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Prescribed Fire Causes Wounding and Minor Tree Quality Degradation in Oak Forests

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Abstract: Despite the adaptation of many oak (*Quercus*) species to repeated surface fire, many public land managers in eastern North America resist using prescribed fire as a regeneration tool because of fire's perceived negative impacts on timber values through the wounding of overstory trees. We retrospectively quantified fire-associated wounds in 139 oak-dominated stands across four national forests, each with a history of zero to six prescribed fires within the last 30 years. For trees >25.4 cm dbh (n = 8093), fire-associated wounds within the first 3.67 m of height were categorized by type, measured for defect size and graded both accounting for and then ignoring the fire-associated wounds. Most fire-associated wounds (n = 3403) were catfaces (32.5%), seams (30.5%) or bark slough (30.1%), although catfaces had 2.1–6.4 times the average volume loss of any other wound type (9.90 ± 0.72 bd ft). Among the 2160 wounded trees sampled, 741 had multiple (≥2) wounds. Although 29.1% of all trees had at least one wound associated with prescribed fire, only 7.0% of those trees exhibited a reduction in tree grade. The likelihood of wounding was greater in stands receiving more prescribed burns, but unaffected by tree diameter for either thin- or thick-barked species. Considering both the likelihoods of wounding and grade reduction, white oak (*Q. alba*), chestnut oak (*Q. montana*), hickory (*Carya* sp.), shortleaf pine (*Pinus echinata*) and yellow-poplar (*Liriodendron tulipifera*) trees were more resistant to prescribed fire damage than other species. While our findings cannot be related directly to individual fire parameters, such as fireline intensity or fire duration, these results do provide estimates of the cumulative effects of multiple management-based prescribed fires that can be incorporated into fire effects models.

Keywords: fire ecology; *Quercus*; timber damage; fire effects; oak regeneration; tree grades

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1. Introduction

Prescribed fire has been a versatile forest management tool, used to promote the regeneration of fire-adapted species [1,2], to suppress competition from more fire-intolerant competitors [3], to maintain/improve wildlife habitat [2,4] and to achieve other woodland management outcomes [5]. The future use of prescribed fire may increase in the light of climate change both to reduce wildfire potential and to maintain/increase ecological resilience in fire-dependent communities [6,7], which comprise a majority of forest types in North America [8]. However, prescribed fire can be difficult to implement due to limited periods of appropriate weather and fuel conditions (i.e., fire windows), policy restrictions, liability concerns regarding escape and human health concerns due to smoke [6]. Despite these hurdles, public land managers have commonly prescribed surface fires in the eastern deciduous forests of North America [9]; the use of the practice on private lands has been far less widespread. Besides the aforementioned limitations to the practice, there continues to be a lingering fear that prescribed fire greatly reduces the quality and subsequent value of the standing timber [3,10,11].

Early research on fire effects in oak-dominated forests modeled damage to timber based on measurements of wounding associated with the fire [12,13]. For example, reports from Kentucky, Missouri and West Virginia suggested high levels of wounding, significant stem mortality and over one-half of the volume and value of an eastern hardwood stand could be lost after a moderate-intensity wildfire [14–16]. As with fire science in general [7], fire practitioners equated these reported wildfire effects with prescribed fire even though fire behavior and environmental conditions vary dramatically between the two fire types. In the late 2000s, this discrepancy was recognized and the resulting studies specific to prescribed surface fires tended to show much lower levels of damage [17,18], particularly on mesic sites and protected north-facing aspects where fire intensity is often lower [19–21]. For example, the authors reported that prescribed fire wounded a majority of trees in a West Virginia hardwood stand, but less than 13% of those trees were damaged enough to affect timber value [22]. Likewise, the repeated application of prescribed fire over five decades resulted in 55% wounding, but only 22% sawtimber volume loss in a xeric Missouri Ozark stand [10].

Wounding and the associated changes in overstory tree quality have been largely studied through a dichotomous lens in regards to prescribed fire, i.e., trees experienced fire or not, and/or within the context of mill studies to estimate lumber recovery and economic damage [10,17,22]. One notable exception, a Missouri study, examined tree mortality and wounding patterns in a replicated design using three sites and zero, one or two prescribed burns plus canopy thinning; they reported 19.3% of overstory trees were scarred and wounding differed slightly by species with shortleaf pine (*Pinus echinata*) having the lowest wounding rates and a group of mesic species sharing the highest [23]. Species differences in wounding from fire have been noted for some time [24]; a classic study from the 1930s demonstrated that overstory yellow-poplar (*Liriodendron tulipifera*) had lower amount of wounding than many oak (*Quercus*) species after wildfire [25]. Subsequent research has shown that species resistance to wounding is primarily a function of bark thickness, as modified by tree size and bark structure [3,24,26].

Many of the aforementioned studies are isolated in scope to a single site or locality and/or species group [27]. To our knowledge, there are no regional-scale studies of fire-caused wounding and the associated changes in timber quality that can account for both multiple applications of prescribed fire and differences in fire behavior that result from topographic effects. We report, in a companion study [28], the impacts of repeated applications of prescribed fire on stand-level changes in sawtimber volume and value for sites from across the Central Hardwood Region (CHR) of North America. This article reports on the tree-level wounding rates and quality changes, as impacted by species, of those same sites, expanding upon an earlier, focused study in southern Indiana [29].

Our specific objectives were to: (1) characterize the distribution of wound types and wound sizes, overall and among tree species, after prescribed fire; (2) estimate if wound size increased with the subsequent applications of prescribed fire or differed by aspect; (3) estimate the likelihood of wounding, as affected by tree species and tree size (i.e., diameter) in relationship to the number of prescribed fires experienced by the tree and the aspect; and (4) determine the conditional likelihood that wounding reduced tree quality (i.e., tree grade). We hypothesized that wound types and wound sizes will vary by species, being less frequent and smaller in thicker-barked species (e.g., white oak (*Q. alba*)), and that fire will primarily increase wound size in subsequent application. We also hypothesized that the likelihood of wounding will increase both by number of prescribed fires and on southern, more xeric aspects, but fire-caused wounds will have little impact on tree grade for most individuals.

2. Materials and Methods

2.1. Study Area

Stands were selected from four national forests in the CHR: the Mark Twain National Forest (MTNF) in southern Missouri, the Hoosier National Forest (HNF) in southern Indiana, the Wayne National Forest (WNF) in southern Ohio and the Daniel Boone National Forest (DBNF) in eastern Kentucky (Figure 1). These four forests/districts lie between 36.75° and 40.75° N latitude and 81.80° and 90.80° W longitude and represent a broad range of edaphic and climatic conditions within the CHR. Detailed descriptions of these forests have been provided elsewhere [28,30].

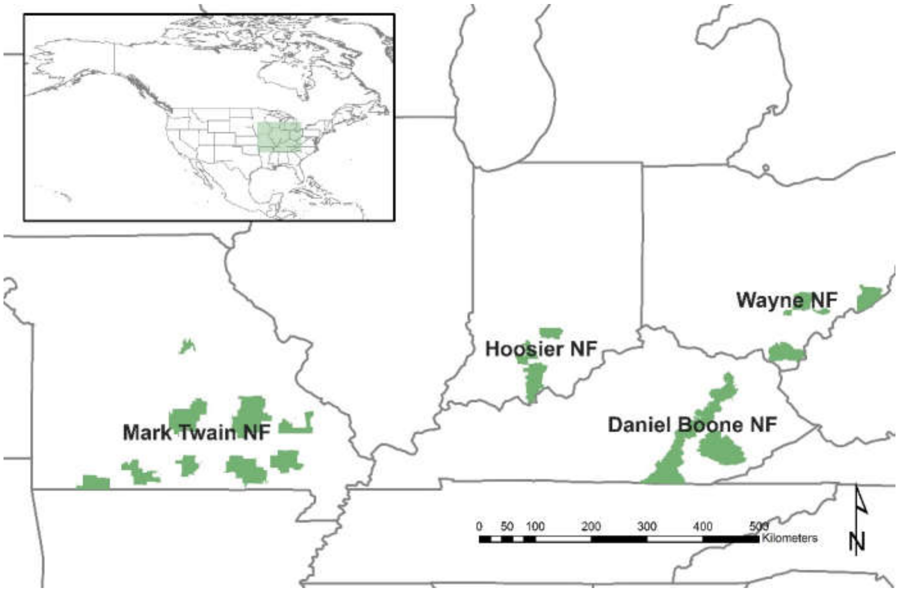

Figure 1. Locations for the four National Forests sampled in this study.

Briefly, forests of the CHR are dominated by oak–hickory (*Quercus-Carya*) forest types. Soils are largely Ultisols (west) and Alfisols (east); much of the national forests lie on unglaciated, hilly areas with limestone and/or sandstone parent material. As a result, tree diversity generally increases from west to east as soils become more productive and moisture becomes more abundant, particularly on the more sheltered, north-facing mesic slopes. Dominant canopy species transition from highly xeric species, such as shortleaf pine (*Pinus echinata*), post oak (*Q. stellata*) and scarlet oak (*Q. coccinea*), in the western CHR, to a mix with mesic canopy species in the eastern CHR; a few examples of these species include northern red oak (*Q. rubra*), yellow-poplar, sugar maple (*Acer saccharum*), red maple (*A. rubrum*), basswood (*Tilia americana*) and American beech (*Fagus grandifolia*). Several oak species (white, black (*Q. velutina*), chestnut (*Q. montana*)) and hickory species (shagbark (*C. ovata*), pignut (*C. glabra*), mockernut (*C. tomentosa*)) are common throughout the CHR [30,31].

The CHR has a long history of fire, first by Native Americans and then by European settlers [30,32,33]. Return intervals ranged from less than 3 to nearly 20 years in the CHR, increasing in frequency from east to west [8,34]. Fire suppression began in earnest in the region in the early 1900s [32,34], although the Ozark Highlands in Missouri and the Allegheny and Cumberland Plateaus in Kentucky still regularly experience wildfires, often arson-caused, during drought years [3,35]. In recent decades, there has been a persistent effort by many public land managers to increasingly use prescribed fire both for the restoration of savannas, barrens and open woodland habitats and for the promotion of oak and/or shortleaf pine regeneration in forests [9,36,37].

2.2. Stand Selection

Stands were defined as a contiguous area of forest with relatively homogenous species composition, age structure and topographic aspect, with a minimum size of 4 ha (actual range 4–13 ha). We sampled 139 stands across the four national forests: 54 stands in the HNF, 33 in the MTNF, 34 in the WNF and 18 in the DBNF. Stands were selected for sampling with restricted randomization using two criteria. First, approximate representations of "xeric" or "mesic" stands needed to be sampled. We defined "xeric" stands as having a majority of potential sampling points with south-, southeast-, southwest- or west-facing aspects, whereas "mesic" stands would have a majority of sampling points with northwest-, north-, northeast-, or east-facing aspects. This dichotomous classification was made due to the well-established effect of aspect on fire intensity [19,21,38]. We also wished to sample stands with a broad range of prescribed fire histories, so potential stands were also stratified by the number of prescribed fires, i.e., burn class, received over the past 30 years, ranging from 0 (unburned controls) to 6. Within each national forest, we attempted to select at least three stands within each aspect x burn class combination. Exceptions included: (a) only the MTNF had stands that had received six burns; (b) the DBNF did not contain any stands receiving exactly three prescribed fires; and (c) no stands were available on the WNF that received more than three prescribed fires.

In addition, all stands had to meet the followings constraints: (1) have an average diameter at breast height (DBH; 1.37 m) of greater than 25.4 cm; (2) be dominated by hardwood species, with a preference given during selection toward stands with oak and hickory dominance (i.e., >50% of basal area in oak or hickory); and (3) have upland oak site indices$_{50}$ of >18.3 m [39]. These criteria excluded stands that had management goals for open woodland restoration or would not be primarily regenerated to oak after overstory removal. Areas within each national forest that had extensive wildfire history were also avoided. This was not possible on the MTNF, as large-scale wildfires have been relatively frequent in that forest, but we were able to avoid stands with known wildfire in the last 20 years.

2.3. Field Measurements

Each stand was sampled using 15 randomly placed, variable-radius prism points. At each point, slope percent and aspect in degrees were recorded. A 20 basal area factor (BAF) prism was utilized to select live stems greater than 25.4 cm DBH for measurement. Diameter at breast height, merchantable height to 20.3 cm diameter inside bark (DIB) and presence or absence of fire-related damage were recorded for each tree. Following the protocol developed in a previous study [17], two U.S. Forest Service hardwood tree grades [40] were assigned to the tree: (1) considering all wounds associated with fire and (2) ignoring the presence of any fire-related damage. The difference between these two grades was assumed to result from prescribed fire damage (i.e., wounds) on the tree.

Wounding assumed to be associated with fire was also measured. A wound was defined as any visible disruption of the bark or cambium that appeared to be directly related to the effects of fire, generally because of the presence/absence of wound ribs, location relative to slope and/or presence/absence of char. Wounds were classified into one of five categories [23,29]—catface, oval, seam, bark slough/multiple seams and basal/flutes—that help approximate the geometric shape of the wound and can be used to calculate defect volume associated with each wound. Bark slough and multiple seams were classified as one category because they co-occurred in a vast majority of observations. It should be noted that the presence of char or discolored bark alone, in the absence of any physical damage, was insufficient to classify a wound as fire-caused, due to the inconsistent relationship of char to physical injury [28].

Width, depth and height of all wounds were measured to the nearest 2.5 mm. The width of each wound was measured at the widest point of the wound and, in cases where a measurable depth existed, it was measured at the deepest point. Wounds or portions of wound below stump-height (i.e., 15.2 cm above ground on the uphill side of the tree) were not measured. Total wound height, i.e., the linear distance from the lowest point of the wound to the highest point on the wound, and start height, i.e., the linear distance between the top of the stump and the lowest point of the wound, were both recorded. It was further noted for each wound if it caused a volume of cull extending from the wound or if it was severe enough to cause of a reduction in tree grade on the face of the tree where the wound was measured.

2.4. Data Summary

For each wound, dimensions (total height, width and depth) and type (i.e., shape) were used to calculate volume loss. Closed wounds (i.e., seams, bark slough) were assumed to have a depth of 1.27 cm. Volume loss was calculated in terms of dm^3. Wound type and size (i.e., volume) were then summarized by species or 10 cm DBH class. Species included oaks, both in the red oak (*Lobatae*) and white oak (*Quercus*) sections, hickories, maples and beech, yellow-poplar, shortleaf pine and several other miscellaneous species (Table 1). Of note, hickories could not be entirely separated into species due to inconsistences of data collection procedures over the sampling period (summers from 2016 to 2019), so most analyses were conducted for hickories as a group. Species without a sample size of at least 50 individuals were not analyzed further.

Table 1. Number of trees measured, average and range of diameters at breast height (DBH; cm), number of trees wounded and number of trees with a fire-related reduction in U.S. Forest Service tree grade [40] by species groups and species. The "Other" group contains miscellaneous and rare species that had less than 50 individuals measured. Latin names are given in parentheses.

Species Group/Species	n	DBH (range)	No. Wounded	No. Grade Reduction
White oaks				
White (*Quercus alba*)	3579	45.9 (25.4–95.3)	956	122
Chestnut (*Q. montana*)	606	47.5 (25.4–129.5)	97	13
Post (*Q. stellata*)	593	38.2 (25.4–63.2)	231	89
Red oaks				
Black (*Q. velutina*)	689	49.4 (25.4–94.0)	235	54
Northern red (*Q. rubra*)	324	51.5 (25.4–112.3)	121	15
Scarlet (*Q. coccinea*)	290	47.6 (27.2–91.4)	91	43
Hickories				
Hickory (*Carya* spp.) [1]	354	40.0 (25.4–99.1)	97	19
Pignut (*C. glabra*)	200	40.9 (25.4–91.9)	21	3
Shagbark (*C. ovata*)	121	42.0 (25.9–64.0)	25	3
Maples and beech				
Sugar (*Acer saccharum*)	298	38.0 (25.4–86.4)	86	22
American beech (*Fagus grandifolia*)	120	44.7 (25.4–107.4)	26	9
Red (*A. rubrum*)	73	38.2 (25.7–91.7)	19	9
Yellow-poplar (*Liriodendron tulipfera*)	394	45.4 (25.4–97.5)	70	7
Shortleaf pine (*Pinus echinata*)	173	39.6 (26.7–61.0)	16	5
Others				
Blackjack oak (*Q. marilandica*)	49	45.5 (28.2–72.4)	29	14
Black gum (*Nyssa sylvatica*)	45	37.7 (25.4–67.6)	11	2
Ash (*Fraxinus* spp.)	38	37.3 (25.4–67.8)	10	0
Sycamore (*Platanus occidentalis*)	24	46.7 (26.9–85.9)	1	0
Black cherry (*Prunus serotina*)	18	39.0 (27.2–82.0)	4	2
Eastern red cedar (*Juniperus virginiana*)	15	39.3 (27.9–56.9)	3	0
Elm (*Ulmus* spp.)	11	34.9 (27.9–55.9)	4	1

Chinkapin oak (*Q. muehlenbergii*)	9	45.0 (26.7–70.9)	0	0
Eastern white pine (*P. strobus*)	9	41.5 (32.0–51.3)	2	0
Sweetgum (*Liquidambar styraciflua*)	9	36.8 (27.7–55.9)	0	0
Basswood (*Tilia americana*)	7	50.8 (29.0–75.9)	0	0
Southern red oak (*Q. falcata*)	7	57.6 (30.2–74.9)	1	1
Mockernut hickory (*C. tomentosa*)	6	47.8 (33.8–57.4)	0	0
Sassafras (*Sassafras albidum*)	6	34.9 (30.0–63.5)	1	0
13 rare species [2]	26	37.7 (25.4–84.3)	3	1
All species	8093	44.9 (25.4–129.5)	2106	434

[1] Hickories were only identified to genus on the Hoosier National Forest. Based on site characteristics of selected stands, it is highly likely that these individuals are mostly shagbark hickory and, to a lesser extent, pignut hickory. [2] Rare species all had n ≤ 3. Species included: eastern hemlock (n=3; *Tsuga canadensis*), Ohio buckeye (n = 3; *Aesculus glabra*), Virginia pine (n = 3; *P. virginiana*), yellow birch (n = 3; *Betula alleghaniensis*), flowering dogwood (n = 2; *Cornus florida*), persimmon (n = 2; *Diospyros virginiana*), quaking aspen (n = 2; *Populus tremuloides*), shingle oak (n = 2; *Q. imbricaria*); silver maple (n = 2; *A. saccharinum*), bitternut hickory (n = 1; *C. cordiformis*); eastern cottonwood (n = 1; *P. deltoides*), honeylocust (n = 1; *Gleditsia triacanthos*) and tree of heaven (n = 1; *Ailanthus altissima*).

Likelihood of wounding, overall and within either a species group or size category, was calculated after summarizing responses at the plot-level using the expansion constant for a 20 BAF prism and expressed on a percentage scale, i.e., (wounded trees ha^{-1} /total trees ha^{-1}) × 100%. Likelihood of grade reduction was calculated similarly, but conditional on being wounded, i.e., if wounded, what was the percentage of those trees that received a tree grade reduction.

2.5. Analysis

To characterize the distribution of observed wounding in sample trees, we first used a one-way analysis of variance (ANOVA) to test for differences in average volume loss by wound type; Tukey's Honestly Significant Difference (HSD) mean separation tests [41] were then used to determine which wound types differed significantly from one another in observed volume loss. Contingency table analysis (i.e., χ^2 tests) and one-way ANOVA were used to test for an overall difference among broad species groups—specifically white oaks, red oaks, yellow-poplar, sugar maple, hickory and pine—in wound type and wound size, respectively. For the latter, HSD tests were then used to clarify differences in mean responses among species.

Using plot-level summaries, we tested the effect of number of applications of prescribed fire, hereafter termed "burn class", and site aspect on the average wound size of a wounded tree using a linear model and a one-way ANOVA, respectively. The effects of burn class on the proportional distribution of wound types at a site were tested overall with ANOVA, with trends for each wound type analyzed with linear models. Likelihood of wounding and likelihood of grade reduction were analyzed using either ANOVA for categorical independent variables (e.g., burn class, aspect) or logistic regression for continuous independent variables (e.g., DBH). We evaluated the influence of burn class, aspect, DBH and species group on each likelihood using separate models for each independent variable, using HSD tests as appropriate to separate means for significant models.

For all analyses, we evaluated heteroscedasticity using the Breusch–Pagan test [42], and we evaluated normality using the Shapiro–Wilk Test. All statistical analyses for this study were run in R 3.5.3 [43]. Differences were deemed significant at $\alpha = 0.05$.

3. Results

A total of 8093 trees were measured in the 139 stands, 4081 trees in 70 mesic stands lying on northerly-facing slopes and 4012 trees in 69 xeric stands lying on southerly-facing slopes (Table 2). There was very little difference observed in stand composition between mesic and xeric aspects. Oak species dominated, comprising 75% of stems in both aspect classes; white oak alone comprised 43% of the composition on both aspect classes. Between 222 and 1968 trees were measured in each burn class (Table 2); composition shifted towards higher white oak dominance as burn class increased, i.e., 39% of stems in stands receiving zero to two prescribed fires, compared to 54% in stands receiving three to six prescribed fires. Conversely, red oak and yellow-poplar became slightly less prevalent as burn class increased (data not shown).

Over 40 tree species were sampled across all sites (Table 1). White oak was the most abundantly sampled species, accounting for over 44% of the total. Of the remaining species, only chestnut oak, post oak and black oak represented more than 5% of the sample. The average dbh of the sample trees was 44.9 ± 1.2 cm (mean ± standard error), but trees ranged in size from the study-defined minimum, 25.4 cm, to a maximum of 129.5 cm (a chestnut oak).

Table 2. Distribution of measured (*M*) and wounded (*W*) trees by aspect and burn class.

Burn Class	**Aspect** [1] **Xeric**		**Mesic**		**Total**	
	M	***W***	***M***	***W***	***M***	***W***
0	852	72	732	80	1584	152
1	870	190	1098	193	1968	383
2	930	260	899	212	1829	472
3	756	263	585	304	1341	567
4	352	151	505	256	857	407
5	197	67	88	20	285	87
6	55	27	174	71	229	92
Total	4012	1024	4081	1136	8093	2160

[1] Xeric stands had southerly-facing aspects, whereas mesic stands had northerly-facing aspects.

3.1. Wounds

A total of 3403 wounds were measured across 2106 individual trees (Tables 1 and 3). Wound types were nearly evenly distributed among catfaces, seams and bark slough, which, in aggregate, composed the vast majority of wounds. The average volume loss varied significantly by wound type (F = 49.16, $p < 0.01$). Catfaces were the most damaging and accounted for an average volume loss of 23.4 ± 1.7 dm^3 per wound, although several catfaces were measured that exceeded 100 dm^3 in deduction. Ovals and basal/flutes were intermediate in damage loss, but only accounted for 6.9% of all wounds observed (Table 3).

The wounding type was significantly not uniform among species groups ($\chi^2 = 209.2$, $p < 0.01$). For example, a higher proportion of wounds on northern red oak were catfaces (42%; 100/240) compared to white oak (26%; 399/1537) (see also Table S1). Catfaces were particularly uncommon among yellow-poplar, comprising just 17% (17/101) of the measured wounds. Seams and bark slough were the dominant wound types among white oak, collectively comprising 69% (1066/1537) of all wounds measured. Likewise, bark slough was the dominant wound type among yellow-poplar, accounting for 63% of all measured wounds (63/101). Catfaces, however, tended to be more prevalent among thin-barked species, accounting for approximately 50% of the measured wounds on sugar maple (76/151), American beech (18/36) and red maple (11/20).

Table 3. Number of wounds (n) and volume loss (mean ± standard error) in dm^3 by wound type classification. Wound types with significantly different volume losses (Tukey's HSD test, $\alpha = 0.05$) are denoted by the same superscripted letter. Ranges of observed volume losses are provided in parentheses.

Wound Type	n	Volume Loss [1]
Catface	1106	23.4 ± 1.7 (<0.1–801.3) ^{a}
Bark Slough	1038	3.7 ± 0.3 (<0.1–140.4) ^{b}
Seam	1024	4.4 ± 0.9 (<0.1–453.1) ^{b}
Oval	202	9.1 ± 1.7 (<0.1–294.6) ^{b}
Basal/Flute	33	10.9 ± 2.8 (0.2–64.8) ^{b}
All Types	3403	10.7 ± 0.7 (<0.1–801.3)

[1] To convert to board feet, divide by 2.356.

Average wound size significantly differed by species group (F = 2.74, $p = 0.02$), but high variability and vastly unequal sample sizes reduced the detection of significant differences among individual species (Table 4). Among thicker-barked species, shortleaf pine and white oak had the smallest average wound size, 2.3 ± 1.3 and 7.5 ± 0.7 dm^3, respectively. Northern red oak, the most mesic oak species sampled, had notably larger wounds, 12.6 ± 0.7 dm^3, but several of the more xeric oak species had even larger wounds.

Table 4. Number of wounds observed (n) and mean volume (±standard error) loss per measured wound for common species observed in the study. Wound types with significantly different volume sizes (Tukey's HSD test, $\alpha = 0.05$) are denoted by different superscripted letters. Note that more than one wound or wound type could be observed on an individual tree. Latin names are given in parentheses.

Species	n	Volume/Wound (dm^3)
White oaks		
White (*Quercus alba*)	1537	7.5 ± 0.7 ^{a}
Post (*Q. stellata*)	311	13.6 ± 2.3 ^{ab}
Chestnut (*Q. montana*)	137	13.0 ± 3.2 ^{ab}
Red oaks		
Black (*Q. velutina*)	442	10.6 ± 1.5 ^{a}
Northern red (*Q. rubra*)	241	12.6 ± 2.3 ^{ab}
Scarlet (*Q. coccinea*)	116	25.6 ± 8.0 ^{bc}
Hickories (*Carya* spp.) [1]	192	13.9 ± 3.9 ^{ab}
Maples and Beeches		
Sugar maple (*Acer saccharum*)	151	7.8 ± 1.2 ^{a}
American beech (*Fagus grandifolia*)	37	20.1 ± 6.8 ^{ab}
Red maple (*A. rubrum*)	20	15.3 ± 5.4 ^{ab}
Shortleaf pine (*Pinus echinata*)	18	2.3 ± 1.3 ^{ab}
Yellow-poplar (*Liriodendron tulipifera*)	102	16.1 ± 8.2 ^{ab}

[1] Hickories were only identified to genus during most of the data collection. Among thin-barked species, sugar maple had a moderate average wound size (7.8 ± 1.2 dm^3), while conversely wound size was larger for red maple (15.3 ± 5.4 dm^3) and American beech (20.1 ± 6.8 dm^3). Wound size was larger on average for yellow-poplar (16.1 dm^3), but extremely variable (SE = 8.2). This is likely due to the presence of a small number of very large catfaces in that species.

3.2. Changes in Wounding with Repeated Fires

Increasing applications of prescribed fire (i.e., burn class) had variable effects on the observed wounding of individual trees (Table 5). Burn class did not have a significant effect on average volume loss per wound (F = 0.88, $p = 0.35$), suggesting that larger wounds were not associated with increasing applications of fire. Burn class did have a significant effect on the distribution of wound types (F = 4.69, $p < 0.01$); seams were significantly (F =

6.12, $p = 0.01$) more common as a proportion of all wounds on sites with no fires, 47.7% of all wounds, and became progressively less common on sites with four or more fires (ranging from 20.7 to 24.8% of all wounds at a site). Bark slough wounds displayed the opposite trend, becoming significantly more common as a proportion of all wounds with increasing burn class (F = 6.91, $p < 0.01$), increasing from 19.1% of all wounds on no-burn sites to 45.2% on six-burn sites. The catface, basal flute and oval proportions did not differ by burn class (F = 0.12, $p = 0.72$; F = 1.01, $p = 0.31$; and F = 0.38, $p = 0.54$, respectively). Likewise, increasing numbers of prescribed fire did not have a significant effect on the overall proportion of wounds that were "open" (catfaces and ovals) compared to "closed wounds", such as seams and bark slough (F = 0.04, $p = 0.84$).

Finally, there was no difference between mesic and xeric aspects in terms of the average volume loss per wound (F = 1.42, $p = 0.23$), or the proportion of open vs. closed wounds (F = 1.07, $p = 0.30$).

Table 5. Percentage of all trees per acre ± 1 SE to receive at least one wound of each measured type by number of prescribed fires.

Burn Class	Bark Slough	Catface	Basal Flutes	Oval	Seams
0	1.9 ± 0.3	2.5 ± 0.2	0.2 ± 0.1	0.7 ± 0.2	4.9 ± 0.6
1	6.7 ± 0.7	7.5 ± 0.7	0.4 ± 0.1	1.3 ± 0.2	5.7 ± 0.6
2	7.9 ± 0.7	9.2 ± 0.6	0.4 ± 0.1	2.3 ± 0.3	10.0 ± 1.0
3	15.5 ± 1.0	19.5 ± 1.6	0.3 ± 0.1	3.3 ± 0.3	13.3 ± 1.1
4	25.5 ± 1.0	19.6 ± 0.9	0.1 ± 0.1	4.8 ± 0.6	13.6 ± 0.8
5	6.5 ± 0.5	19.3 ± 1.5	0	0.3 ± 0.1	6.7 ± 0.2
6	22.3 ± 0.7	14.4 ± 1.7	0	0	11.0 ± 0.3

3.3. Likelihood of Wounding

Wounding increased with repeated applications of prescribed fire (Figure 2). The likelihood of wounding on unburnt, control sites averaged 9.2 ± 1.9%, reflecting a background level of wounding from either wildfire or other injuries that mimicked wounds caused by prescribed fire. Still, prescribed fire increased the likelihood of wounding with every application above this background rate until the third burn, after which additional burns did not appear to significantly affect wounding likelihood (Figure 2). The likelihood of wounding peaked on sites with four burns at 48.9 ± 5.6%. However, aspect had little effect on the likelihood of wounding (F = 0.29, $p = 0.59$). Xeric stands that experienced prescribed fire had an average of 28.5 ± 2.8% trees per acre wounded, compared to 29.7 ± 3.1% of trees per acre in mesic stands.

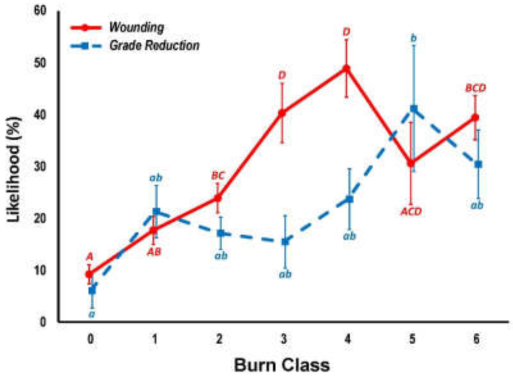

Figure 2. The likelihood of wounding (red) and conditional likelihood of grade reduction assuming wounding (blue) with increasing burn class (i.e., numbers of prescribed fires). Error bars are ± 1 standard error. Letters indicate significant differences ($p < 0.05$, Tukey's HSD) among mean likelihoods of the burn classes for both wounding (capitalized, red) and grade reduction (lower case, blue).

Wounding likelihood varied significantly among species (F = 2.41, $p < 0.01$), although high site variability masked species differences with Tukey HSD tests (Table 6). Among oaks, chestnut oak and white oak both had a low likelihood of wounding, 16.9 ± 3.3% and 25.0 ± 2.0%, respectively. Conversely, the likelihood of wounding exceeded 30% for all members of the red oak group and for post oak. Among non-oaks, shortleaf pine and yellow-poplar had the lowest likelihood of wounding among common species sampled, 9.7 ± 4.5% and 20.0 ± 3.8%, respectively (Table 6).

Table 6. Mean (± standard error) likelihood of wounding and conditional likelihood of grade reduction assuming wounding for all common species (n > 50). Latin names are given in parenthesis. Species with significantly different likelihoods (Tukey's HSD test, $\alpha = 0.05$) are denoted by different superscripted letters.

Species	Wounding (%)	Grade Reduction (%)
White oaks		
White (*Quercus alba*)	25.0 ± 2.0 ^{a}	13.5 ± 2.2 ^{a}
Post (*Q. stellata*)	36.9 ± 4.1 ^{a}	34.5 ± 4.2 ^{ab}
Chestnut (*Q. montana*)	16.9 ± 3.3 ^{a}	13.6 ± 4.9 ^{a}
Red oaks		
Black (*Q. velutina*)	31.2 ± 3.3 ^{a}	22.7 ± 4.3 ^{a}
Northern red (*Q. rubra*)	36.5 ± 3.9 ^{a}	13.8 ± 4.4 ^{a}
Scarlet (*Q. coccinea*)	30.9 ± 4.3 ^{a}	42.4 ± 6.8 ^{b}
Hickories (*Carya* spp.) [1]	24.4 ± 2.9 ^{a}	21.4 ± 4.5 ^{a}
Maples and beech		
Sugar maple (*Acer saccharum*)	30.3 ± 4.6 ^{a}	24.1 ± 5.4 ^{ab}
American beech (*Fagus grandifolia*)	23.6 ± 6.5 ^{a}	36.4 ± 13.8 ^{ab}
Red maple (*A. rubrum*)	26.2 ± 6.6 ^{a}	41.2 ± 13.7 ^{ab}
Shortleaf pine (*Pinus echinata*)	9.7 ± 4.5 ^{a}	26.2 ± 13.7 ^{ab}
Yellow-poplar (*Liriodendron tulipifera*)	20.0 ± 3.8 ^{a}	11.1 ± 5.3 ^{a}

[1] Hickories were only identified to genus during most of the data collection. Thin-barked species, such as maple and beech, generally had much higher likelihood of grade reduction (Table 6).

Tree size (i.e., DBH) also did not affect the likelihood of wounding in logistic regression models (F = 0.48, $p = 0.63$). High site-to-site variability masked any tree size differences between thick-barked and thin-barked species as well (Figure 3).

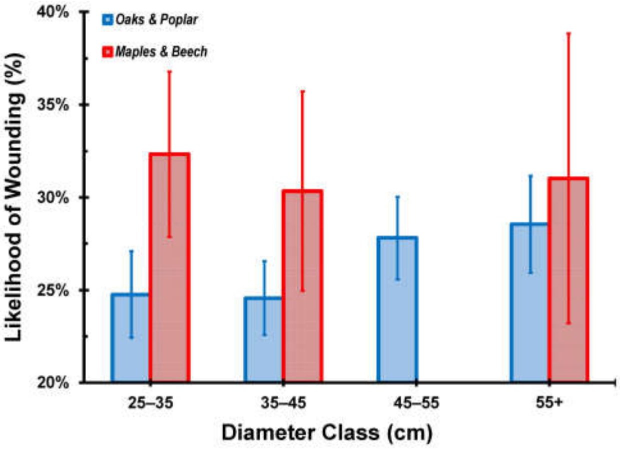

Figure 3. The likelihood of wounding by increasing 10 cm diameter class, as separated by thick-barked (oaks and yellow-poplar; blue) and thin-barked (maples and American beech; red) species. Error bars are ± 1 standard error. There are no significant differences ($p < 0.05$, Tukey's HSD) among mean likelihoods for either species group. Note that no 45–55 cm diameter, thin-barked species were sampled.

3.4. Likelihood of Tree Grade Reduction

Assuming a tree was wounded by prescribed fire, the likelihood that wounding caused a reduction in USFS tree grade averaged 19.7 ± 3.1% across all burn classes. Although there was a positive relationship between conditional grade reduction and burn class (F = 2.87; $p < 0.01$; Figure 2), this relationship was largely a result of very low conditional grade reduction in the controls, 6.1 ± 3.4%. All other burn classes were not significantly different from one another, although there was a trend towards much higher-grade reduction with five or more burns (Figure 2).

Wounding also differed on its impact on USFS tree grade among species (F = 3.98, $p < 0.01$; Table 6). White oak and chestnut oak were notably resistant to grade reduction from wounding, 13.5 ± 2.2% and 13.6 ± 4.9%, respectively. Conversely, post oak had a much higher likelihood of grade reduction, 34.5 ± 4.2%. Conditional rates of grade reduction were highly variable among the red oak group, ranging from 13.8 ± 4.4% for northern red oak up to 42.4 ± 6.8% for scarlet oak. Of non-oaks, yellow-poplar had the lowest likelihood of grade reduction among all common species, 11.1 ± 5.3%.

4. Discussion

Wounds are commonplace on tree stems in most forests; our sample sites were no different in that approximately 10% of trees on unburnt sites had wounds. Wounds are an anatomical response to injury, characterized by a physical disruption of living tissues and where the tree attempts to compartmentalize that injury to prevent decay [44,45]. Prescribed surface fires can specifically form a wound, i.e., a fire scar, when heat from fire penetrates the insulating bark and kills a region of the vascular cambium [46,47]. This initially may result in bark slough, i.e., a patch of deadened bark disconnected from the underlying tissues that eventually falls away from the tree. At the margins of this deadened vascular cambium, however, callus tissue forms ribs of “woundwood” that, depending on the geometry of the injured tissues, forms a “closed” seam or an “open” catface or oval. This woundwood persists until growth “closes” the wound, allowing for new, uninjured cambium to grow new xylem and phloem and connect all the margins of the wound [47].

4.1. Wounding Patterns with Increased Prescribed Fires

We found a relatively equal proportion of bark slough, seams and catfaces in our sample overall (Table 3), but an increasing proportion of wounding with repeated applications of fire (Table 5). These observations reflect both the variable spatial intensity of any given fire, leading to some stems remaining uninjured in any given fire, as well as the cumulative effects of multiple fires on a single tree stem [3,11,45,46]. Wound closure is variable, dependent on the geometry (generally surface area) of the wound and growth rate of the tree; it can occur as quickly as one year for very small wounds on fast-growing trees or take a decade or more for average-sized wounds on larger, older stems [45]. Therefore, as observed in this study, single applications of prescribed fire often led to fewer open wounds than closed wounds (Table 5), but this pattern can easily be overridden by increased fire intensity at stand or sub-stand levels. Likewise, if fire return intervals are more frequent than the healing rate of closure, wounds can become persistent or even enlarge, as each successive burn can further damage the cambium at the margins of the wound, usually since insulating bark is much thinner in those areas [45]. In this study, seams were significantly less common as the number of prescribed fires increased, suggesting that the repeated applications of fire led to enough bark loss on the periphery of the seam that they became other, more open wound types. We also recorded slightly, albeit not significant, increases in proportions of open wounds with increasing burn number; on sites receiving three or more fires, the proportion of trees with catfaces and ovals exceeded 20% on many sites.

Catfaces, in particular, can be problematic from both a timber and fire management perspective, especially if quite numerous in the stand. These wounds are commonly associated with more extensive volume loss generally from the combined impacts of the injury itself and the subsequent colonization of the exposed wood by wood-decaying fungi [3,17]. Since these wounds are found at the base of the tree in the butt log, they have a much higher potential to cause grade loss than other wound types [3,11,45]. We, too, observed both higher average volume loss (23.4 ± 1.7 dm^3) and higher extreme volume loss (801 dm^3) with catfaces than for other wound types. Still, the average volume loss in catfaces only represents 2%–7% of the volume of the average-sized butt log in our stands, although the extreme volume losses observed represented full cull for that tree. This observation is within the range of volume reported in previous research. For example, a previous study reported only a 3.9% volume loss across all sampled logs in their study of prescribed fire damage on red oak species in the Missouri Ozarks; all sample trees in that study had catfaces [17].

4.2. Wounding and Grade Reduction

The cumulative effects of increasing the applications of prescribed fires should lead to a higher probability that any given area within a burn unit will, at some point, reach temperatures sufficient to injure stems and lead to wounding [11,17]. We observed that the likelihood of wounding was positively associated with the increasing applications of prescribed fire. Every successive burn on a site increased the likelihood of wounding by roughly 10% over the background wounding rate of 9.2 ± 1.9% (i.e., the controls), until the site received three burns after which there was no significant increase in the likelihood of wounding (Figure 2). Our observations are within the range of reported scarring in the previous studies of prescribed fire damage [3,45,48].

Cumulative effects, particularly at short fire return intervals that prevent complete healing [45], should also exacerbate existing wounds, leading to a higher conditional likelihood of grade reduction. However, in this study, tree grade did not change significantly, increasing only slightly with increasing applications of prescribed fire; after the initial burn, between 20 and 30% of wounded trees would have grade reduction regardless of the number of successive burns (Figure 2). By definition, tree grade is directly related to lumber recovery, and highly dependent on both diameter and the damage seen on the second "worst" face, as the damage on the "worst" face can be isolated in the milling process [40,49]. Initial applications of prescribed fire can be more damaging; sites that have not received fire for several years or even decades often have accumulated deep litter, duff and coarse woody debris near the bases of trees [48,50], particularly on the upslope side of stems. This accumulated fuel can burn intensively for an extended period [3,10,20], and more likely cause injury, particularly if those trees are in susceptible landscape positions or are predisposed to injury (e.g., thin-barked species). This initial damage "sets" the worst face on the tree (often upslope face) and, we propose, leads to the jump in the conditional likelihood of grade reduction after the first burn (Figure 2). Successive burns, if burnt before fine fuel loading recovers to near maximum levels, burn cooler and merely "reinforce" the existing wounds or, alternatively, wound in the same general location on the stem. This does not lead to large increases in grade reduction as any new damage is likely contained within the previously damaged face. Tree grade, therefore, seems relatively insensitive after a few successive burn applications (i.e., ≤4) with the slight increases in the likelihood of grade reduction observed probably isolated to a few stems that, by chance, received their first significant wounds in each successive fire.

Aspect, surprisingly, did not have a significant effect on the likelihoods of wounding or grade reduction. Fire intensity is known to increase on southern exposures within the Northern Hemisphere because of the more direct radiation and generally more xeric conditions [38]. Despite this, only one study has found a significant impact of aspect on scarring after prescribed fire in eastern deciduous forests [19]. We would argue that these retrospective studies of damage are not powerful enough to detect the impacts of aspect and topography; a previous study suggested that localized fire severity may be masking impacts [23], especially when cumulated across multiple burns.

We also did not see an effect of tree diameter on wounding patterns, either for thick- or thin-barked species (Figure 3). Bark thickness is known to be strongly related to tree diameter, and previous studies have demonstrated that thicker bark insulates stems from heat damage that may occur during fires [24,51,52]. Prior studies have shown that most damage, including mortality, from prescribed fire is in pole-sized stems <20 cm diameter [3,23,53], smaller than the size threshold used in this study. In addition, we feel that high site-to-site variability, cumulative damage effects and our respective experimental approach contributed to masking tree diameter impacts on wounding.

4.3. Species Differences

Not surprisingly, wound patterns from prescribed fire differed by species on our study sites. Relative to other oaks, white oak and chestnut oak had both a much lower likelihood of wounding and a conditional likelihood of grade reduction. These two species display several traits to endure fire including thick bark, the strong compartmentalization of wounds, heartwood decay resistance, strong sprouting capacity and highly flammable litter [3,54–56]; both are known to be among the most fire resistant of the eastern oak species [19,24,57,58]. Many red oaks, on the other hand, do not share these pyrophytic traits, generally having thinner bark, weak compartmentalization and low resistance to decay [3,24]. This suggests, as we observed, a higher likelihood of wounding and/or conditional likelihood of grade reduction in the red oak group than the white oak group. These differences in the fire damage of oaks have been reported previously; prior studies in the Missouri Ozarks reported the higher scarring of red oak species than white oak species after prescribed burns [19,23]. Another study from West Virginia reported relatively low rates of lumber value and lumber volume loss among white oaks milled from prescribed fire-damaged logs [22].

Maple and beech species exhibited similar, albeit slightly higher, likelihoods of wounding compared to oaks across all tree diameters. Coupled with the slower growth rates and poorer compartmentalization of these species compared to oaks, a slightly higher wounding rate from prescribed fire likely resulted in the higher conditional likelihoods of grade reduction that we observed in maple and beech. Prior research has suggested that these mesophytic species are fire-intolerant because of their comparably thinner bark at similar tree diameters [24,53], although several researchers have reported the resistance of mature individuals to damage and/or mortality from individual prescribed fires [59,60]. Cumulative effects usually, however, lead to a reduction in maple and beech basal area after multiple prescribed fires, particularly on drier sites [61,62].

Both yellow-poplar and shortleaf pine had very low likelihoods of wounding and tree grade reduction. Although this was expected for shortleaf pine, given its strong dependence on and multiple adaptations to surface fire [63,64], these low rates were surprising for yellow-poplar. Prior research has suggested that yellow-poplar's tolerance to fire depends greatly on diameter. In smaller size classes, the species often exhibits relatively high mortality from fire in comparison to other hardwood species [65]. At larger, mature tree sizes, yellow-poplar has been shown to exhibit low likelihood of wounding to mature trees from fire due to exceedingly thick bark [22,25,57]. Most of the trees measured in this study came from the latter group. It is further possible that cumulative effects from prior burns may have caused the past mortality of moderately sized, yellow-poplar overstory trees. In that respect, our retrospective study design may be biased in detecting wounding and grade reduction not only in yellow-poplar, but also other fire-intolerant tree species.

5. Conclusions

Maintaining oak-dominated forest ecosystems in eastern North America is challenging given the persistent failure to regenerate and recruit many oak species over much of the last half of the 20th century [54]. Managers chronically avoided the use of fire both for fear of damaging overstory trees and reducing timber values [66] and because of ignorance of the critical role fire plays in the ecology of many eastern oak species [67]. While research over the past two decades has illuminated the role of fire in the ecology of the eastern forests, knowledge gaps still exist regarding the indirect economic and ecological effects of prescribed fire [2,67]. This study helps to fill that gap.

Rather than documenting individual trees' responses to prescribed fire over several fires (and several decades), this study used a retrospective approach to estimating wounding and resulting damage, in terms of both volume and grade reduction, to individual trees following prescribed fire. While this approach has some inherent weaknesses, such as not being able to relate wounding rates to individual fire parameters (e.g., fire temperature, fireline intensity, fire residence time), our approach does allow the estimation of cumulative effects to the "average" management burn regime in closed canopy oak forests. Furthermore, this study provides guidance on the relative susceptibility of overstory tree species to prescribed fire damage.

Collectively, this information in our study could be invaluable to managers debating the relative costs of prescribed fire, in terms of both direct (e.g., labor costs, increased planning, permits) and indirect (e.g., timber damage, wildlife mortality) costs, with the relative benefits of increased oak regeneration, increased wildlife habitat and other variables that develop from multiple applications of prescribed fire. Where the potential costs of prescribed fire significantly outweigh the benefits, managers can seek alternative silvicultural approaches to achieve similar compositional and structural outcomes [3,67]. On the other hand, where benefits exceed costs, managers should be encouraged to use fire judicially for oak management.

Supplementary Materials: The following are available online at https://www.mdpi.com/article/10.3390/f14020227/s1, Table S1: Counts and volumes of wound types by species groups.

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Data Availability Statement: The data presented in this study are archived on the Purdue University Research Repository at https://purr.purdue.edu/projects/timdam/publications (last accessed 19 January 2023); access is provided upon written request to the corresponding author.

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Conflicts of Interest: The authors declare no conflict of interest.

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