Forest Ecology and Management 531 (2023) 120796

Contents lists available at ScienceDirect

Forest Ecology and Management

journal homepage: www.elsevier.com/locate/foreco

Profiling overstory survival trends following varying thinning and burning disturbance regimes in a mixed pine-hardwood forest in the US South

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ARTICLE INFO

Keywords:
Prescribed fire
Tree mortality
Silviculture treatments
Mixedwoods
Survival analysis
Interval censoring

ABSTRACT

Prescribed burning as a silvicultural tool may be effective for achieving various management objectives, yet some practitioners have concerns about inadvertently increasing overstory tree mortality. Using extensive data from a long-term, ongoing study in northcentral Alabama, USA, that systematically applies a variety of thinning and prescribed burning disturbances on mixed pine-hardwood stands, we assess survival trends for different groups of trees. The primary research question is whether more frequent prescribed burns adversely affects overstory survival versus infrequent or no burns; secondary questions explore whether overstory survival trends differ based on thinning level, species group, or size class. Interest is in broad groups of trees, not individual tree survival or mortality; consequently, survival analysis methods are used, including nonparametric Kaplan-Meier (KM) techniques for examining single grouping factors, and parametric accelerated failure time models for analyzing simultaneous effects of multiple covariates. Leveraging relatively recent methodological advances, the statistical techniques are adjusted for interval censored data. KM survival curves showed that more frequent prescribed fires did not result in differing survival trends. Also, trees in unthinned stands had the lowest 14-year survival compared to thinned stands, oaks had the highest survival compared to pines and the others species group, and the smallest size class of overstory trees had the lowest survival. These results support managing transitional mixed pine-hardwoods using thinning and multiple prescribed fires to restore specific species composition and structure.

1. Introduction

Prescribed fire is widely used to achieve various forest management objectives (Brose, 2014; Arthur et al., 2015), including shifting the forest species mix, promoting regeneration of fire-tolerant species, increasing diversity of wildlife habitat, and reducing hazardous fuels (Calkin et al., 2015; Keyser et al., 2018). Yet, despite the variety of potential benefits, prescribed burns are not without costs, including smoke production, carbon release, risk of escape, and unintended tree mortality (Ager et al., 2013; Calkin et al., 2015; Mann et al., 2020). A special concern is whether prescribed burns are likely to have deleterious effects on overstory trees, which are usually intended to be left intact and uninjured to maintain desired forest structure or preserve future economic value (Mann et al., 2020). A further question is whether repeated burns, as opposed to a single burn, changes the survival prospects for overstory trees. Repeated prescribed fire is used to create and maintain the structure and composition of open forest ecosystems, but understanding about long-term effects on overstory tree mortality is lacking (Arthur et al., 2015; Keyser et al., 2018).

Common high priority management goals in forests in the American South include restoring and sustaining oak-pine (*Pinus* spp.) savannas, woodlands and forests for conservation of biodiversity and viable populations of native flora and fauna (Dey et al., 2017; Dey and Schweitzer, 2018; Johnson et al., 2019). Restoration activities that target shifting stand structure and composition often include low-intensity prescribed fires applied to mature stands, with a goal of altering light conditions in the understory and/or decreasing midstory stem density (Hutchinson et al., 2005; Vander Yacht et al., 2017). However, management objectives frequently cannot be achieved with a single burn for myriad reasons, including: a long history of fire suppression; contemporary forest structure and composition; variations in fire intensities; and vigorous sprouting of top-killed hardwood understories (Arthur et al., 2021). Understories with hardwood species will sprout following top-kill by fire, and the premise is that with repeated fires, sprouting vigor will

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https://doi.org/10.1016/j.foreco.2023.120796
Received 1 June 2022; Received in revised form 6 January 2023; Accepted 9 January 2023

decrease or be eliminated (Hutchinson et al., 2005; Brose et al., 2013; Arthur et al., 2015; Schweitzer et al., 2016; Waldrop et al., 2016). Creating woodland and savanna conditions with prescribed fire is predicated on long-term residual tree survival under frequent fire (Dey et al., 2017). The conundrum is that repeated fires are needed to create these conditions, while repeated fires may also contribute to greater overstory tree wounding, stress, and mortality.

Mortality associated with frequent fire occurs primarily on small trees (Arthur et al., 2015; Schweitzer et al., 2016; Knapp et al., 2017). Trees experience lower rates of fire induced mortality as bark thickness – the fundamental trait conferring fire resistance (Babl et al., 2020) – increases. Bark thickness increases with stem size, and most overstory trees will have reached the threshold bark thickness needed for cambium protection from the low- to moderate-intensity fires typical of prescribed burns in the US South (Hengst and Dawson, 1994). Although most large overstory trees remain visibly uninjured and undamaged from low-intensity dormant season prescribed fires (Brose and Van Lear, 1998; Sutherland and Smith, 2000; Smith and Sutherland, 2006; Mann et al., 2020), there is potential to cause damage that may include outright mortality or wounding of the lower bole that leads to loss of volume and value to the most valuable part of the tree (Marschall et al., 2014). Understanding long-term mortality trends of overstory trees following repeated prescribed fires may be helpful for managers considering this silvicultural tool.

Many studies involving fire in eastern upland systems are in hardwood-dominated forests, rather than mixed pine-hardwood systems. Mortality effects have been studied in relationship to one to four prescribed burns in undisturbed mature forests (Hutchinson et al., 2005; Arthur et al., 2015; Keyser et al., 2018); to multiple burns following midstory reductions (Waldrop et al., 2016; Iverson et al., 2017); and to single burns following canopy-level reductions (Albrecht and McCarthy, 2006; Brose, 2010; Holzmueller et al., 2014). However, few studies have reported on fire-induced mortality in managed mixed pine-hardwood systems (Clabo and Clatterbuck, 2015; Schweitzer et al., 2016, 2019). Moreover, much previous research has focused on the establishment of mixed pine-hardwood forests (Waldrop, 1989; Steinbeck and Kuers, 1996), while relatively less addresses the management of these systems (Willis et al., 2019; Kenefic et al., 2021).

This paper profiles the survival experience of overstory trees (stems $>$ 14.0 cm [5.5 in.] at 1.4 m [4.5 ft.] above groundline; DBH) in a fire and thinning restoration study on the William F. Bankhead National Forest (BNF) in northcentral Alabama, USA. The primary research question is whether frequent prescribed burns affect the survival of overstory trees when compared to infrequent burns or no burns. Important secondary questions are whether survival trends differ according to degree of initial thinning, species group, or size class. We evaluate hypotheses that increasing burn frequency does not lead to higher mortality a.) overall; b.) by thinning level; c.) by species group; and d.) within size class (i.e., within size subcategories within the overstory class). Additionally, we describe a regression-type model that is useful for estimating survival quantiles (such as median survival) after controlling for certain commonly available covariates. The model is useful for comparing how overstory trees with different characteristics or with different site conditions may respond to varying frequencies of prescribed burns. Rather than a point-in-time estimate of survival or death for an individual tree, the methodology presents survival distributions over spans of time and for groups of trees sharing similar characteristics.

2. Methods

The BNF is a 72,800-ha (180,000-ac) national forest located in northcentral Alabama. The treatment stands, all located in the northern portion of the BNF, were selected so as to be similar based on average stand age, composition, and size. They range in area from 8.9 to 18.6 ha (22 to 46 ac) and in age from 30 to 60 years old. The study sites are mixed pine-hardwood forests, dominated by loblolly (*Pinus taeda* L.), with a smaller portion of Virginia (*P. virginiana* Mill.) and shortleaf (*P. echinata* Mill.) pine. Upland oak species are common and include chestnut (*Quercus prinus* L.), white (*Q. alba* L.), northern red (*Q. rubra* L.), scarlet (*Q. coccinea* Munchh.), black, (*Q. velutina* Lam.) and southern red (*Q. falcata* Michx.) oaks. Other hardwoods include yellow poplar (*Liriodendron tulipifera* L.), red maple (*Acer rubrum* L.), and black cherry (*Prunus serotina* Ehrh.). Soil types are generally well-drained; nine soil series (Soil Survey Staff, 2022) are represented, as follows: Muskingum (accounting for 29.9% of the tree sample size); Enders (24.2%); Tidings-Bankhead (19.1%); Sipsey (7.7%); Pottsville (6.7%); Ruston (4.1%); Linker (3.0%); Townley-Apison (2.7%); and Smithdale (2.6%).

Part of the original goal of the study was to test varying levels of management disturbances for their effectiveness at shifting the species structure toward more hardwood dominance, particularly oak (*Quercus* spp.) (USDA Forest Service, 2004). The nine treatment levels (eight active treatments and one control) were the result of a 3x3 factorial design incorporating two factors at three levels each. The three thinning levels were: no thinning, light thinning (target residual basal area [BA] of 17.2 m^2/ha [75 ft^2/ac]), and heavy thinning (target residual BA of 11.5 m^2/ha [50 ft^2/ac]). Commercial thinning was conducted by marking from below the smaller trees (14–15 cm DBH) and trees that appeared stressed, diseased, or damaged. Canopy trees in the 15.2–30.5 cm (6–12 in.) DBH range were also removed to meet residual basal area targets. Pine accounted for nearly 90 percent of the total reduction in stems, and all thinning treatments were completed prior to burning (Schweitzer et al., 2019). Prescribed burns occurred at three frequencies: no burns, infrequent burns (once per nine years), and frequent burns (once per three years). A total of 49 landscape-scale prescribed fires, usually encompassing multiple treatment stands, were conducted over 14 years. The low- to moderate-intensity prescribed fires all took place during the dormant season from January through early April and used backing fires or strip head fires to ensure that only surface fire occurred. Four replications (blocks) of the nine treatment levels were initiated from 2006 to 2008, yielding 36 total treatment stands. Each treatment stand was surveyed and marked with five permanent measurement plots of 0.08 ha (0.2 ac) each, with one centrally located and the other four positioned to capture the range of conditions within each stand. All trees with DBH of 14.0 cm (5.5 in.) or greater were counted and their locations recorded using GPS. Trees were measured before thinning and in the summer following each prescribed burn. Except for dead and down trees, all surveyed trees, regardless of treatment level received, were remeasured in the observation years for that block; hence, tree observations occurred once every three years, consistent with the timing of the prescribed burns for that block. The current analysis utilizes data through five burn cycles for all four blocks; thus, frequently burned stands received five fires, while infrequently burned stands received two fires. Further background on the study and analysis on other research questions may be found elsewhere (Schweitzer et al., 2016, 2019).

Measurements of DBH at the beginning of the study were used to place overstory trees into four size classes, as follows: [14.0 cm, 19.1 cm); [19.1 cm, 24.1 cm); [24.1 cm, 29.2 cm); [29.2 cm and greater) ([5.5 in., 7.5 in.); [7.5 in., 9.5 in); [9.5 in., 11.5 in.); [11.5 in. and greater)), where the "[*lower*, *upper*)" notation indicates that the interval includes the *lower* boundary but not the *upper* boundary. For this analysis, the sample of trees consists of those overstory trees present after thinning. Although additional trees grew into the overstory class during the study (and some recorded trees grew into larger size classes from their starting class), this analysis fixes the size classes as recorded at initial observation. Tree species were grouped into pines, oaks, and others both to keep the number of comparison groups manageable analytically and because there was special research interest in the survival experience of pines and oaks given the forest management goal of transitioning from pine-dominant to mixed pine-hardwood.

Survival analysis refers to a class of methods directed at analyzing time-to-event data. While these methods were developed in the biomedical research domain (Klein and Moeschberger, 2003), they have been applied in forestry and fire ecology, including in Woodall et al. (2005), Moritz et al. (2009), Uzoh and Mori (2012), Morin et al. (2015), and Maringer et al. (2021). Survival analysis methods are particularly suitable for the current work both because of the nature of our underlying research questions (survival trends over spans of time, and for whole groups rather than individual trees) and because of the structure of the empirical data. These methods are indicated when the data consist of individual sample units for which the primary outcome is a measure of time until some event (in this case, tree death) occurs. A further characteristic of the data is the common occurrence of censoring, in which the exact event time is not observed. Censoring may happen in one of several ways. In the archetypical case, known as right censoring, the exact event time is not observed for a sample unit because either the study ends or the sample unit drops out of the study without the event ever occuring. In left censoring, all that is known about the event time is that it occurred before some specific observation time. Finally, if an event is only known to have occurred between two specific time points, then the unit is interval censored. Moritz et al. (2009) demonstrated that failing to account for censoring may lead to biased parameter estimates. Since the trees in our sample were assessed for mortality status every three years, those that died during the study are interval censored, while all that survived are right censored. In this analysis, we use modified methodologies illustrated by Gómez (2009) for interval censored data.

We first applied survival analysis considering only one factor at a time (burn level, thin level, species, or size class). This provided insight into the association of these factors with long-term survival marginally over all other variables and thus provided guidance for the multivariable model building effort described below. We used the nonparametric Kaplan-Meier (KM) survival estimator (Kaplan and Meier, 1958), with weighted log-rank tests modified for interval-censored data (Gómez et al., 2009) together with permutation tests (Fay and Shih, 1998) for determining whether survival distributions for different groups varied by more than might be expected by chance, using $\alpha = 0.05$ as the threshold for statistical significance. Next, we focused specifically on studying interaction effects between burn level and the other three main grouping factors. To do this, we constructed three separate accelerated failure time (AFT) models of the survival times. The AFT model is a parametric, regression-like model used in survival analysis to enable estimation of survival time distributions for groups conditional on included covariates. The AFT model is a log-linear model, in which the natural logarithm of the survival time, T, is expressed as a linear combination of the covariates and parameters and an error term:

$$Y = \ln T = \mu + \boldsymbol{\beta}^{'}\boldsymbol{Z} + \sigma W$$

where μ is a baseline log survival time, $\boldsymbol{Z}$ is a matrix of covariate values for the observations, $\boldsymbol{\beta}$ is a vector of regression coefficients describing the relationships between the covariates and the log survival time, σ is the scale parameter, and W is the error term distribution. A variety of choices may be made for the distribution of event times, T, each of which implies a corresponding distribution for the error term, W (Klein and Moeschberger, 2003; Gómez et al., 2009). Three common choices are the Weibull, the log-logistic, and the log-normal distributions. These imply, respectively, an extreme value distribution, a logistic distribution, and a normal distribution for W. We tested each of these three choices and selected the best fitting model with respect to the Akaike Information Criterion (AIC) statistic (Akaike, 1998). At this stage of the analysis, where we were only concerned with studying interaction effects involving burn level, the only explanatory variables used in the AFT models were the main effects and interaction term for burn level and one of the other three factors.

In the last stage of the analysis we again used the AFT approach, but this time attempted to construct the most comprehensive, best fitting model while balancing that goal with the equally important objective of interpretability. In other words, if a covariate or interaction term enhanced model fit only trivially (in terms of AIC), we favored parsimony in the model and dropped that term. Potential covariates included tree-level variables (size class, species group); plot-level variables (South aspect [yes/no], Southern pine beetle [*Dendroctonus frontalis* Zimm.] infestation [yes/no], average elevation, soil type, average plot slope); and stand-level variables (block, burn level, thin level). After conducting variable selection, we used the best fitting model to construct model-based survival curves for subgroups based on treatment factors, species, and size, and to estimate median survival times for these groups. We used the acceleration factor (AF), defined as the exponentiation of the estimated coefficient, β, to aid interpretation of the AFT model parameters. The AF indicates how percentiles of survival times (such as the median survival time) for the reference group change for trees with different values for the covariates. AF values greater than one increase the survival times percentiles, while values less than one decrease them. To take into account the hierarchical nature of the data (trees nested within plots, plots nested within stands), we built the AFT model using a generalized estimating equation approach, with the 180 stand-specific plots identified as clusters, within which the individual trees may have some correlation (Therneau, 2021).

Statistical analysis was conducted using R, version 4.1.1 (R Core Team, 2021), with particular reliance on the survival (Therneau, 2021), interval (Fay and Shaw, 2010), and Icens (Gentleman and Vandal, 2021) packages.

3. Results

Prior to any treatment we recorded 10,241 overstory trees. Of these, 4,446 were harvested and 46 were knocked over in the thinning operations, leaving 5,749 trees included in this analysis. The overall survival rate of these trees at 14 years after first observation was 77.5% (Table 1). The first portion of the survival analysis focused on examining survival trends along single variables. KM survival curves for groups of trees determined by burn level alone were extremely similar. In other words, when not conditioning on any other tree or plot characteristics, there was no indication of decreased overstory tree survival in plots receiving frequent burns relative to no burns (Table 1a, Fig. 1a). Trees in the no thin group had the lowest survival, while those in the light and heavy thin groups had similar survival (Table 1b, Fig. 1b). Oaks had higher overall survival compared to pines and all other species (Table 1c, Fig. 1c). The smallest size class of overstory tree had the lowest survival, while there was very little difference between the largest two size classes (Table 1d, Fig. 1d).

The permutation tests used in conjunction with the weighted log-rank tests resulted in no significant difference in the survival distributions for burn level groups ($p = 0.60$), while for thin level, species group, and size class the tests were all significant ($p < 0.0001$ for each factor).

The second portion of the analysis employed three separate AFT models to examine how burn level interacted with other grouping factors to affect survival times. The interaction term in each model was significant, although the p-values were near 0.05 (Table 2). The main effects of thinning level, species group, and size class were also significant in each model, with p-values much lower than 0.05 in each case. For Model 2 (testing the interaction of burn level with species group), the main effect for burn level was also significant, with the p-value between 0.01 and 0.05; in the other two models, the burn level main effect was not statistically significant.

The last stage of the analysis explored the simultaneous effect of multiple grouping variables and covariates, as well as interaction effects, on the survival times. The best model contained the treatment factors burn level and thin level, and their interaction, as well as species group, size class, and an indicator for presence of the Southern pine beetle (Table 3). Average plot elevation, average slope percent, south facing aspect, and soil type were found to be nonsignificant as explanatory variables. Additional interaction terms, such as those shown in Table 2,

Table 1
Overstory tree counts and deaths by time and grouping factors.

			TIME PERIOD												14-year
			Pre-cut	Cut/KO	T0	Died	T1	Died	T2	Died	T3	Died	T4	Died	T5	Survival
TOTAL			**10241**	**4492**	**5749**	**60**	**5689**	**156**	**5533**	**247**	**5286**	**254**	**5032**	**577**	**4455**	**77.5%**
a.	**Burn level**	No burn	3281	1473	1808	22	1786	36	1750	84	1666	68	1598	214	1384	76.5%
		Infreq.	3458	1546	1912	19	1893	79	1814	70	1744	96	1648	143	1505	78.7%
		Frequent	3502	1473	2029	19	2010	41	1969	93	1876	90	1786	220	1566	77.2%
b.	**Thin level**	No thin	3400	6	3394	34	3360	103	3257	161	3096	211	2885	501	2384	70.2%
		Light thin	3430	2088	1342	15	1327	25	1302	39	1263	31	1232	57	1175	87.6%
		Heavy thin	3411	2398	1013	11	1002	28	974	47	927	12	915	19	896	88.5%
c.	**Species group**	Oaks	732	143	589	1	588	11	577	11	566	10	556	8	548	93.0%
		Pine	8729	4014	4715	53	4662	128	4534	217	4317	220	4097	547	3550	75.3%
		Other	780	335	445	6	439	17	422	19	403	24	379	22	357	80.2%
d.	**Size class (cm)**	[14.0 -- 19.1)	3602	1816	1786	34	1752	90	1662	117	1545	148	1397	278	1119	62.7%
		[19.1 -- 24.1)	3024	1480	1544	13	1531	29	1502	51	1451	50	1401	154	1247	80.8%
		[24.1 -- 29.2)	2168	838	1330	7	1323	17	1306	37	1269	33	1236	89	1147	86.2%
		[29.2+)	1447	358	1089	6	1083	20	1063	42	1021	23	998	56	942	86.5%

Time T0 refers to after thinning and before first fire. T1,…,T5 refer to summer following Burn #1,…,#5. After 5 time intervals, the Infrequent Burn treatments had received 2 fires (just before T1 and T4), while the Frequent Burn treatments had received 5 fires. Trees counted at T5 are right censored; trees counted in the "Died" columns are interval censored. Size classes were determined based upon Pre-cut DBH only.

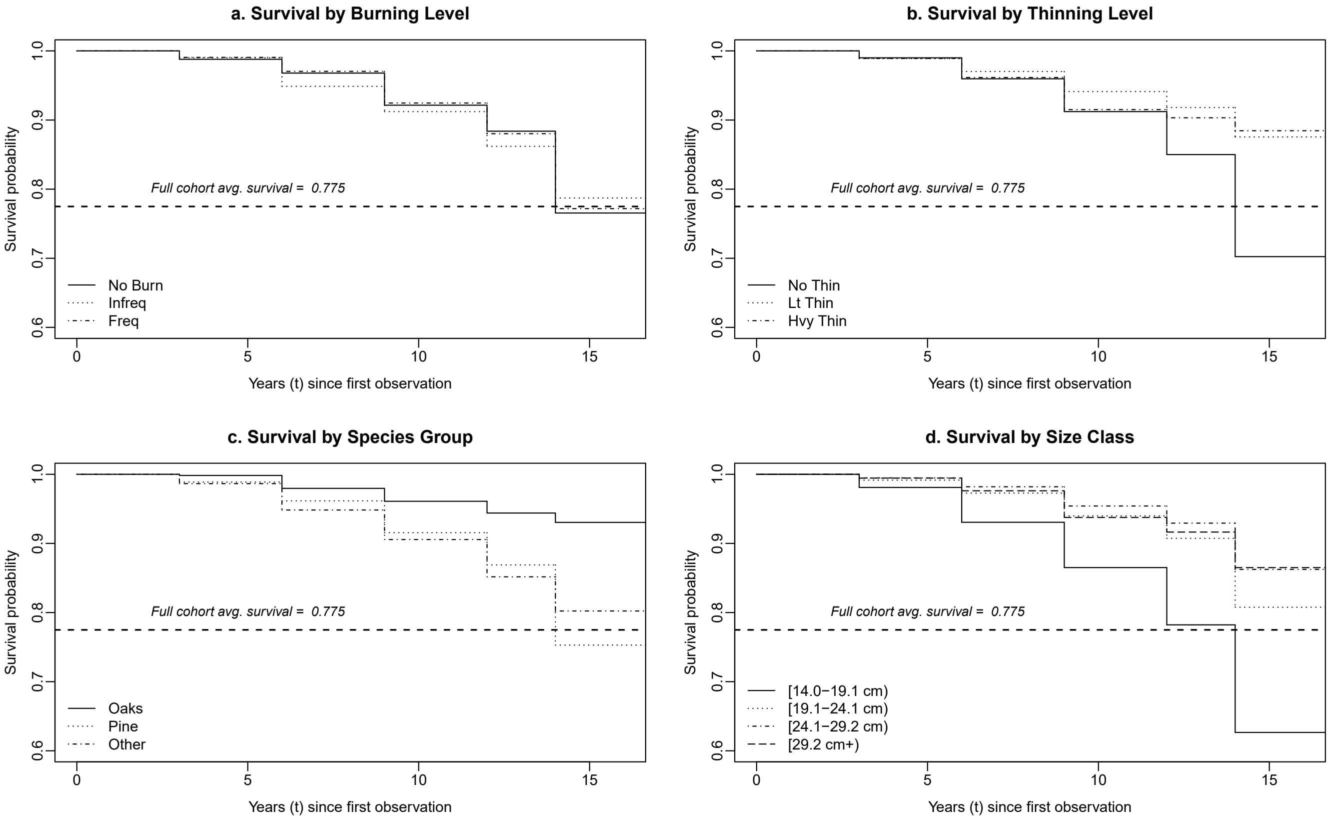

Fig. 1. Overstory tree survival by single factors (burn level, thin level, species group, and size class). The horizontal reference line in each plot at 0.775 indicates the average 14-year survival rate for the full cohort of overstory trees in this study.

were tested but did not substantially improve the model fit after the inclusion of the other covariates.

Relative to oaks and keeping all other factors constant, the AFT model estimates a 46% and 35% reduction in survival times for pines and other species, respectively. For size class, consistent with the one factor and two factor analyses earlier, each of the larger size classes was associated with increased survival times relative to the smallest size class used as the reference group. The increases were 39% for the second

Table 2
Three AFT models examining interaction terms involving Burn level.

	MODEL 1: Burn Level * Thin Level Variable	β	Sig.	MODEL 2: Burn Level * Species Group Variable	β	Sig.	MODEL 3: Burn Level * Size Class Variable	β	Sig.
M. E.	Infreq Burn	0.12		Infreq Burn	−0.54	*	Infreq Burn	0.00	
	Freq Burn	0.08		Freq Burn	−0.60	*	Freq Burn	−0.06	
	Light Thin	0.57	****	Pine	−1.00	****	[19.1, 24.1 cm)	0.17	**
	Heavy Thin	0.68	****	Other	−0.76	**	[24.1, 29.2 cm)	0.31	**
							[29.2 cm +)	0.37	***
I. T.	Infreq + Light Thin	−0.40	**	Infreq + Pine	0.61	*	Infreq + [19.1, 24.1 cm)	0.17	
	Freq + Light Thin	−0.11		Freq + Pine	0.66	*	Freq + [19.1, 24.1 cm)	0.24	*
	Infreq + Heavy Thin	−0.32	*	Infreq + Other	0.48		Infreq + [24.1, 29.2 cm)	0.14	
	Freq + Heavy Thin	−0.45	*	Freq + Other	0.34		Freq + [24.1, 29.2 cm)	0.30	**
							Infreq + [29.2 cm +)	0.04	
							Freq Burn + [29.2 cm +)	0.24	

Sig.: Significance. ****: $p < 0.0001$; ***: $p < 0.001$; **: $p < 0.01$; *: $p < 0.05$.
M.E.: Main Effects; I.T.: Interaction Terms.
Parameter estimates in three different models. Each model incorporates Burn Level with one other main effect, either Thin Level (Model 1), Species Group (Model 2), or Size Class (Model 3), and the interaction of those two variables. Parameter estimates (β) greater than zero indicate an effect of increasing survival times, while values less than zero decrease survival times relative to the reference group of No Burn, and either No Thin (Model 1) or Oaks (Model 2) or the [14.0, 19.1 cm) size class (Model 3).
Sig.: Significance. ****: $p < 0.0001$; ***: $p < 0.001$; **: $p < 0.01$; *: $p < 0.05$.
M.E.: Main Effects; I.T.: Interaction Terms.

Table 3
Results of AFT model.

Variable		β	Z	Sig. level	AF
TRTMT. FACTORS	Light Thin	0.38	4.17	****	1.46
	Heavy Thin	0.44	4.09	****	1.56
	Infreq Burn	0.09	1.26		1.09
	Freq Burn	0.17	2.56	*	1.19
SPECIES GRP.	Pine	−0.61	−4.67	****	0.54
	Other	−0.43	−3.4	***	0.65
SIZE CLASS (cm)	[19.1 – 24.1)	0.33	5.76	****	1.39
	[24.1 – 29.2)	0.45	5.82	****	1.57
	[29.2 +)	0.45	5.53	****	1.57
PLOT FACTORS	Beetle	−0.35	−3.99	****	0.71
INTERACTION TERMS	Light Thin + Infreq Burn	−0.29	−2.19	*	0.75
	Heavy Thin + Infreq Burn	−0.22	−1.78		0.80
	Light Thin + Freq Burn	−0.20	−1.65		0.82
	Heavy Thin + Freq Burn	−0.52	−3.32	***	0.59

Notes: Reference group = No Thin; No Burn; Oaks; [14.1 – 19.1 cm); No Beetle.
Sig. level: ****: $p < 0.0001$; ***: $p < 0.001$; **: $p < 0.01$; *: $p < 0.05$.
AF: Acceleration Factor = exp(**β**).

size class, and 57% for the largest two size classes. The presence of the southern pine beetle was associated with a 29% decrease[1] in survival times (Table 3, column AF).

To interpret the effects of the active treatments versus the control, we must add the estimated coefficients and exponentiate the result (or multiply the appropriate AF values). All the active management treatments increased modeled survival times. The heavy thin, no burn treatment was associated with the largest impact on modeled survival times, increasing the distributions 56% (Table 4). The lowest impact was found in the no thin, infrequent burn (+9%) and the heavy thin, frequent burn (+10%) treatments. As burn frequency increased, AF values increased for no thin treatments; decreased, for heavy thin treatments; and decreased then increased for light thin treatments.

The AFT model enables us to estimate survival time distributions over an extended time range and explore how those distributions change by modifying one or more of the included covariates, while leaving other covariates at their baseline, or reference group, settings (Fig. 2). For example, assuming no infestation of the pine beetle, the estimated median survival time (across all treatment groups) for the largest oaks would be just less than 50 years from first observation, while for the smallest overstory size class of pines the median survival time would be less than 20 years since first observation. The survival distributions are stretched to the right (indicating longer survival) for oaks relative to pines and others, and for larger size classes relative to smaller classes. Within a species group + size category, the spread of the survival distributions for the nine treatments always follows the pattern shown in Table 4: The heavy thin, no burn treatment is always the rightmost curve (longest survival), while the no thin, no burn treatment is always the leftmost curve (shortest survival).

4. Discussion

As part of the decision-making process for managing a forest for desired reproduction or a specific woodland structure, forest managers have incomplete and sometimes conflicting research outcomes to guide them regarding prescribed fire. Distilling responses of complex systems

Table 4
Acceleration factors for treatment levels.

Thin Level	Burn Level None	Infrequent	Frequent
None	1.00	1.09	1.19
Light	1.46	1.19	1.42
Heavy	1.56	1.36	1.10

Acceleration factors (AF) modify baseline survival functions. AF values greater than one increase expected survival time, while values less than one decrease them. The reference group here is the no burn, no thin treatment. The values shown in Table 4 incorporate both main and interaction effects from the AFT model in Table 3.

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[1] Note that pine beetle presence did not fully account for the lower survivorship of either unthinned stands (relative to light and heavy thinned stands) or pine (relative to the other species groups). Out of 180 plots, 8 were affected by the beetle. Repeating the analysis after excluding all 447 trees from these 8 plots resulted in estimated coefficients of: Light Thin $\beta = 0.42$ ($p < 0.001$); Heavy Thin $\beta = 0.50$ ($p < 0.001$); and Pine $\beta = -0.65$ ($p < 0.0001$). See Supplement for full details of this model.

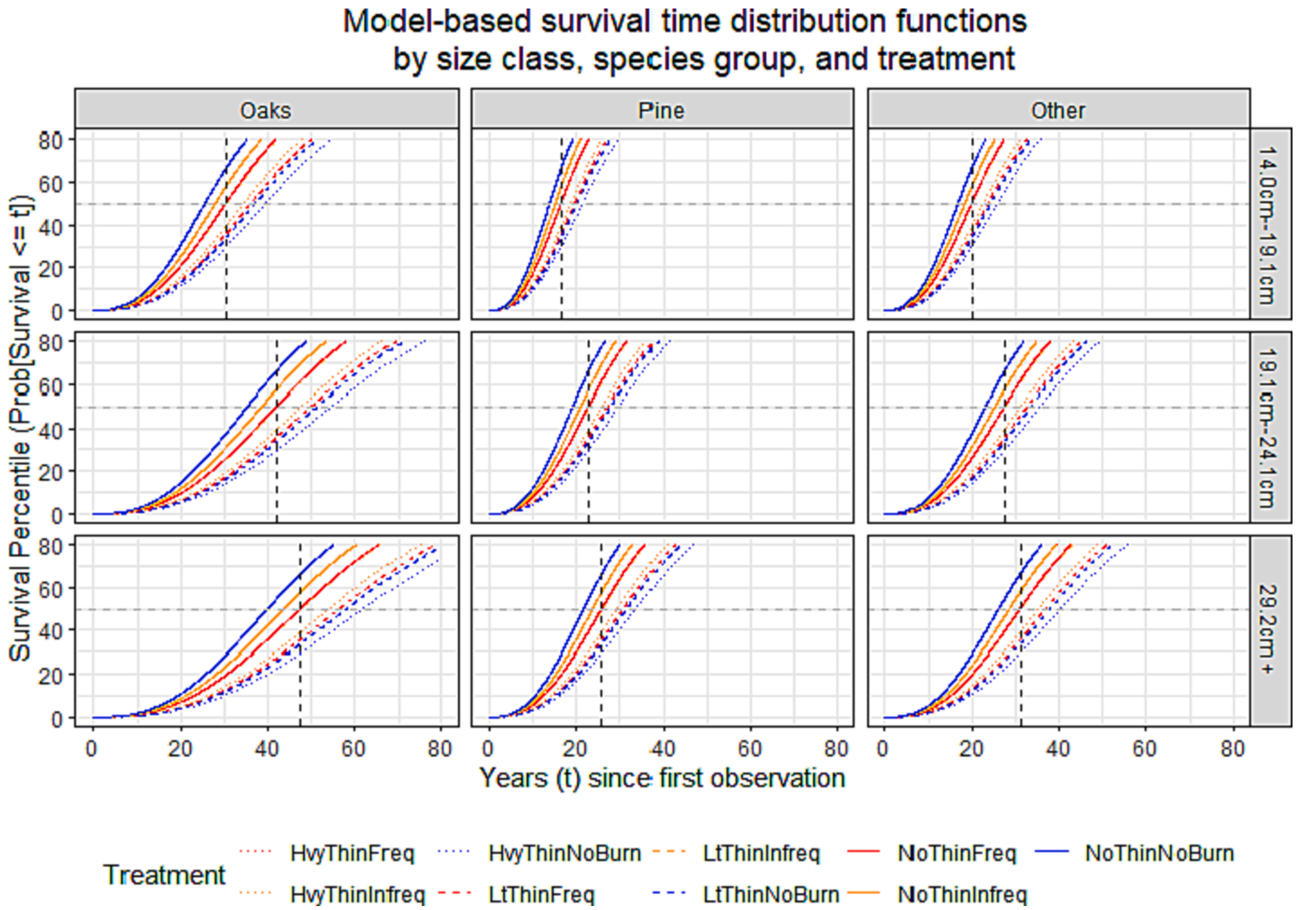

Fig. 2. Model-based distribution functions of survival times forecasted from AFT model in Table 3. Each panel contains nine curves, although two pairs of curves overlap and are indistinguishable. Dotted line types are for heavy thin, dashed for light thin, solid for no thin. Blue curves are for no burn, orange for infrequent, red for frequent. Horizontal reference lines highlight 50th percentile of survival times. Intersecting vertical reference lines indicate the median survival time over all nine treatments shown in each panel. Vertical axes are cropped at the 80th percentile level to enable easier comparison of median survivals and because the AFT model is not intended to forecast the upper tails of the distributions. Interested readers may find the full, uncropped plots in the online Supplement file. Panels for third size class (24.1 cm—29.2 cm) are suppressed because they were virtually identical to those for the largest size class.

and applying results to different systems contributes to these conflicts, as does the scarcity of prescribed fire research over long time periods. In some systems, such as the mixed pine-hardwoods examined here, the precise sequence and timing of treatments, including prescribed fire, needed to achieve a specific stand composition and structure are not clearly established. Prescribed fire is used in mixedwoods to reduce understory and midstory tree density, but unintended overstory mortality, particularly as a result of repeated fires, is a highly relevant concern. The analysis presented in this article relates the experience of a long-term study in a mixedwoods system and provides insight into the ways overstory survival trends have differed by frequency of prescribed burns, degree of prior thinning, species group, and size class. We found that all active treatments (thinning and burning) were associated with increased modeled survival times and that the absence of any management resulted in the lowest overstory survival. When considering single factors, we found no change in overstory tree survival for frequent fire compared to no fire, and oaks had higher overall survival compared to pines and others. We also found that the smallest size class of trees had the lowest survival.

4.1. Species + size class

The three two-factor ATF models supported the single factor analysis when considering how burn levels interacted with thinning, species groups, and sizes. Oaks had higher overall survival compared to pines and others, and for all species, the smallest size classes had the lowest survival. Compared to oaks in unburned stands, pines decreased in their forecast survival under all burn levels, but less so for infrequent and frequent fire. Direct fire mortality depends not only on fire behavior but also on the fire-adaptation protection traits of species, which vary among species and within species depending on size and tree development. Resistance of trees to some stressors (e.g., fire, or insects) increases with lignification, diameter, bark thickness and other factors associated with age (Bova and Dickinson, 2005). Larger trees usually have thicker bark and can withstand greater heating (Hare, 1965; Hengst and Dawson, 1994), with a critical bark thickness needed to protect the cambium from injury (Lawes et al., 2011; Hoffmann et al., 2012). Thickness and insulation properties of the bark of southern pines contribute to its fire resistance (Hare, 1961). Although oaks were found to be less resistant to fire than loblolly pine (Hare, 1961), upland oak species, including white oak and northern red oak, were found to have a linear relationship between bark thickness and DBH, and bark thickness was found to be a good indicator of protection from lethal fire effects (Hengst and Dawson, 1994). In hardwoods, Huddle and Pallardy (1996) found size-dependent mortality under annual fires for 40 years and no thinning, with the smallest diameter oaks (up to 20.1 cm [7.9 in.] DBH) having low survival. In the survival analysis conducted in this study, survival of overstory trees increased from pines, to other species, to oaks; and as size class changed from the smallest overstory size class to the larger size classes. These trends held regardless of burn level.

Although the AFT model presented in Table 3 does not include interaction terms between species group and size class, we highlight that this was a subjective decision in the modeling process. In our analyses, three out of six individual species group × size class interaction terms had p-values slightly below or slightly above 0.05, our threshold for statistical significance (the other three had p-values well above 0.05). This was dependent, of course, on other covariates included in the model. We judged that the overall model fit was not enhanced enough to justify the inclusion of the extra parameters, because interpretation of the size class and species group main effects became more confusing. Nevertheless, though opting for interpretability over complexity in this particular model, and in light of the research mentioned above, it remains important when considering prescribed fire as a tool that both species and size factors be considered in conjunction with each other.

Some research suggests that mortality of merchantable overstory trees is minimal under a regime of repeated, low intensity, dormant season fires (Hutchinson et al., 2005; Smith and Sutherland, 2006). Also, loss of value and volume to bole wounding and damage by decay and degrade are minimal if damaged trees are harvested within 10 to 15 years of the fire (Marschall et al., 2014; Mann et al., 2020). We found that within a species group and size category, the spread of the survival time distributions for all treatments was always to the right of the control group distribution, indicating longer survival times under active treatment scenarios. Estimated median survival time for the largest oaks in stands with no treatment was approximately 40 years from the first observation and increased by up to 20 years with thinning and fire. Compared to the control group, for all species, heavy thinning alone increased survival time distributions by 56%, heavy thinning with infrequent fire increased survival times by 36%, and heavy thinning with frequent fire increased survival times by 10%. Our starting point of T0 is not the same as age zero, and we are not predicting tree age at death. We assessed how the differences in grouping factors and covariates affected survival times relative to other groups, and we found large oaks in this study have the longest expected survival times.

4.2. Influence of thinning

Management activities often are necessary to create desired stand conditions, and the decision to withhold disturbance also has consequences on stand dynamics. In our model-based survival time distribution functions, the heavy thin, no burn treatment was always the rightmost curve (longest survival), while the no thin, no burn treatment was always the leftmost curve (shortest survival). Higher mortality rates are found in stands having higher densities (Oliver and Larson, 1990). Stand dynamics in intentionally undisturbed stands include a period of density-dependent tree mortality driven by increased competition as stands age and grow (Oliver, 1980; Peet and Christensen, 1987). The experience in this study was consistent with those observations; overstory mortality was highest in non-thinned stands, most likely due to stress-induced competition. For example, Southern pine beetle infestations were highest in the unthinned stands; out of eight plots affected with outbreaks, six were in unthinned stands (the other two were in lightly thinned stands). A predisposition to Southern pine beetle attack due to high stand density can be mitigated with thinning (Ku et al., 1980; Burkhart et al., 1986). In the no thin treatment pine had significantly lower survival compared to the oaks and other species groups. In both the light and heavy thinned stands, the other species group had the lowest survival, while oaks again had the highest.

The three non-thinned treatments had similar survival probabilities regardless of burn frequency, most likely because the low intensity fires had negligible impact on overstory trees across all species groups. Light thin treatments had slightly lower survival after 14 years when infrequently burned, while survival rates for the no burn and frequent burn treatments were similar. The lower survival in light thin stands with infrequent burns may have been due to fire behavior differences, related to fuel load, while this behavior may have been altered (lessened) in the heavy thin frequent burn treatments as fuel loadings were kept in balance (Schweitzer and Dey, 2021).

Because low- to moderate-intensity dormant season fires, the type most used by forest managers, are limited in the size of tree (e.g., <10.2 cm [4 in.] DBH) that can be topkilled in the short term, dual disturbance of canopy-level density reduction and multiple fires normally are required for regeneration or for woodland creation (Dey et al., 2017). The intent of these disturbances is to increase and maintain understory light levels to stimulate oak-pine reproduction development and recruitment; reduce dense horizontal and vertical structure; prevent dominance by red maple and other non-desirable competitive species; and to increase cover of native woodland flora (Reich et al., 1990; Kruger and Reich, 1997; Brose and Van Lear, 1998; Arthur et al., 2012; Kinkead et al., 2013). These conditions are also desired when developing and sustaining woodlands (Dey et al., 2017). Survival time distributions showed that the estimated median survival time for oaks was 25–62 years since the first observation and increased with stem size. For all oak sizes, higher survival times were estimated under thinning and burning treatments. Multiple fires are used to create desirable understory conditions for woodlands, and maintaining overstory density to provide understory light conditions conducive to key indicator species is crucial (Dey et al., 2017). Thus, retaining larger oaks under a frequent fire regime is warranted, as these oaks will have comparable survival to a thin-only regime with the added benefit of restoring desirable understory vegetation.

Variable responses of forests to prescribed burning, thinning and their combination may be attributed to myriad site factors that impact reproduction responses to disturbance (McEwan et al., 2011; Hutchinson et al., 2012; Brose et al., 2013; Keyser et al., 2018). A shelterwood-burn prescription may work in systems that have adequate sizes and numbers of advance oak-pine reproduction (Brose and Van Lear, 1998; Brose et al., 1999; Dey and Fan, 2009; Brose, 2010), while also creating open canopy conditions that mimic woodland structure. The interaction of disturbances may be paramount. For example, after repeated fires had greatly reduced the dominance of shade-tolerant saplings, small gaps caused by drought-induced mortality of overstory trees facilitated the development of large oak and hickory seedlings due to increased light and reduced understory competition (Hutchinson et al., 2012). The probability of large oak advance reproduction occurring is higher when overstory density is<13.8 m^2/ha (60ft^2/ac) (Larsen et al., 1997), which is commensurate with the recommended tree density and canopy cover reduction needed to achieve open woodlands (Dey et al., 2017). Sequencing a regeneration prescription in these mixedwoods that aims at increasing the density and dominance of oak requires phases of management over longer time periods that are anchored in some overstory tree density retention. Modeled estimates support greater survival times for oaks compared to pines and other species under such sequences in this system.

4.3. Prescribed fire as a restoration tool

Adding to the conundrum of using prescribed fire is the history of its use in pine forests to control unwanted hardwoods, including oak (Chen et al., 1975). Despite that history, today prescribed fire is frequently "reintroduced" or "restored" to a forest specifically to favor oak over other hardwoods (Brose, 2010, 2014; Arthur et al., 2015). Yet even repeated low-intensity fires may be insufficient to promote oak competitiveness if not accompanied by canopy disturbance (Iverson et al., 2008; Hutchinson et al., 2012). In these loblolly pine-hardwood mixtures on the BNF, we know multiple fires coupled with overstory stem density reduction will be necessary to move stands in a desired direction (Schweitzer et al., 2016, 2019). While the goal of prescribed fire in this project is to target changes in the understory species, we have found that more than three fires are needed to impact these contemporary forest tree species. For example, we have documented that red maple continues to readily sprout even following five prescribed fires (Schweitzer et al., 2019), and we attribute this to a lack of disturbance and mesophication moving the understory towards red maple dominance. With this many fires, a concern over impacts to overstory tree mortality is warranted. Longer survival for oaks compared to pines and larger trees compared to smaller ones allows managers to use repeated fires in these systems to achieve a desired composition and structure while maintaining needed canopy cover.

5. Conclusion

The current study is unique for several reasons. It is a randomized controlled study employing careful experimental design, rather than a retrospective or cross-sectional study. It is longitudinal and has amassed at this point nearly two decades of empirical data, at plot-, stand-, time-, and fire-levels. For the current analysis, the sample size of over 5,700 trees is quite large, providing strong insights into how survival trends vary among different groups. Frequent (once every three years), low intensity burning does not appear to adversely affect overstory tree survival, even after five burn cycles. Meanwhile, the non-thinned stands did experience lower survival compared to the thinned stands. In the mixed pine-hardwood stands of this study, the overstory pines have experienced moderately lower 14-year survival than the oaks. Consistent with many other studies, the smallest trees experienced the greatest mortality, and this pattern did not appear to be modified by the frequency of prescribed burns. Additionally, there was very little difference in survival experience for the two largest size classes. This research adds to the body of evidence supporting the idea that even fairly frequent (once every three years), low intensity, controlled burns likely do not increase mortality in overstory trees.

CRediT authorship contribution statement

John Craycroft: Conceptualization, Methodology, Software, Validation, Formal analysis, Writing – original draft, Writing – review & editing, Visualization. **Callie Schweitzer:** Conceptualization, Resources, Supervision, Writing – original draft, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data that has been used is confidential.

Acknowledgements

We thank USFS Forest Technicians Ryan Sisk and Matt Zirbel for their diligent data collection through the duration of this study. We also thank Fire Management Officer Kerry Clark, as well as USFS personnel at the Bankhead National Forest for incorporating the study stands into their prescribed burns on the schedule required by the study. This research was supported in part by an appointment to the United States Forest Service (USFS) Research Participation Program administered by the Oak Ridge Institute for Science and Education (ORISE) through an interagency agreement between the U.S. Department of Energy (DOE) and the U.S. Department of Agriculture (USDA). ORISE is managed by ORAU under DOE contract number DE-SC0014664. All opinions expressed in this paper are the authors' and do not necessarily reflect the policies and views of USDA, DOE, or ORAU/ORISE.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.foreco.2023.120796.

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