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Mortality, scarring, and growth in an oak woodland following prescribed fire and commercial thinning in the Ozark Highlands

C.S. Kinkead [a,*], M.C. Stambaugh [a], J.M. Kabrick [b]

[a] Department of Forestry, School of Natural Resources, University of Missouri, 1111 Rollins Ave, Columbia, MO 65211, United States
[b] USDA Forest Service, Northern Research Station, 202 Anheuser-Busch Natural Resources Building, Columbia, MO 65211, United States

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ABSTRACT

Oak-dominated (*Quercus* Spp.) woodlands are commonly thinned and burned in the Ozark Highlands to prevent canopy closure and regenerate desired species, despite a lack of information regarding tree mortality, scarring, and growth in residual stands. Our study compared stand- and tree-level responses after two prescribed burns across four treatments: control, burn, thin, and thin + burn. Results showed that two prescribed fires led to 19% greater cumulative mortality than in unburned stands. In the burn treatment, 19.3% of residual live overstory trees were scarred, compared to 32.4% of trees in the thin + burn treatment. Analysis of scar area revealed that thinning before burning significantly increased the surface area (cm^2) of fire scars. In general, trees in the red oak group (*Erythrobalanus* spp.) had the greatest percentage of scarred trees, followed by the white oak group (*Leucobalanus* spp.), hickories (*Carya* spp.), and shortleaf pines (*Pinus echinata* Mill.). Our data indicate that two fires did not significantly decrease the radial growth of white oaks, except in stands which were thinned prior to prescribed burns. Average percent change in ring-widths (mm) suggest a 1.9% growth decrease in control, 1.4% decrease in burn, 84% increase in thin, and a 35% increase in thin + burn. Covariates such as age, slope, surrounding basal area, canopy openness, and fire scars were analyzed, but tree diameter was the only significant predictor of growth response. Overall, results suggest that effects of prescribed burning are more pronounced in thinned stands as a function of increased fuel loads and fire intensity, causing greater mortality, fire scarring, and reductions in potential growth than fire or thinning alone. This study highlights important tradeoffs between prescribed fire and thinning in oak dominated ecosystems, especially where fire related damages are in potential conflict with other stand objectives.

1. Introduction

Oak (*Quercus* spp.) ecosystems across the central and eastern U.S. are actively managed with silvicultural thinning and prescribed fire to address changes in stand structure and species composition (Dey et al., 2010; Brose et al., 2014). In the Ozark Highlands region of Missouri, thinning and burning are used to promote open and closed woodlands (Kabrick et al., 2014; Dey et al., 2016), characterized by large, full-crowned oaks, hickories (*Carya* spp.), and shortleaf pines (*Pinus echinata* Mill.), and diverse layer of forbs, grasses, shrubs, and seedlings (Packard, 1993; Nelson, 2012). Departure from historical fire regimes and the legacy of intensive timber harvests has caused oak woodlands to become more dense (Hanberry et al., 2014), and reduced the importance of fire-adapted vegetation in the herbaceous and regeneration strata (Guyette and Dey, 1997; Nelson, 1997; Hanberry, 2014). Reintroduction of fire into oak woodlands has been suggested to improve oak and pine reproduction (Stambaugh et al., 2007; Fan et al., 2012), restore desired ground flora compositions (Hutchinson et al., 2005; Kinkead et al., 2013), and reduce fuel loads (Kolaks et al., 2004; Stambaugh et al., 2006); however, current woodland management strategies still lack information regarding the appropriate timing (Dey and Schweitzer, 2015) and spatial scale (Stambaugh et al., 2016) of prescribed burning, especially where oak shelterwood harvests or other commercial removals are combined to meet structural and economic stand objectives in a timely manner (Dey and Kabrick, 2015). Stakeholders are concerned that the reintroduction of fire and continued periodic burning during woodland tending phases, without consideration or protection of the residual overstory, could result in unnecessary degradation and premature mortality of trees.

* Corresponding author at: Department of Forestry, University of Missouri, 1111 Rollins Ave, Columbia, MO 65201, United States.

E-mail addresses: Carterkinkead@mail.missouri.edu (C.S. Kinkead), stambaughm@missouri.edu (M.C. Stambaugh), jkabrick@fs.fed.us (J.M. Kabrick).

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Overstory trees are critical to the ecological function of oak woodland communities, and are increasingly managed for multi-resource objectives such as mast production, aesthetics, carbon sequestration, biomass production, understory biodiversity, wildlife habitat, and other ecological services (Johnson et al., 2009; Dey et al., 2010). Indeed, several wildlife taxa (*Myotis* spp., *Rana* spp., *Accipiter* spp., *Otus* spp.) depend on the overstory component within the forest-grassland continuum for nesting, foraging, protection, and roosting (Evans and Kirkman, 1981; Thompson et al., 2012; Harper et al., 2016; Silvis et al., 2016). Temple (1998) investigated 410 animal species in the savanna-woodland ecotone across 10 states in the Midwest, and found that the largest percentages of vertebrates (48%) and invertebrates (52%) had affinities with the deciduous forest biome, suggesting the importance of woodland canopy trees. While prescribed fire is important for maintaining the ecotonal properties (i.e. structural complexity, forage variety) that allow the distributions of several prairie, forest, and savanna-woodland specialists to overlap in a single stand (Gaskins, 2005; Grundel et al., 2007), managers are still seeking burn prescriptions that optimize woodland habitat (Harper et al., 2016) and minimize tree damage (Dey and Schweitzer, 2015; Stambaugh et al., 2017) when restoring fire regimes in oak communities.

Although oak woodlands managed with prescribed fire can produce merchantable saw logs, ties, and blocking material (Kabrick et al., 2014), timber production objectives are often secondary to restoring fire as an ecological process in oak woodland management (Brose et al., 2014). This has caused much contention regarding prescribed fire in the Ozark Highlands and throughout the eastern US, where a decline in merchantable volumes due to fire-induced mortality, bole damage, or reduced growth could affect local economies that rely on forest products (MFPA, 2013). In Missouri, growing stocks of commercially important species are disproportionately found in the Ozark Highlands, including up to 64% of white oak (*Quercus alba* L.), 72% of post oak (*Quercus stellata* Wangenh.), 80% of black oak (*Quercus velutina* L.), 92% of scarlet oak (*Quercus coccinea* Münchh.), and 90% of shortleaf pine (Miles, 2013). As much of the red oak group (*Erythrobalanus* spp.) approaches maximum ages (Kabrick et al., 2004), the commercial potential of many oak woodlands is likely greater now than during any time in the last century, particularly where fire suppression and forest management have reduced live cull percentages (Dey and Schweitzer, 2015). Wounding or killing overstory trees when using prescribed fire would not only devalue timber commodities (Marschall et al., 2014), but also increase the likelihood for stand regeneration failures, encroachment of competing vegetation, and surface fuel accumulations that undermine restoration efforts (Dey et al., 2010). Still, as evidence that continued fire exclusion may be related to declining oak-dominance (Spetich and He, 2008; Fei et al., 2011) and the loss of biodiversity in oak ecosystems (Rodewald, 2003, McShea et al., 2007; Jones et al., 2008), acreages under prescribed fire management continue to increase on public and private lands (Melvin, 2015).

When developing and implementing woodland management strategies, especially first-entry prescribed burns, it is important to recognize the potential for increased tree mortality, stem wounding, and altered growth of the residual overstory. Though several studies indicate that removal of woody vegetation promotes re-growth of small diameter trees and sprouts (Dey and Jensen, 2002; Kabrick et al., 2002), some evidence suggest that by preferentially removing small mid- and understory species with thinning or fire, overstory trees benefit from the reallocation of sunlight and water (Parker and Muller, 1982; Ko and Reich, 1993; Iverson and Hutchinson, 2002; Anning and McCarthy, 2013). Brudvig et al. (2011) showed tree growth in remnant oak woodlands maintained with prescribed fire and mowing exceeded growth in stands encroached by fire-sensitive species, and that thinning non-oaks and small diameter stems increased radial growth increments of residual white oaks. Transient nutrient releases following prescribed burns have also reportedly led to increased productivity and tree growth in oak-dominated stands (Boerner et al., 1988; Franklin et al., 2003; Scharenbroch et al., 2012). In contrast, several studies imply that burning may in fact reduce growth and vigor of residual trees, accelerate tree mortality, and devalue timber resources (Loomis, 1974; Shigo, 1984; Brose and Van Lear, 1999; Marschall et al., 2014). A combination of wildfire and prescribed fire reduced timber volumes 38% and caused an average 47% value loss per acre in Kentucky and Tennessee, with 72% of economic losses resulting from long-term structural and composition changes rather than cull deductions from fire damage (Stringer et al., 2011). Similar conclusions were drawn by Knapp et al. (2017), who showed that fire scarring resulted in less than 3% value loss in stands after 60 years of prescribed burning, however, stumpage values were approximately 30–35% greater in unburned stands because they retained a greater volume of high-value red-oak species, and lesser volume of low-value post oaks than in burned stands. Thus, managers should be informed and prepared for the response of overstory trees in terms of stand-level mortality, scarring, and growth, especially where the commercial value of timber products are used to fund restoration and maintenance of oak ecosystems (Schroeppel, 2004).

To address some of the questions related to prescribed fire management, we examined cumulative mortality, scarring, and radial growth of trees following low- to moderate intensity surface fires in thinned and unthinned oak woodlands in the Ozark Highlands Ecoregion of southeastern Missouri, USA. We hypothesized that prescribed fires would increase scarring and cumulative mortality of fire-sensitive species groups, especially small-diameter trees. We also expected that removal of smaller, non-oaks following prescribed fire and commercial thinning from below would result in increased radial growth of residual white oaks. White oak is managed for its economic and wildlife value throughout the central and eastern U.S., therefore findings should apply in oak ecosystems where thinning and burning are used for a variety of stand objectives. The response of trees to thinning and prescribed burning is particularly important in oak woodland management because compromising the residual overstory during tending operations might require adaptive management approaches, such as shifting emphasis toward recruitment of canopy replacement trees (Brudvig et al., 2011; Kabrick et al., 2014). This information is intended to guide prescribed fire management in oak ecosystems where changes in composition, structure, and function are determined by the response of residual overstory trees in commercial and non-commercial stands.

2. Methods

2.1. Site description

Three sites were selected, each fully stocked oak-hickory and oak-pine forests owned and managed by The Missouri Department of Conservation. Prior to our first treatment in 2002, there was no indication of past management or fire on the landscape for over 40 years. Each site occurs within the Black River Oak/Pine Woodland/Forest Hills Landtype Association, characterized by steep, dissected hillslopes and occupied by second growth forests (Nigh and Schroeder, 2002). Mean annual precipitation is typically about 100–120 cm, with temperatures averaging between 2.9–4.7 °C in winter months, and 16.3–25.5 °C in summer months (NCDC/NOAA). Elevations on each site range from 160 to 360 m above sea level. Site quality is relatively low, with the most productive sites on protected, north-facing aspects (*Quercus velutina* L., site $index_{50}$ = 22–23 m) and the least productive sites on exposed, south-facing aspects (*Quercus velutina* L., site $index_{50}$ = 20–21 m) (Kabrick et al., 2002). Soils in the higher slope positions formed in parent material derived from sandstones and cherty dolomites of the Roubidoux and Gasconade formations, and are generally highly weathered Ultisols, including the Series Poynor (loamy-skeletal over clayey, siliceous, semiactive, mesic Typic Paleudults), Scholton (loamy-skeletal, siliceous, active, mesic Typic Fragiudults), and Clarksville (loamy-skeletal, siliceous, semiactive, mesic Typic Paleudults) (Kabrick et al., 2002). Soils on the lower slope positions are less weathered Alfisols which formed in clayey residuum of the Gasconade formation, and include the Series Alred (loamy-skeletal over clayey, siliceous, semiactive, mesic Typic Paleudalfs) and Rueter (loamy-skeletal, siliceous, active, mesic Typic Paleudalfs) (Kabrick et al., 2002). For more detail regarding site characteristics, study design, and treatments see Kinkead et al. (2013).

2.2. Study design and treatments

We used a split-split design, replicated across three 25-hectare blocks. The experimental design includes two levels of prescribed burn treatments (BURN or no-burn), each applied to one of two treatment units. Whole plot treatment units were split at two levels for commercial thinning treatments (THIN or no-thin), and split again to include three aspects: north-facing slopes (aspect 315 to 45 degrees), ridge tops (slopes < 8 percent), and south-facing slopes (aspect 135 to 225 degrees). In summer and fall of 2002, thinning treatments were implemented to create woodland structure and composition, with efforts made to retain large dominant and codominant white oak (*Quercus alba* L.) and shortleaf pine (*Pinus echinata* Mill.). Thinning was conducted from below, removing small diameter stems until achieving the residual density goal of 40 percent stocking (Gingrich, 1967).

On April 22–23, 2003, the first prescribed burns were performed using the ring-fire method and strip-fire method along ridge-tops. The second prescribed burn was conducted 2 years later for blocks 1 and 2 (March 12–15, 2005), and 3 years later (April 4, 2006) for block 3. Rate of spread and fireline intensity were estimated using two correlated equations developed by Byram (1959) and by Nelson (1986), each based on different constants for local fuel type, heat of combustion, and fuel consumed. Estimates of fireline intensity, flame height (each fire), and the rate-of-spread (first fire only) are summarized in Table 1.

2.3. Vegetation sampling

In the summer of 2001, three overstory plots (0.134 hectare) were placed at random on each aspect (north, south, and ridge) for all treatments in each block. Small (12–25 cm DBH), intermediate (26–40 cm DBH), and large trees (>40 cm DBH) were recorded by species and assigned a status (live or dead). All saplings (<11 cm DBH) were sampled in sub-plots (0.0008 hectare) along the same permanent transects. Vegetation was re-inventoried in the summers of 2003 and 2006, and again in 2012 following a 5- to 6-year fire-free interval. In summer 2012, canopy openness was estimated from photos taken with a hemispherical lens in each overstory plot (Frazer et al., 1999). Fire scars that were present in 2012 were tallied according to type (Fig. 1) and measured dimensionally to calculate the surface area of each scar. No fire scars could be identified in CONTROL or THIN units, therefore it was assumed that all scars in the BURN and THIN + BURN treatments resulted from prescribed fire.

2.4. Tree growth

In summer 2011, increment cores were collected within each overstory plot from two canopy dominant or codominant white oaks in each treatment unit. White oak was selected because it was abundant in all treatment units, easily crossdated, and well-understood with regard to increases in radial growth following commercial thinning (Rubino and McCarthy, 2004). For each cored tree, additional information related to tree growth was collected including diameter at breast height (DBH), and the percent slope, aspect, and basal area immediately surrounding the tree (determined with 10-factor prism). When possible, we attempted to collect data from one tree with a fire scar, and one without. Where there were fire scars present on burn treatments, size and type of each scar was recorded. In the laboratory, all 216 cores were mounted and finely sanded (1200 grit). Ring widths were measured to the nearest 0.01 mm using a microscope and stage micrometer.

From each core, we estimated the ring-width change (RWC) (Lorimer and Frelich, 1989; Cook and Kairiukstis, 1990; Nowacki and Abrams, 1997). This technique, referred to as the percent-increase method, compares the average ring-width of a fixed time interval (or running mean) to the average ring-width of a subsequent interval:

$$RWC = \frac{M_2 - M_1}{M_1} \times 100 \quad (1)$$

where RWC is percent growth change in ring-width, M_2 is the mean annual radial growth of the period of interest, and M_1 is the mean annual radial growth of the preceding period (Lorimer and Frelich, 1989; Nowacki and Abrams, 1997; Rentch et al., 2002). In this case, we used medians (M_1, M_2) instead of means for more precise estimates of central tendency to account for the non-normal distribution of ring-width (Rubino and McCarthy, 2004). Tree-ring series were then classified as having either "moderate" (51–100% RWC) or "major" (>100% RWC) growth responses according to Lorimer and Frelich (1989).

In addition, ring-width data were also converted to basal area increment (BAI). BAI is often preferred in dendrochronology for

Table 1
Fire behavior parameters averaged across blocks in 2003 (Kolaks et al., 2004), and 2005–2006 (Kinkead et al., 2013).

	Treatment	Rate of spread		Fireline intensity		Flame height
		Nelson[a] cm/min	Byram[b]	Nelson[a] BTU/m/s	Byram[b]	cm
1st fire (2003)	Burn	73	37	141	72	50
	Thin + Burn	110	58	249	135	61
2nd fire (2005/2006)	Burn	ND[c]	ND	92	46	38
	Thin + Burn	ND	ND	236	131	46

[a] Based on an equation by Nelson (1986).
[b] Based on an equation by Byram (1959).
[c] ND = Not Determined.

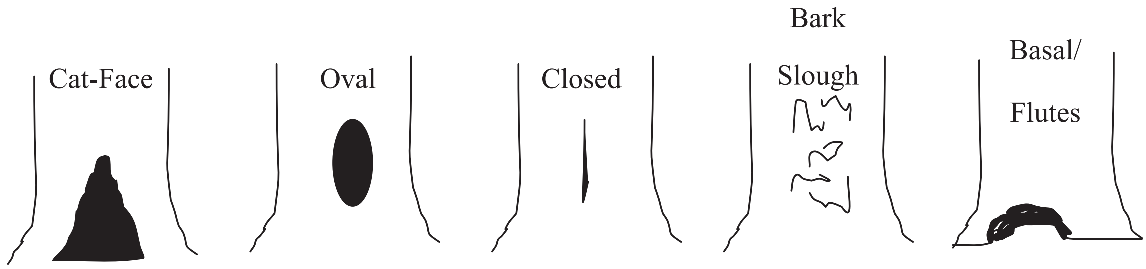

Fig. 1. Scar type used to classify fire scars from prescribed burning.

quantifying wood production, offering estimates of absolute growth when sampled trees vary in age or size in different stands (Visser, 1995; Rubino and McCarthy, 2000; Rentch et al., 2002). By accounting for increased tree diameter, BAI captures the additional volume added annually by each tree, whereas raw ring-width can mask the increased growth as a tree gets larger and older (Fulé et al., 2005; Johnson and Abrams, 2009). Because BAI increases with increasing tree diameter, values are usually detrended prior to making pre- and post-event growth comparisons (Cook and Kairiukstis, 1990; Wyckoff and Clark, 2005). We detrended our data by fitting a line that was derived from the linear regression of average pre-treatment BAI for all trees. Predicted BAI values were subtracted from actual BAI for every living year of each individual tree, similar to standard detrending techniques applied to raw ring-widths (Cook and Kairiukstis, 1990). Residual values for each year then supply a median for pre- and post-treatment intervals (M_1 and M_2). Fraver and Palik (2012) showed that when expressed as a percent, changes in growth may be overly-sensitive to high or low growth rates prior to a disturbance event, and suggest using differences instead. Therefore, rather than calculating percent change ($M_2 - M_1/M_1$) with BAI values, we simply subtracted pre-treatment median annual BAI from post-treatment (M_2-M_1).

To find the best fit for our data, pretreatment intervals of 8, 10, 15, 25, 50, and 100 years (Fig. 2) were considered. There was minimal difference in median BAI's among these intervals, so for the purpose of this study we calculated median BAI values for 10 year pre- and post-treatment intervals, and used the difference as the response variable. A review of current literature found that 10 year intervals were commonly used for detection of growth increases due to intermediate canopy disturbance in the central hardwoods region (Lorimer and Frelich, 1989; Nowacki and Abrams, 1997; Rentch et al., 2002; Rubino and McCarthy, 2004).

2.5. Statistical analysis

For each plot combination in 2003 and 2006 (after each fire), the proportion of dead standing trees (cumulative mortality) was analyzed using a general linear mixed modeling procedure (Proc GLIMMIX, SAS version 9.3, SAS Institute, Cary, NC). Values were tested in a repeated mixed model where BURN treatment, THIN treatment, aspect, and year were fixed effects and block was the random effect. BURN treatment (whole plot) was tested with the burn x block as the error and thin treatment and aspect (split plots) were tested with the thin x aspect x burn x block interaction. Year was tested as a repeated effect using the residual error (year x thin x aspect x burn x block). Significant ($\alpha = 0.05$) differences in cumulative mortality were determined by comparing Tukey's Least Squares means (LSmeans).

Logistic regression was used to compute the probability of scarring trees as a function of the treatment (BURN vs. THIN + BURN), and aspect. The binary response (scarred or unscarred) was analyzed using the general linear mixed modeling procedure (Proc GLIMMIX). For this analysis, we used the 2012 data set that includes scar observations from a single year. The model used to test the data was similar to the one described previously except

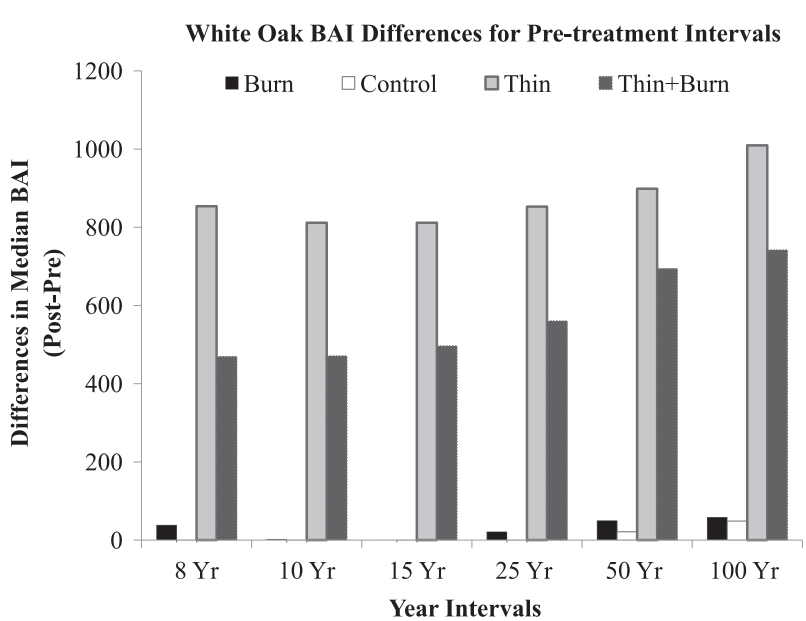

Fig. 2. Differences in median BAI for various pre-treatment intervals averaged by treatment.

that it did not include the year effect. We also examined the percent scarring by species group using this model. Lastly, scar area was tested as a function of treatment, DBH, and species group.

RWC and differences in median BAI (pre-post treatment) were also analyzed in a similar mixed model for all treatment combinations to assess changes in growth. Burn, thin, and aspect were fixed effects and block was the random effect. Error for the BURN treatment was burn x block interaction, and residual error (tree x thin x aspect x burn x block) was used for thin, aspect, and all interactions. These models included the covariates DBH, aspect, percent slope, canopy openness, tree age, surrounding basal area, presence of scars, and scar size (Table 2). All variables included in the growth analysis were also included in a Pearson's correlation matrix (Table 3) and assigned coefficients to detect multicollinearity (Proc CORR, SAS version 9.3, SAS Institute, Cary, NC)

3. Results

3.1. Cumulative mortality

The two prescribed fires conducted in this study increased cumulative mortality at the stand-level. LSmeans comparisons showed significant mortality differences between BURN and CONTROL stands in 2003 ($P = 0.002$), and 2006 ($P < 0.001$). Compared to CONTROL, the BURN treatment increased the cumulative mortality by 18–20 times ($P = 0.042$; Fig. 3). Compared to the THIN treatment, the THIN + BURN treatment increased the cumulative mortality by 30–35 times ($P < 0.001$). THIN + BURN stands also had significantly greater mortality than BURN stands after the first and second prescribed fires were conducted ($P < 0.001$ and $P = 0.031$, respectively). While not significant, mortality on south aspects was nominally greater than on north aspects and ridges.

Cumulative mortality was inversely related to DBH in all BURN and THIN + BURN treatments. The 2003 prescribed fires caused 26% mortality of saplings (<11 cm DBH) in BURN stands, and 54% in THIN + BURN stands. After the 2006 prescribed fires, sapling mortality increased to 35% and 58% in BURN and THIN + BURN treatments, respectively. Saplings had an average of 16% greater mortality than small trees (12–25 cm). Intermediate (26–40 cm) and large trees (>40 cm) were the least affected by two prescribed fires, where BURN treatments caused less than 10% mortality in intermediate trees and less than 5% in large trees; however, thinning these stands prior to ignition (THIN + BURN) led to 28% mortality of intermediate trees, and 15% of large trees.

On average, the red oak group was scarred more frequently following prescribed burning than the white oak group (*Leucobalanus* spp.), regardless of size (Table 4). Mortality in stems <12 cm DBH was 12% greater in red oaks than white oaks after one fire, and 23% greater after two fires. Red oaks >12 cm DBH had 6% more snags after the first burn than the white oak group, and 11% more snags after the second burn. Similar trends were observed in THIN + BURN stands, where cumulative mortality of the white oak group increased approximately 9% following the second prescribed fire. Scarlet oaks >12 cm DBH had more than double the dead:live ratio of black oaks, which were the most abundant oak species. Hickories and shortleaf pines <12 cm DBH were the only species with reduced mortality in THIN + BURN treatments after the second fire, as there were considerably fewer stems after the first fire (Table 4). Intermediate and large shortleaf pines had greater cumulative mortality than any members of the white oak group in the THIN + BURN treatments, with the exception of the white oak group in BURN stands following the second fire.

3.2. Fire scarring

Because cambial injury due to prescribed burning may take one or more growing seasons to produce a visible fire scar (Hare, 1965; Smith and Sutherland, 2001) we calculated the probability of BURN and THIN + BURN treatments producing one or more visible scars 5–6 years post-fire. The probability of scarring was significantly greater ($P =< 0.001$) in the THIN + BURN (probability = 0.29) treatment than in the BURN treatment (probability = 0.17). The BURN treatment resulted in 19.3% of live overstory trees scarred, compared to 32.4% of trees in the THIN + BURN treatment (Fig. 4). In general, species in the red oak group had the greatest percentage of scarred trees, followed by the white oak group, hickory species, and shortleaf pines (Fig. 4), however, species group did not significantly influence the probability of scarring. The category "other" species, dominated by blackgum, elm, and dogwood, was the only group with greater scar frequencies in BURN treatments than in THIN + BURN (Fig. 4), as most of these species were mechanically removed from THIN + BURN stands prior to prescribed fires. Only the red oak group had significantly greater scar frequencies in the THIN + BURN treatment ($P = 0.001$). Shortleaf pines were the least scarred trees with 6.3% and 13.2% in BURN and THIN + BURN stands, respectively.

Of 316 total scarred trees in both treatments, only 3% had more than one discernible fire scar (three in the BURN and eight in the THIN + BURN). Scar frequencies were significantly greater on south-facing slopes than on north-facing slopes ($P = 0.013$), although aspect did not appear to influence the size of scar wounds on individual trees. In contrast, thinning before burning significantly increased the surface area (cm^2) of fire scars ($P = 0.017$). On average, scar sizes in THIN + BURN stands were twice as large as in BURN stands for live trees, and over six times as large in trees that were killed by fire (Table 5). Tree diameter and surrounding basal area were not related to scar size. The only species with significantly different average scar sizes were white oak and dogwood ($P = 0.020$).

"Cat-face" scars were the most common scar type recorded, comprising 40% of scars found on live trees in BURN treatments, and 37% in THIN + BURN (Table 5). Although not shown, over half of the scars recorded on dead trees were also cat-face. Closed

Table 2
Summary of variables used to model growth.

Variable	Mean	Std Dev	Minimum	Maximum
BAI difference	310.4	738.41	−939.9	4236
Tree diameter (cm)	37.9	10.46	11.8	85.3
Tree age (years)	97	32	39	258
Percent canopy openness (%)	16.2	7.26	5.1	41.1
Surrounding basal area (m^2/ha.)	14.6	8.27	0	39.03
Aspect[a]	1.0	0.69	0.02	1.99
Percent slope (%)	22.0	10.53	0	54
Number of scars on tree	0.4	0.65	0	2
Scar size (cm^2)	1605.1	1445	18	8352

[a] Aspect is transformed according to Beers et al. (1966); cos (45°-aspect) + 1.

Table 3
Pearson's correlation coefficients (prob > |r| under h0: rho = 0, n = 216) among variables related to tree growth.

	BAI difference	Tree diameter (cm)	Tree age	Percent slope	Percent canopy openness	Aspect	Surrounding basal area	Scar area (cm^2)	Number of scars
RW% change	0.09 (0.19)	−0.07 (0.33)	**−0.19** **(0.01)**	**−0.14** **(0.03)**	0.08 (0.22)	**0.17** **(0.01)**	**−0.19** **(0.01)**	0.08 (0.22)	−0.02 (0.83)
BAI difference		−0.09 (0.21)	**−0.19** **(0.01)**	**−0.21** **(<0.01)**	**−0.14** **(0.04)**	0.12 (0.08)	**−0.42** **(<0.001)**	0.05 (0.47)	−0.1 (0.15)
Tree diameter (cm)			**0.54** **(<0.001)**	−0.08 (0.24)	**−0.21** **(<0.001)**	−0.08 (0.26)	−0.09 (0.21)	**0.15** **(0.03)**	−0.03 (0.69)
Tree age				**0.21** **(<0.01)**	**−0.15** **(0.03)**	−0.07 (0.32)	**0.17** **(0.01)**	−0.04 (0.53)	−0.09 (0.19)
Percent slope					0.02 (0.8)	0.05 (0.48)	**0.16** **(0.02)**	−0.09 (0.17)	−0.07 (0.34)
Percent canopy openness						−0.13 (0.06)	**−0.17** **(0.01)**	0.11 (0.12)	**0.29** **(<0.001)**
Aspect							−0.06 (0.35)	0.11 (0.1)	−0.04 (0.58)
Surrounding basal area								**−0.2** **(<0.01)**	**−0.25** **(<0.01)**
Scar area (cm^2)									**0.52** **(<0.001)**

Significant correlations are indicated in bold.

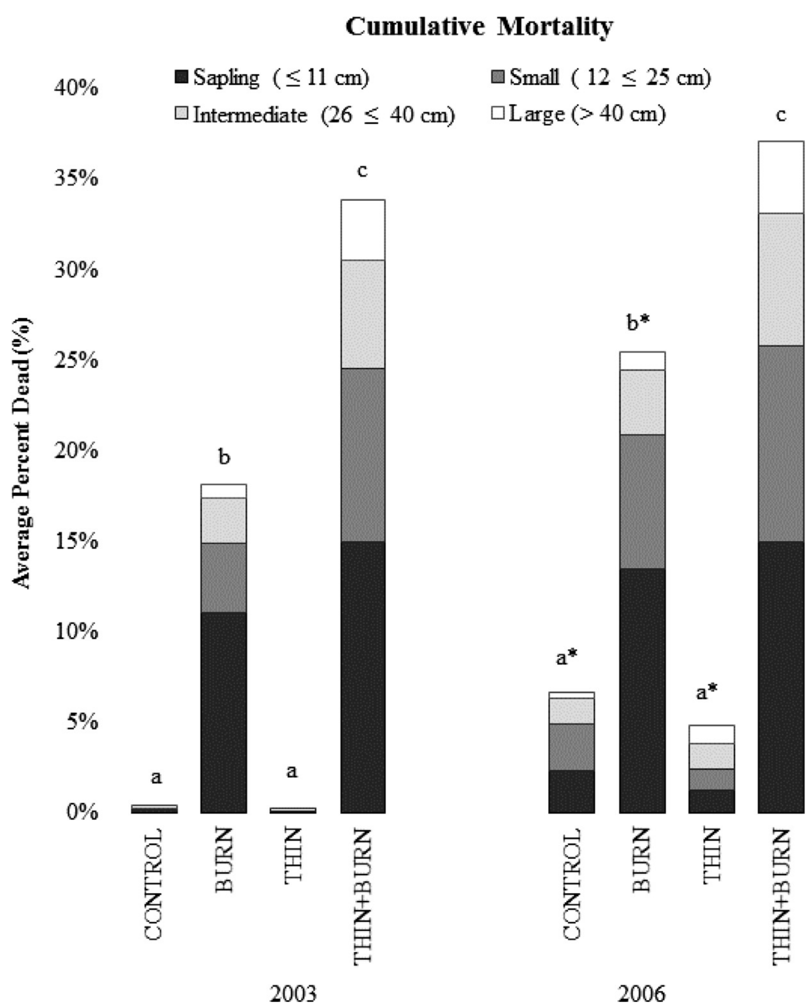

Fig. 3. Cumulative mortality of trees in upland oak woodland restoration sites of the Missouri Ozarks. Measurements were made in 2003 and 2006 following prescribed burn treatments. [1]Letters indicate significant differences between each treatment [2]Asteriks indicate significant differences from 2003 to 2006 within each treatment.

and oval scars were the next most abundant scar types, each comprising approximately one quarter of the scars on live trees in BURN stands. Oval scars also had the largest average scar size among live trees in BURN stands, despite "bark slough" more than doubling the average size of any other scar type in any other category. For both treatments, the smallest scar type was closed.

Table 4
Relative percent mortality for selected species after each burn, including the total number of trees (n) for each.

	One prescribed burn 2003				Two prescribed burns 2005–2006			
Trees ≤ 11 cm in diameter (DBH)	Control	Burn	Thin	Thin + Burn	Control	Burn	Thin	Thin + Burn
White oak	0.4%	28.5%	0.8%	43.3%	9.9%	36.5%	2.6%	59.3%
(*Quercus alba* L.)	284	323	120	60	283	301	116	59
Post oak	–	25.0%	–	30.0%	8.3%	45.0%	12.5%	62.5%
(*Quercus stellata* Wangenh.)	45	20	4	10	36	20	8	8
Black oak	2.0%	45.0%	–	65.2%	22.9%	71.4%	–	66.7%
(*Quercus velutina* L.)	51	40	14	23	35	28	14	12
Scarlet oak	–	37.5%	–	66.7%	35.3%	65.0%	14.3%	100.0%
(*Quercus coccinea* Münchh.)	12	8	3	3	17	20	7	9
Hickory species	–	20.9%	–	52.5%	1.6%	25.9%	1.9%	39.5%
(*Carya* spp.)	305	449	54	120	305	405	53	81
Shortleaf pine	–	16.2%	–	47.4%	1.4%	17.9%	–	37.5%
(*Pinus echinata* Mill.)	293	296	22	19	289	229	28	8
Blackgum	–	16.7%	–	22.2%	60.0%	50.0%	–	–
(*Nyssa sylvatica* Marsh.)	5	6	3	9	5	6	2	4
Elm species	–	17.4%	–	–	4.2%	7.7%	–	100.0%
(*Ulmus* spp.)	104	46	0	1	96	39	0	1
Red maple	0.7%	47.1%	–	33.3%	1.5%	49.4%	–	100.0%
(*Acer rubrum* L.)	146	121	7	3	136	83	6	3
Sassafras	–	56.4%	–	100.0%	17.0%	86.7%	33.3%	100.0%
(*Sassafras albidum* (Nutt.) Nees.)	88	78	10	2	94	98	9	3
Flowering Dogwood	0.4%	20.3%	–	63.6%	11.3%	29.6%	6.5%	80.0%
(*Cornus florida* L.)	495	538	68	11	512	521	77	10
	One prescribed burn 2003				Two prescribed burns 2005–2006			
Trees ≥ 12 cm in diameter (DBH)	Control	Burn	Thin	Thin + Burn	Control	Burn	Thin	Thin + Burn
White oak	0.3%	5.6%	–	20.8%	3.4%	9.0%	2.2%	28.4%
(*Quercus alba* L.)	353	338	184	125	357	356	183	141
Post oak	–	5.13%	–	18.6%	3.1%	9.1%	7.3%	27.9%
(*Quercus stellata* Wangenh.)	76	78	37	59	64	77	41	61
Black oak	0.6%	6.9%	0.7%	27.6%	9.2%	15.2%	9.9%	31.7%
(*Quercus velutina* L.)	341	319	139	214	349	309	131	202
Scarlet oak	1.0%	22.6%	–	49.0%	13.1%	32.6%	8.5%	64.0%
(*Quercus coccinea* Münchh.)	97	115	58	49	130	144	82	75
Hickory species	–	4.4%	–	38.0%	1.5%	11.6%	1.0%	–
(*Carya* spp.)	136	250	94	79	131	258	103	5
Shortleaf pine	–	8.7%	–	25.0%	3.3%	7.7%	–	30.3%
(*Pinus echinata* Mill.)	25	57	2	4	30	65	2	76
Blackgum	1.8%	3.51%	–	2.1%	3.5%	11.9%	–	–
(*Nyssa sylvatica* Marsh.)	110	57	38	48	113	59	33	5
Elm species	–	–	–	–	4.2%	30.0%	–	4.2%
(*Ulmus* spp.)	23	11	0	0	24	10	0	48
Red maple	–	12.5%	–	66.7%	–	11.1%	–	–
(*Acer rubrum* L.)	19	8	1	3	21	9	1	0
Sassafras	–	50.0%	–	–	20.0%	66.7%	–	–
(*Sassafras albidum* (Nutt.) Nees.)	7	4	0	0	10	3	0	0
Flowering Dogwood	4.5%	–	–	–	20.8%	–	–	–
(*Cornus florida* L.)	22	12	5	0	24	11	5	0

3.3. Growth response

3.3.1. Percent-increase method

Treatment averages for RWC indicate that BURN treatments led to an overall 1.5% reduction in growth rate, compared to 1.9% decrease in CONTROL stands (Table 6). Only 5% of white oaks had a moderate growth response (>50% RWC) to BURN treatments, and there were no major growth responses (>100% RWC) after two prescribed fires. Tree growth in CONTROL was not statistically different than BURN treatments, despite having two trees (of 18) with major growth responses. The majority of white oaks in CONTROL and BURN treatments had between 0 and −24% change in radial growth (Table 6). Intermediate size trees had a positive growth trend at 1.6% RWC in CONTROL stands, however, both small and large trees had negative RWC percentages (Table 6). Prescribed BURN treatments caused negative RWC growth responses in all size classes.

THIN treatments resulted in an overall 84% RWC growth increase on average; an effect that was reduced to 35% by subsequent burns that were conducted following the thinning (THIN + BURN). THIN treatments ($P = 0.033$) caused growth increases that were moderate in 22% of trees, and major responses in 28% of trees. By comparison, only 13% of trees showed a moderate growth response to THIN + BURN treatments, and 9% had major growth responses. In THIN + BURN stands, 32% of trees responded negatively to treatments, while only 15% of trees showed reduced growth rates in THIN stands.

3.3.2. Basal area increment differencing method

Overall, two prescribed burns did not significantly change the growth of mature white oaks compared to the control. Commercial thinning ($P < 0.001$), and the interaction between burn and thin treatments ($P = 0.006$) were the only statistically significant effects in the base model (Table 7). Tukey's LSmeans showed that both THIN ($P < 0.001$) and THIN + BURN ($P = 0.008$) treatments had significantly greater radial growth than in CONTROL. Growth in THIN treatments was also significantly greater than in THIN + BURN ($P = 0.007$) and BURN ($P < 0.001$) treatments (Fig. 5). Growth rates did not vary by aspect (i.e. north, ridge, south) in any discernable pattern.

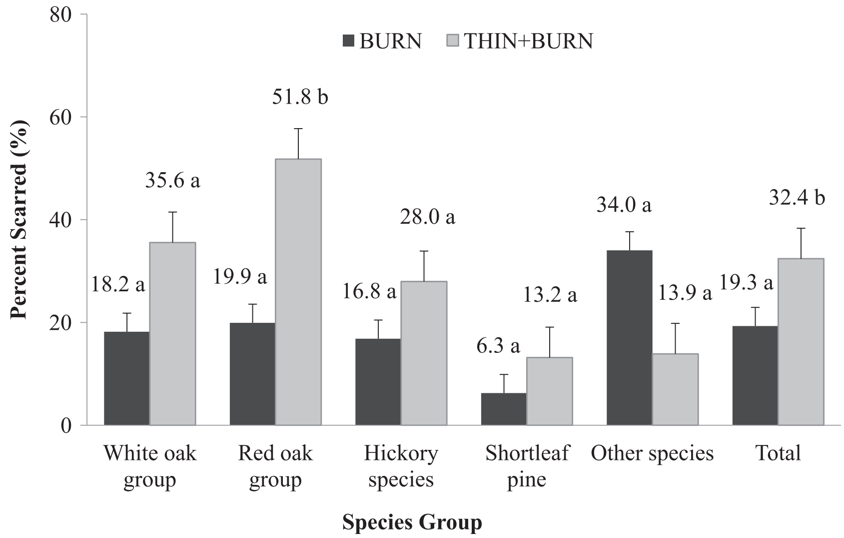

Fig. 4. Percent of scarred individuals within different species groups following two prescribed fires in the Ozark Highlands. [1]Letters indicate significant differences between treatments for each species group.

Table 5
Percentage and average wound size (cm^2) for all fire scar types observed in 2012.

	BURN		THIN + BURN	
	%	cm^2	%	cm^2
Total	19 a	63.5 *	32 b	142.4 *
Type[a]				
Cat face	40	85.4	37	165.4
Oval	26	99.2	17	174.6
Closed	24	11.5	30	23.2
Bark slough	4	55.0	13	221.4
Basal/flutes	6	66.2	3	127.4
Total scarred	*174*		*142*	
Total observed	*904*		*438*	

Significant differences in scar percentages among treatments indicated by lowercase letters.
Significant differences in scar area between treatments indicated by asterisks.
[a] Not analyzed by scar type

Several covariates including aspect, percent slope, canopy openness, surrounding basal area, and tree age were also analyzed, but they did not explain differences in radial growth in addition to treatment. Tree diameter (DBH) was the only significant predictor of growth response in the model (P = 0.003) (Table 7), although it was not correlated to BAI differences in a Pearson's test (Table 3). The relationship between DBH and growth indicates that, on average, small-diameter trees had greater increases in BAI than large-diameter trees. Pearson's correlation analysis showed significant relationships between BAI differences and percent slope, tree age, canopy openness, and surrounding basal area (Table 3). Except for surrounding basal area, the same covariates were correlated with RWC. Overall, the two metrics for growth (BAI differences and percent change in RWC) were not significantly correlated.

No statistically significant difference in growth occurred between trees with fire scars or without. Scarred trees had slightly lower average BAI values before and after prescribed fire in BURN treatments, whereas in THIN + BURN stands the average growth of scarred trees was below that of unscarred trees after the first burn in 2003 (Fig. 6). Although the average scar size was more than twice as large in THIN + BURN stands than in BURN stands (Table 5), the effects of scar area and scar type (Fig. 1) were unrelated to tree growth.

Table 6
Average growth response of three tree size classes within each treatment using both RWC and BAI methods.

Method		Tree size		Control	Burn	Thin	Thin + Burn
		Small	*(12–25 cm DBH)*	−8.0% a	−2.1% a	183.9% a	65.2% a
RWC	Percent change		*(n=)*	1	9	3	6
		Intermediate	*(26–40 cm DBH)*	1.9% a	−1.7% a	133.6% a	53.3% a
			(n=)	35	27	24	26
		Large	*(> 41 cm DBH)*	−6.6% a	−0.6% a	25.1% a	4.7% a
			(n=)	18	18	27	22
		Total	*Avg. RWC*	−1.4% a	−1.1% a	82.1% a	34.8% a
			(n=)	54	54	54	54
BAI	Difference in detrended medians	Small	*(12–25 cm DBH)*	−85.0 a	−18.9 a	1196.0 b	526.9 a
			(n=)	1	9	3	6
		Intermediate	*(26–40 cm DBH)*	−9.2 a	−6.9 b	1053.5 c	677.8 d
			(n=)	35	27	24	26
		Large	*(>41 cm DBH)*	−107.4 a	26.7 a	553.9 b	211.4 a
			(n=)	18	18	27	22
		Total	*Avg. BAI*	2.3 a	−43.3 ab	811.6 c	471.0 b
			(n=)	54	54	54	54

Letters indicate significant differences between treatments for each size class.

Table 7
Recorded P > F values for each variable when added to the base tree growth model (top).

β0 (Intercept)	β1 (Burn)	β2 (Thin)	β3 (Burn*Thin)	β4 (aspect)	βx (dbh)	Bx (surrounding basal area)	βx (age)	βx (slope)	βx (aspect)	βx (canopy openness)	AIC
0.001	0.217	**<0.001**	**0.006**	0.162							311.1
0.001	0.160	**<0.001**	**0.006**	0.103	**0.003**						311.5
0.001	0.184	**0.002**	**0.008**	0.132		0.248					321.1
0.001	0.194	**<0.001**	**0.005**	0.202			0.256				321.8
0.001	0.264	**<0.001**	**0.005**	0.133				0.389			319.5
0.001	0.217	**<0.001**	**0.006**	0.162					0.133		311.1
0.001	0.241	**<0.001**	**0.006**	0.164						0.956	319.7

Significant covariates are indicated in bold.

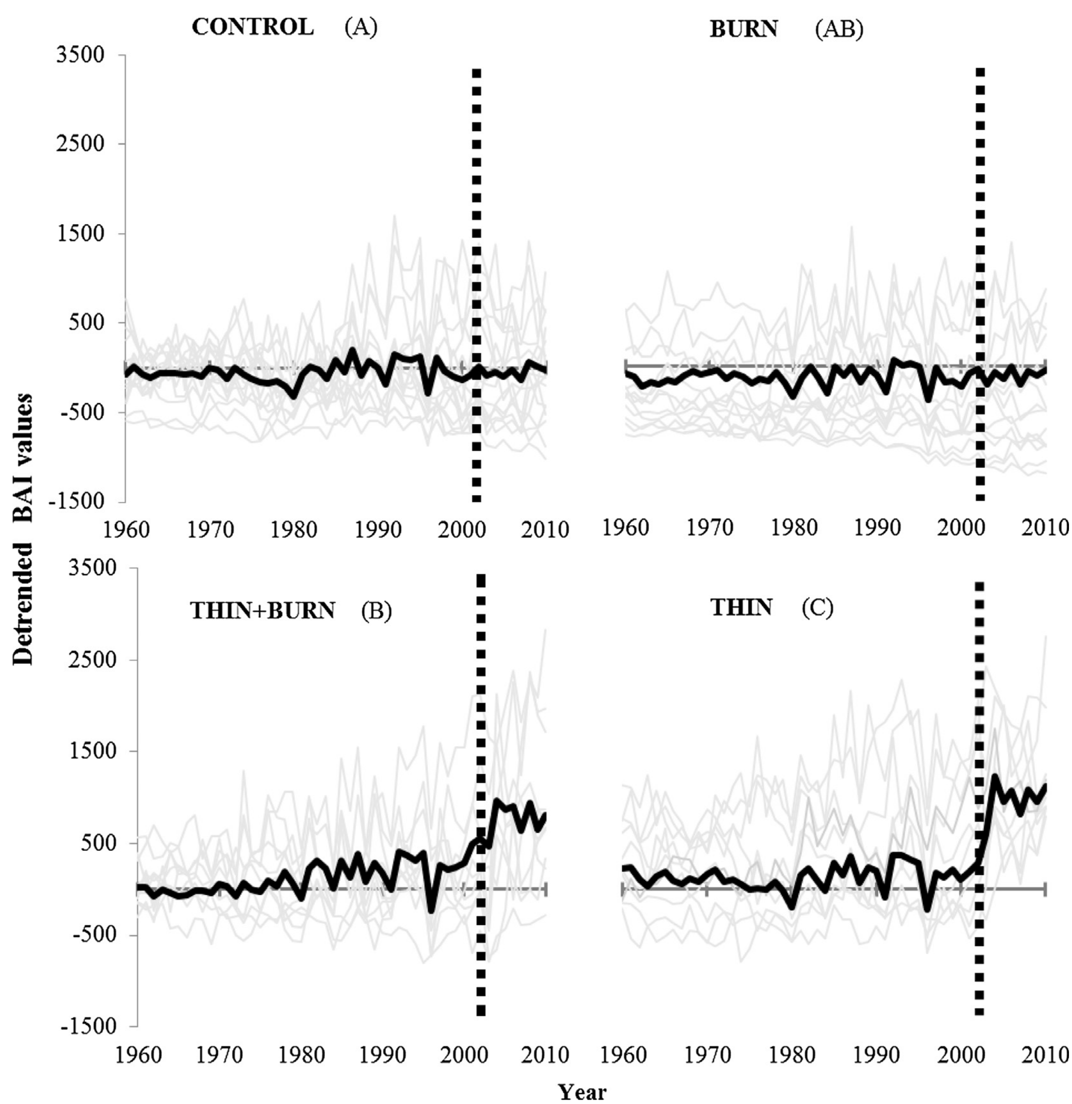

Fig. 5. Individual tree detrended BAI values (population averages in bold). Dotted line delineates pre- and post-treatment periods. [1]Letters indicate significant differences in mean BAI between treatment.

4. Discussion

4.1. Cumulative mortality

Prescribed fire is applied in oak woodlands to reduce the density of small diameter stems from mid and understory strata, while retaining broadly spaced dominant and codominant trees. Our results confirm that trees < 25 cm DBH accounted for 95% of mortality after two moderate intensity (relative humidity ≈ 22.4, mid flame winds ≈ 2.5 mph) prescribed burns, and only 3% of large overstory trees became snags after two fires, compared to 1% in control (Table 4, Fig. 3). These findings are consistent with other studies regarding fire-induced mortality in oak-pine (Arthur et al., 2015) and mixed hardwood stands (Brose and Van Lear, 1999; Hutchinson et al., 2012; Brose et al., 2014).

Commercial thinning (from below) caused no additional mortality to residual trees in a fully stocked oak woodland; however, thinning prior to prescribed burns significantly increased the ratio

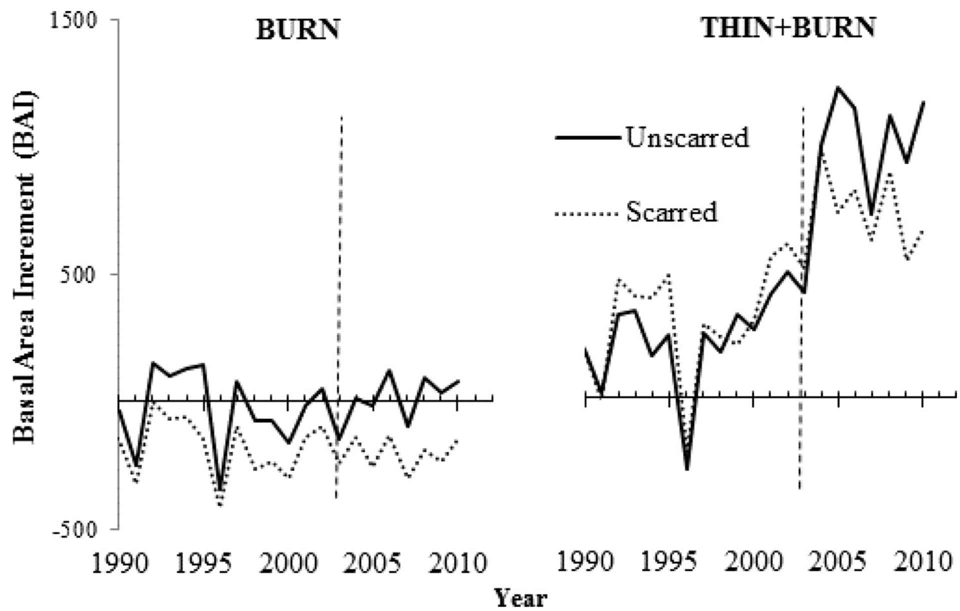

Fig. 6. Detrended BAI averages over time for scarred vs. unscarred trees in each treatment. Dotted line delineates pre- and post-treatment periods.

of dead: live trees in THIN + BURN. Even after mechanical removal of fire-intolerant size classes and species in the mid- and understory, cumulative mortality (Fig. 3) and the basal area of snag trees was greater in THIN + BURN treatments than in BURN treatments. This is likely due to increased fuel loads (up to 300%) which led to greater fire-intensity (Kolaks et al., 2004; Kinkead et al., 2013).

In addition to diameter, adaptations such as bark thickness, ability to sprout from dormant buds, and investment in chemical defense compounds also permit some species, especially in the white oak group, to withstand fire disturbances and maintain a competitive advantage (Hare, 1965; Hengst and Dawson, 1994; Smith and Sutherland, 2001; Black et al., 2008). In this study, post oaks had the lowest cumulative mortality in BURN and THIN + BURN treatments (Table 4), followed by white oaks, which were four times more abundant in these treatments. Scarlet oak had the greatest overall mortality in burned stands, followed by black oaks which were the most abundant overstory species. Similar patterns in mortality have been reported by Paulsell (1957) and Kabrick et al. (2004).

4.2. Fire scarring

Our analysis indicated that THIN + BURN treatments resulted in greater scar percentages than BURN treatments for nearly all species groups. However, mechanical removals of 'other' species prior to prescribed fire in THIN + BURN stands resulted in lower scar percentages of that group compared to BURN stands (Fig. 4). This distinction is important for prescribing fire in thinned woodlands because scar frequencies will reflect the size, density, and composition of trees in the residual stands. In this case, BURN treatments retained more than twice as many trees as the THIN + BURN treatment, especially small-diameter oak-competitors ('other' species) such as red maple, elm, and blackgum. Thus, it is not surprising to find greater scar percentages of 'other' species in BURN treatments where residual stands are more abundant with fire-intolerant species and size classes. Although thinning from below to achieve woodland composition and structure may eventually reduce the likelihood of fire wounding by selecting for larger, fire-tolerant trees (e.g. oak, pine), our findings show that harvest residues altered subsequent fire behavior and increased the scarring effects of prescribed fires in THIN + BURN stands.

Fire scars can leave trees susceptible to pathogens and long-term decay (Loomis, 1974; Berry, 1982; Shigo, 1984), hence, many stakeholders question if fire-managed oak woodlands can sustain enough healthy overstory trees to meet structural and financial objectives through multiple rotations. The only conifer in this study, shortleaf pine, exhibited scar frequencies twice as low as any hardwood group in its' respective treatment, an indication that fire-adaptive traits (i.e. bark properties, needle attributes, oleoresins) are effective against scarring following prescribed burning (Guyette and Dey, 1997; Keeley, 2012). Except for 'other' species, the red oak group was the most susceptible to fire scars following two prescribed burns in our study, with over half of trees having scars in THIN + BURN stands. Research from Missouri reports fire-damaged butt logs of merchantable red oak only lose approximately 10% of their commercial value at a maximum of 14 years between damage and tree harvest (Marschall et al., 2014). If this is assumed applicable to oak stands throughout the eastern US deciduous biome, the cost of scar damage due to prescribed burning is relatively minor, especially since the probability of scarring a tree is only 0.17 in BURN stands. However, this probability nearly doubles if a stand is thinned prior to burning (THIN + BURN, $P = 0.004$), which causes greater fireline intensity and average wound size (Tables 1 and 5).

Although scarred proportionately less than the red oak group, the white oak group was still more susceptible to fire wounds than hickory species or shortleaf pine. Stambaugh et al. (2017) showed that while most fire wounds on mature white oak heal within a decade, wound closure rates can range from 1 to 24 years, varying greatly by scar type (Fig. 1). Our results suggest oval scars are slightly larger on average (Table 2), and seem to confirm that cat-face (triangular) and oval scars are the most common occurring prescribed fire wounds (Stambaugh and Guyette, 2008). Regarding scar size, smaller diameter stems generally have greater cambial damage than do large trees due to lesser bark thickness and lower surface to mass ratio (Hare, 1965; Hengst and Dawson, 1994; Smith and Sutherland, 2001). Yet, despite evidence that fire wound size is related to tree diameter (Guyette and Stambaugh, 2004), scar sizes could not be attributed to DBH in this study. Similar to Stevenson et al. (2008), we also found that wound dimensions reflect localized fire severity which was much greater on south-facing aspects in both studies, although these were not statistically significant relationships in our study.

4.3. Growth response

The application of two prescribed fires did not significantly improve or diminish growth of overstory white oaks examined in this study, except where thinned. This suggests that adaptations to fire disturbance could be more strictly limited to tolerance, rather than a superior ability to capitalize on newly available resources. Moreover, marginal decreases in radial growth (−1.4% RWC) might indicate that fire-induced stress can potentially reduce diameter growth. The reduced growth of white oak in this study may reflect a decrease in available water following prescribed burns, as physical changes such as increased soil hydrophobicity and the removal of moisture-trapping leaf litter are well documented (Scowcroft, 1966; Stambaugh et al., 2006; Ponder et al., 2009). In addition, Boerner and Brinkman (2003) showed that in Ohio, prescribed burning led to extensive loss of recalcitrant organic compounds and reduced enzyme activity. Alternatively, it is possible that potential growth benefits of prescribed fire including increased availability of light, water, and nutrients are not yet evident in our data because of a limited number of growing seasons since the last fires (2005–2006) or canopy disturbance (2009). Between overstory inventories in 2006 and 2012, a derecho occurred on our sites (May 8, 2009) that generated wind speeds as great as 120 km/h, which may have caused enough sufficient overstory damage to prevent our detection of fires' influence on tree growth within the post-treatment interval. According to Foster (1988), recovery of pre-disturbance growth rates can take approximately 5–10 years following fire and severe wind damage in New England forests, as trees adjust to the structural and environmental changes before recouping or even exceeding prior growth rates.

Mechanical thinning of mesic and other late successional species is often coupled with prescribed burning to achieve desired woodland structure and composition (Kinkead et al., 2013; Holzmueller et al., 2014). While the increased growth and other benefits to the residual stand following commercial thinning have long been documented (Gingrich, 1971; Schlesinger, 1978) few studies have reported growth responses to the combination of prescribed fire and thinning. Fulé et al. (2005) showed that thinning increased the growth of the residual trees in stands that were burned in Arizona, but did not compare thin to thin + burn treatments. Anning and McCarthy (2013) compared control, burn, thin, and thin + burn treatments on radial growth of several tree species including black oak, chestnut oak (*Quercus prinus* L.), white oak, hickory, and yellow-poplar (*Liriodendron tulipifera* L.) in southern Ohio. They found that thin + burn treatments caused greater radial growth than in thin-only stands during the first 5 post-treatment years, concluding that the additional reduction of neighboring trees due to prescribed fire likely enhanced tree growth (increased growing space and resource accessibility). Contrarily, our data suggested that significant reductions in radial growth were associated with burning in thinned stands (Fig. 5, Table 7). On average, RWC was 47% lower in stands that were burned 1 and 3 years after thinning. Similarly, BAI differences suggest that the magnitude of growth increases were two times greater in the THIN treatment than in THIN + BURN treatment. Treatment differences in our study and Anning and McCarthy (2013) may be explained by interspecific variation, given that every species in their study *except white oak* responded positively to burn-only treatments 5 years after the prescribed fires. They also suggest that decreasing growth in white oak could be attributed to heavy post-treatment insect defoliation. However, both studies found no significant BAI increases in control or prescribed fire treatments overall. We suspect that the added severity caused by residual fuels after thinning exacerbated stresses on overstory trees caused by burning, therefore reducing growth. Increased stresses may have included loss of fine-root mass (Swezy and Agee, 1991; Varner et al., 2005) and slowed nutrient mineralization (Reich et al., 2001) or leaching.

Many studies have shown that older, often larger, trees respond more conservatively to canopy disturbances such as thinning and burning (Lorimer and Frelich, 1989; Nowacki and Abrams, 1997; Rentch et al., 2002; Fulé et al., 2005; Black et al., 2008). Although age was not statistically important, similar patterns were captured in our data for both age and DBH (Fig. 7). Most likely, significance of DBH ($P = 0.001$) reflects the importance of expressing growth in terms of BAI (diameter-dependent metric), rather than the actual influence of diameter on tree growth. In other words, BAI values are inherently greater for trees in treated stands due to higher average DBH, potentially biasing treatment effects on tree growth (Fulé et al., 2005; Voelker et al., 2008). Taking this into account, a few generalizations can be made about how various size classes respond using both RWC and BAI differencing methods to measure growth response (Table 6). First, burning has the most negative effect on growth of small and intermediate size trees. Second, the response of these size classes to commercial thinning is much greater than in large trees. Overall, the combination of thin and burn treatments increased growth of trees < 40 cm DBH. This may be favorable where mechanical removal is necessary to meet woodland objectives for two reasons, 1) thinning accelerates recruitment of small trees < 25 cm into more fire tolerant size classes, and 2) subsequent burns may be used to kill basal sprouts and ruderal sapling species < 11 cm DBH that respond to mechanical canopy removal (Fig. 3).

As mixed hardwood stands age, crown architecture and species composition can vary substantially, creating a diverse canopy structure with numerous stratified layers (Rentch et al., 2002). Therefore, it is difficult to predict the magnitude in growth response to thinning and burning without information about competition and light conditions for residual trees (Harrison et al., 1986). Many studies, including Rubino and McCarthy (2004), report slowing radial growth as a result of increased canopy closure. Unfortunately, our canopy openness data was collected nearly a decade after thinnings occurred in our study, and did not accurately represent light availability to overstory trees used to analyze growth. Consequently, canopy openness was not helpful in attributing growth increases to canopy disturbances that reduce competition for light (Table 7). Basal area around each stem was also recorded with the intention of explaining radial growth as a function of competition, but decreases in growth due to increased volume around each stem were only marginal.

We found no evidence that additional site variables (Tables 2 and 3) were important in determining tree growth patterns (Table 7). The hypothesis that fire scar size, frequency, and type could be used to predict residual growth following prescribed burning and thinning was not confirmed in this analysis, perhaps due to the overriding effect of other treatment induced changes. Guyette and Kabrick (2002) report similar findings, asserting that while some growth reductions begin in the year that fire scars were formed, no direct association can be made between decreased growth and scarring. Jemison (1943) and Stambaugh et al. (2017) also concluded that scarring had no effect on diameter growth in oak stands. Despite having the greatest scar sizes, long-lived white oaks show only slight reductions in growth compared to unburned or unscarred trees (Figs. 5 and 6)

4.4. Management implications

Prescribed fire is a primary tool for restoring and maintaining oak woodlands, shown to improve herbaceous species diversity and consistently remove small diameter woody vegetation. However, results presented here show that mortality and scarring were significantly increased following two prescribed burns. These find-

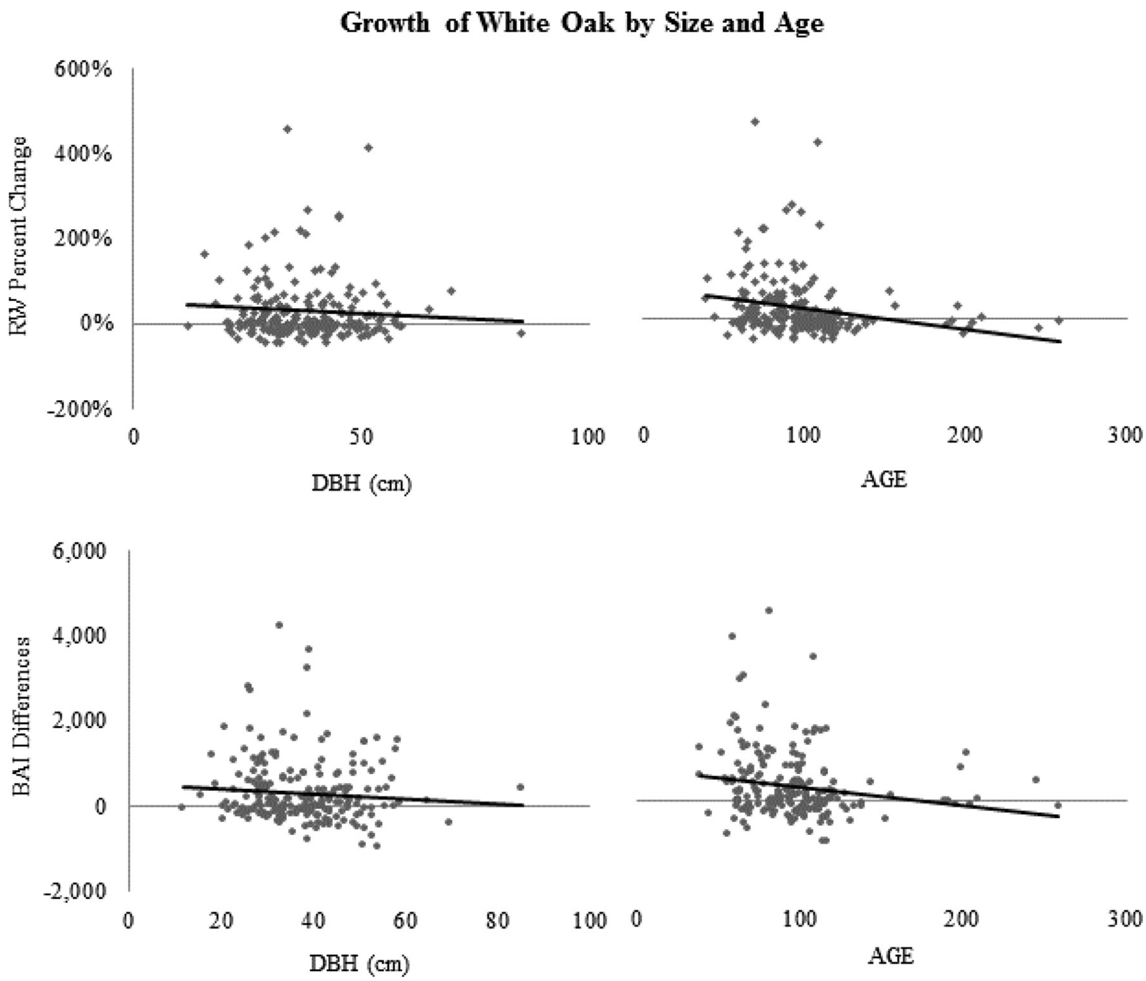

Fig. 7. Growth responses averaged across all treatments to portray size and age dynamics over time Fig. 7. Radial growth responses of 216 mature white oaks show declining growth with increasing tree diameter (left) and age (right), regardless if expressed as ring-width percent change (top) or median BAI difference (bottom).

ings represent a fundamental challenge for managers attempting to restore or maintain the partial stocking levels of oak woodlands; that is finding a balanced disturbance regime capable of re-opening canopy structure without causing damage to residual trees. Our data indicated that prescribed burning has minimal impacts on most overstory trees (>25 cm DBH), especially white oak and shortleaf pine. Nonetheless, damage to smaller trees may reduce recruitment potential and cause substantial shifts in species composition or loss of structural diversity (Knapp et al., 2017).

Although burning may eliminate individuals with less tolerance to fire, it does not ensure that the stand density will be reduced sufficiently to meet the desired stocking goal, or that growing stock which is best suited for woodland habitat will be retained in the conversion from close-canopied stands. As a result, mechanical thinning is also frequently conducted to meet structural objectives in the short-term (mitigating the need to risk higher intensity burns), and to manipulate composition more precisely. However, the subsequent flush of woody re-growth common in thinned stands of the central hardwood region (Dey and Jensen, 2002; Kabrick et al., 2002), can further challenge woodland managers in years that follow. Our data show that smaller size classes typically respond much greater to thinning than do larger trees in terms of radial growth, potentially making it even more difficult to setback woody vegetation during restoration phases of woodland management. Still, burns conducted after thinning cause significantly greater cumulative mortality than burning alone, especially of saplings and small diameter trees. Therefore, repeated prescribed fires should adequately offset the response of young trees over time, depending on the affinity of reproductive sprouts and abundance of maternal propagules in the understory (Arthur et al., 2015). Where thinning is necessary to re-establish structural conditions and/or species composition, managers should account for increased mortality during prescribed burns that follow mechanical removals. Revenue from commercial thinning operations is often used as a source of funding for future management, so it may be important to consider the relative percentages of each tree species, and their respective market values, when exposing designing fire management plans.

5. Conclusion

To sustain oak woodlands through future cutting and burning rotations, prescribed fires must avoid excessive mortality and damage of preferred residual woodland tree species. Retaining an intact partial overstory in managed oak woodlands is critical to the function and biodiversity of each community because residual trees create spatial heterogeneity in microclimate and resource availability (i.e. water, light, nutrients), both above and belowground (Leach and Givnish, 1999; Boerner et al., 2007). Differential accessibility across resource gradients prevent single species dominance by partitioning ecological niches to a greater number of species, increasing overall floral and faunal diversity (Jenkins et al., 1997; Bond and Midgley, 2001; Nakashizuka, 2001). Incidentally or intentionally eliminating excessive numbers of overstory trees may lead to ecological and financial consequences, particularly where commercial thinning is necessary to offset costs associated with woodland management (e.g. removing unmerchantable biomass, prescribed burning) (Schroeppel, 2004). We found that cumulative mortality, scarring, and radial growth of overstory trees > 25 cm DBH were generally unaffected by two prescribed fires. Red oaks tended to have greater mortality and scarring rates than white oaks, hickories, and shortleaf pine, especially where commercial thinning occurred. Thinning treatments significantly increased tree growth, but burning appeared to greatly reduce the added growth benefits of those removals. Although trends in mortality or tree growth could not be attributed to scarring, likelihood estimates of scarring should guide managers with concerns about bole damage. Cumulative mortality rates of diameter classes and species groups reported in this study should be applicable to broader oak ecosystems, and aid in the development of thinning and burning prescriptions for specific restoration objectives.

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