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# Effect of Prescribed Fire on Timber Volume and Grade in the Hoosier National Forest

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Low-intensity surface fire is prescribed in eastern North American hardwood stands prior to overstory harvest in order to improve regeneration and recruitment of oak and other fire-tolerant and fire-adapted species. However, this use of prescribed fire potentially can reduce timber value. We inventoried overstory trees (>10 in. diameter at breast height) in 54 oak-dominated stands with varied prescribed fire histories and aspects in southern Indiana. We then documented the extent of prescribed fire damage (i.e., wounds) to overstory trees and quantified both the relative stand volume of timber loss and the proportion of trees that had tree grade reductions because of prescribed fire. Generally, as a stand received more prescribed fires, more trees were scarred, the relative volume lost increased, and a higher proportion of trees declined in grade. Overall, burned stands experienced less than 10 percent sawtimber volume loss, regardless of the number of prescribed fires and aspect. Less than 3 percent of trees, study-wide, had reduced grade because of prescribed fire. Grade and volume reductions varied by species, however. Our results suggest that prescribed fire has a minor economic impact on standing timber, particularly when timber is harvested within two decades of the first fire.

**Keywords:** central hardwoods, bole wounds, USFS tree grades, fire ecology, *Quercus*

Fire is a disturbance agent that influences many ecosystem processes and shapes the structure and composition of numerous biomes throughout the world (Bowman et al. 2011, Dey and Schweitzer 2018). Fires set by Native Americans were an integral part of most terrestrial ecosystems in eastern North America for thousands of years prior to European colonization (Brose et al. 2014) and contributed to the dominance of fire-adapted oak (*Quercus*) species in forests throughout the region (Abrams 1992). Fire exclusion over the last century has contributed to the lack of advanced oak regeneration and the increased regeneration of mesic species such as beech and maple (*Fagus* and *Acer*) within many forests (Nowacki and Abrams 2008, Arthur et al. 2012, Brose et al. 2013).

Fire can encourage development of advanced oak regeneration (Brose et al. 1999, 2013, 2014) and is increasingly prescribed by federal and state agencies and non-government organizations for ecosystem restoration (Dey and Schweitzer 2015). Oak forests without fire are experiencing compositional changes as more mesic species continue to dominate in the midstory, particularly on more productive sites (Steiner et al. 2018). Much of eastern North America's oak forests are on the verge of transitioning to late successional, mesic forests. This change in overstory composition could have dramatic ecological consequences; oaks are a foundational species that many animal species rely upon for both food and habitat (Hanberry and Nowacki 2016). Loss of oak could also have huge financial ramifications, as these species are used for a vast array of timber products (Buehlmann et al. 2017) and, for white oak (*Q. alba*) in particular, cooperage for the expanding distilling industry (Delany and Haynes 2017).

Modern natural-resource management frequently aims to meet multiple objectives while balancing tradeoffs (Bradford and D'Amato 2012). There are numerous factors that limit the

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implementation of prescribed fire (e.g., short burn windows, smoke concerns, resource allocation, liability, expertise, and regulatory requirements) for ecosystem management. There is also a pervasive concern that prescribed fire will negatively impact timber resources; therefore, many land managers and forestland owners hesitate to use fire (Dey and Schweitzer 2015, 2018). Previous studies that investigated the effect of periodic, low-intensity prescribed fires on standing hardwood timber volume and value reported minimal losses (Stambaugh and Guyette 2008, Marschall et al. 2014, Wiedenbeck and Schuler 2014, Knapp et al. 2017). However, most previous work focused on the less fire-tolerant red oak (*Erythrobalanus*) group, which was less prevalent on the landscape prior to fire suppression than the white oak group (*Lepidobalanus*) (Abrams 2003). As white oaks occupy a large volume of the standing sawtimber-sized trees in eastern North America—2206 million bd ft (Doyle) in Indiana alone (Gormanson and Kurtz 2017)—the effects of prescribed fire on white oak timber need to be more fully explored.

To quantify the effects of prescribed fire on timber volume and quality, we measured prescribed fire damage of overstory trees within oak-dominated hardwood stands in the Hoosier National Forest (HNF) in southern Indiana. Stands varied by the number of fires received over 25 years (zero to five burns) and by aspect. We hypothesized that, as the number of prescribed fires a stand receives increases, the proportion of trees wounded by fire would increase, the relative amount of timber volume lost would increase, and more trees would decline in grade. We further hypothesized that wounding, timber loss, and grade loss are exacerbated in stands with more xeric (i.e., south- and west-facing) than mesic (i.e., north- and east-facing) aspects and that there would be some differences among commercially valuable species groups in fire-induced damage.

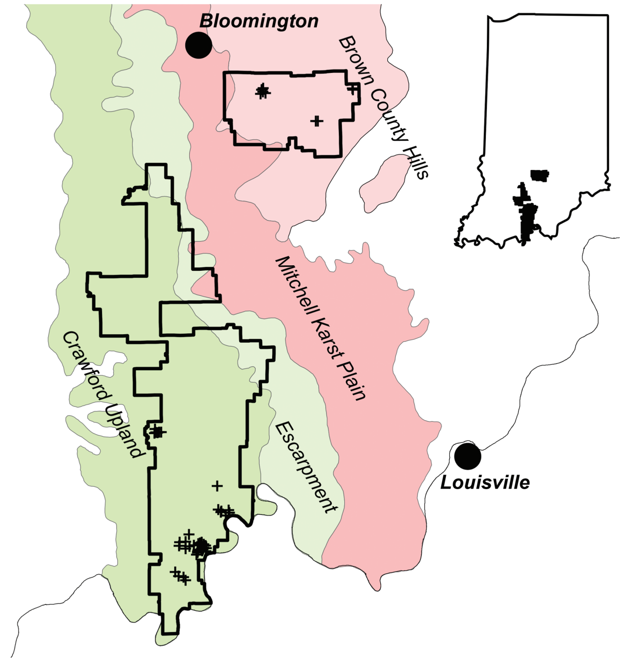


**Figure 1. Study sites (+) within the Hoosier National Forest in southern Indiana, USA. Sections of the Highland Rim Natural Region (light reds) and Shawnee Hills Natural Regions (light greens) are also shown (Homoya et al. 1985). At the scale of this map, study site symbols overlap considerably as sites occurred within only 13 burn units across the Hoosier National Forest.**

## Materials and Methods

### Study Site

The HNF encompasses nearly 202,000 ac of southern Indiana (Figure 1). Most of the region was cleared for agricultural use in the early 1900s and subsequently abandoned. Forests regenerated on these lands, and the HNF was acquired in patches by the United States Forest Service (USFS) throughout the 20th century. Most of the HNF is second- or third-growth, although very few remnant 300+-year-old stands still exist (Maxwell and Harley 2015). All stands chosen for this study were second-growth.

The HNF is within the Brown County Hills and Mitchell Karst Plain sections of the Highland Rim Natural Region and the Crawford Upland and Escarpment sections of the Shawnee Hills Natural Region (Figure 1; Homoya et al. 1985). Forests of both sections of the largely unglaciated Highland Rim Natural Region are dominated by oak and hickory (*Carya*) species, particularly on ridges and south-facing aspects; ravines and north-facing aspects in both sections include more mesic species such as American beech (*F. grandifolia*), northern red oak (*Q. rubra*), and sugar maple (*A. saccharum*). In the Mitchell Karst Plain section, post oak (*Q. stellata*) and chinquapin oak (*Q. muehlenbergii*) are common on xeric sites (Homoya et al. 1985).

The Shawnee Hills Natural Region is mostly unglaciated and primarily composed of upland forests. Upper slope positions in this region are dominated by black oak (*Q. velutina*), white oak, chestnut oak (*Q. montana*), scarlet oak (*Q. coccinea*), post oak, pignut hickory (*C. glabra*), and shagbark hickory (*C. ovata*). Lower slope positions and north-facing aspects are composed of beech, tulip poplar (*Liriodendron tulipifera*), northern red oak, sugar maple, and black walnut (*Juglans nigra*). Post and black oaks are more common than chestnut oak on dry sites within the Escarpment section (Homoya et al. 1985).

### Management and Policy Implications

Perpetuation of oak-dominated ecosystems in the eastern United States can rely on prescribed fire to create forest-floor conditions conducive to oak regeneration. Resistance by some managers to use prescribed fire, for fear of reducing overstory timber value, is often driven by observations and research on wildfire-damaged trees and may be misplaced for prescribed fire. On mesic sites and in mesic regions where prescribed fire intensities are kept low to only regenerate oak stands (i.e., not to thin the overstory), prescribed fire likely reduces a stand's standing sawtimber volume through wounding by less than 5 percent and has negligible effects on its average tree grade. On more xeric sites and in more xeric regions, sawtimber volume loss could be higher, exceeding 10 percent, but this level of damage likely occurs only after multiple fires. Under a goal to promote regeneration, economic damage to timber value from prescribed fire likely is minimal, particularly compared to the costs of regenerating oak artificially as an alternative option. Nevertheless, managers concerned about damage to veneer-quality trees may consider taking steps to protect those individuals during prescribed fire treatments or planning to harvest those trees soon (i.e., <10 years) after treatment.

### Stand Selection

Outside three significant wildfires in the 1950s and 1960s, stands within the HNF had not experienced fire since its establishment in the 1930s (J. Travis Swain, pers. commun., HNF Forest Silviculturist, USDA Forest Service, January 31, 2019). During spring 1990, managers began a prescribed fire program to restore rare, fire-dependent barrens in the forest; the program has since expanded to meet multiple restoration, habitat creation, and regeneration objectives within oak forests and grasslands throughout the forest. For this study, stands had to have received at least one prescribed fire over the past 25 years, and not occur in those areas with a history of wildfire. Most selected stands had received prescribed fire in order to reduce understory and midstory densities of mesic species and to promote advanced oak regeneration. However, some of the stands with the longest prescribed fire histories were adjacent to barrens where fire was being used to encourage warm season grasses and prairie forbs, and to limit the encroachment of woody species. Fires were almost exclusively prescribed in the spring burning season from early February to late March.

Selection of stands was stratified by two factors, burn class and aspect. Burn class was the number of prescribed fires a stand received and categorically assigned as 0 (i.e., controls), 1, 2, 3, or 4+ prescribed fires. Aspect was divided into two classes: mesic or xeric. Stands with predominantly north to east aspects (292.5° to 112.5° azimuth) are generally more mesic and somewhat protected from intense fire; stands with predominantly south- to west-facing aspects (112.5° to 292.5° azimuth) are more xeric and, thus, will generally experience more intense fires (Pyne et al. 1996). In addition, selected stands had to be merchantable (i.e., mean stand diameter at breast height [dbh] > 10 in.) and dominated by oak and hickory species in terms of basal area.

In sum, we selected 44 stands that had received at least one prescribed fire. We then selected an additional 10 stands within close proximity, on similar aspects, and within the same tree size and species criteria, but without a history of prescribed fire, to serve as controls (i.e., burn class = 0) for the study. Therefore, five to seven stands were selected in each aspect × burn class combination. Across all 54 stands, white oak site indices ranged from ~60 to 85 ft (base age of 50 year; Schnur 1937). Details on each stand can be found in the Supplementary (Table S1).

### Field Data Collection

We sampled each stand with 15 variable radius points using a BAF 20 prism (i.e., 20 $ft^2$ $ac^{-1}$) to inventory living trees >10 in. dbh at each point. Restricted randomization was used to select prism points based on three criteria: (1) local, neighborhood aspect for at least eight of the 15 points had to correspond to the prevailing aspect for the stand (e.g., a xeric stand had to have a minimum of eight points on south- or west-facing aspects); (2) points were placed at least 100 ft apart to prevent double sampling of individual trees; and (3) points needed a minimum of three "in" trees to be included (i.e., not in a large opening or old landing). Points were moved to the nearest location that met these criteria (fewer than 20 instances in the entire study). We recorded species, dbh, US Forest Service (USFS) tree grade (1, 2, 3, and local use; Hanks 1976, Miller et al. 1986), merchantable height to a 9-inch-diameter outside bark (dob) top for each "in" tree, and the presence or absence of any externally visible fire wounding. If a tree had visible wounding that was likely caused by fire (e.g., by presence of char in or near wound), the tree was given two USFS grades, following Loomis (2008), where the first grade included all defects, and the second grade ignored any defect likely caused by fire.

All wounds beginning below breast height and above stump height (i.e., 6 in.) were characterized by measuring the position on the stem (upslope, sideslope, downslope), type, width at the widest point, start height and total height (in relation to upslope), and depth to the nearest 0.1 inch. All measurements included any decay thought to result from the wound. Wounds were only measured to a maximum of 12 ft in height, but notes were taken if the wound extended further up the stem. Exterior wounds that occurred only in the stump were not measured, but noted if damage from the wound likely led to cull above stump height (e.g., detectable internal decay through sounding the tree).

Wound types included: (1) catfaces (triangle-shaped, open at base of tree), (2) ovals (oval-shaped, closed at base of tree), (3) seams, (4) basal/flutes, and (5) bark slough (Stambaugh and Guyette 2008). Catfaces and ovals have distinct wound ribs (thickened rings produced by the cambium in response to injury; Smith and Sutherland 2001) when viewed on the cross-section and have associated depth to their wounds. Seams also have distinct wound ribs, but rarely have a visible depth, as many seams are fully overgrown catface or oval wounds. Basal/flutes are wounds that occurred on extended butt flare. Bark slough was used to indicate when dead bark was disconnected from the bole of the tree, when multiple seams occupied a confined area, and/or when physical damage was evident, but the damage did not meet definitions for the other categories. A standard depth of 0.5 inch was assigned to all wounds without a measurable depth and exhibiting no decay.

### Data Compilation

Species with more than 100 sampled individuals across all sites were grouped into categories based on current local timber markets: hickories (pignut and shagbark hickory); red oaks (northern red, scarlet, and black oak); sugar maple; tulip poplar; white oaks (white and chinquapin [only three instances] oak); and other merchantable white oaks (post and chestnut oak). Species with fewer than 100 sampled individuals across all sites, including many not merchantable in local markets, were grouped together into an "other" type; these species were red maple (*A. rubrum*), silver maple (*A. saccharinum*), dogwood (*Cornus* spp.), persimmon (*Diospyros virginiana*), American beech, ash species (*Fraxinus* spp.), black walnut, sweetgum (*Liquidambar styraciflua*), black gum (*Nyssa sylvatica*), American sycamore (*Platanus occidentalis*), big-toothed and trembling aspen (*Populus* spp.), black cherry (*Prunus serotina*), blackjack oak (*Q. marilandica*), sassafras (*Sassafras albidum*), and American elm (*Ulmus americana*).

Stand-level estimates of basal area (BA; $ft^2$ $ac^{-1}$), density (TPA; trees $ac^{-1}$), and quadratic mean diameter (QMD; in.) were calculated for each stand. Board foot volume of the first 16-ft log ($V_{16}$) and total volume to merchantable height ($V_t$; 9-in. dob) of each tree were calculated in International quarter-inch scale using Equation 1 (Wiant 1986):

$$V = \left(1.52968L^2 + 9.58615L - 13.35212\right) + \left(1.79620 - 0.27465L^2 - 2.59995L\right) \times \text{dbh} + \left(0.04482 - 0.00961L^2 + 0.45997L\right) \times \text{dbh}^2 \quad (1)$$

where $L$ is the number of 16-ft logs to the nearest 0.25 log and assuming a Girard form class of 78. If a tree was not of sawtimber quality, then volume was set to zero; if the tree did not have a 16-ft merchantable butt log, $V_{16}$ was calculated based on an 8-ft or 12-ft log.

To estimate the volume loss because of prescribed fire in both $V_{16}$ and $V_t$, we first calculated the volume of each wound using formulas consistent with their shape, converted those volumes to board feet, and aggregated volumes for all wounds on each tree. The volume of the tree with fire damage (i.e., $V_{16,\text{fire}}$ and $V_{t,\text{fire}}$) was calculated by subtracting the aggregated wound volume from $V_{16}$ and $V_t$. Volume was also adjusted as needed for sections of the trees determined to be unusable (e.g., swell in the bottom 4 feet). Each of these tree volumes (i.e., $V_{16}$, $V_t$, $V_{16,\text{fire}}$, and $V_{t,\text{fire}}$) was converted to a per-acre basis and then summed to calculate stand-level values. Finally, we corrected for differences in overall stocking among all stands by calculating the relative total stand volume loss (percentage) in each stand as (Equation 2):

$$\text{RV}_x = \left(V_x - V_{x,\text{fire}}\right) / V_x \times 100 \qquad (2)$$

where $x$ corresponds to either the bottom 16-ft log volume (16) or the total merchantable volume (t). To check for species-specific differences in vulnerability to fire, we calculated $\text{RV}_{16}$ and $\text{RV}_t$ for two additional subsets of the data: (1) for merchantable species only (all species groups besides the "other" type) and (2) for the white oak group only.

To estimate the grade loss because of prescribed fire, we calculated the percentage of trees that had differing USFS tree grades (i.e., grade accounting for fire damage and grade ignoring fire damage) per acre in each stand. This was calculated for all overstory trees, only merchantable species, and only white oak.

### Statistical Analyses

To investigate the potential impact of prescribed fire on stand structure, we performed separate analyses of variance (ANOVA) on the influence of burn class, aspect, and interaction between these variables on stand-level BA, TPA, and QMD. To test for prescribed fire effects on tree wounding, timber volume loss, and tree grade, we conducted an ANOVA on the percentage of trees wounded by fire, on both $\text{RV}_{16}$ and $\text{RV}_t$, and on the average percentage of trees per acre that changed grade, respectively, in each stand with burn class and aspect as main effects. Stands were the experimental unit. ANOVA tests used Type III sums of squares because of the unbalanced data structure. All tests were repeated for the three datasets—all species, merchantable species, and white oak only. Arcsin transformations were used on wound proportions, relative volume loss, and grade loss data to normalize the data and reduce heteroscedasticity. Tukey honestly significant difference (HSD) tests were performed to determine significant trends between factor levels. Analyses were conducted in R 3.1.4 (R Core Team 2017), using the car (Fox and Weisberg 2011) and agricolae (de Mendiburu and Simon 2015) packages for some tests. All analyses used an $\alpha = 0.10$.

## Results

### Sample Profile

Overall, 3,654 trees were sampled with prism plots across the 54 stands. Stands were distributed nearly equally across aspect classes (mesic: 28; xeric: 26). Basal area in most stands was dominated by white oak (36), although some stands were composed of mixtures of oak and hickory species (13). A few stands (five) were composed of a diverse mixture of mesic species, with oaks and hickories comprising a minor component (Supplementary, Table S1). Overall, there were 26 species inventoried representing the seven species groups, with white oak comprising 56.5 percent of inventoried stems. Red oaks (12.8 percent), hickories (9.6 percent), and the other white oaks (9.0 percent) were the next most frequently inventoried species groups (Table 1).

Across all treatments, 2,345 wounds were measured, of which 92.5 percent occurred in stands with a history of prescribed fire (burn classes 1, 2, 3, 4+). For all treatments, seams were the most common type of wound followed by bark sloughing/multiple seams and catfaces (Table 2). Catfaces had the largest average defect volume per wound, 5.77 ± 0.43 bd ft (mean ± standard error), whereas seams had the lowest at 0.58 ± 0.04 bd ft. The average defect for all wound types was 2.73 ± 0.15 bd ft. All wound types, on average, ended below a height of 27.4 ± 0.4 in. and were 11.4 ± 0.2 in. wide and 1.6 ± 0.1 in. deep (Table 2).

Wounds were found on 36.1 percent of all trees sampled with prism plots (1,318/3,654), 36.2 percent of merchantable trees (1,275/3,526), and 34.1 percent of white oaks (703/2,060). If wounded, trees typically had one or two wounds; only 7.1 percent (259), 7.2 percent (252), and 5.8 percent (120) of all sample trees, merchantable species, and white oaks, respectively, had three or more wounds. Consequently, wounds only led to grade reductions for 2.8 percent of all sampled trees (100), 2.7 percent of merchantable species (95; Table 3), and 2.0 percent of white oaks (42).

### Stand-Level Patterns

Overstory BAs ranged from 73 to 117 $\text{ft}^2\ \text{ac}^{-1}$ across the 54 stands, with an average of 90 ± 1.5 $\text{ft}^2\ \text{ac}^{-1}$ (Table A1). Density of stems >10 in. dbh (DEN) ranged from 32 to 91 stems $\text{ac}^{-1}$ and averaged 61 ± 2 stems $\text{ac}^{-1}$ (Table A1). QMD ranged from 12.4 to 22.5 in. and averaged 16.6 ± 0.3 in. (Table A1). Neither BA, DEN, nor QMD varied significantly with either burn class, aspect, or

**Table 1. Number of trees inventoried across 54 stands on the Hoosier National Forest, partitioned by species group to stands with mesic (north- or east-facing) and xeric (south- or west-facing) aspects.**

| Species group[a] | Aspect | | Total |
|---|---|---|---|
| | Mesic | Xeric | |
| White oak | 945 | 1,115 | 2,060 |
| Red oak | 298 | 172 | 470 |
| Hickory | 208 | 143 | 351 |
| Other white oak | 174 | 156 | 330 |
| Tulip poplar | 111 | 61 | 172 |
| Sugar maple | 74 | 69 | 143 |
| Other | 83 | 45 | 128 |
| Total | 1,893 | 1,761 | 3,654 |

[a]Species groups were defined as white oak—white (*Quercus alba*) and chinquapin oak (*Q. muehlenbergii*); red oak—northern red (*Q. rubra*), scarlet (*Q. coccinea*) and black oak (*Q. velutina*); hickory—pignut (*Carya glabra*) and shagbark hickory (*C. ovata*); other white oak—post (*Q. stellata*) and chestnut oak (*Q. montana*); tulip poplar—tulip poplar (*Liriodendron tuliperfera*); and sugar maple—sugar maple (*Acer saccharum*). The "Other" species group contains 18 rarely sampled ($n$ < 50) and/or nonmerchantable species; see Methods for more details.

**Table 2. Mean (standard error) height, width, depth, and defect volume for individual wounds by type across all sampled trees.**

| Wound type | *n* | Height[a] (in.) | Width (in.) | Depth[b] (in.) | Volume[c] (bd ft) | Volume range (bd ft) |
|---|---|---|---|---|---|---|
| Seam | 801 | 30.41 (0.71) | 4.95 (0.15) | 0.53 (0.01) | 0.58 (0.04) | 0.01–28.50 |
| Bark slough/multiple seams | 667 | 24.40 (0.69) | 15.42 (0.30) | 0.69 (0.03) | 1.89 (0.11) | 0.03–38.00 |
| Catface | 667 | 26.49 (0.69) | 16.03 (0.34) | 3.68 (0.14) | 5.77 (0.43) | 0.01–111.54 |
| Oval | 177 | 29.47 (1.51) | 8.27 (0.34) | 2.22 (0.24) | 3.87 (0.81) | 0.02–124.86 |
| Basal/flutes | 33 | 19.76 (1.65) | 9.80 (1.00) | 2.02 (0.26) | 4.61 (1.20) | 0.09–27.47 |
| All types | 2,345 | 27.36 (0.39) | 11.40 (0.18) | 1.62 (0.05) | 2.73 (0.15) | 0.01–124.86 |

*Note:* Individual wounds could be caused, in whole or part, by prescribed fire (i.e., on burn class > 0) or only by other agents (i.e., burn class = 0). Range in defect volume by wound type as observed across all sample trees is also provided.

[a]Height was defined as the height to the top of the defect on the upslope side of the tree. Height is an indication of what length of the butt log was affected by the wound.

[b]Closed seams and other wounds were assumed to have a minimal depth of 0.5 in.

[c]Defect volume included any visible decay that resulted from the wound. It was calculated consistent with its general geometric shape of the wound (e.g., catfaces as a triangular prisms, seams as rectangular prisms).

**Table 3. Classification matrix of USFS tree grades for sampled trees of merchantable species measured across 54 stands of the Hoosier National Forest (*n* = 3,526), both considering (i.e., observed) and ignoring fire damage.**

| Observed grade | Grade ignoring fire damage | | | |
|---|---|---|---|---|
| | 1 | 2 | 3 | Local use |
| 1 | 2,135 | – | – | – |
| 2 | 28 | 823 | – | – |
| 3 | 13 | 21 | 344 | – |
| Local use | 14 | 8 | 11 | 129 |

*Note:* Values on the diagonal are the number of trees where grade did not change because of fire damage (i.e., observed grade = grade ignoring fire damage); values below the diagonal are the number of trees where grade declined because of fire damage (i.e., observed grade < grade ignoring fire damage).

their interaction (BA: $F_{9,44}$ = 1.440, $P$ = .201; DEN: $F_{9,44}$ = 0.261, $P$ = .982; QMD: $F_{9,44}$ = 0.684, $P$ = .719) (see also Table A2).

### *Wounding*

Generally, the percentage of trees per acre wounded increased as the number of prescribed fires increased (all species: $F_{4,44}$ = 4.013, $P$ = .007; merchantable species: $F_{4,44}$ = 3.879, $P$ = .009; white oak: $F_{4,44}$ = 5.157, $P$ = .002), but did not vary across aspects ($P$ > .1 for all species groups; Table A2). Control stands with no prescribed fire history (i.e., burn class 0) had an average percentage of trees per acre wounded of 17 percent. Prescribed fire increased this percentage to 49 percent for burn classes 3 and 4+; burn classes 1 and 2 were intermediate in wounding (Figure 2). Tukey HSD tests indicated that wounding was significantly different only for stands in burn classes 3 and 4 as compared to unburned control stands (all species: $P$ = .001 and .004; merchantable species: $P$ = .003 and .004; white oak: $P$ = .007 and .030, for three and four prescribed fires, respectively); stands with fewer burns were not significantly different from one another or from the control ($P$ > .1; Figure 2). The interaction between burn class and aspect for percentage of trees per acre with wounds was not significant (see Table S2).

### *Relative Volume Lost*

Prescribed fire caused relative volume loss, although the response was often weak and highly variable. Across all species, $RV_t$ was <1.9 percent and $RV_{16}$ was <2.5 percent in stands with three or fewer prescribed fires, whereas stands with four or more prescribed fires experienced an average $RV_t$ and $RV_{16}$ of 5.0 ± 1.6 percent and 6.0 ± 1.6 percent, respectively (Figure 3a, b). $RV_t$ and $RV_{16}$ exceeded 10 percent in only two stands, both on xeric aspects that had been burned four or more times. Results from ANOVAs (Table S2) indicated that burn class strongly influenced both $RV_t$ ($F_{4,44}$ = 9.120, $P$ < .001) and $RV_{16}$ ($F_{4,44}$ = 9.313, $P$ < .001). The interaction between burn class and aspect strongly influenced $RV_t$ ($F_{4,44}$ = 2.866, $P$ = .034) for all species, but less so for $RV_{16}$ ($F_{4,44}$ = 2.001, $P$ = .111); this interaction was a result of the aforementioned xeric sites that had been burned four or more times. Aspect had no direct influence on $RV_t$ or $RV_{16}$ ($P$ > .1; Table S2).

For merchantable species, relative volume results largely mirrored those for all species (Figure 3c, d). Aspect did appear to influence merchantable species $RV_t$ and $RV_{16}$, although it was only significant for the latter ($RV_t$: $F_{4,44}$ = 1.904, $P$ = .175; $RV_{16}$: $F_{4,44}$ = 3.185, $P$ = .081; Table S2). Likewise, the interaction between burn class and aspect strongly influenced $RV_{16}$ of merchantable species ($F_{4,44}$ = 2.594, $P$ = .049; Table S2).

White oak relative volume loss also mirrored the trends observed for all species, although relative losses were half those values (Figure 3e, f). Only one stand, lying on a xeric aspect and with four burns, had $RV_t$ and $RV_{16}$ exceeding 10 percent for white oak; the remainder were below 3.6 percent for $RV_t$ and 4.5 percent for $RV_{16}$. Only burn class significantly affected $RV_t$ ($F_{4,44}$ = 5.845, $P$ < .001) or $RV_{16}$ ($F_{4,44}$ = 6.329, $P$ < .001; Table S2), although Tukey HSD tests suggested that the xeric sites with four burns were significantly different from the controls (Figure 3e, f). This result may be an artifact of the exceptionally high $RV_t$ and $RV_{16}$ observed in the one stand mentioned earlier.

### *Grade Change*

Prescribed fire led to grade loss in most stands. The percentage of trees per acre that changed grade averaged 3.3 ± 0.7 percent (range: 0–18.9 percent) for all species combined, 3.4 ± 0.7 percent (range: 0–18.3 percent for merchantable species, and 1.8 ± 0.5 percent (range: 0–13.6 percent) for white oak. The average percentage of trees per acre that changed grade was less than 3 percent for stands with three or fewer prescribed fires for all species, merchantable species, and only white oak; the grade change was higher, however, in stands with four or more burns, nearly 7.0 percent for both all species and merchantable species groups, but only 3.7 percent for white oak (Table 4).

Grade loss was influenced by burn class ($F_{4,44}$ = 6.246, $P$ < .001) and the interaction of burn class and aspect for all species ($F_{4,44}$ = 3.019, $P$ = .028; Table S2). Results were similar for merchantable species. Burn class was the only significant factor explaining changes in grade for white oak, however ($F_{4,44}$ = 4.590, $P$ = .003; Table S2). Stands receiving four or more burns experienced

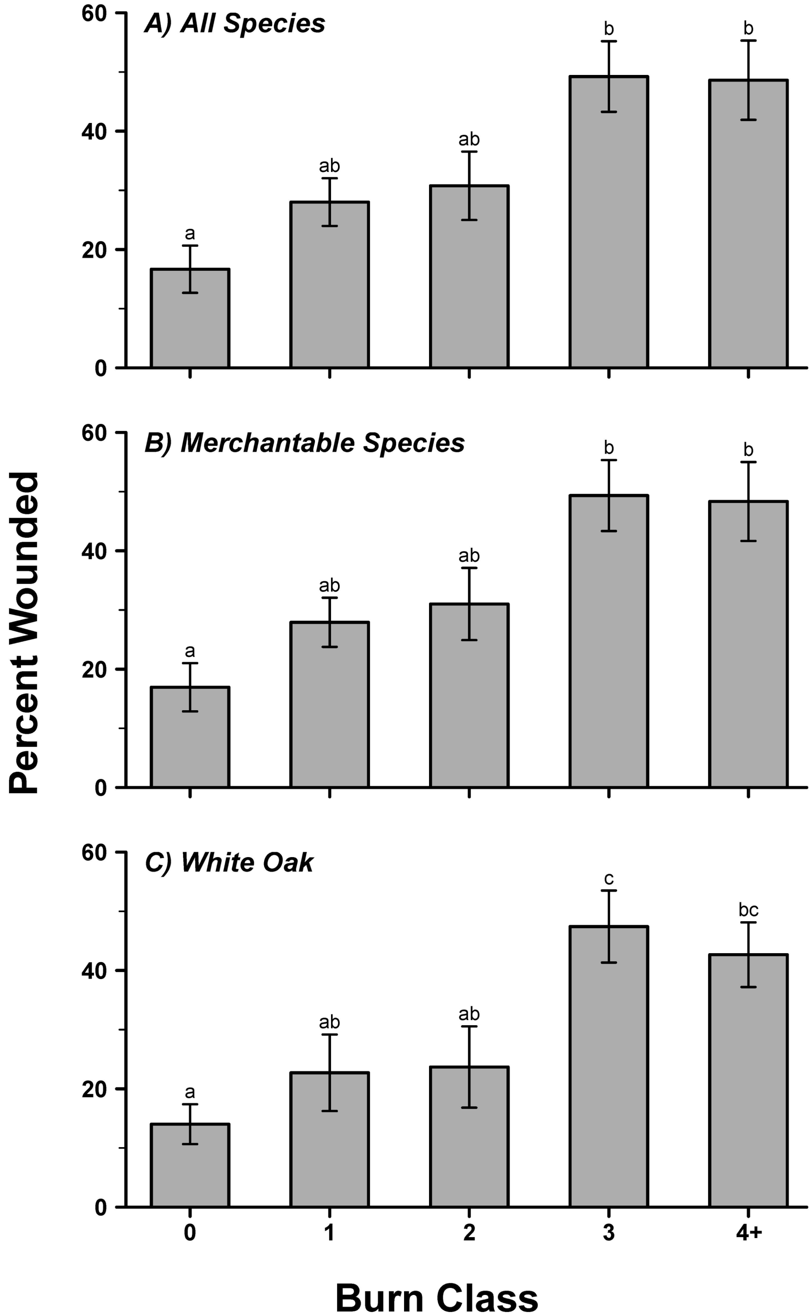


**Figure 2. Average percentage of trees per acre wounded within each burn class for (a) all species, (b) merchantable species, and (c) white oak only. Burn class refers to the number of prescribed fires received over the past 24 years. Bars indicate ±1 standard error; within each panel, and different letters indicate significantly different means at $\alpha = 0.1$ with the Tukey honestly significant difference test.**

significantly more grade loss in all species than all other burn classes (all $P < .10$). However, for merchantable species, burn class 4+ stands were only different from those receiving no or one prescribed fire ($P = .002$ and $P = .017$, respectively). Burn class 4+ stands only differed from control stands for white oak ($P = .032$).

The significance of the interaction term in both all species and merchantable species models was largely due to higher observed grade loss on xeric burn class 4+ sites than on mesic burn class 4+ sites (all species: xeric = 10.7 ± 3.3 percent, mesic = 3.0 ± 1.6 percent; merchantable species: xeric = 10.5 ± 3.3 percent, mesic = 3.1 ± 1.6 percent); all other burn classes did not differ greatly between aspects (<3 percent difference). For white oak, a difference between xeric and mesic burn class 4+ sites was also observed, but the difference was not as pronounced (xeric = 5.4 ± 2.3 percent, mesic = 1.9 ± 1.2 percent). Much of this difference was a result of one site where 12.8 percent of the white oak had grade loss.

## Discussion

Most trees measured in this study either did not get damaged by prescribed fire or were able to compartmentalize (*sensu* Shigo 1984) and heal wounds quickly. Although we observed wounds that led to cull, these wounds were not common. Most observed wounds were either seams or the generic group of bark sloughing/multiple seams, with distinct woundwood ribs that touched and had closed over the wound (Table 2). Wound closure helps protect the tree from pathogens, rot, and additional mechanical wounds

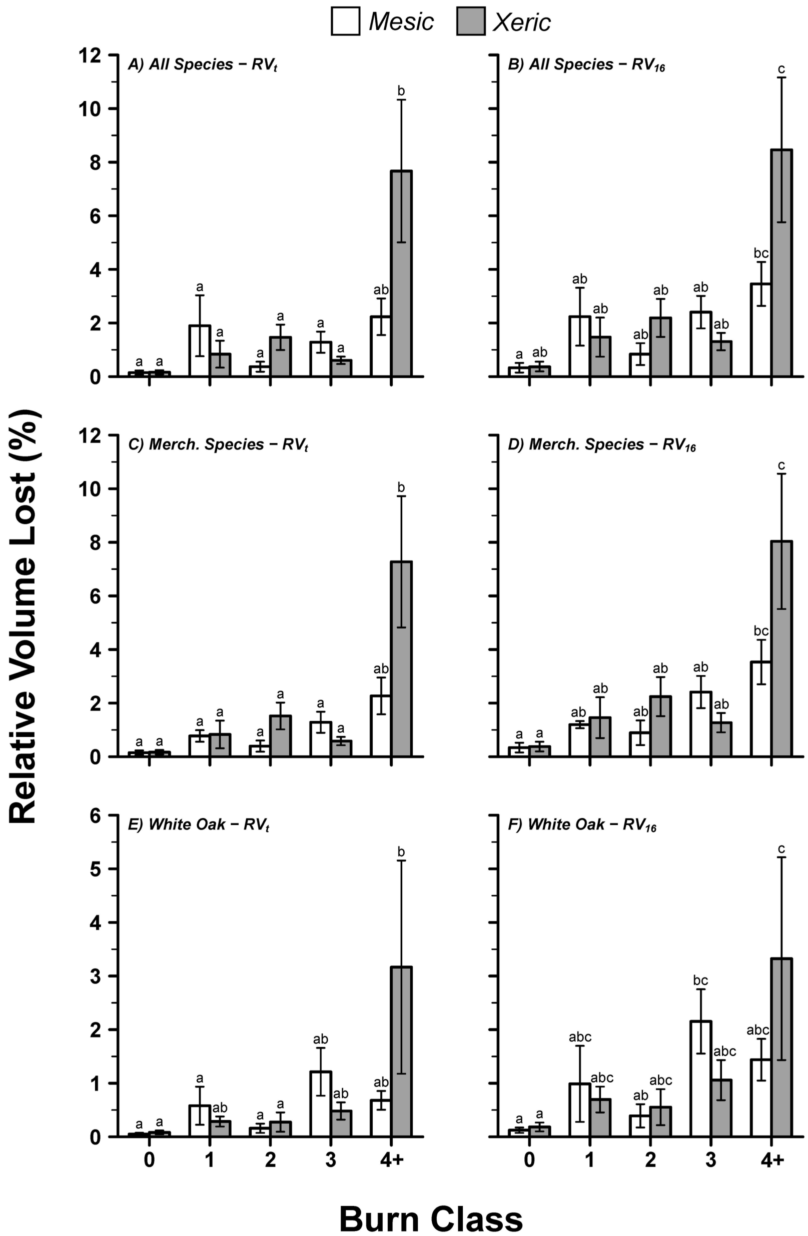


**Figure 3. Relative total stand volume lost ($RV_t$; a, c, and e) and relative volume lost from the bottom 16-ft log ($RV_{16}$; b, d, and f) by burn class and aspect for all species (panels a and b), merchantable species (c and d), and white oak only (e and f). Burn class refers to the number of prescribed fires received over the past 24 years. Bars indicate ±1 standard error; different letters indicate significantly different means within each subfigure at $\alpha = 0.1$ with the Tukey honestly significant difference test. In ANOVA models, the interaction between burn class and aspect was significant ($P < .1$) only for $RV_t$ of all and of merchantable species (see Table S2).**

**Table 4. Mean percentage (SE) of trees per acre that changed grade because of prescribed fire damage for all species ($F_{9,44} = 4.229$, $P < .001$), merchantable species ($F_{9,44} = 3.881$, $P = .001$), and only white oak ($F_{9,44} = 3.021$, $P = .007$).**

| Burn class | All species | Merchantable species | White oak |
|---|---|---|---|
| 0 | 0.00 (0.00) a | 0.00 (0.00) a | 0.00 (0.00) a |
| 1 | 1.41 (0.41) ab | 1.35 (0.47) ab | 0.77 (0.41) abc |
| 2 | 2.55 (0.82) bc | 2.84 (0.96) bc | 0.55 (0.55) ab |
| 3 | 2.62 (1.12) bc | 2.66 (1.12) bc | 2.22 (1.12) bc |
| 4+ | 6.88 (2.13) c | 6.79 (2.08) c | 3.66 (1.36) c |

*Note:* Letters indicate significant differences ($\alpha = 0.1$) between burn classes within each species group using Tukey's honestly significant different tests.

(Shigo 1984, Dey and Schweitzer 2018) and can happen as quickly as one year after a fire, depending on scar width (Stambaugh et al. 2017). Most measurable volume loss occurred with catfaces, basal/flutes, and ovals, all of which are open and vulnerable to decay. Since these wounds have measurable depth, we observed the highest average volume (board feet) in defect per wound for these wound types (Table 2). Closed wounds, on the other hand, can easily hide deeper pockets of decay that may extend into the cant during lumber milling, so we suspect our estimates of volume loss in trees with these defects may be conservative; destructive sampling and lumber recovery studies would be needed to confirm our estimates.

Marschall et al. (2014), in a lumber recovery study, determined that wounds below 19.7 in. in height would have minimal impact on the value loss 14 years after the initial prescribed fire in stands that receive multiple fires. Considering both that our observed wound heights exceeded this threshold, averaging about 27.4 in. in height (Table 2), and that residency time (length of time since a wound was inflicted) was likely longer than 14 years in some stands (see Table S1), our average volume defect for all wound types remained relatively low, only 2.7 ± 0.2 bd ft (Table 2). Therefore, individual wounds usually had minimal impact on stumpage value for a given tree; only when wounds were numerous and spread across multiple faces was there a potential to significantly affect value through change in volume or grade. Multiple wounds were not common in our study; only 7.1 percent of sample trees had three or more wounds, and USFS tree grade changed on only 2.8 percent.

### Stand-Level Patterns

Overall, prescribed fire did not influence overstory structure at the HNF. BA, DEN, and QMD of the stands did not differ significantly among similar stands with increasing numbers of prescribed fire on any aspect. Other studies in the Missouri Ozarks also found no impact of prescribed fire on BA, DEN, and QMD in oak–pine and oak stands (Stevenson 2007, Knapp et al. 2017). Fire behavior of prescribed fires in most eastern closed canopy, oak-dominated forests commonly follows Anderson Fuel Model 9 (Anderson 1982); this behavior leads to little mortality (<3–8 percent) for trees greater than 10 in. dbh and declines as tree sizes (and bark thicknesses) increase (Hutchinson et al. 2005, Kinkead et al. 2017, Dey and Schweitzer 2018). Therefore, much more intensive prescribed fires, likely with average flame heights exceeding 6 ft, more typical of Anderson Fuel Model-10, and/or mechanical thinning may be required to reduce overstory BA significantly for woodland or barren restoration efforts should that be the goal of managers (Brose et al. 2014).

#### *Wounding*

We examined the impacts of increasing number of prescribed fires on wounding rather than treating prescribed fire as a binary variable (i.e., fire or no fire) as was done in most prior studies. We found that, whereas prescribed fire wounds trees, it does not wound all trees in a stand, an observation made in several earlier studies (Kinkead et al. 2017, Smith and Sutherland 1999, Stevenson et al. 2008). As hypothesized, the percentage of trees wounded by prescribed fire generally increased as the number of prescribed fires increased, but the shape of the response (i.e., linear versus a threshold) was not clear because of the high variability seen among the stands; only stands with three or more prescribed fires were statistically different from unburned, control stands. This trend was the same for all species combined, for all merchantable species, and white oak alone. Therefore, an expansion of this study to more stands to refine these relations is likely warranted. Notably, trees within unburned, control stands also demonstrated a fair amount of damage (17 percent of all trees per acre), as damage can be caused by many environmental factors (e.g., frost, wildlife interactions, falling limbs), not just fire.

In stands with three or more prescribed fires, the average percentage of trees per acre wounded was 49 percent. Plots burned periodically since 1949 in the Missouri Ozarks had similar wounding rates at 54.8 percent (Knapp et al. 2017). Stevenson (2007) also found a similar response, but a higher proportion of trees wounded on xeric aspects (67 percent) and mesic aspects (53 percent) in stands with histories of one to nine prescribed fires in the Missouri Ozarks. Most low- to moderate-intensity fires burn with variable severity, creating a mosaic of areas with no to high fuel consumption (Pyne et al. 1996). As a result, many trees may escape injury in a single burn, although over multiple burns the likelihood of injury, and resulting damage, would increase. Thick bark also reduces the likelihood of injury, by insulating the cambium from lethal fire temperatures, even in areas with higher fuel loads (Hengst and Dawson 1994). Regardless, more trees may have internal damage than can be seen externally, as fire wounds, especially small ones, can compartmentalize and heal quickly after a fire (Stambaugh et al. 2017).

Aspect did not heavily influence the proportion of trees wounded, even though it has been previously reported that more xeric, southern-facing aspects have higher rates of scarring from prescribed fire (Stevenson et al. 2008, Kinkead et al. 2017). Aspect influences fire behavior through altered solar radiation, air temperature, and fuel moisture (Pyne et al. 1996); therefore, we expected a stronger relation between aspect and wounding. On these highly dissected sites, local topography in the immediate neighborhood of individual trees could have either dampened or increased local fire intensity and severity, thereby masking the influence of aspect on wounding at the stand level. Other environmental factors that influence fire behavior, such as seasonality of fire and method of ignition, could have additionally confounded the influence of aspect (Pyne et al. 1996). Future studies should stratify on more of these environmental variables in stand selection and, potentially, analyze data at the plot or tree level so as to better understand how fire behavior affects tree damage in eastern oak forests.

#### *Relative Volume Lost*

Our results were consistent with previous studies of prescribed fire's effects on standing timber or lumber volume. As residence time, the length of time since the inception of a fire scar, increases, more rot and decay can enter the wood, leading to cull and larger defect volumes (Stambaugh and Guyette 2008, Dey and Schweitzer 2018). In a lumber recovery study, Marschall et al. (2014) reported a reduction of 3.9 percent in red oak log volume across all samples taken from stands with three to four prescribed fires over a period of 14 years; this reported volume falls between those losses that we measured in merchantable species for stands with three and with four or more burns (Figure 3). Using data collected from 10.5-ft butt logs of fire-damage trees on a single site, Stambaugh and Guyettte (2008) developed a volume-reduction model that predicted a loss of 4–7 percent after 15 years, depending on dbh and tree scar sizes.

Across all stands that had prescribed fire, $RV_{tot}$ was very low (5.3 percent), and only two stands had merchantable volume losses of over 10 percent. Unlike what we hypothesized, xeric aspects did not strongly increase prescribed fire damage, except on the most frequently burned sites (Figure 3). Instead, there was a positive relation between damage and number of prescribed fires. In another study from the Missouri Ozarks, Knapp et al. (2017) reported much higher, stand-level volume losses, 21.6 percent, for trees that had received prescribed fire every four years since 1949. However, most of the volume for these trees occurred in the 16-ft butt log; our HNF study trees were substantially taller and could produce as many as three additional 16-ft logs. Given that prescribed fire damage is exclusive to the butt log, this likely explains our lower relative volume loss. In addition, our study sites are considerably moister and of higher site quality, and generally have a lower fire intensity than the Missouri Ozarks. For example, an expansion of this study to the Mark Twain National Forest has measured volume reductions of two- to threefold reported here (D. Mann, unpubl. data), much more in agreement to the study by Knapp et al. (2017).

These fire-caused volume losses can be reduced with some attention and care during harvesting and milling. Trees can be optimally bucked (Sessions 1988, Sessions et al. 1989) to exclude excessively scarred areas, and log lengths can be shortened to produce higher-grade material; at the mill, boards can be cut with seams on the edges, allowing enough clear wood throughout the rest of the board to maintain the grade. Furthermore, shallow fire scars from recent fires and scars on large trees are often removed in the slab during timber processing, leading to no realized volume deductions in the lumber (Loomis 1974, Stambaugh and Guyette 2008, Marschall et al. 2014, Wiedenbeck and Schuler 2014). Further lumber recovery studies are needed to relate observed fire-damage volume losses at harvest to the eventual economic value of the milled lumber.

*Grade Change*

Prescribed fire did not greatly impact tree quality at the stand level, even in the cases where the residence time was 24 years and more than four prescribed fires have been applied. Study-wide, less than 3 percent, on average, of a burned site's trees received enough damage to reduce the USFS tree grade. As hypothesized, the number of prescribed fires increased grade loss, but similar to wounding, the slope of the response was unclear because of high variability among sites. Only in stands with four or more prescribed fires did grade reductions differ from controls, exceeding 5 percent of overstory stems. White oak trees were particularly resistant to grade change, having grade reductions of approximately one-half the rate of all other species (Table 4).

Fire frequently wounds just one face of the tree, the leeward side of the tree (Gutsell and Johnson 1996). Trees could frequently keep their grade because the process of grading trees ignores the face with the most defects and specifies that the grade is based on the best 12 ft in the bottom 16-ft log (Hanks 1976). In our study, most fire damage on trees was isolated to only one face and within the bottom 4-ft section of the bole—both portions that can be defective yet ignored while grading if other portions of the tree stem are of a higher quality. Thus, grade only declined for trees that had excessive cull because of fire damage that exceeded the cull limits for each grade or where fire significantly damaged two or more faces of the tree. Fire also degraded a tree if the tree otherwise had many defects (e.g., dead limbs) and the best face was that which received fire damage; the additional fire wounds shifted the best face to a more defect-laden face. Our findings should not be extrapolated to veneer tree quality and value, since veneer grades are more stringent than the highest USFS Grade 1 requirements.

Past research has found minimal effects of prescribed fire on overstory tree quality for similar reasons. For example, Wiedenbeck and Schuler (2014) found that 12 percent of trees had grade change or scale volume deduction after two prescribed fires, but 70 percent of these trees were red maple, a known fire-intolerant species. The remaining trees that changed grade were more fire-tolerant species, 5 percent of all trees, and similar to that found in our study (3 percent). The only wound type to affect timber quality in the Wiedenbeck and Schuler (2014) study was large catfaces, of which we had very few (only 110 instances of catfaces with a defect of >10 bd ft across 3,654 trees). However, Stambaugh and Guyette (2008) reported a much higher rate, approximately 10 percent of oak trees (black, scarlet, and white oak), that changed grade because of prescribed fire damage after two fires in the Missouri Ozarks.

## Conclusion

In southern Indiana, prescribed fire can potentially wound individual trees and significantly reduce their timber volume and quality; in practice, however, losses are minimal when aggregated to the stand level. Generally, the percentage of trees wounded increases with the number of prescribed fires a stand receives, but even then, not all trees in a stand are wounded. Most overstory trees in mature, oak–hickory stands have relatively thick bark that insulates them from fire damage. For trees that are wounded, particularly oak species, the ability to compartmentalize and heal wounds minimizes fire's impact on overstory tree volume and value, even after 24 years and more than four prescribed fires. Nevertheless, continued use of prescribed fire over multiple decades would likely accumulate defects and lead to higher losses (Knapp et al. 2017). For example, pole- and small sawtimber-sized trees are more susceptible to damage and decay, especially if left in the stand for long periods of time before harvest (Dey and Schweitzer 2015, 2018).

These results indicate that prescribed fire can be used in conjunction with other forest-management strategies to meet multiple objectives (Dey and Schweitzer 2018). For example, if fire is used within a shelterwood regime and conducted less than 20 years before final overstory harvest, oak regeneration may be strongly promoted, whereas losses to timber resources can be minimized. Multiple applications of fire are likely needed, and, once regeneration is present, timing between burns should exceed 5 years (Brose et al. 2014). Fire can also be helpful in combination with midstory removal of mesic species to allow more light to the forest floor and reduce the litter layer depth for successful oak regeneration (Dey and Schweitzer 2018), although placement of slash from the midstory removal near boles of trees can be problematic by increasing local fire intensity and causing more fire damage (Brose and van Lear 1999). Regardless, further research is still needed to weigh the economic benefits of promoting oak regeneration against the economic damage to residual timber across a broad range of forest types, sites, and differing fire prescriptions.

## Supplementary Materials

Supplementary data are available at *Forest Science* online.

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