OVERSTORY TREE MORTALITY AND WOUNDING AFTER THINNING AND PRESCRIBED FIRE IN MIXED PINE-HARWOOD STANDS

Callie Jo Schweitzer, Yong Wang, and Dan Dey

Abstract—The William B. Bankhead National Forest in northcentral Alabama is using active management to shift mixed *Quercus-Pinus* forests toward forests more dominated by upland hardwoods. We studied the impact of three levels of thinning (none, light thin, and heavy thin) and three levels of prescribed fire (none, infrequent fire, and frequent fire) and all combinations in a factorial experimental design to assess overstory (trees >5.5 inches d.b.h.) mortality. All burns were conducted during the dormant season. In all 36 treatment stands, we surveyed five permanent vegetation plots before treatments were initiated and in each subsequent growing season post-burn. Overstory stem density was reduced primarily through the thinning operations, and little mortality was detected. Mortality was significantly greater for unthinned stands, regardless of burning regime, compared to the thinned treatments. Although basal wounding from logging may increase susceptibility to fire damage and mortality, the trees that initially died (after thinning and one fire) did not have bole wounds. Thinning with frequent fire resulted in the greatest number of trees with bole wounds, however, trees that died in these treatments did not have any discernable bole wounds.

INTRODUCTION

The use of prescribed fire to achieve management goals in hardwood forests continues to be scrutinized. Restoring fire as a process in these forests has been suggested as a means to move towards oak-dominated stands (Dey and Hartman 2005, Nowacki and Abrams 2008). However, research has shown that fire's application for reaching desired future conditions, which are weighted towards maintaining or enhancing oak (*Quercus* spp.) in these systems, must be timed to ecosystem stage (Arthur and others 2012, Dey and Schweitzer 2015), and obtaining and favoring oak over other competitors, such as red maple (*Acer rubrum* L.), in the reproduction cohort may prove challenging (Keyser and others 2017, Matlack 2012, Schweitzer and others 2016), whether used alone or in combination with tree harvesting. Fire's longer-term impact on residual stand quality is receiving heightened attention, although past research has addressed this issue.

Reports on stand quality from the early 1900s mention fire as a detriment to growing high quality timber in the southern upland forests of the United States. Concern over the adverse effect fire was having on the composition and structure of the forest was reported early by Zon (1907) who detailed the growth of sprouts under badly burned and slightly burned scenarios. At that time in the Southeast, little effort was made to keep fire out of the forest, and Zon lamented, "Protection against fire is essential to conservative forest management in the southern Appalachians." Frothingham (1917) noted how the omnipresence of disturbance, including fire and grazing, along with indiscriminant logging and the leaving of poor quality residuals, resulted in second growth forest that then needed management to sustain the timber demand. Frothingham stated, "Recurrent surface fires have badly injured the timber and the forest floor . . . and . . . (fire) is hardly to be recommended until experiments have thoroughly demonstrated its superiority to clearcutting and girdling without burning." These sentiments were echoed by Buell (1928) who stated "The first principle of wise use, control of fire is so well proved that it needs no comment", although no actual research on fire was reported. Zon and Scholz (1929) reported that repeated fire may delay regrowth of a stand indefinitely. However, these statements and conclusions were based more on anecdotal observations and less on actual research on fire damage and mortality.

One of the earliest studies addressing the effects of fire detailed the relationship between tree size and mortality caused by fire for American chestnut and oaks (McCarthy and Sims 1935). Their study showed that smaller saplings, 3 inches diameter at breast height (d.b.h.) and smaller, suffered the most mortality with

Author information: Callie Jo Schweitzer, Research Forester, U.S. Department of Agriculture Forest Service, Southern Research Station, Huntsville, AL 35801; Yong Wang, Professor, Alabama A&M University, Normal, AL 35762; and Dan Dey, Project Leader, U.S. Department of Agriculture Forest Service, Northern Research Station, Columbia, MO 65211.

Citation for proceedings: Kirschman, Julia E.; Johnsen, Kurt, comps. 2018. Proceedings of the 19th biennial southern silvicultural research conference. e–Gen. Tech. Rep. SRS–234. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station. 444 p.

fire, and that susceptibility depended on bark thickness, fire intensity and duration, and crown height above the ground level. In another study of 5,882 cut and scaled trees, those trees wounded at the base had 10 times the amount of butt rot, and 97 percent of those basal wounds were caused by fire according to Hepting and Hedgcock (1935). In their sample, 67 percent of trees with basal fire wounds had butt rot, while only 6 percent of trees without basal wounds had butt rot. These stands were mainly of seedling origin, and they concluded that butt rot in sprout-origin stands occurred independently of fire scars. Roth and Sleeth (1939) confirmed this, reporting from 10 to 40 percent of oak sprouts were butt-rotted as a result of decay transmission from parent stump to sprout. The lasting effects of fire on residual trees was noted and addressed by early silviculture research (Hedlund 1959, Jemison 1946, Paulsell 1957, Wahlenberg 1953).

More recently, it has been realized that the successes in controlling wildfire has come with an ecological consequence of shifting species composition in eastern hardwood and pine forests (Huntley and McGee 1982, Little 1973, Merritt 1979, Sander 1977). This is a major impetus for using prescribed burning in eastern forests, to sustain oak-pine forests and to restore oak-pine natural communities. Consequently, caution on the use of fire is still reported though we lack much research to enable understanding of fire injury to trees and silvicultural methods to minimize damage. Wendel and Smith (1986) showed that overstory trees died or had decreased vigor 5 years after a single fire in an upland hardwood forest in West Virginia. Ward and Stephens (1989) noted that 30 years after a summer wildfire, mortality continued and residual trees had more stem defects compared to unburned areas, although oak regeneration dramatically increased and grew fast in the burned stand. DeSelm and others (1991) reported a doubling of overstory tree mortality compared to controls after 27 years of annual and periodic fires in an upland forest on the Highland Rim in Tennessee. In more recent research, Hutchinson and others (2012) reported a 10 percent decline in overstory trees (> 9 inches d.b.h.) after 2-4 burns over 13 years in mixed oak stands in southern Ohio. Others have reported that single fires have no effect on large diameter stems, such as overstory oaks (Thomas-Van Gundy and others 2015), but multiple fires can eventually cause a reduction in saplings (Arthur and others 2015, Schweitzer and others 2016, Waldrop and others 2008). Research into the mechanism of fire effects and resistance increased our understanding of some of the results of fire on defect and mortality (Butler and Dickinson 2010, Hengst and Dawson 1994, Pomp and others 2008, Smith and Sutherland 1999, 2006), although few studies examined the effect on wood quality (Marschall and others 2014). Collectively, studies on fire effects on tree mortality are scattered spatially, in various forest types and species, include trees of differing sizes and ages and time of burning, and vary temporally in fire regime such that it is hard to conclude definitively on the effects of future fire applications.

We examined overstory tree mortality and wounding in a mixed pine-hardwood forest that received thinning, prescribed fire and combinations of thinning and fire. These silvicultural techniques are being tested to promote and accelerate the succession of these stands towards dominance of oaks in the overstory. The objective of the study reported here was to (1) examine stand-level overstory tree mortality under thinning, burning and their combination compared to no management disturbance, and (2) examine post-treatment damage to the lower bole of overstory trees as related to disturbance.

METHODS

The 180,000-acre Bankhead National Forest (BNF), in north-central Alabama, is in the Cumberland Plateau Section of the Appalachian Plateaus physiographical province (Fenneman 1938), and study stands are more specifically characterized by the Strongly Dissected Plateau subregion of the Southern Cumberland Plateau, within the Southern Appalachian Highlands (Smalley 1979). 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 (*Pinus taeda* L.), red oaks [northern red oak (*Q. rubra* L.), black oak (*Q. velutina* Lam.), scarlet oak (*Q. coccinea* Munchh.), and southern red oak (*Q. falcata* Michx.)], and white oaks [white oak (*Q. alba* L.) and chestnut oak (*Q. prinus* L.)] are 75 feet, 65 feet, and 65 feet, respectively (Smalley 1979). Soils are loamy, formed in residuum weathered from sandstones and conglomerates (Smalley 1979). Climate of the region is temperate with mild winters and moderately hot summers with a mean temperature of 55.4 °F and mean precipitation of 59 inches (Smalley 1979). Study stands were located on broad, flat ridges with elevations ranging from 720 to 1,220 feet above sea level.

The BNF study was a randomized complete block design with a 3 by 3 factorial treatment arrangement and four replications of each treatment. Treatment details and implementation are given in table 1. Each treatment was replicated 4 times, for a total of 36 treatment stands. Stand size ranged from 22 to 46 acres. Treatments were representative of management practices described in the BNF's Forest Health and Restoration Project for restoring oak forests and woodlands (USDA Forest Service 2003). Criteria for stand selection were based on species composition, stand size, and stand age. Treatment stands were at least 22 acres in size with basal areas ranging from 122 to 132 square feet per acre. Commercial thinning was conducted by marking from below smaller trees or trees that appeared diseased or damaged; canopy

Table 1—Thinning and prescribed fire treatment designations, residual basal area (std) and stems per acre densities (SPA)(std) after thinning (Time 1), and fire return interval and fires to date, William B. Bankhead National Forest, Alabama

Treatment thin/fire return frequency	Thinning target basal area (ft^2 a^{-1})	Time 1 basal area (ft^2 a^{-1})	Time 1 SPA	Fire return interval (years)	Fires to date (number)
No thin/No Rx	No thin	137.5 (20.9)	264 (54)	0	0
No thin/Infrequent Rx	No thin	127.1 (29.1)	275 (69)	9	1
No thin/Frequent Rx	No thin	130.3 (26.9)	317 (76)	3	3
Light thin/No Rx	75	67.5 (18.9)	106 (37)	0	0
Light thin/Infrequent Rx	75	71.7 (16.6)	124 (15)	9	1
Light thin/Frequent Rx	75	64.4 (11.7)	108 (18)	3	3
Heavy thin/No Rx	50	50.6 (9.9)	86 (24)	0	0
Heavy thin/Infrequent Rx	50	49.3 (9.3)	85 (16)	9	1
Heavy thin/Frequent Rx	50	49.9 (9.2)	84 (19)	3	3

trees were also removed to meet target residual basal areas. Hardwoods were preferentially retained. Thinning treatments were completed prior to the initiation of the burning treatments (thinning conducted from June through December).

Prescribed burning was conducted during the dormant season (January through March) using backing fires and strip head fires to ensure that only surface fire occurred. Immediately prior to each fire, we installed 6 to 8 HOBO data recorders (HOBO U12 Series Datalogger, Onset Computer Corporation, Cape Cod, MA) connected to a temperature probe (HOBO TCP6-K12 Probe Thermocouple Sensor, Onset Computer Corporation, Cape Cod, MA) at each vegetation sampling plot (30-48 probes per stand). Installation was based on the design of Iverson and others (2004). Out 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. Ignition type included hand strip firing at approximately 26 feet intervals and aerial ignition for 6 fires; all others were ignited by hand strip firing. All study burns were included as part of a larger target burn area on the BNF, and burn areas ranged from 150 to 3,000 acres. Absolute maximum fire temperatures ranged from 2 °F (27 January 2007) to 575.4 °F (March 16, 2013). On average, the maximum temperature was 203.9 °F (std 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.

Overstory trees (5.6 inches d.b.h. and greater) were surveyed on five permanent measurement plots (0.2 acre circular plots) systematically located in each stand. Distance and azimuth to all trees were recorded from plot center; species, diameter, tree grade, status, and damage attributes were recorded at pretreatment (time 0), after the thinning and first burn (time 1), the next sampling period followed the second burn (time 2) and the final sampling period followed the third burn (time 3), which was seven growing seasons after pretreatment.

We assessed damage to the lower bole by enumerating each external wound and measuring the wound area (width X length) using a hand-held ruler.

We used an analysis of variance (ANOVA) by implementing PROCMIXED in SAS 9.0 (SAS Institute Inc. 2000), 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 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). We used ANOVA to test for differences in overstory basal areas and densities, mortality, and incidence of wounding, among pre- and post-treatment samples (within subject factor) and among treatments (between subject factor). 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

The response of stand structure and composition to the thinning, and initial sequence of prescribed fire (one fire for the infrequent fire treatment and three fires for the frequent fire treatment) were detailed in Schweitzer and others (2016). Stands had 131.2 square feet per acre of basal area with 290 stems per acre (SPA), on average, at the beginning of the study (table 1). Thinning targeted pines; out of 174 SPA harvested in the light thin, 125 SPA were loblolly pine and 32 SPA were Virginia pine (*P. virginiana* Mill.). For the heavy thin, 132 SPA of loblolly pine and 45 SPA of Virginia pine were removed as the majority of the 199 SPA harvested. There were significant interactions between time and treatment for basal area ($F_{24, 42}$ = 82.38, $P \leq 0.001$) and SPA ($F_{24, 42}$ = 99.07, $P \leq 0.001$). For all thinned treatments, basal area and stem densities for all species were lower at times 1, 2, and 3 compared to time 0 and there were no differences, within each thinned treatment, between values at times 1, 2, and 3. Residual basal areas and SPA at time 1 averaged 67.9 square feet per acre and 113 SPA for the light thin and 49.9 square feet per acre and 85 SPA for the heavy thin. At time 3, stem density was lowest in stands subjected to heavy thin and frequent prescribed fire (84 SPA) (time 3 $F_{3, 25}$ = 28.52, $P \leq 0.001$) and highest in the unthinned stands, regardless of burn treatment (266 SPA no fire; 277 SPA one fire; 333 SPA three fires).

There were no significant differences among treatments for standing dead trees (snags) at the beginning of the study ($F_{3, 25}$ = 1.36, P = 0.20). Across all 180 measurement plots, only 186 snags were tallied, resulting in an average of 5 snags per acre. Seventy-eight percent of these snags were loblolly pine, 15 percent were Virginia pine, and 7 percent were unidentifiable. These snags were removed from the mortality database, as were any trees that were knocked over during the thinning operation.

Mortality was compared for each time period; we did not collect data immediately after the thin and prior to the burn for the thin and burn treatments. Mortality was calculated for each sample period; dead trees at time 1 were removed from analysis at time 2; dead trees at time 1 and 2 were removed from analysis at time 3. Species that died at time 1 included flowering dogwood (*Cornus florida* L.), eastern hemlock (*Tsuga canadensis* (L.) Carr.), loblolly pine, red maple, scarlet oak, sourwood (*Oxydendrum arboreum* DC), Virginia pine, and yellow-poplar (*Liriodendron tulipifera* L.). The number of dead trees across all treatments was low and ranged from 1 to 4 SPA; there was a difference among treatments ($F_{3, 25}$ = 3.05, $P \leq 0.0031$), with unthinned stands having the highest mortality (table 2). The portion of live stems by species across all treatments was 85.1 percent pines, 7.2 percent oaks, and 5.3 percent other species combined. The mortality was concentrated in the pines, with 89.3 percent of dead trees loblolly or Virginia pine, and 9.5 percent other species; no overstory oaks died at time 1 (fig. 1).

At time 2, stands either had received another fire or were undisturbed for 4 growing seasons. Mortality was noted for 14 different species, and included black cherry (*Prunus serotina* Ehrh.), bigleaf magnolia (*Magnolia macrophylla* Michx.), black oak, chestnut oak, flowering dogwood, loblolly pine, post oak (*Q. stellata* Wang.), red maple, scarlet oak, southern red oak, sourwood, Virginia pine, white oak and yellow-poplar. Mortality was greatest in the no thin, infrequent fire treatment ($F_{3, 25}$ = 4.20, $P \leq 0.0001$) and did not differ among the other treatments (table 2). Mortality in the unthinned stands was dominated by pine species, accounting for 92 percent of the total mortality. In the light thin with infrequent fire, the majority of the mortality was in the other species category (46.2 percent), although the alive stem density was only 5.5 percent other species (fig. 2). Twenty-five percent of the mortality was oaks for the light thin with no fire and heavy thin with no fire treatments (fig. 2).

At time 3, the frequent fire treatments had received a third fire and the other treatments were now undisturbed for 7 growing seasons. Mortality differed among treatments ($F_{3, 25}$ = 7.11, $P \leq 0.0001$) and was greatest in the unthinned stands (table 2). Mortality was concentrated in the pines in these treatments, accounted for 91.5 percent of the total mortality, and 83.6 percent of the total live stems in pine (fig. 3). The heavy thin with three fires treatment had 8 SPA of mortality, the next highest level after the unthinned treatments, although it only differed from the unthinned with no fire treatment. A shift in alive stem densities in the heavy thin with frequent fire treatment from pretreatment to time 3 was

Table 2—Mortality stems per acre (std) of trees > 5.5 inches d.b.h., by time and treatment, following thinning and prescribed fire, William B. Bankhead National Forest, Alabama

Treatment thin/fire return frequency	Time 1 post thin and one fire for all treatments	Time 2 post thin and two fires for 3 Rx treatments	Time 3 post thin and three fires for 3 Rx treatments
No thin/No Rx	3.75 (3.93) a	6.75 (6.93) b	17.25 (15.34) a
No thin/Infrequent Rx	2.25 (3.43) ab	13.5 (22.54) a	10.50 (9.45) bc
No thin/Frequent Rx	3.75 (5.10) a	5.25 (6.58) b	13.75 (13.46) ab
Light thin/No Rx	1.75 (2.45) ab	1.00 (3.48) b	2.75 (3.80) d
Light thin/Infrequent Rx	1.25 (2.75) b	3.25 (4.38) b	5.00 (6.07) cd
Light thin/Frequent Rx	0.75 (1.83) b	1.75 (2.94) b	2.50 (4.14) d
Heavy thin/No Rx	0.50 (1.54) b	1.00 (2.62) b	2.00 (2.99) d
Heavy thin/Infrequent Rx	1.50 (3.28) b	2.75 (3.43) b	2.50 (3.44) d
Heavy thin/Frequent Rx	0.75 (2.45) b	2.75 (3.80) b	7.75 (14.55) bcd

Different letters within time column indicates significant difference (α=0.05) among treatments.
D.b.h.=diameter at breast height.

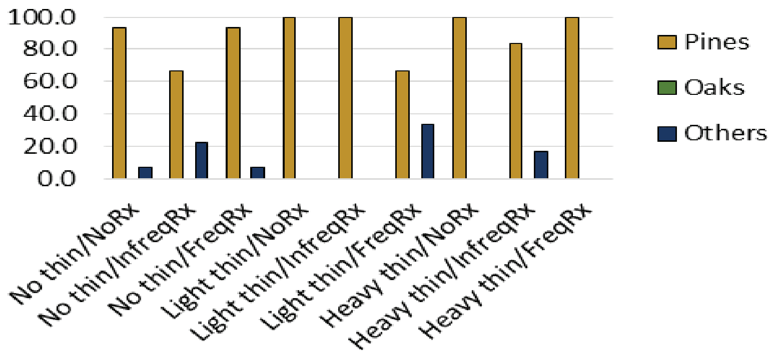

Figure 1—Percent mortality by species groups for each treatment at time 1, one growing season post thinning and post prescribed burn 1, for all treatments on the William B. Bankhead National Forest, Alabama.

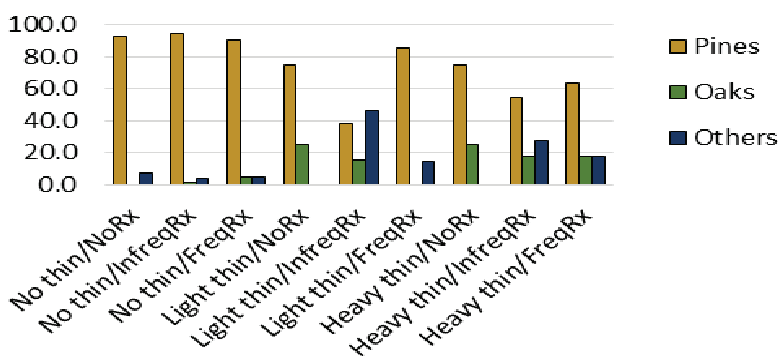

Figure 2—Percent mortality by species groups for each treatment at time 2, post prescribed burn 2 for the frequent Rx treatments, four growing seasons post thin, and post thin and burn for the infrequent Rx treatments, for all treatments on the William B. Bankhead National Forest, Alabama.

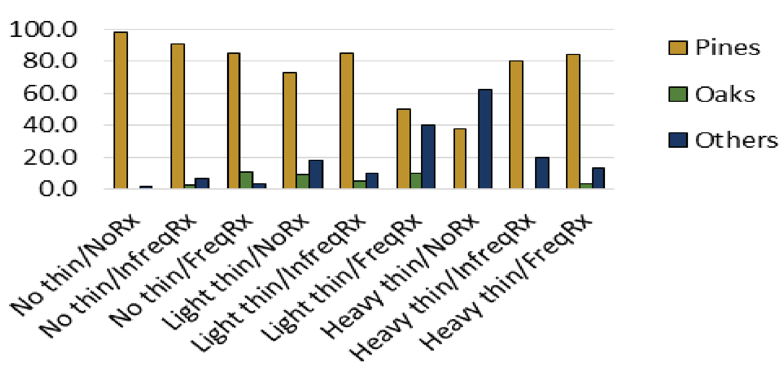

Figure 3—Percent mortality by species groups for each treatment at time 3, one growing season post prescribed burn 3 for the frequent Rx treatments, seven growing seasons post treatment for all other treatments on the William B. Bankhead National Forest, Alabama.

80.7 to 63.7 percent for pines, 8.9 to 22.6 percent for oaks, and 8.0 to 11.6 percent for other species. Over the study period, there was an increase in the proportion of alive oak stems as most mortality was in the pines. Oak mortality was found in all treatments except the unthinned with no fire, heavy thin with no fire, and heavy thin with infrequent fire treatments. The total number of oaks that died was <1 per acre for all three time periods, except for the no thin with frequent fire treatment, which had 1.5 SPA oak death in 7 years. The average diameter of dead oak trees was 7.5 inches.

The amount of visible lower bole damage was minimal across the study. On all 180 measurement plots, we noted 14 different species with damage (table 3). The trees that died in the unthinned treatments at time 1 (no harvesting, two treatments were burned) had no recorded wounds. In general, trees with wounds at time 1 did not die by time 3; across all 180 plots, 6 total trees with damage at time 1 were either knocked over or died by time 3 (0.2 SPA impacted). At time 1, all treatments with thinning had more trees with lower bole damage compared to the unthinned stands ($F_{3, 25} = 12.60$, $P \leq 0.0001$) (table 4). In the light thin with frequent burn treatment, there were 16 SPA with damage, the majority of trees with damage were loblolly pine, and the average wound size was 129 square inches. At time 2 and time 3, the thin with frequent burning treatments had the most damage, ranging from 10 to 15 SPA of damaged trees. Damaged trees included oaks (2 SPA, average diameter 9.9 inches), loblolly pine (9 SPA, average diameter 10.9), and less than one SPA of red maple (average diameter 7.0 inches), sweetgum (*Liquidamber styraciflua* L.) (average diameter 16.1 inches), Virginia pine (average diameter 9.4 inches) and yellow-poplar (average diameter 11.6 inches). We did not note any damage in the unthinned treatments at time 2, but at time 3, after three fires, there were 4 SPA with damage, compared to one SPA of noted damage for the one and no burn treatments.

DISCUSSION

The effect of low intensity prescribed fire on mortality of overstory trees is related to site factors, stand composition and structure, and fire characteristics. 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 (Arthur and others 2012, Blankenship and Arthur 2006, Brose 2010, Brose and others 2013, Hutchinson and others 2012, Keyser and others 2017, McEwan and others 2011, Schweitzer and others 2016). Repeated fire will be necessary to alter the stem dynamics in the understory to favor oak over other species, although oak seedlings may be caught in a “fire trap” (Grady and Hoffman 2012) and a fire-free period will be needed to facilitate recruitment (Arthur and others 2015, Thomas-Van Gundy and others 2015). This prescription, of repeated fires with a subsequent fire-free antecedent period, complicates reducing residual tree damage due to fire. Value loss of fire scarred trees can be minimized if trees are harvested within 5 years (Marschall and others 2014, Weidenbeck and Schuler 2014). Application of three (or more) prescribed fires within 5 years is

Table 3—Total number of trees with lower bole damage on 180 measurement plots across all treatments, by species and time, following thinning and prescribed burning on the William B. Bankhead National Forest, Alabama

Damaged tree species	Number of damaged trees tallied on all plots		
	Time 1: post thin and one prescribed fire	Time 2: post second prescribed fire	Time 3: post third prescribed fire
Beech (*Fagus grandifolia*)	0	1	0
Black cherry (*Prunus serotina*)	5	1	9
Black oak (*Quercus velutina*)	2	1	2
Chestnut oak (*Quercus prinus*)	19	13	15
Loblolly pine (*Pinus taeda*)	223	127	158
Post oak (*Quercus stellata*)	0	2	0
Red maple (*Acer rubrum*)	4	3	9
Scarlet oak (*Quercus coccinea*)	7	6	17
Sourwood (*Oxydendrum arboretum*)	1	2	1
Southern red oak (*Quercus falcata*)	0	0	2
Sweetgum (*Liquidambar styraciflua*)	0	2	2
Virginia pine (*Pinus virginiana*)	12	8	8
White oak (*Quercus alba*)	4	4	6
Yellow-poplar (*Liriodendron tulipifera*)	5	6	8

Table 4—Number of trees with lower bole damage in stems per acre (std) for trees > 5.5 inches d.b.h., by time and treatment, following thinning and prescribed fire, William B. Bankhead National Forest, Alabama

Treatment Thin/Fire return frequency	Time 1 post thin and one fire	Time 2 post thin and two fires or 3 growing seasons	Time 3 post thin and three fires or 6 growing seasons
No thin/No Rx	0.25 (1.12)d	0.00 (0.00)d	1.25 (2.75)d
No thin/Infrequent Rx	0.50 (1.54)d	0.00 (0.00)d	1.00 (3.48)d
No thin/Frequent Rx	0.00 (0.00)d	0.00 (0.00)d	3.75 (8.87)dc
Light thin/No Rx	13.75 (9.72)ab	7.00 (6.77)bc	7.50 (6.59)c
Light thin/Infrequent Rx	9.50 (9.72)bc	3.75 (3.58)bd	8.25 (7.30)bc
Light thin/Frequent Rx	16.0 (11.77)a	13.25 (12.28)a	14.50 (11.91)a
Heavy thin/No Rx	7.75 (9.24)c	4.50 (5.36)c	5.00 (6.28)cd
Heavy thin/Infrequent Rx	8.25 (7.66)c	6.00 (7.54)bc	5.50 (5.83)cd
Heavy thin/Frequent Rx	14.5 (9.99)ab	9.50 (7.93)ab	12.50 (10.20)ab

Different letters within time column indicates significant difference (α=0.05) among treatments.
D.b.h.=diameter at breast height.

challenging in most upland hardwood systems, thus residual trees with fire injury will most likely not meet the <5 year fire-scar residence time.

The stands under study on the BNF are unique for their mixed pine-hardwood composition. The dominance of pine in the overstory of these stands, coupled with the targeted removal of pine in the thinning operation and the higher level of mortality of pine over other species, has assisted the management goal of moving these stands towards greater hardwood (oak) dominance. The highest incidence of overstory tree mortality was documented in the unthinned stands, indicative of the overstocked status of these stands (Gingrich 1967) and stress due to competition. Adding fire to these unthinned stands did not alter the overstory mortality, as stands burned three times had the same mortality as unthinned stands without fire. Tree vigor and species composition are also playing a role in this response (Yaussy and Waldrop 2010). We did not assess tree vigor directly; we used a modified tree grading system that accounted for tree size and surface characteristics (Miller and others 1986), and found that the Virginia pine in these stands were of the lowest grade. Overstory tree mortality did not differ among heavy or light thinning regardless of fire (none, one, or three), and delayed mortality has not been noted at this time. Others have found a 9 to 25 percent decline in density of overstory trees on burned plots (Arthur and others 2015, Brose and Van Lear 1999, Hutchinson and others 2012), and Fan and Dey (2014) reported that overstory basal area continued to increase in stands burned annually to periodically (e.g., every 3 years) for 10 years in the Missouri Ozarks.

The use of prescribed fire and thinning to move these stands towards oak, and perhaps even towards oak woodland structure (Dey and others 2017), can be inferred from the heavy thin with frequent fire treatment. These stands had a relative basal area of oak (white oak, chestnut oak, and scarlet oak) that was 4.4 percent and a relative oak stem density of 3.4 percent. After thinning, these increased to 10.5 and 14.6 percent, respectively, and after three fires oak relative basal area was 12 percent and oak relative density was 15.7 percent. A concurrent reduction in the density of understory stems has been reported (Schweitzer and others 2016). With continued burning concern exists with regard to the fire-induced damage and mortality that could reduce the overstory oak component as indirect fire mortality. Others have found that overstory trees are often scarred on the lower bole by fire, but mortality from low-intensity burns was low (Dey and Fan 2009, Hutchinson and others 2005, Regelbrugge and Smith 1994).

Damage and value loss related to both wildfire and low-severity prescribed fires have been reported in very few studies, although predictive variables have been detailed (Loomis 1973, 1974). In a study of fire-damaged oaks in the Missouri Ozarks, the proportion of the butt log with defect after fire was shown to increase with increasing size of fire scar, increases in time since fire injury, and decreases in tree diameter, with one third of the volume defect 25 years after the trees (white, black, and scarlet oaks) were fire scared (Stambaugh and Guyette 2008). Reeves and Stringer (2011) found that most loss (value and volume) was due to structural change (tree mortality and size class changes), with about one third of value loss due to degrade and rot. Boards sawn from the side of logs directly impacted by low to medium intensity fire developed defect (mineral stain and some level of decay) that differed depending on species, and lumber loss was to be expected (Wiedenbeck and Schuler 2014). For dimensional red oak lumber, a study of individual tree loss due to fire damage showed volume loss at 3.9 percent and value loss at 10.3 percent after 14 years since fire injury (Marschall and others 2014). Coupling the restoration of fire as a process in these upland hardwood systems with efforts to minimize residual tree damage will continue to be investigated (Dey and Schweitzer 2015, Sutherland and Smith 2000). We have noted minimal lower bole damage, with most damage found in the most disturbed treatments; trees in treatments that received three fires but were not thinned did have an increase in the incidence of wounding, but the SPA impacted was quite low (4 SPA).

CONCLUSION

Managers in some Southern mixed pine-hardwood forests are using prescribed fire to change stand structure and composition. Although research has been reported documenting the effects of fire on these systems, questions remain as to the long-term impact on forest composition, structure, and health, with mortality rates and wood quality surrogate metrics of forest health and resilience. There exists a conundrum of ensuring the frequency of fire needed to target understory competitors such as red maple, and the need to harvest residual trees quickly following fire to reduce defects caused by rot. In this study, repeated fires that were all conducted in the dormant season have not had appreciable impact on overstory tree mortality or degrade. We found that fire has unequally impacted overstory pine over the more desired oaks, accelerating the management goal of moving these stands away from pine dominance and towards more oak-upland hardwood dominance.

ACKNOWLEDGMENTS

The authors wish to thank the BNF staff for their continued support of this project, especially Kerry Clark and Allison Cochran, and Southern Research Station personnel Ryan Sisk, Matt Zirbel and Nancy Bastin. Drs. Justin Hart and Brian Lockhart provided valuable review comments.

LITERATURE CITED

Arthur, M.A.; Alexander, H.D., Dey, D.C. [and others]. 2012. Refining the oak-fire hypothesis for management of oak-dominated forests of the Eastern United States. Journal of Forestry. 110: 257-266.

Arthur, M.A.; Blankenship, B.A.; Schorgendorfer, A. [and others]. 2015. Changes in stand structure and tree vigor with repeated prescribed fire in an Appalachian hardwood forest. Forest Ecology and Management. 340: 46-61.

Blankenship, B.A.; Arthur, M.A. 2006. Stand structure over 9 years in burned and fire-excluded oak stands on the Cumberland Plateau, Kentucky. Forest Ecology and Management. 225: 134-145.

Brose, P.H. 2010. Long-term effects of single prescribed fires on hardwood regeneration in oak shelterwood stands. Forest Ecology and Management. 260: 1516-1524.

Brose, P.H.; Dey, D.C.; Phillips, R.J.; Waldrop, T.A. 2013. A meta-analysis of the fire-oak hypothesis, does prescribed burning promote oak reproduction in eastern North America. Forest Science. 59: 322-334.

Brose, P.H.; Van Lear, D.H. 1999. Effects of seasonal prescribed fires on residual overstory trees in oak-dominated shelterwood stands. Southern Journal of Applied Forestry. 23(2): 88-93.

Buell, J.H. 1928. What can be done with southern Appalachian cutover areas? Southern Lumberman. (Dec 22): 212-213.

Butler, B.W.; Dickinson, M.D. 2010. Tree injury and mortality in fires: developing process-based models. Fire Ecology. 6(1): 55-79.

DeSelm, H.R.; Clebsch, E.E.C., Rennie, J.C. 1991. Effects of 27 years of prescribed fire on an oak forest and its soil in middle Tennessee. In: Coleman, S.S.; Neary, D.G., eds. Proceedings of the sixth biennial southern silvicultural research conference. Gen. Tech. Rep. SE-70. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southeastern Forest Experiment Station: 409-417.

Dey, D.C.; Fan, Z. 2009. A review of fire and oak regeneration and overstory recruitment. In: Hutchinson, T.F., ed. Proceedings of the third fire in eastern oak forests conference. Gen. Tech. Rep. NRS-P-46. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station: 2-20.

Dey, D.C.; Hartman, G. 2005. Returning fire to Ozark Highland forest ecosystems: effects on advance regeneration. Forest Ecology and Management. 217(1): 37-53.

Dey, D.C.; Kabrick, J.M.; Schweitzer, C.J. 2017. Silviculture to restore oak savannas and woodlands. Journal of Forestry. 115(3): 202-211.

Dey, D.C.; Schweitzer, C.J. 2015. Timing fire to minimize damage in managing oak ecosystems. In: Holley, G.; Haywood, D.; Connor, K. eds. Proceedings of the 17th biennial southern silvicultural research conference. e-Gen. Tech. Rep. SRS-203. Asheville, NC: U.S. Department of Agriculture Forest Service, Southern Research Station: 143-153.

Fan, Z.; Dey, D. 2014. Effects of prescribed fire on upland oak forest ecosystems in Missouri Ozarks. Gen. Tech. Rep. SRS-198. Asheville, NC: U.S. Department of Agriculture Forest Service, Southern Research Station: 119-127.

Fenneman, N.M. 1938. Physiography of Eastern United States. New York: McGraw-Hill. 714 p.

Frothingham, E.H. 1917. Report on study of cut-over areas in the Southern Appalachians. RS-Mc2-D-7. Washington, DC: U.S. Department of Agriculture Forest Service. 229 p.

Gingrich, S.F. 1967. Measuring and evaluating stocking and stand density in upland hardwood forests in the central states. Forest Science. 13: 38-53.

Grady, J.M.; Hoffmann, W.A. 2012. Caught in a fire trap: Recurring fire creates stable size equilibria in woody resprouters. Ecology. 93(9): 2052-2060.

Hedlund, A. 1959. Look at the scars! Southern Lumberman. 199 (Dec. 15): 225-226.

Hengst, G.E.; Dawson, J.O. 1994. Bark properties and fire resistance of selected tree species from the central hardwood region of North America. Canadian Journal of Forest Research. 24: 688-696.

Hepting, G.H.; Hedgcock, G.G. 1935. Relation between butt rot and fire in some eastern hardwoods. Tech. Note 14. Asheville, NC: U.S. Department of Agriculture Forest Service, Appalachian Forest Experiment Station. 2 p.

Huntley, J.C.; McGee, C.E. 1982. Impact of fire on regeneration and wildlife habitat in upland hardwoods. In: Proceedings of the 1982 Convention of The Society of American Foresters: America's hardwood forests- opportunities unlimited. Cincinnati, OH: Society of American Foresters: 158-162.

Hutchinson, T.F.; Sutherland, E.K.; Yaussy, D.A. 2005. Effects of repeated prescribed fires on the structure, composition, and regeneration of mixed-oak forests in Ohio. Forest Ecology and Management. 218: 210-228.

Hutchinson, T.F.; Yaussy, D.A.; Long, R.P. [and others]. 2012. Long-term (13-year) effects of repeated prescribed fires on stand structure and tree regeneration in mixed-oak forests. Forest Ecology and Management. 286: 87-100.

Jemison, G.M. 1946. Rehabilitation of defective Appalachian hardwood stands. Journal of Forestry. 44(11): 944-948.

Iverson, L.R.; Yaussy, D.A.; J. Rebbeck, J. [and others]. 2004. A comparison of thermocouples and temperature paints to monitor spatial and temporal characteristics of landscape-scale prescribed fires. International Journal of Wildland Fire. 13: 311-322.

Kenward, M.G.; Roger, J.H. 1997. The precision of fixed effects estimates from restricted maximum likelihood. Biometrics. 53: 983-997.

Keyser, T.L.; Arthur, M.A.; Loftis, D.L. 2017. Repeated burning alters the structure and composition of hardwood regeneration in oak-dominated forests of eastern Kentucky, USA. Forest Ecology and Management. 393: 1-11.

Little, S. 1973. Use of fire: comments from the Northeast. Journal of Forestry. 71: 633-634.

Loomis, R.M. 1973. Estimating fire-caused mortality and injury in oak-hickory forests. Res. Pap. NC-94. St. Paul, MN: U.S. Department of Agriculture Forest Service, North Central Forest Experiment Station. 6 p.

Loomis, R.M. 1974. Predicting the losses in sawtimber volume and quality from fires in oak-hickory forests. Res. Pap. NC-104. St. Paul, MN: U.S. Department of Agriculture Forest Service, North Central Forest Experiment Station. 6 p.

Marschall, J.M.; Guyette, R.P.; Stambaugh, M.C.; Stevenson, A.P. 2014. Fire damage effects on red oak timber product value. Forest Ecology and Management. 320: 182-189.

Matlack, G.R. 2012. Reassessment of the use of fire as a management tool in deciduous forests of eastern North America. Conservation Biology. 27(5): 916-926.

McCarthy, E.F.; Sims, I.H. 1935. The relation between tree size and mortality caused by fire in southern Appalachian hardwoods. Journal of Forestry. 33(2): 155-157.

McEwan, R.W.; Dyer, J.M.; Pederson, N. 2011. Multiple interacting ecosystem drivers, toward an encompassing hypothesis of oak forest dynamics across eastern North America. Ecography. 34: 244-256.

Merritt, C. 1979. An overview of oak regeneration problems. In: Holt, H.A.; Fischer, B.C., eds. Proceedings 1979 John S. Wright forestry conference, regenerating oaks in upland hardwood forests. West Lafayette, IN: Purdue University: 11-17.

Miller, G.W.; Hanks, L.F.; Wiant, H.V., Jr. 1986. A key for the Forest Service hardwood tree grades. Northern Journal of Applied Forestry. 3: 19-22.

Nowacki, G.J.; Abrams, M.D. 2008. The demise of fire and the mesophication of forests in the Eastern United States. BioScience. 58(2): 123-138.

Paulsell, L.K. 1957. Effects of burning on Ozark hardwood timberlands. Res. Bull. 640. Columbia, MO: University of Missouri, College of Agriculture, Agriculture Experiment Station. 24 p.

Pomp, J.A.; McGill, D.W.; Schuler, T.M. 2008. Investigating the relationship between bole scorch height and fire intensity variables in the ridge and valley physiographic province, West Virginia. In: Jacobs, D.F.; Michler, C.H., eds. Proceedings of the 16th central hardwoods forest conference. Gen. Tech. Rep. NRS-P-24. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station: 506-515.

Reeves, C.; Stringer, J. 2011. Wildland fires' long-term costs to Kentucky's woodlands. Kentucky Woodlands Magazine. 6(3): 6-7.

Regelbrugge, J.C.; Smith, D.W. 1994. Postfire tree mortality in relation to wildfire severity in mixed oak forests in the Blue Ridge of Virginia. Northern Journal of Applied Forestry. 11: 90-97.

Roth, E.R.; Sleeth, B. 1939. Butt rot in unburned sprout oak stands. Tech. Bull. No. 684. Washington, DC: U.S. Department of Agriculture Forest Service. 43 p.

Sander, I.L. 1977. Manager's handbook for oak in the north central states. Gen. Tech. Rep. NC-37. St. Paul, MN: U.S. Department of Agriculture Forest Service, North Central Forest Experiment Station. 35 p.

SAS Institute Inc. 2000. SAS Version 8.01. Cary, NC: SAS Institute Inc. 1686 p.

Schweitzer, C.J.; Dey, D.C.; Wang, Y. 2016. Hardwood-pine mixedwoods stand dynamics following thinning and prescribed burning. Fire Ecology. 12(2): 85-104.

Smalley, G.W. 1979. Classification and evaluation of forest sites on the Southern Cumberland Plateau. Gen. Tech. Rep. SO-23. New Orleans: U.S. Department of Agriculture, Forest Service, Southern Forest Experiment Station. 59 p.

Smith, K.T.; Sutherland, E.K. 1999. Fire-scar formation and compartmentalization in oak. Canadian Journal of Forest Research. 29: 166-177.

Smith, K.T.; Sutherland, E.K. 2006. Resistance of eastern hardwood stems to fire injury and damage. In: Dickinson, M.B., ed. Fire in eastern oak forests: delivering science to land managers: Proceedings of a conference. Gen. Tech. Rep. NRS-P-1. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station: 210-217.

Stambaugh, M.; Guyette, R.P. 2008. Prescribed fire effects on the wood quality of three common oaks in the Ozark region, *Q. coccinea*, *Q. velutina*, *Q. alba*. Jefferson City, MO: Missouri Department of Conservation. 23 p.

Sutherland, E.K.; Smith, K.T. 2000. Resistance is not futile: the response of hardwoods to fire-caused wounding. In: Yaussy, D.A., comp. Proceedings: workshop on fire, people and the central hardwoods landscape. Gen. Tech. Rep. NE-274. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station: 111-115.

Thomas-Van Gundy, M.A.; Wood, K.U.; Rentch, J.S. 2015. Impacts of wildfire recency and frequency on an Appalachian oak forest. Journal of Forestry. 113: 393-403.

USDA Forest Service. 2003. Final environmental impact statement, forest health and restoration project, National Forests in Alabama, Bankhead National Forest. Manage. Bull. R8-MB-110B. Atlanta, GA: U.S. Department of Agriculture, Forest Service, Southern Region. 353 p.

Wahlenberg, W.G. 1953. Three methods of rehabilitation for depleted Appalachian hardwood stands. Journal of Forestry. 51(12): 874-880.

Waldrop, T.A.; Yaussy, D.A.; Phillips, R.J. [and others]. 2008. Fuel reduction treatments affect stand structure of hardwood forests in Western North Carolina and Southern Ohio, USA. Forest Ecology and Management. 255: 3117-3129.

Ward, J.S.; Stephens, G.R. 1989. Long-term effects of a 1932 surface fire on stand structure in a Connecticut mixed hardwood stand. In: Rink, G.; Budelsky, C.A., eds. Proceedings of the 7th central hardwood conference. Gen. Tech. Rep. NC-132. St. Paul, MN: U.S. Department of Agriculture, Forest Service, North Central Forest Experiment Station: 267-273.

Wiedenbeck, J.K.; Schuler, T.M. 2014. Effects of prescribed fire on the wood quality and marketability of four hardwood species in the central Appalachian region. In. Groninger, J.W.; Holzmueller, E.J.; Nielsen, C.K.; Dey, D.C., eds. Proceedings of the 19th central hardwoods forest conference. Gen. Tech. Rep. NRS-P-142. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station: 202-212.

Wendel, G.W.; Smith, C.H. 1986. Effect of a prescribed fire in a Central Appalachian oak-hickory stand. NE-RP-594. Broomall, PA: U.S. Department of Agriculture, Forest Service, Northeastern Forest Experiment Station. 8 p.

Yaussy, D.A.; Waldrop, T.A. 2010. Delayed mortality of eastern hardwoods after prescribed fire. In: Stanturf, J.A., ed. Proceedings of the 14th biennial southern silviculture research conference. Gen. Tech. Rep. SRS-121. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station: 609-612.

Zon, R. 1907. Management of second growth in the Southern Appalachians. Cir. 118. Washington, DC: U.S. Department of Agriculture Forest Service: 1-22.

Zon, R.; Scholz, H.F. 1929. How fast do northern hardwoods grow? Res. Bull. 88. Madison, WI: University of Wisconsin, Agricultural Experiment Station. 34 p.