

TREE-QUALITY IMPACTS ASSOCIATED WITH USE OF THE SHELTERWOOD-FIRE TECHNIQUE IN A CENTRAL APPALACHIAN FOREST

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Abstract.—Wounding from prescribed fires and forest harvest operations creates concerns about the future health, grade, volume, and value recovery potential of affected trees. The wounds, regardless of origin, may compartmentalize and heal over. Or they may be slower to heal or too significant to defend against pathogens that invade the wound zone and promote decay formation and spread. Even tree species that are good at compartmentalization after being wounded can succumb after a series of wounding events. We often create this scenario when conducting prescribed fires in conjunction with thinning and regeneration operations. A combination prescribed fire–shelterwood treatment study to evaluate oak regeneration (*Quercus* spp.) and establishment in a mesic mixed-oak forest was conducted in 2000 in West Virginia. Before and after each of two prescribed fires that were intended to eliminate a shade-tolerant understory, a shelterwood harvest to open the canopy to promote oak regeneration, and a subsequent prescribed fire designed to further cull less fire tolerant non-oak species, tree-quality conditions were evaluated for all stems 5-inch diameter at breast height and larger. The initiation and development of wounds and broken tops were tracked and correlated with silvicultural activities and weather events. The cumulative and interaction effects of repeated mechanical stressors on these stems are significant factors in long-term research that seeks to determine the costs and benefits of prescribed fire treatments to promote oak regeneration.

INTRODUCTION

Many forestry, wildlife, and ecology professionals accept the use of prescribed fires in eastern hardwood forest management. Resource managers use fire to shape regeneration, habitat, and ecological restoration outcomes and to reduce fuel buildup to lower the risk of wildfires. Managers of numerous national forests in the eastern region have revised their planning documents to include fire as a restoration tool (Nowacki et al. 2009). In the Appalachian region, a post-shelterwood prescribed fire treatment has been cited as another means of promoting oak regeneration (Brose et al. 1999). Eastern hardwood tree mortality caused by fire has been evaluated in multiple studies. Factors assessed in these fire-caused mortality studies include fuel types and loadings (Brose and Van Lear 1999, Wendel and Smith 1986, Yaussy and Waldrop 2010); bark thickness (Harmon 1984, Yaussy and Waldrop 2010); tree diameter (Harmon 1984, Hutchinson et al. 2005, McCarthy and Sims 1935); season in which fire occurred (Brose and Van Lear 1999); fire severity (Regelbrugge and Smith 1994, Yaussy and Waldrop 2010); and tree vigor before fire exposure (Yaussy and Waldrop 2010). Fire damage severity based on the degree of bole damage and the crown condition has also been widely studied (Brose and Van Lear 1999, Pomp et al. 2008, Wendel and Smith 1986). The process of wound formation after fire injury has been studied by Smith and Sutherland (2001, 2006) and Sutherland and Smith (2000).

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These studies, though, lack repeated measurements over time of the effects of the prescribed fire on tree condition. Only one study evaluated the effect of a post-shelterwood establishment prescribed fire on the change in bole condition after the fire (Brose and Van Lear 1999). After a prescribed fire conducted in the spring, the proportion of the undamaged oak boles dropped from 73 percent to 50 percent and the proportion of dead oaks increased by 18 percent. More than 90 percent of the oaks that died or showed severe bole damage had accumulated logging slash at their bases (Brose and Van Lear 1999). Their study incorporated a cumulative effects component (shelterwood cut + fire) but only evaluated the preburn and postburn tree conditions at a single point in time.

OBJECTIVE

The main objective of this study was to assess over an extended period (15 years) the cumulative and interaction effects of repeated mechanical stressors on trees of the Central Appalachian broadleaf forest. The hypotheses under investigation were as follows:

H₁: The quality condition of trees does not change between treatments over time.

H₂: The quality condition of trees does not change between treatments.

H₃: The quality condition of trees does not change over time.

METHODOLOGY

A study of the combined effects of prescribed fire and shelterwood harvest on oak regeneration has been under way in the Fernow Experimental Forest (Schuler et al. 2013) since 2000. The research site is in the Canoe Run watershed of the Fernow Experimental Forest (39.03°N, 79.67°W) in West Virginia. The elevation of the study site is 1,920-2,200 feet with a western aspect and a mean slope of 39 percent. It is described as a mixed mesophytic site with overstory dominated by northern red oak (*Quercus rubra* L.), chestnut oak (*Q. prinus* L.), and white oak (*Q. alba* L.) (Schuler et al. 2013). The study site is a second-growth forest that is about 100 years old.

Two prescribed fire treatments have been applied to the study site. The first was conducted in April 2002 and 2003—in 2002 the prescribed fire was interrupted because of bad weather, so the second half of the site was not burned until the following April. The second fire treatment was conducted in April 2005. The maximum temperature probe readings recorded during these two burns were 576 °F in 2002 and 621 °F in 2005, and the associated rates of spread were 30 feet per minute and 144 feet per minute, respectively (Schuler et al. 2013). These prescribed fires were characterized as “moderate to low intensity with flame lengths shorter than 3 feet that resulted from the combustion of leaf litter and 1-hour surface fuels” (Schuler et al. 2013, p. 432).

During winter 2009-2010, a shelterwood cut removed 50 percent of the overstory trees in 20 of the 24 plots (each plot is 0.5 acres). The other four plots were untreated reference (referred to as *control*) plots on which neither prescribed fires nor shelterwood operations were conducted. The residual “leave” tree basal area was 45-50 square feet per acre and comprised largely oaks. Only trees of 11 inches diameter at breast height (d.b.h.) or larger were marked for cut.

In spring 2014 a third prescribed fire was applied to half (10) of the treated plots. The maximum probe reading recorded in this burn was higher than for the earlier burns (929 °F), and the mean maximum temperature recorded on the 48 thermocouples was 272 °F.

The 20 plots that were burned twice and received the shelterwood cut are referred to collectively as the *manipulative treatments*. Of these, the 10 plots burned again after the shelterwood cut in 2014 are referred to as the *post-shelterwood burn* treatment. The 10 plots burned before the shelterwood harvest only are referred to as the *no post-shelterwood burn* treatment. Figure 1 shows the treatment areas and plot layout.

Oak Shelterwood—Prescription Fire Study

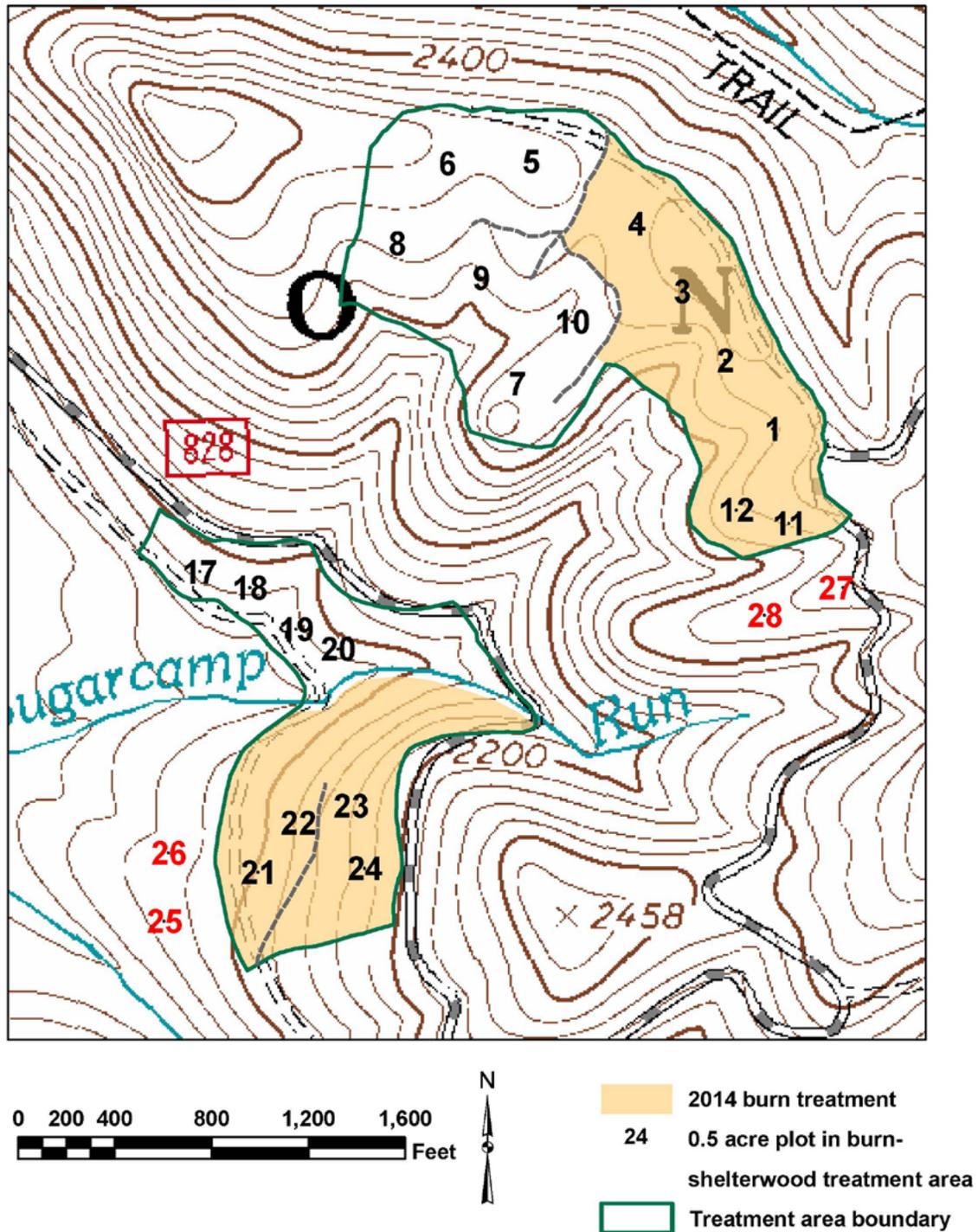


Figure 1.—Treatment map with plot locations.

The experimental unit is a 0.5-acre growth plot surrounded by a buffer that is approximately 100 feet wide. Within the 0.5-acre plot, all trees ≥ 5 inches d.b.h. were individually numbered, tagged, and tracked. On seven occasions since the study began, growth plot data have been collected (only four times for the four reference plots) for each tree. Each remeasurement included d.b.h., crown class (CC), and nonquantitative quality conditions. Quality assessments were binary—the given characteristic was either present or not. Live tree characteristics conditions included (1) stem skinned, (2) top broken, (3) bent/lean, and (4) vines in crown. Trees that died since the previous measurement cycle were assigned a cause of death of (1) unknown, (2) cut, (3) destroyed, or (4) fire killed. For the live tree assessments, multiple characteristics could be present. For the dead tree assessments, only one cause of death was assigned. The same team of forestry technicians conducted all of the assessments.

In addition to the silvicultural treatments, Superstorm Sandy caused varying amounts of tree damage throughout the forests of the region in 2012. This early-season storm (October 30) dumped large amounts of wet, heavy snow over a multicounty region of West Virginia, Maryland, and southwest Pennsylvania at a time when many trees had not yet dropped their leaves. The storm resulted in significant tree damage and woody debris. This damage is partially reflected in a comparison of the May 2010 and May 2013 growth plot measurements.

Statistical Methodology

To begin, one-way analysis of variance was performed on the plot-level data from 1999 (before treatments were applied to the stands) to ascertain if the number of trees per plot and mean d.b.h. of all trees 5 inches and larger was the same among plots assigned to treatments. Because the number of trees per plot (plot size = 0.5 acres) varied by treatment at the beginning of the study, stand density index (SDI) was used as a stand density measure and was treated as a covariate in the analysis. CC (dominant, codominant, intermediate, suppressed) (Smith et al. 1997) was included as an explanatory variable in the models.

Given the repeated measures over time, factors affecting quality conditions were tested using logistic regression mixed models in SAS (PROC GLIMMIX) (SAS Institute, Cary, NC). Several possible covariance structures were selected to account for the repeated measures: variance components, compound symmetry, spatial exponential (SP(EXP)), spatial power (SP(POW)), and spatial Gaussian (SP(GAU)). Significance levels were set at $\alpha = 0.05$. The interaction term treatment*time was included in the model, and the remaining terms were tested as main effects. The corrected Akaike information criterion (AICc) was used in model selection. Multiple comparisons (MCs) were conducted using the Tukey-Kramer adjustment. For the MC test of the treatment*time interaction, the continuous variable time was fixed at the four time points in the study where all treatments were measured. The significance level was Bonferroni adjusted to account for the four sets of MC tests. The mixed logistic model is of the form

$$g(p) = X\beta + Z\gamma + \varepsilon$$

Where

X = a matrix consisting of values for treatment, time, stand density index, and crown class,

β = the vector of the unknown fixed effects parameters,

Z = the known design matrix for the random effects,

γ = the vector of the unknown random effects parameters,

p = the probability of the quality condition occurring,

$g(p)$ = the logit function = $\frac{p}{1-p}$, and

ε = the unobserved vector of random errors.

Plot averages for the treatments were calculated to gain insight into the statistical results. Tree survival (mortality) results are evaluated here using simple summary statistics to inform the discussion of tree condition. Survival analysis for trees among treatments will be evaluated in a subsequent paper.

RESULTS AND DISCUSSION

Tree Mortality

Figure 2 shows the percentage change in the number of live trees per plot at key points in this study. The baseline for each treatment is set to the mean number of trees present in 1999 (T_0). The percentage-based decline in live trees for both manipulative treatments is 13 percent after 7 years and two moderate- to low-intensity prescribed fires, notably more than for the control plots in which the number of 5-inch and larger stems declined only 4 percent (Fig. 2). In 2009, the decline in live tree stems in the manipulative treatment plots compared to the number present in 1999 was 20 percent; for the control plots the reduction was only 7 percent. These reductions in tree numbers occurred after two prescribed fires but before the shelterwood harvest, Superstorm Sandy, and post-shelterwood prescribed fire affected the plots.

Once a tree dies, it is removed from consideration in future surveys. As a result, the listed numbers of dead trees during each assessment are only those trees that died since the previous plot survey. In both 2003 and 2006 most trees that died on the treatment plots were killed by fire (73 percent in 2003 and 83 percent in 2006). In 2009, the tally that was conducted before the shelterwood operation found another 93 trees newly dead in the treatment plots, but the cause

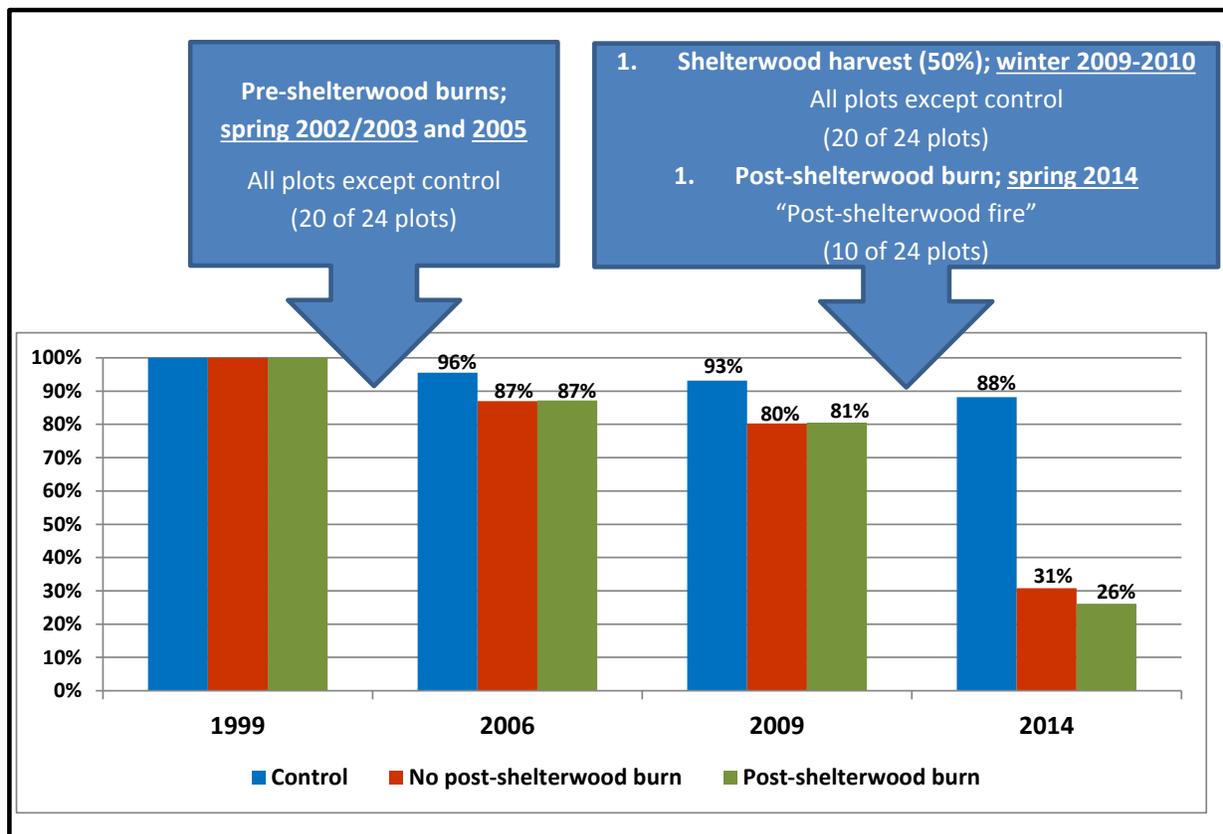


Figure 2.—Proportional change in the number of live trees greater than 5 inches d.b.h. from study installation in 1999 through post-shelterwood, post-prescribed fire treatments in 2014 by treatment.

Table 1.—Final models for all quality conditions

Effect	Number DF ^c	Denominator DF	F value	Pr > F
Quality condition = stem skinned				
Treatment*time	4	3596	14.47	<0.0001
Treatment	4	3596	9.42	<0.0001
Time	1	3596	406.93	<0.0001
CC ^a	3	3596	25.09	<0.0001
Quality condition = top broken				
Treatment	4	2878	7.51	<0.0001
Time	1	2878	159.93	<0.0001
CC	2	2878	41.49	<0.0001
Quality condition = bent/lean				
Treatment	4	2799	3.14	0.0137
Time	1	2799	7.14	0.0076
CC	2	2799	18.96	<0.0001
Quality condition = vines in crown				
Time	1	3576	50.14	<0.0001
SDI ^b	1	3576	19.42	<0.0001
CC	3	3576	2.84	0.0367
Quality condition = fire damage				
Treatment	4	3215	12.4	<.0001
Time	1	3215	49.5	<.0001
SDI	1	3215	13.62	0.0002
CC	3	3215	24.85	<.0001

^aCC = crown class

^bSDI = stand density index

^cDF= degrees of freedom

of death for these was not determined. Again in 2013, in the second survey after the shelterwood harvest, the manipulative treatment plots had a substantial number of newly dead trees (64) with unknown causes of death; the control plots had no newly dead trees. Tree mortality at this juncture can be attributed to the cumulative and delayed effects of the silvicultural manipulations in combination with higher vulnerability of these lower-density stands to Superstorm Sandy's snow and wind loads.

Statistical Results for Tree Condition

For all quality conditions, the AICc value for the full model was the lowest when using the variance components covariance structure. The full model consisted of the treatment*time interaction term, SDI, along with CC. For all models, the AICc value was lowest for the variance components covariance structure. Therefore, variance component was maintained as the covariance structure for testing the significance of the independent variables. Nonsignificant variables were dropped from the model, and the model was refit until all terms were significant (Table 1).

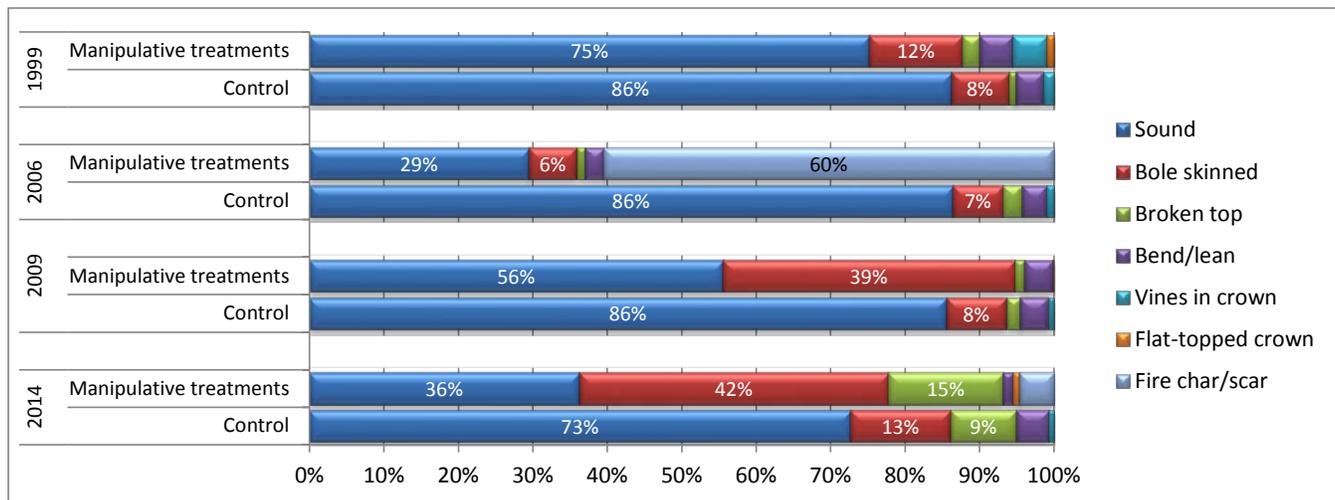


Figure 3.—Condition of live trees tallied at the time of study installation and three subsequent points in time: (A) 2006 after all plots except control plots subjected to two prescribed fires, (B) 2009 before shelterwood harvest on all but the control plots, and (C) 2014 after post-shelterwood prescribed fire on 10 of 24 plots.

MC tests were conducted for treatment. Fixed time points had to be selected to conduct the paired comparisons for the stem-skinned quality condition because the treatment*time term was significant (Table 1). Four years had measurements that included all treatments, so these four time points were used. In general, only the control treatment differed significantly from the others through time. Skinned stems were commonly associated with trees that showed significant fire scars or char in previous inventories of the plots that were treated with prescribed burns (Fig. 3).

Fixing time was not required for the MC tests for treatment for the top broken, bent/lean, and fire damage quality conditions because the interaction term was not significant. For the top broken condition, the control treatment differed significantly from the manipulative treatments. For the bent/lean condition and the fire damage condition, the MC test results were convoluted, suggesting that special contrasts may be needed to identify and explain the differences indicated by the models.

For CC comparisons, we observed a significant difference between codominant trees and any other CC for the stem-skinned condition (Table 2). For both the top broken and bent/lean conditions, codominants were significantly different (occurring less frequently) than intermediate and suppressed trees. No dominant trees exhibited these quality conditions. Only the intermediate versus suppressed tree comparison was different for the vines to crown quality condition. For fire damage, the codominant, intermediate, and suppressed classes all differed. The dominant class showed no differences between the others, but there were so few dominant trees that this is likely a sample size/statistical power issue.

Discussion of Tree Condition Results

When the study began in 1999, 75 percent of the trees tallied in the plots assigned to the manipulative treatments were rated as sound compared to 86 percent of the trees in the control plots (Fig. 3). The percentage of sound trees in the four control plots remained steady through the 2009 measurement cycle but dropped to 73 percent in the 2014 tally. The sound percentage of trees in the plots that were treated with two prescribed fires was only 29 percent in 2006 and rose back up to 56 percent in the 2009 assessment. In the most recent survey, which was after

Table 2.—Multiple paired comparisons for crown class for all quality conditions

Quality condition	Crown class	Paired comparison*
Stem skinned	Dominant	a,b
	Codominant	a
	Intermediate	b
	Suppressed	b
Top broken	Codominant	a
	Intermediate	b
	Suppressed	b
Bent/lean	Codominant	a
	Intermediate	b
	Suppressed	b
Vines in crown	Dominant	a,b
	Codominant	a,b
	Intermediate	a
	Suppressed	b
Fire damage	Dominant	a,b,c
	Codominant	a
	Intermediate	b
	Suppressed	c

*Same letters indicate no significant differences between crown classes.

the shelterwood harvest, Superstorm Sandy, and a post-shelterwood burn on 10 plots, the sound percentage of trees in the plots was 36 percent (Fig. 3).

The 20 treatment plots were subjected to two prescribed fires in the 2002–2005 time frame and had substantial amounts of charred bark on 60 percent of the living tree stems in 2006. This average varied among the 20 treatment plots from 20 percent to 93 percent (standard deviation = 18 percent). When evaluated again in 2009 after 4 years without any manipulative operations, none of the trees in either the control or treatment plots showed signs of remnant fire char. The incidence of skinned boles tallied in the 20 treatment plots rose significantly in the 2009 assessment, however (\bar{x} = 39 percent, s = 11 percent). The skinned boles were the next phase in the progression of the fire damage as the charred bark sloughed off and a cat-face type wound began to form. Conversely, some of the trees that had large areas of black bark in 2006 did not lose bark or appear wounded in 2009 (Fig. 3).

The occurrence of broken tops in these plots was consistently lower than 5 percent during plot surveys conducted through 2009 on the control and treatment plots. The 2014 results (Fig. 3) indicate that the mean percentage of live trees with broken tops jumped to 15 percent on the treatment plots and to 9 percent on the four control plots. These data were collected after the shelterwood harvest and after Superstorm Sandy.

The increase in broken tops was investigated more closely by looking at the results from two growth plot surveys that were conducted on treatment plots in 2010 and 2013. This focused look at tree condition classes during the 2009–2014 time frame showed us that the plots on which the shelterwood harvest was conducted in winter 2009–2010 had an increase in the relative occurrence of broken tops in the survey conducted immediately after the harvest, changing

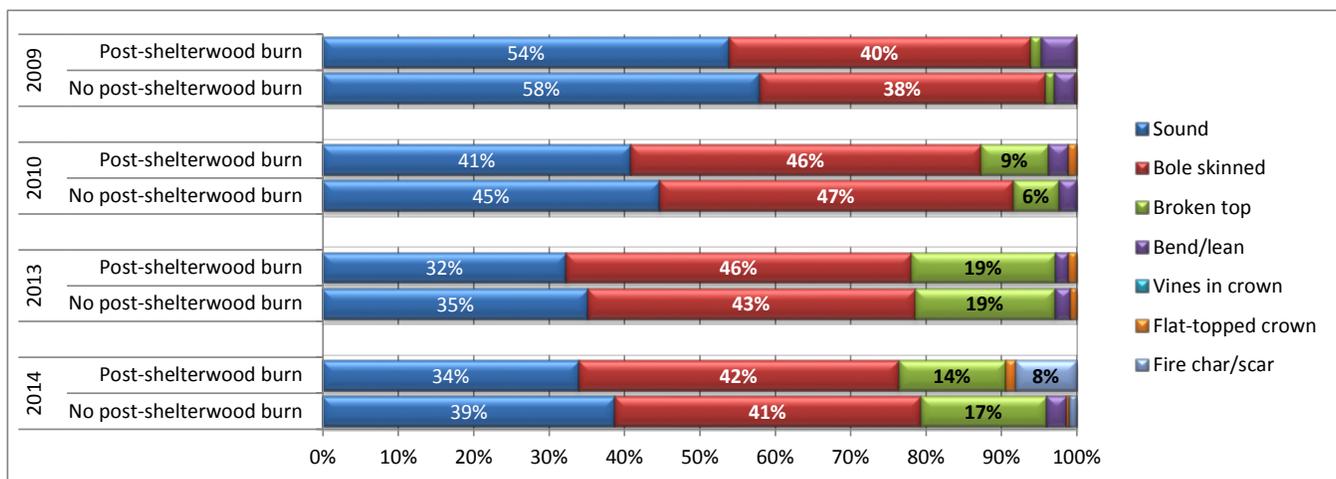


Figure 4.—Tree condition proportions for the two manipulative treatments based on all trees. Includes results of four plot assessments conducted between 2009 and 2014 including the 2010 and 2013 partial assessments (control plots not remeasured).

from 1 percent of trees before the harvest to almost 8 percent of trees after. The 2013 plot survey, however, again showed a large increase in the relative incidence of broken tops: the rate increased from 8 percent in 2010 to almost 19 percent 3 years later (Fig. 4). The opening of the canopy resulting from the shelterwood operation made a higher percentage of the trees in the manipulative plots more susceptible to the heavy snow and wind loads that occurred in 2012 during Superstorm Sandy.

The multiple comparisons conducted on CC appear to be illogical in that the dominant trees are grouped with the suppressed trees for the stem-skinned, vines in crown, and fire damage conditions (Table 2). Less than 1 percent of all trees during each tally period were classed as dominant, however. The codominant MC results compared to the intermediate and suppressed results indicate that skinned stems, broken tops, tree lean, and fire damage affect intermediate and suppressed trees more than codominant trees. The prescribed fires and harvest damage from the shelterwood operation are affecting significant percentages of trees in the treatment plots, but the affected trees are understory trees. Forest managers seek to eliminate many of these intermediate and suppressed trees over time to improve oak regeneration.

The proportion of hardwood stems in a central Appalachian forest exhibiting skinned boles, broken tops, lean, vines in crown, and fire damage changed over 15 years, with treatment being a factor. Stem-skinned (bole) proportions were different among treatments and the differences varied over time, so hypothesis 1 (H1: the quality condition of trees does not change between treatments over time) is rejected for the stem-skinned condition class. The other quality conditions showed significant main effects for time and for treatment, so hypothesis 3 (H3: the quality condition of trees does not change over time) is rejected, and hypothesis 2 (H2: the quality condition of trees does not change between treatments) is rejected for all but the vines in crown quality condition class. Quality condition varied among treatments, with the reference/control treatment having lower proportions of the non-normal (less desirable) conditions noted than for the manipulative treatments that included prescribed fires and a shelterwood harvest operation.

Parsing out the cumulative effects of the combination of treatments—preharvest prescribed fires, a shelterwood harvest of 50 percent of overstory trees, and a postharvest prescribed fire—on the condition of residual trees is a multifaceted challenge. The prescribed fires and harvest damage from the shelterwood operation are affecting significant percentages of trees

in the manipulative treatment plots, but these are not the favored dominant or codominant trees. Instead, the affected trees are predominantly shade-tolerant species in intermediate and suppressed CCs, which the shelterwood-prescribed fire management regime seeks to eliminate over time to maintain the dominance of oak. The proportion of trees with fire char and scar in the post-shelterwood fire treatment was low (8 percent) compared to the fire char and scar proportion found in 2006 (60 percent), even though the maximum temperatures recorded on the thermocouples were generally higher. This outcome supports the supposition by Brose and Van Lear (1999, p. 88) that although “fire may be intense due to the presence of slash and increased exposure to sunlight and wind ... conversely, the open nature of the shelterwood stand coupled with the thick bark of a mature tree may limit damage.”

Predictably, the opening of the canopy resulting from the shelterwood operation made a higher percentage of the trees in the manipulative plots more susceptible to the heavy snow and wind loads that occurred during Superstorm Sandy.

Tree mortality summaries indicate the need to further this investigation by conducting a survival analysis to learn more about the influence of silvicultural activities and tree condition over time on the survival of trees of different species having different CCs.

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