PATTERNS OF OVERSTORY MORTALITY IN A SHELTERWOOD-BURN CENTRAL APPALACHIAN FOREST

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Abstract—Prescribed fire is a tool used to regenerate and sustain mixed-oak forests in the central Appalachian region. Two specific applications for prescribed fire are site preparation and the reduction of oak competition after the first removal cut in a shelterwood. This latter use is called the shelterwood-burn method. However, prescribed fire presents additional mortality risk to the stand's overstory trees. In a shelterwood-burn study on the Fernow Experimental Forest in West Virginia, three individual tree factors—species, crown class, and dbh—and three stand manipulation treatments were examined to determine their effects on overstory tree mortality from both background and fire induced causes. A shelterwood treatment and a shelterwood-burn treatment, both site-prepared with prescribed fire, had significant differences in combined background and fire mortality when compared to an unburned, uncut control. Considering fire mortality alone, there was no difference in survival rates between the shelterwood and the shelterwood-burn treatments over the entire study period. Tree diameter influenced both natural mortality and fire-induced mortality. Crown class, species, and treatment were factors in background mortality only.

INTRODUCTION

The change in perception of the disturbance role that fire plays in forests of the Eastern United States has led to an increased utilization of prescribed fire as a tool for regenerating upland oak forests (Brose 2014). A silvicultural prescription that has arisen out of multiple investigative studies of fire in oak forests is the shelterwood-burn technique described by Brose and others (1999a) and Brose and others (1999b). This technique is specifically designed to address lack of recruitment of oak advance regeneration into the overstory. In a shelterwood-burn, prescribed fire is used as a release burn after the first shelterwood removal cut (post-shelterwood burn) to control competition (Brose and Van Lear 1998, Miller and others 2017) and it may optionally be used to help prepare the seedbed for establishment of oak seedlings when advance regeneration is not sufficient (Schuler and others 2010, 2013).

Previous research on prescribed fire in oak forests has examined its effects on advance regeneration in an attempt to better understand prescribed fire's potential use to promote oak forests (Brose 2013, Brose and Van Lear 1998, Brose and others 1999b, Jackson and Buckley 2004, Van Lear and others 2000). Overstory mortality has been examined in conjunction with advance regeneration mortality from fire (Arthur and others 2015, Barnes and Van Lear 1998, Huddle and Pallardy 1996, Hutchinson and others 2005, Paulsell 1957, Van Lear and others 2000) or reported solely (Wendel and Smith 1986). Due to the relatively recent formulation of the shelterwood-burn technique, examination of the effect of prescribed fire on the survival of the overstory after the post-shelterwood burn has been limited (Brose and Van Lear 1999). In a shelterwood-burn prescription for oaks, roughly 50 percent of the basal area of the overstory is still present when the post-shelterwood burn is conducted. Optionally in a shelterwood-burn, prescribed fire may be used for site preparation to promote advance regeneration before the first cut of the shelterwood. For each application of prescribed fire, there is a risk of overstory tree mortality and it is a concern that should be addressed as these losses could impact mast production, reduce yields of valuable timber, or potentially change forest composition. The cumulative effects of multiple fires is expected to increase the risk. Our objective is to determine the effect that prescribed fire in combination with individual tree characteristics

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have on overstory tree mortality in stands treated with a shelterwood-burn prescription, first looking at combined background and fire induced mortality, then examining the effect of the post-shelterwood burn on the shelterwood treatments.

METHODS

Site Description

The study site is located in West Virginia on the Canoe Run watershed of the Fernow Experimental Forest (39.03° N, 79.67° W). Mean annual precipitation is 57 inches, distributed evenly throughout the year and mean annual temperature is 49 °F which ranges from a monthly mean of 27 °F in January to a monthly mean of 69 °F for July. The study site ranges from 1920-2200 feet in elevation. Five species comprised over 80 percent of the overstory basal area at the start of the study: northern red oak (*Quercus rubra* L.), chestnut oak (*Q. prinus* L.), white oak (*Q. alba* L.), yellow-poplar (*Liriodendron tulipifera* L.) and red maple (*Acer rubrum* L.). Four additional species contributed roughly another 10 percent: American beech (*Fagus grandifola* Ehrh.), sourwood (*Oxydendrum arboreum* L.), sweet birch (*Betula lenta* L.), and sugar maple (*Acer saccharum* Marsh.).

Experimental Design

The study was established in 1999; for a more detailed description of the larger study please see Schuler and others (2013). Overstory trees were measured periodically on 24 1/2- acre plots. Four plots were assigned as controls, 10 plots were treated as a two-cut shelterwood without a burn (shelterwood) and 10 plots were treated as a two-cut shelterwood-burn (shelterwood-burn). Trees with diameter at breast height (dbh) >5 inches are permanently tagged and periodically remeasured for dbh and status (alive or dead). Mortality status is noted as natural, cut, destroyed, or fire damage. Trees with a mortality status of "cut" or "destroyed" were removed from this analysis. Post-fire inventories were conducted after all burns.

Two prescribed fires were applied to the shelterwood and shelterwood-burn plots prior the first removal cut in each treatment. The first prescribed fire was applied in April 2002 with some plots burned in April 2003 due to unfavorable conditions in 2002. The second prescribed fire occurred in April 2005 with all plots except the control plots burned. The shelterwood cut was performed during the winter of 2009-2010 and reduced the average overstory basal area of both shelterwood treatments from 145 square feet per acre to 62 square feet per acre (Schuler and others 2013). Trees were felled by the Fernow Experimental Forest logging crew with care taken to protect the boles of the residual trees. The post-shelterwood prescribed fire occurred in the spring of 2014 in only the shelterwood-burn plots. Burn prescriptions were written to result in fires of low to moderate intensity as the continued production of timber products was an objective of the study.

Data Analysis

To determine the effect of prescribed fire on mortality, analysis was divided into two stages, both of which used the Cox Proportional Hazards (CPH) Model (Cox 1972). This model is a better alternative to the more traditional use of logistic regression models for survival analysis because it permits analysis of time to the event vs. the fixed time period required for logistic regression. Parameter estimation occurs simultaneously over the entire period of study and there is no need to consider mortality for arbitrarily fixed time periods, such as 5- or 10-year mortality. Also, the CPH model accounts for the removal of a subject from the sample population due to death (which is one form of censoring).

$$\lambda(t;z)=e^{(\mathbf{z\beta})}\lambda_0(t) \tag{1}$$

where

t = time

z = a 1xp vector of covariates

β = a px1 vector of unknown parameters

$\lambda_0(t)$ = the baseline hazard function, an unspecified but non-negative function

In the first stage of analysis, combined background and fire-induced mortality was the event analyzed using the CPH model. Four variables were of interest in the model: treatment, species, crown class, and dbh. There were three levels of treatment: control, two-cut shelterwood (two site-preparation burns and first removal cut), and two-cut shelterwood-burn (two site-preparation burns, first removal cut, and one post-shelterwood burn). Considering treatment with these three levels as a factor affecting combined mortality allowed examination of differences in mortality between the unburned control compared to the two shelterwood treatments which were burned. A significant difference among the treatments would indicate additional mortality occurred due to prescribed burning. With a large number of species present and an interest in determining the survival of oaks, the species considered were chestnut oak, northern red oak, white oak, and all others. Due to a conservative designation of the dominant crown class in data measurement, dominant and codominant trees were grouped together, with intermediate and suppressed trees each assigned as unique levels of crown class. All trees >5 inches dbh are considered overstory trees and included in the survival analysis. In the second stage, the CPH model was again used for survival analysis, however only fire-induced mortality was considered as the event of interest and the unburned control plots were removed from the sample, which permitted consideration of whether the post-shelterwood burn affected mortality. Species, crown class, and dbh were included in the analysis.

All four variables were included in the initial full model, which was analyzed using Proc PHREG in SAS® software Version 9.4 (SAS Institute Inc. 2012). The repeated measures of trees on a plot were accounted for by using the robust sandwich estimator option available in the software (Lin and Wei 1989). Non-significant variables were removed from the model with $\alpha = 0.05$. For any significant class variables, multiple comparisons were conducted using a Tukey-Kramer adjustment (Kramer 1956) with dbh set at the approximate mean value of 13 inches to produce estimated survival probabilities.

RESULTS

Combined Mortality

There was a significant dependency between survival rates for trees on the same plot (p<0.0001) which is indicative of some degree of spatial autocorrelation of mortality for trees on each plot. Therefore, main effects were tested using the robust sandwich estimate for the variance. All of the main effects (crown class, dbh, species, and treatment) in the full model were significant (table 1). Multiple comparisons testing using a Tukey adjustment then proceeded for each of the class variables (table 2). For crown class, dominant/codominant trees had significantly greater survival rates than suppressed trees (p=0.0060). This was also the case for intermediate vs. suppressed trees, (p<0.0001). The declining rate of survival as crown class decreases (fig. 1) is expected due to suppression (Oliver and Larson 1996, Smith 1986). Chestnut oak exhibited the highest survival rates and white oak the lowest survival rates (fig. 2). Only the chestnut oak vs. white oak species comparison proved significant (p=0.0121). Both the shelterwood and the shelterwood-burn treatments were significantly different from the control, with (p<0.0001) and (p<0.0001), respectively. Survival on the control plots was greater than on both the shelterwood and shelterwood-burn plots (fig. 3). This is attributable to mortality from fire as trees cut or destroyed during harvesting were excluded from analysis. An increase of 1 inch in dbh reduced the mortality probability by 3 to 16 percent [95 percent confidence interval for exp(β_{DBH})].

Table 1—Main effects tests for survival of overstory trees, natural and fire mortality

Effect	df	Wald χ^2	p
Crown class	2	25.36	<0.0001
DBH	1	7.53	0.0061
Species	3	10.27	0.0164
Treatment	2	103.36	<0.0001

DBH=diameter at breast height.

Fire Mortality

Similar to the combined mortality, there was a dependency in survival rates for trees within the same plot, (p<0.0001); thus, the robust sandwich variance

Table 2—Multiple comparisons tests for main effects of the overall survival model

Effect	Effect Level 1	Effect Level 2	Estimated difference	Standard error	p
Crown Class	Dominant/Codominant	Intermediate	-0.18	0.35	0.8639
Crown Class	**Dominant/Codominant**	**Suppressed**	**-1.04**	**0.34**	**0.0060**
Crown Class	**Intermediate**	**Suppressed**	**-0.85**	**0.19**	**<0.0001**
Species	Chestnut oak	Northern red oak	-0.48	0.31	0.4117
Species	**Chestnut oak**	**White oak**	**-0.95**	**0.31**	**0.0121**
Species	Chestnut oak	All Other	-0.28	0.21	0.5509
Species	Northern red oak	White oak	-0.46	0.40	0.6424
Species	Northern red oak	All Other	0.20	0.34	0.9353
Species	White oak	All Other	0.67	0.29	0.0972
Treatment	Shelterwood	Shelterwood-burn	-0.04	0.20	0.9766
Treatment	**Shelterwood**	**Control**	**2.88**	**0.29**	**<0.0001**
Treatment	**Shelterwood-burn**	**Control**	**2.93**	**0.31**	**<0.0001**

Bold effect levels were significant at the α=0.05 level.

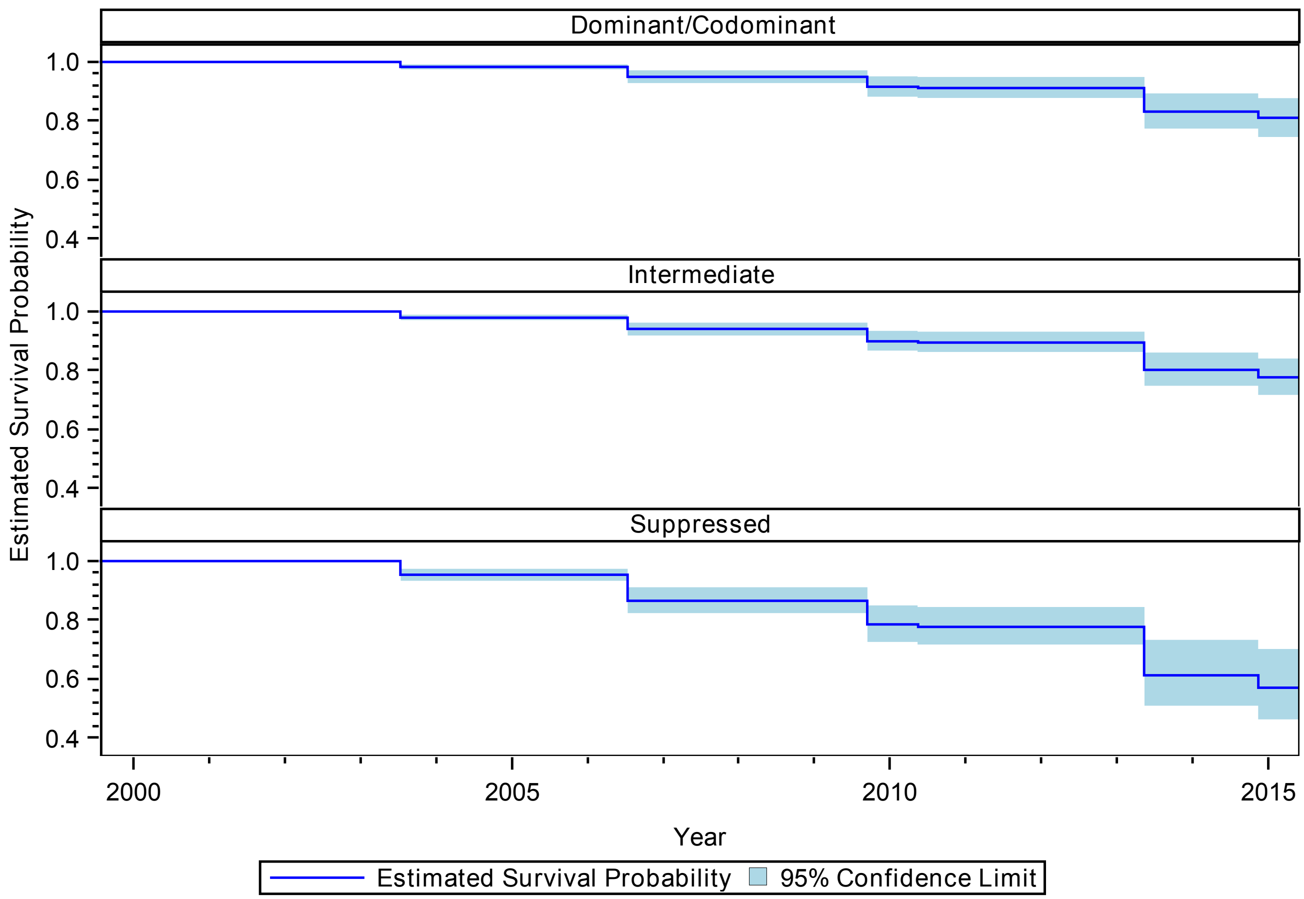

Figure 1—Estimated survival probabilities for each crown class. Estimated probabilities are direct adjusted for each species and treatment, with dbh held at the average value of 13 inches.

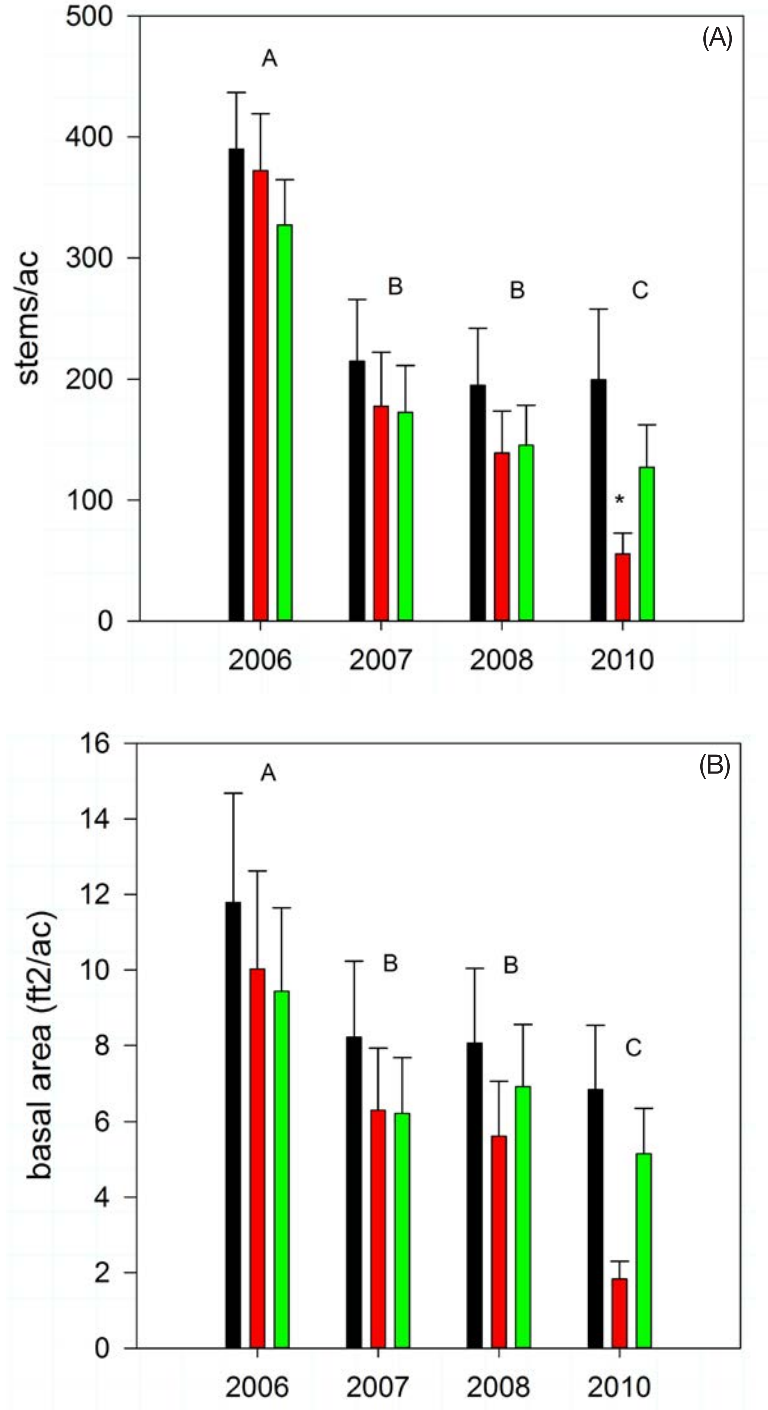

Figure 2— Estimated survival probabilities for each species. Estimated probabilities are direct adjusted for each crown class and treatment, with dbh held at the average value of 13 inches.

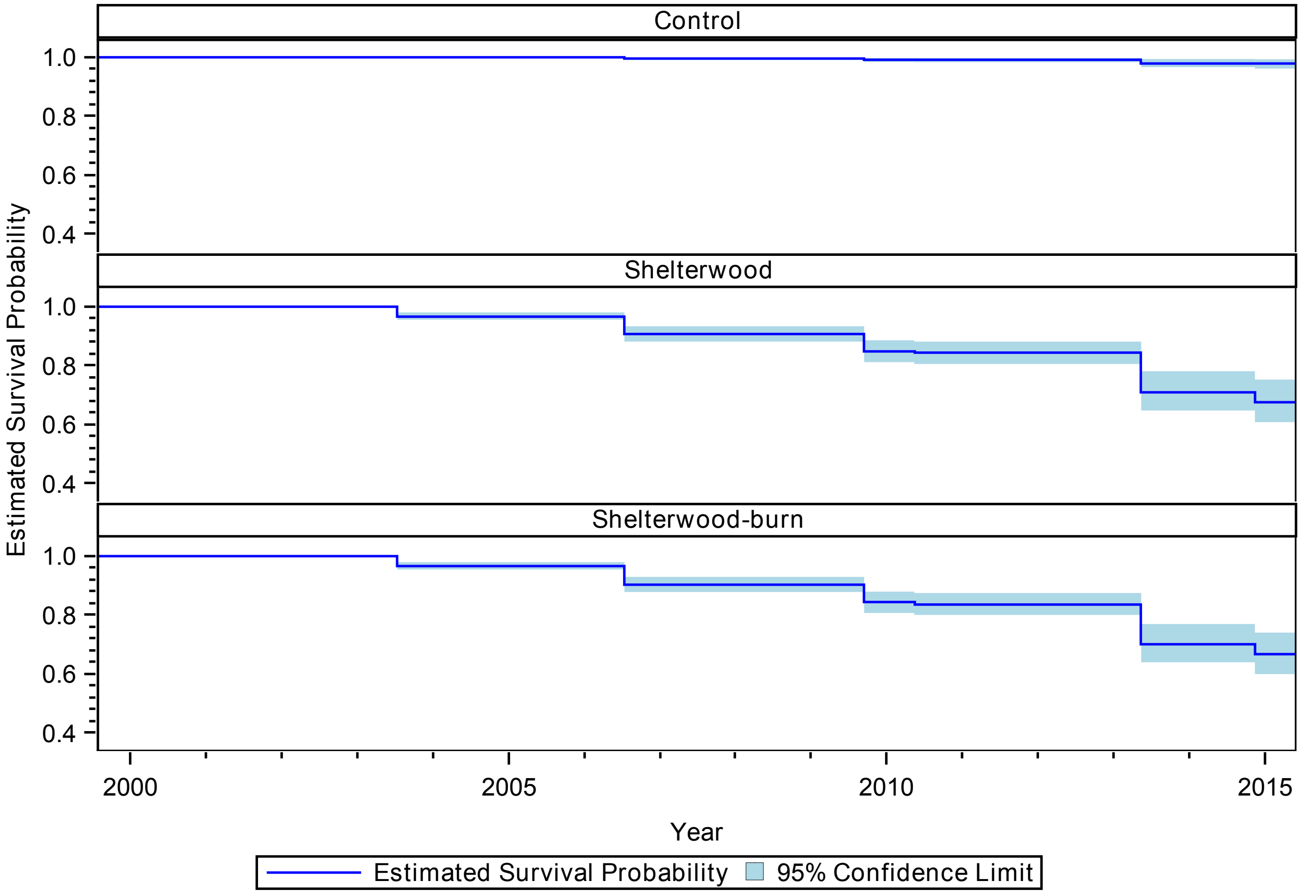

Figure 3— Estimated survival probabilities for each treatment. Estimated probabilities are direct adjusted for each crown class and species, with dbh held at the average value of 13 inches.

estimate was again used to test significance for the main effects. Crown class was not significant (p=0.7941) and was dropped from the model. The model was iteratively refit, using backward selection. Both treatment and species were not significant (p=0.5215) and (p=0.0820), respectively. The lack of a treatment difference indicates that the post-shelterwood burn did not create additional tree mortality. Diameter at breast height was the only significant effect for fire-induced mortality (p=0.0024). An increase of 1 inch dbh reduced the probability of dying from 16 to 31 percent [95 percent confidence interval for exp(β_{DBH})]. The diameter distribution for all plots treated with prescribed fire (fig. 4) shows that the majority of trees killed by fire were ≤10 inches dbh. Further, the shelterwood treatment did not have a prescribed fire after the first removal cut. Mortality shown in figure 4 for the measurement date of November 15, 2014 is solely fire mortality from the shelterwood burn. The number of trees killed is limited and reflects the lack of a significant treatment difference between the shelterwood and the shelterwood burn.

DISCUSSION

As expected, there was a significant increase in overstory tree mortality over background mortality stemming from the application of prescribed fire, particularly in the smaller dbh classes which were the target of the site-preparation burns. Wendel and Smith (1986) observed a similar reduction in the number of overstory stems in a prescribed fire treated stand compared to a control stand in an Appalachian second growth oak-hickory forest. Loucks (2004) did not find a difference in mortality for fire-excluded and burned treatments for trees with dbh >4 inches, however the sample size was very small for that comparison (n=3). Paulsell (1957) found in Missouri that for trees with dbh >6.5 inches, mortality was greatest (13.3 percent) over an 8-year period for a control treatment versus an annual-burn treatment (5.2 percent), and a 5-year burn treatment (3.0 percent); none of these studies included a harvest. In a study of eastern hardwoods, Yaussy and Waldrop (2010) found a significant difference

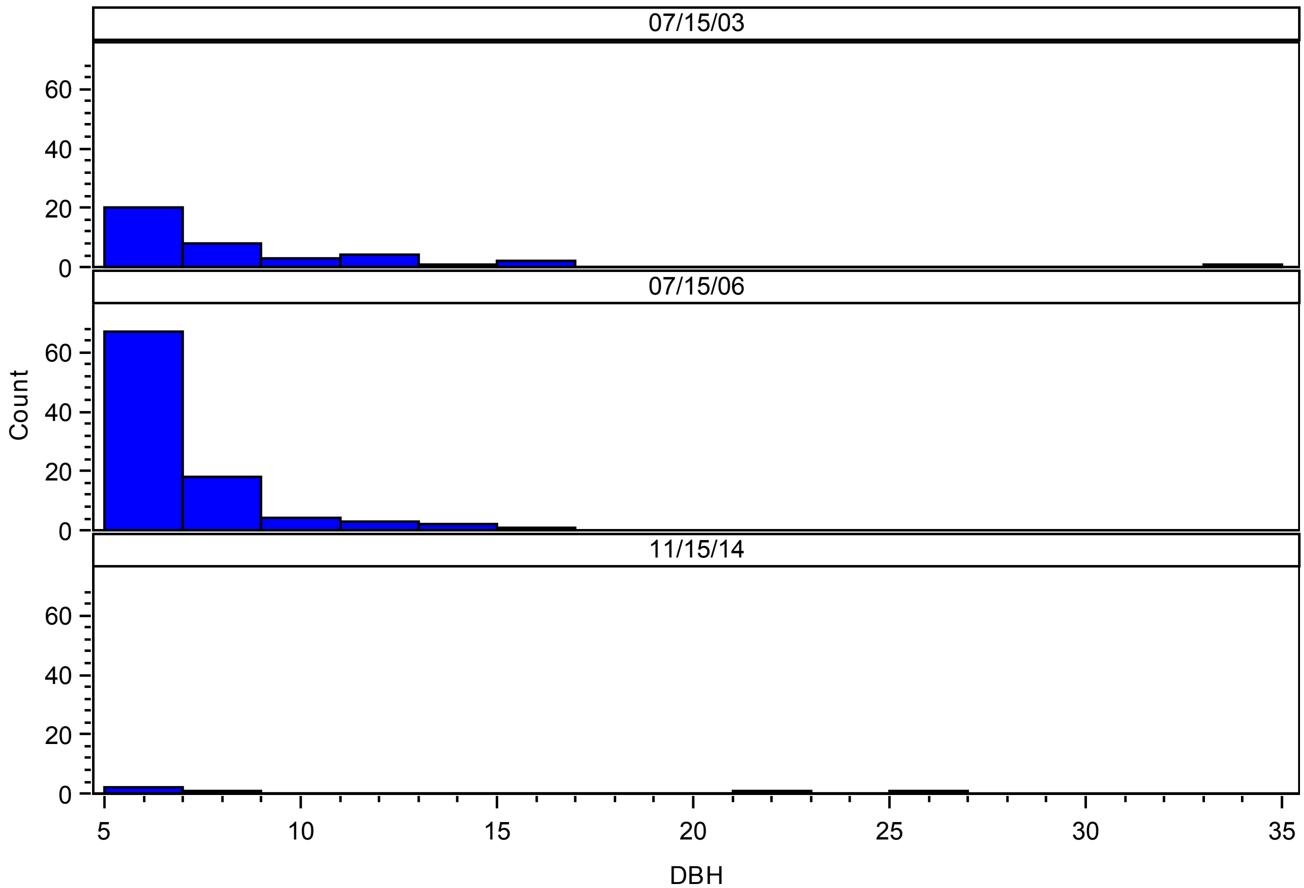

Figure 4—Diameter distributions of fire-killed trees in both shelterwood treatments at post-fire measurement dates.

between four treatments: a control, mechanically treated, prescribed fire, and mechanically treated plus prescribed fire. While no multiple comparisons were performed, the control and the mechanical+burn treatment differed the most at 4 years. In a shelterwood-burn study in Virginia, Brose and Van Lear (1999) reported that mortality was significant greater during a spring burn for all species groups studied (oak, hickory/poplar, and beech/maple) and significantly different for the beech/maple group in summer and winter burns as well. Our study adds further understanding of the effects that multiple prescribed fires and individual tree characteristics have when using the shelterwood-burn method. In particular, we have isolated the effect of the post-shelterwood burn, which has been demonstrated to not significantly affect mortality in the overstory, based on measurements taken 1 year after the prescribed burn. Differences between the control and the two shelterwood treatments for all mortality, therefore, are attributed to the two prescribed fires applied prior to the first removal cut in both shelterwood treatments.

No competitive advantages or disadvantages were discovered for any of the oak species examined in regard to other species present in the study area. This was true for both combined mortality and fire mortality considered alone. While examining species differences for total mortality in a Southern Appalachian oak forest, Greenberg and others (2011) detected a significant difference among oak species. Their study included the three oak species included in our study—northern red, white, and chestnut—and had total mortality rates of 13.8 percent, 10.4 percent, and 5.7 percent, respectively, over a 15-year period. Our results were similar with white oak having higher mortality than chestnut oak; however, mortality for northern red oak in our study did not differ significantly from either white or chestnut oak.

Tree diameter was a significant factor for both combined mortality and fire-induced mortality alone. This is expected for background mortality where the largest dbh trees tend toward greater dominance in the overstory and outcompete smaller trees. In regard to fire, bark thickness is known to increase with tree diameter and this increase provides additional protection for the cambium from heat damage (Hengst and Dawson 1994, Spalt and Reifsnyder 1962). For eastern hardwoods, Yaussy and Waldrop (2010) found that a 0.039-inch increase in bark thickness reduced mortality after a prescribed fire by 4.5 percent. Huddle and Pallardy (1996) found that fire accelerated the loss of small diameter trees in all species. Hutchinson, and others (2005) found that small trees (4-10 inches dbh) in study areas with multiple prescribed fires exhibited higher mortality than an unburned control. As was found in our study, Hutchinson and others (2005) determined that mortality for large diameter trees (dbh >10 inches) was not significantly related to fire frequency. Arthur and others (2015) found a relationship of increasing mortality with increasing char height for midstory trees (4-8 inches dbh) on sub-xeric and intermediate landscape positions compared to sub-mesic landscape positions. Also in their study, increasing char heights were correlated with increasing fire temperature. However, char height was not a significant factor for mortality of overstory trees in that study. It appears that the temperature is more of a factor with char height simply a surrogate measure. Given the mortality discrepancy between dbh size classes reported in Arthur and others (2015), a dbh size threshold may have been crossed. In our study, fire mortality subsequent to the two pre-shelterwood cut burns exhibits a reverse j-shaped pattern, with the smallest diameters exhibiting the greatest mortality (fig. 4).

This analysis concerned only mortality and land managers and owners likely have concerns on tree damage, decay, and value loss from the use of prescribed fires. This study area is also used to track wounds, damage, and value loss caused by fire at two points in the study. Seventy-four logs from the shelterwood harvest were tracked from the study site to the mill to evaluate the effects of the two prescribed fires (Wiedenbeck and Schuler 2014). Overall, value loss from decay caused by the two fires in trees assessed 5 years after the last fire was <0.25 percent (Wiedenbeck and Schuler 2014). Differences in species response to fire damage were noted with red maple having a greater level of decay than yellow-poplar (Wiedenbeck and Schuler 2014). With the completion of the shelterwood cut and the post-shelterwood burn, an analysis was made of wounds from all management actions (Wiedenbeck and others 2017). Researchers found that the percentage of trees with fire char and scar was low, 8 percent, after the post-shelterwood fire given the open nature of the stand post-harvest and the thick bark of the mature residual trees (Wiedenbeck and others 2017).

CONCLUSIONS

Our results indicate that increasing tree size decreases the risk of natural and fire mortality by 3 to 16 percent per inch increase in dbh. This is an important consideration for sites for which prescribed fire is used to reduce competition from the seedbed and to establish adequate oak advance regeneration. While mortality differed between the unburned and burned treatments, awareness of this lessened risk of mortality for larger trees may provide guidance to managers wanting to maintain oak in future stands. Knowing that there is reduced mortality for dominant and codominant trees also informs decisions made in the initial shelterwood removal cut. Generally larger diameter dominant and codominant trees are chosen as residuals in a shelterwood harvest and our results show the added benefit of their selection if prescribed fire is also planned. Based on measurements taken 1year after the post-shelterwood burn, this analysis demonstrates that post-shelterwood controlled burning can be used without additional mortality to the residual overstory trees and provides support for using the shelterwood-burn technique in stands where timber products are an objective for the land manager. The study will continue to be monitored for delayed mortality several years and for other aspects of the study.

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