permit positive net root growth. Then, when the oak seedling sprouts are competitive, they need further release from overstory competition and a fire-free period to allow for recruitment into the overstory. Reproduction needs to reach a threshold size before it can escape from fire. Longer fire-free periods (antecedent periods as described by Arthur *et al.* 2015) may allow seedlings and sprouts enough time to grow into a fire-resistant size (Jacqmain *et al.* 1999, Fan *et al.* 2012, Grady and Hoffman 2012).

Long-term persistence without recruitment influences forest dynamics. In this study and others, repeated fire with overstory removal appears to be eliminating red maple from the sapling-midstory stratum, but recruitment seems inevitable due to the sprouting response of the juvenile cohort. Fire can promote relative oak density and dominance directly through differential mortality among the competing species. We found that if the harvest and burn prescription involved multiple burns, initiating the burns immediately after harvest may favor oaks over red maple in the sapling layer. However, under these disturbance regimes in these ecosystems, sprouting may substantially contribute to the future species composition, with red maple sprouts exhibiting the most recalcitrant response to thinning, burning, and their combination. If sustained oak height growth and sprouting continues, stems may move into the sapling size class, facilitated through a pause in prescribed burning. These changes in stand composition and structure with fire and thinning need to be carefully monitored and management adjusted to ensure desired stand characteristics.

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