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Evaluating Economic Impacts of Prescribed Fire in the Central Hardwood Region

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Abstract

Surface fires are often prescribed to favor oak (*Quercus*) regeneration in eastern forests, but there is potential for fire to damage residual overstory timber. This study evaluated the potential economic effects of prescribed fire on sawtimber volume and value across 139 stands, each with a known history of one to six prescribed fires, on the Hoosier, Mark Twain, Wayne, and Daniel Boone National Forests. Sawtimber volume and value losses were highly variable, ranging from 0 to 2,269 bd ft ac^{-1} and from US\$0 to US\$272.95 ac^{-1}, respectively, for stands that had received at least one prescribed fire. Volume and value losses increased linearly by +0.9 percent and +1.5 percent per burn, respectively, that a stand received over the past 25 years. Stands with south-facing aspects had greater relative volume and value losses (+1.4 to +1.5 percent, respectively), but this influence was statistically less important than the number of burns in predictive models. The eastern national forests had much lower average relative volume and value losses, <3.0 percent, than the more western Mark Twain National Forest (10–15 percent loss). Species composition affected value loss associated with prescribed fire; red oaks experienced significantly higher value loss than all other species groups.

Keywords: timber damage, white oak, mixed-effect models, aspect, economic tradeoffs

Prescribed fire is widely recognized as an important tool for regenerating and recruiting fire-tolerant and fire-adapted species, reducing competition from fire-intolerant species, and maintaining certain desired forest structures and habitat types (Dey and Schweitzer 2018). For oak (*Quercus* spp.) management, a large body of research has highlighted fire's ecological and managerial importance (Brose et al. 2013). Many national forests in the Central Hardwood Region (CHR), which encompasses almost the entirety of Illinois, Indiana, Ohio, Kentucky, Tennessee and West Virginia, and portions of the bordering states (Fralish and Franklin 2002; Figure 1, inset), have expanded the use of prescribed fire. National forest plans now prescribe fire for maintenance of rare fire-dependent communities (e.g., canebreaks and barrens), restoration of "pre-fire suppression conditions," "emulating historic fire regimes," and actively promoting oak regeneration (USDA Forest Service 2004, 2005, 2006). Despite this, prescribed fire is currently not applied widely enough in the CHR to reverse trends of mesophication (*sensu* Nowacki and Abrams 2008) and future maple

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Management and Policy Implications

Land managers throughout the eastern United States frequently cite persistent and chronic lack of oak (*Quercus*) regeneration in their forests. Given the adaptations of the genera to surface fire, prescribed fire is widely recognized as one tool that can increase oak's competitiveness, particularly on mesic sites. Prescribed fire, however, comes with costs both in terms of personnel time to prepare and conduct the burn, and in terms of physical damage to the resource (i.e., timber) after the burn. Regarding the latter, prescribed fires conducted for developing and releasing advanced oak regeneration in mesic, mature stands of the Central Hardwood Region usually cause minimal loss (<3 percent relative loss) to sawtimber volume or value. However, prescribed fire has the potential to cause significantly more damage, potentially exceeding 10 percent of stand volume and value, when repeated more than twice in stands on xeric aspects and in drier portions of the Central Hardwood Region. Therefore, managers should still keep prescribed fire intensities low to avoid wounding stems, particularly on sites with high-quality timber.

dominance, particularly outside the National Forest System. For example, despite over 6 million ac of land receiving a forestry-aligned prescribed fire treatment in the eastern United States in 2017, most burns were associated with southern pine (*Pinus* spp.) management; no state within the oak-dominated CHR reported more than 50,000 acres treated with fire for forestry objectives (Melvin 2018).

Although numerous barriers exist to implement prescribed fire programs, forest managers often hesitate to prescribe fire in fear that the practice can reduce tree quality and value in hardwood stands (Brose et al. 2014, Knapp et al. 2017). These concerns are often based on early research of the effects of wildfire on timber quality; these studies showed, in some cases, significant damage to timber value from fire (Loomis 1974). However, there are key differences in the timber quality effects of wildfire and prescribed fire because of differences in fire intensity and duration. Prescribed fire tends to be less intense and severe on average than wildfire (Malone et al. 2011), at least partially because of the tendency to conduct prescribed fires in conditions in which they can be controlled (Nesmith et al. 2011). Within the CHR, Reeves and Stringer (2011) estimated that standing timber volume loss from multiple wildfire events in Kentucky averaged 38.8 percent (Reeves and Stringer 2011), whereas Stanis et al. (2019) estimated that sawtimber volume loss to prescribed fire in oak-dominated stands in southern Indiana did not exceed 8.0 percent.

The paucity of research on prescribed fire-caused timber damage also shows highly variable effects. For example, Marschall et al. (2014) reported an approximately 10 percent value loss to red oak butt logs harvested from sites in the Missouri Ozarks receiving either three or four prescribed fires to restore woodland conditions. Likewise, Wiedenbeck and Schuler (2014) found that log value loss did not exceed 1 percent for any species harvested from a site that had two prescribed fires to develop advanced oak regeneration on the Fernow Experimental Forest in West Virginia. Although variability in value loss can be expected, given the wide range of edaphic factors, stand structural conditions, and fire parameters (e.g., number of fires, firing patterns, time elapsed since last fire, seasonality of burns, flame heights, etc.), there is a notable absence of research evaluating these effects across a wide range of sites and differing management objectives on a regionwide basis. Instead, most studies evaluate fire in a binary sense, i.e., the stand received prescribed fire or did not, and relate the damage to the time since last fire (e.g., Marschall et al. 2014).

Furthermore, there are a few predictive models for volume or value loss associated with fire, either wildfire or prescribed. Loomis (1974) modeled the effects of tree-level measurements and wounding on value and volume loss. Marschall et al. (2014) also presented a tree-level model, specific to prescribed fire in the Missouri Ozarks, to predict percent value loss based on size of wounds and time between fire events. To the authors' knowledge, no models exist that predict effects of prescribed fire on stand-level value as affected by a variety of burn histories and site factors—a significant knowledge gap since this is the level at which most management actions are focused.

Therefore, our objective was to predict both volume loss and "value loss" to standing timber from prescribed fire in mature, sawlog-sized hardwood stands across the CHR. In this study, we defined "value loss" as a potential reduction in estimated stumpage value from changes in timber volume and/or grade because of wounds caused by prescribed fire. To accomplish this, we examined stand-level merchantable timber volume and estimated value loss in 139 stands that varied by: (i) fire history (number of prescribed fires), (ii) aspect, (iii) species composition, and (iv) location within the CHR. We hypothesized that stands would experience increasing volume and value loss with increasing numbers of prescribed fires received, from both increased chance of wounding over multiple events (Stanis et al. 2019) and increased decay forming after multiple applications of fire (Stambaugh et al. 2017). We also expected that stands lying on xeric, south- to west-facing aspects would be associated with a larger volume and value loss than stands lying on mesic, north- to east-facing aspects, since the former aspects generally experience more intense fire (Pyne et al. 1996, Lecina-Diaz et al. 2014, Estes et al. 2017). Following the work of Wiedenbeck and Schuler (2014), we hypothesized that volume and value loss would vary by species group, with white oak (*Q. alba*) experiencing less loss than other species. Finally, we hypothesized that volume and value loss would vary by location within the CHR, with the highest rates of loss occurring in the drier, western portion of the CHR.

Methods

Study Sites

Stands were inventoried within four national forests, representing a significant portion of the range of moisture and edaphic conditions that occur within 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).

The MTNF is located within the Ozark Highlands section of the southern half of Missouri and is characterized by rugged hills and karst topography. The overstory of most MTNF forests is primarily composed of black oak (*Q. velutina*), scarlet oak (*Q. coccinea*), post oak (*Q. stellata*), white oak, hickory species (*Carya* spp.), and shortleaf pine (*Pinus echinata*) (Kinkead 2013). Competitors to oaks in the regeneration layer tend to be weak and transient; therefore prescribed fire is often not required to achieve successful oak regeneration (Larsen et al. 2011). Prescribed fire is still used, however, to shift oak community composition toward more fire-tolerant white oaks (Knapp et al. 2017), promote regeneration of shortleaf pine, and maintain or establish more open, woodland communities (Kinkead 2013, Dey et al. 2017). These latter purposes tend to require higher burn frequencies, higher burn intensities, and different seasonality than is practiced in more eastern forests solely for oak-regeneration purposes.

The HNF lies in the unglaciated region of southern Indiana and is characterized by steep slopes and a predominance of sandstone geology, with some areas of karst topography (Homoya et al. 1985). Overstory species composition varies greatly based on slope position and edaphic factors. Upper slope positions tend to be dominated by black oak, white oak, scarlet oak, pignut hickory (*C. glabra*), and shagbark hickory (*C. ovata*), whereas lower slope positions tend to be dominated by beech (*Fagus grandifolia*), tulip poplar (*Liriodendron tulipifera*), northern red oak (*Q. rubra*), and sugar maple (*Acer saccharum*) (Homoya et al. 1985).

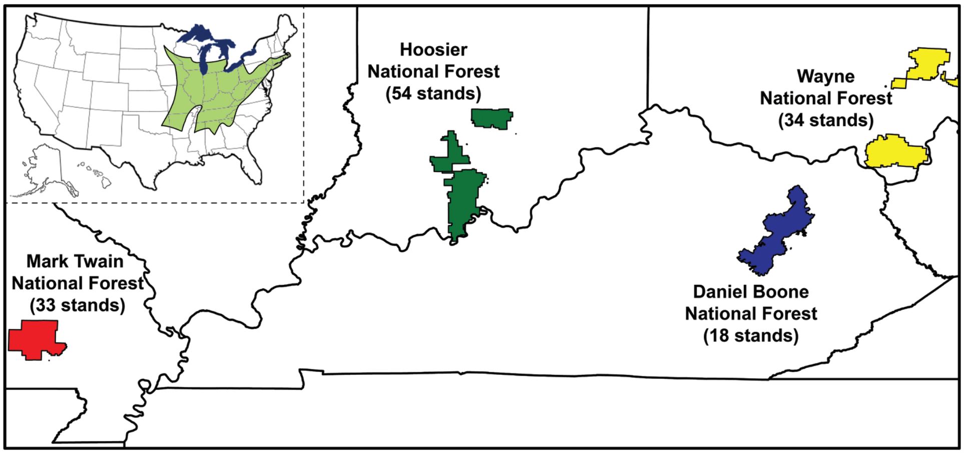

Figure 1. National forests in this study: the Mark Twain National Forest in Missouri (red), the Hoosier National Forest in Indiana (dark green), the Daniel Boone National Forest in Kentucky (blue), and the Wayne National Forest in Ohio (yellow). The light green area within the inset map shows the region of the United States that lies within the Central Hardwood Region as defined by Fralish and Franklin (2002).

Management of the HNF focuses heavily on promoting oak and hickory regeneration; prescribed fire is increasingly being used for this purpose, although fire is also used to reduce fuel loads and maintain barren habitat in some areas (Marion Mason, HNF, Bedford Office, phone: 812-275-5987).

The WNF lies within the southern Allegheny Plateau region of southern Ohio (McNab et al. 2007). This highly dissected, unglaciated region consists of a mixture of xeric uplands and mesic lowland sites underlain primarily by sandstone and shale (Hutchinson et al. 2005). The species composition of the overstory is similar to that of the HNF (Iverson et al. 2017), although the regeneration layer tends to be largely dominated by red maple (*A. rubrum*), sassafras (*Sassafras albidum*), and ash species (*Fraxinus* spp.), except on very xeric sites (Hutchinson et al. 2005). Within the WNF, prescribed fire is primarily used to promote oak regeneration.

The DBNF is located within the Appalachian foothills of eastern Kentucky, split between the Allegheny and Cumberland Plateaus. Stands for this study were isolated to the Cumberland Ranger District near the town of Morehead, KY. This district is characterized by rugged, highly dissected terrain, with slopes sometimes exceeding 50 percent, and with deep, well-drained silt loam soils (Keyser et al. 2017). Overstories are dominated by oaks, hickories, and tulip poplar; midstories and regeneration layers are dominated by nonoak species such as red and sugar maple, blackgum (*Nyssa sylvatica*), and serviceberry (*Amelanchier arborea*) (Keyser et al. 2017). Prescribed fire has been used primarily for research on oak regeneration in the district (Green et al. 2010, Arthur et al. 2015, Arthur et al. 2017, Keyser et al. 2017), although it has also been used in some stands to reduce the risk of wildfire and improve forest health.

Stand Selection

Stands were the sampling unit for this study and defined as a contiguous area of forest with relatively homogenous species composition, age structure, and topographic aspect, ranging from 10 to 50 ac. A total of 139 stands were sampled, stratified both by aspect and by the number of prescribed burns that had occurred in the stand over the past 25 years. Aspect classes were either "south-facing" for predominant aspects from 135 to 314° azimuth or "north-facing" from 0 to 135° and from 314 to 359° azimuth. These classifications were made because of the established effect of aspect on fire intensity (Pyne et al. 1996, Lecina-Diaz et al. 2014, Estes et al. 2017). Stands were further stratified by number of prescribed fires received (up to 6) and included control stands that had not received prescribed fire treatments. All fire histories were determined from management records alone; in many cases, particularly for older burns, there were no records of burn day parameters, fuel conditions, or a postburn evaluation of each stand. Nevertheless, to the recollection of local managers, all burns used hand ignition. Within each national forest, at least three stands were selected for each aspect × burn history combination, although there were some exceptions. Only the MTNF had stands that had received six burns, the Cumberland Ranger District in the DBNF did not contain any sites receiving exactly three prescribed fires, and no sites were available on the WNF that received more than three prescribed fires. Burn return intervals on multiple burn sites varied from 1 to 20 years, with a vast majority having return intervals of 2–9 years.

Selected stands had to be of sawtimber size (mean dbh > 10 in.) and comprised largely oak and hickory (i.e., >50 percent of basal area) since these stand structures were typically chosen by the national forest managers for prescribed fire treatments. In some cases, selected stands were part of larger burn units being managed to meet multiple restoration, regeneration, and habitat creation goals of the national forest. To reduce confounding with woodland or barren restoration efforts, which commonly require higher fire intensities, selected stands had upland oak site indices$_{50}$ of >60 ft (Carmean et al. 1989) since these stands are most often managed for timber production (because of better growth and high productive potential). Areas with known wildfire history were avoided; however, large-scale wildfires have been relatively frequent and widespread on the MTNF, so we avoided sites with known wildfire within the last 20 years.

Field Measurements

Each stand was sampled using 15 randomly placed, 20 BAF prism points. At each point, slope percent and aspect in degrees were recorded. For each "in" tree larger than 10 in., species, dbh, merchantable height to 8 in. diameter inside bark, and the presence or absence of fire-related damage were recorded. Trees were graded into United States Forest Service (USFS) hardwood tree grades (Hanks 1976) using the protocol developed by Loomis (1974). Grade was first determined using the second worst face of the best 12 ft section in the bottom 16 ft butt log (Miller and Wiant 1986), i.e., this grade considered all wounds including those related to fire. The tree was then regraded, ignoring wounds determined to be caused by fire.

All wounds between stump-height (6 in.) and 12 feet high on the bole of each tree (uphill side) were categorized and measured for dimensions. Wounds were assumed to be fire-caused if there was any visible disruption of the bark and/or cambium that appeared directly related to the effects of fire; often multiple lines of evidence (e.g., other wounds, areas of char, sloughed bark, etc.), from either the same or surrounding trees, were used to help with the determination. The wound had to cause an obvious impact on the tree. For example, the mere presence of char or blackened bark by itself was not sufficient for classification as a wound for the purposes of this study. Following Marschall et al. (2014) and Stanis et al. (2019), wounds were classified into one of five categories: catface, oval, seam, multiple seams, and bark slough. Catfaces were defined as open, roughly triangular wounds near the base of the tree with a measurable depth and visible wound ribs, or strips of tissue generated to grow over the area damaged by fire (Smith and Sutherland 1999). Ovals also were open wounds with visible wound ribs, but generally elliptical, and found above the base of the tree. Seams were defined as cracks in the bark and/or cambium with noticeable wound ribs, whereas bark slough was defined as disrupted bark with chipped, peeling, and/or missing pieces associated with fire damage. The dimensions of all wounds, i.e., length, width, and depth, were measured to the nearest 0.04 in. The height of the top of each wound and the bottom of each wound relative to the uphill side of the tree were recorded. Wound length was then defined as the linear distance from these two height measurements. The width of each wound was measured at the widest point of the wound, and in cases where a measurable depth existed (e.g., catfaces and ovals), the wound was measured at the deepest point. Wounds without measurable depths (e.g., closed seams, bark slough) were assigned a depth of 0.5 in. (Stanis et al. 2019). Wounds and sections of wounds below stump-height were ignored for dimensional measurements but noted when present.

Data Summary

Value loss associated with prescribed fire for any given tree could arise from two sources: (1) a reduction in quality and/or (2) a reduction in volume. Reduction in tree quality was estimated as the change in USFS tree grade using the two field measures of tree grade, one grade that assumed no fire damage, hereafter gross USFS tree grade (tgr_g), and the second grade that accounted for all fire damage, hereafter net USFS tree grade (tgr_n). Volume loss was estimated by first calculating gross individual tree sawtimber volume, in International ¼" log scale (Wiant 1986), using dbh and converting each tree's merchantable height to the nearest half log, based on 16 ft logs. This gross tree volume, $tvol_g$, ignored volume loss associated with prescribed fire. We then calculated net tree volume ($tvol_n$) that accounted for fire-related damage by subtracting volume losses associated with specific fire-related wounds from $tvol_g$. These deductions were based on the measured dimensions and geometric characteristics of each specific wound type. Fire-related cull sections of the bole resulted in further volume deductions (generally as reductions in log-length). We repeated these volume calculations for just the butt log (i.e., bottom 16-ft log) as well, $tvol_{g,16}$ and $tvol_{n,16}$, respectively.

The value loss of a tree was calculated only for the butt log, since USFS tree grade is based only on that section of the merchantable stem. To estimate value loss, two individual tree values were generated: (1) gross tree sawtimber value ($tval_g$) using both tgr_g and $tvol_{g,16}$; and (2) net tree sawtimber value ($tval_n$) using both tgr_n and $tvol_{n,16}$. By extension, the value loss for a given tree then was the difference between $tval_g$ and $tval_n$ expressed on an absolute ($tval_g - tval_n$) or relative basis ($[tval_g - tval_n] / tval_g$). Average stumpage price estimates for each USFS tree grade were derived from 2014–18 price reports for delivered logs from across the region (Table 1; see Appendix A for details).

Table 1. Estimated regional stumpage values (US$ mbf^{-1}, International ¼" scale) for each species group by US Forest Service tree grade.

	USFS tree grade		
Species group	1	2	3
White oaks	269	132	36
Other white oaks	269	132	36
Red oaks	191	96	27
Hickories	102	50	7
Tulip poplar	86	27	-6
Sugar maple	218	89	21
All other species	12	12	12

Note: Reported prices for chestnut oak and other white oak species delivered logs did not differ from white oak for material below prime log grade, which exceeds USFS tree grade 1 standards. Values were derived from 2014–18 reported delivered log prices in Indiana, Ohio, Kentucky, and Tennessee, and assumed US$250 mbf^{-1} logging and hauling costs (see Appendix for details on calculation).

Tree-level volume and value data were aggregated to the stand level for most analyses and further partitioned among species groups for some analyses. Species groups were based on prevailing timber markets in the Central Hardwood Region and included: (a) white oaks (white and chinkapin oak [*Q. muehlenbergii*]); (b) other white oaks (chestnut and post oak); (c) red oaks (northern red, scarlet, black, and southern red oak [*Q. falcata*]); (d) hickories; (e) sugar maple; and (f) tulip poplar. All other species that either did not have viable markets across the region or were sparsely represented in our data set ($n < 50$) were ignored. Several stand-level summary variables were calculated (both by species group and for all merchantable species) including gross ($svol_g$) and net ($svol_n$) merchantable sawtimber volume, gross ($svol_{g,16}$) and net ($svol_{n,16}$) merchantable saw-timber volume in the butt log, and gross ($sval_g$) and net ($sval_n$) stand sawtimber value. Absolute losses were calculated as the difference between gross and net measurements for the different variables (e.g., $aval = sval_g - sval_n$). Since sawtimber stocking differed between sites, relative losses were calculated for sawtimber volume (rvol), sawtimber volume in the butt log ($rvol_{16}$) and sawtimber value (rval) and expressed on a percentage scale (e.g., $100 \times [sval_g - sval_n] / sval_g$).

Statistical Analysis

We used mixed-effect, multiple linear regression to test for relations between number of prescribed fires, aspect, and location (i.e., national forest) on rvol, $rvol_{16}$, and rval. The number of prescribed fires and aspect class (i.e., north-facing versus south-facing) were included as fixed effects in all models, and location was included as a random effect. Models were fit using restricted maximum likelihood methods using an unstructured covariance structure. Nonlinearity in each model was first assessed by inspection of Pearson residual plots and then tested by inclusion of polynomial terms in models; none were significant. Heteroscedasticity was assessed using the Breusch–Pagan test (Breusch and Pagan 1979) and normality with the Shapiro–Wilks test. Akaike information criterion (AIC) and conditional R^2 were used to assess model fit, with the best-fit model deemed to have the minimum AIC and maximized conditional R^2.

We used Tukey honestly significant difference multiple comparison tests to evaluate the average effect of prescribed fire on different species groups for rvol, $rvol_{16}$, and rval. All hypothesis tests in this study were conducted with R 3.5.3 (R Core Team 2019), with mixed-effect regression conducted with the lme4 package (Bates et al. 2015). Statistical tests were deemed significant at $\alpha = 0.05$.

Results

Sample Profile

In total, 8,093 trees were measured in 139 stands in the study. We measured 33 stands and 1,721 trees in the MTNF, 54 stands and 3,657 trees in the HNF, 34 stands and 1,832 trees in the WNF, and 18 stands and 883 trees in the DBNF. Approximately 92 percent ($n = 7{,}470$) of the trees sampled were of merchantable species groups (white oak, other white oak, red oak, hickory, sugar maple, and tulip poplar). Oaks comprised 76 percent of the sample ($n = 6{,}151$), and white oak was the most common species (44 percent; $n = 3{,}591$). Although fire-related wounding was observed on 31 percent of the inventoried trees on sites receiving prescribed fire ($n = 2{,}008$), a reduction in USFS tree grade from fire damage was observed in only 6.6 percent ($n = 429$) of trees sampled on those sites.

Volume Loss

Absolute losses for total volume (avol) ranged from 0 to 2,269 board feet per acre (bdft ac^{-1}) and for butt-log volume ($avol_{16}$) from 0 to 1,684 bdft ac^{-1} (Table 2). Absolute losses typically were higher on south-facing slopes, particularly as the number of burns increased. For example, in stands with four or more prescribed burns, avol averaged 869 bdft ac^{-1} in south-facing stands compared to 452 bdft ac^{-1} in north-facing stands. Absolute losses were quite variable; even among stands with four or more prescribed fire treatments, avol ranged from 14 bdft ac^{-1} to 2,063 bdft ac^{-1} (Table 2).

Relative volume losses showed similar trends. The number of burns strongly influenced both rvol ($F = 3.55$, $P < .001$) and $rvol_{16}$ ($F = 4.16$, $P < .001$), with each prescribed burn increasing loss by 0.8 percent and 1.1 percent for rvol and $rvol_{16}$, respectively (Table 3, Figure 2). Aspect also influenced volume losses, but less strongly (rvol: $F = 1.93$, $P = .056$; $rvol_{16}$: $F = 1.73$, $P = .085$). However, exclusion of aspect from models decreased model fit; for example, AIC increased from 810.4 to 815.4 and conditional R^2 decreased from 0.40 to 0.38 in the rvol model. On average, rvol and $rvol_{16}$ were 1.4 percent and 1.5 percent greater, respectively, on south-facing stands than on north-facing stands (Table 3). The influence of aspect became greater on sites with three or more fires; for example, south-facing

Table 2. Mean ± standard error (range) of observed absolute total volume loss, absolute butt-log volume loss, and absolute value loss for merchantable species across 139 hardwood stands, as affected by the number of prescribed burns received in the last 25 years.

Number of prescribed burns received	*n*	Absolute total volume loss (bdft ac^{-1})	Absolute butt-log volume loss (bdft ac^{-1})	Absolute value loss (US$ ac^{-1})
0	28	33 ± 16 (0–421)	27 ± 10 (0–238)	4.19 ± 1.52 (0–38.06)
1	34	197 ± 49 (0–1,104)	140 ± 35 (0–850)	29.06 ± 7.62 (0–171.26)
2	32	148 ± 30 (0–581)	119 ± 21 (0–460)	22.04 ± 4.11 (0–94.24)
3	22	301 ± 110 (0–2,269)	253 ± 85 (0–1,684)	64.35 ± 18.48 (0–272.95)
4+	23	633 ± 121 (14–2,063)	432 ± 74 (14–1,325)	83.79 ± 14.27 (0–250.10)
All fire	111	294 ± 41 (0–2,269)	217 ± 28 (0–1,684)	45.36 ± 5.80 (0–272.95)

Note: Sample sizes in each group (*n*) are provided. Stands with four, five, and six burns were combined into one class (4+) because of small sample sizes in each category.

Table 3. Parameter estimates and fit statistics for mixed-effect, linear models of the effect of number of prescribed fires, stand aspect (south-facing versus north-facing), and national forest on relative total volume, relative butt-log total volume, and relative value losses.

	Random effect by national forest (b_0)						Model fit	
Model	Mark Twain National Forest	Hoosier National Forest	Wayne National Forest	Daniel Boone National Forest	Number of prescribed fires (b_1)	Stand aspect (b_2)	Main effects R^2	Conditional R^2
Relative total volume (percent)	5.09	−0.94	−1.29	−1.36	0.86	1.44	.07	.40
Relative butt-log total volume (percent)	6.46	−0.85	−1.39	−0.95	1.14	1.46	.09	.43
Relative value losses (percent)	10.80	−0.95	−1.86	−1.08	1.52	1.51	.06	.42

Note: All models are significant relative to the null model ($P < .01$).

slopes with four or more burns had +3.4 percent and +3.1 percent higher rvol and $rvol_{16}$, respectively, than analogous north-facing slopes (Figure 2).

Value Loss

Given that USFS tree grade rarely declined with prescribed fire (i.e., only 5.7 ± 0.9 percent [mean ± standard error] of trees, at the stand level, had grade reductions), rval was highly correlated to $rvol_{16}$ ($r = .94$, $P < .001$) and $avol_{16}$ ($r = .91$, $P < .001$). Averaged across all stands receiving fire, absolute value loss (aval) was US\$45.36 ac^{-1}, but there was nearly a threefold increase in aval from single-burn sites to those receiving four or more burns (Table 2). Stands on south-facing aspects that received fire also had a slightly higher aval, US\$46.31 ac^{-1} on average, than north-facing aspects (US\$44.37 ac^{-1}). Absolute value loss was, like $avol_{16}$, quite variable, ranging from US\$0 to US\$272.95 ac^{-1} across the burned stands in our study.

Relative value loss also increased linearly with the number of prescribed fires ($F = 3.48$, $P < .001$), with each burn increasing rval by 1.5 percent (Table 3). Aspect had weaker impacts on rval ($F = 1.10$, $P = .26$), but its inclusion in predictive models improved model fit and performance (i.e., AIC reduced from 974.1 to 970.4, and conditional R^2 increased from 0.41 to 0.42). Relative value differences between south-facing and north-facing slopes were absent for sites with up to three burns; for sites with four or more burns, south-facing slopes had approximately 2 percent higher rval than north-facing slopes (Figure 2). Notably, only south-facing slopes receiving four or more burns are the only sites predicted to have >10 percent rval.

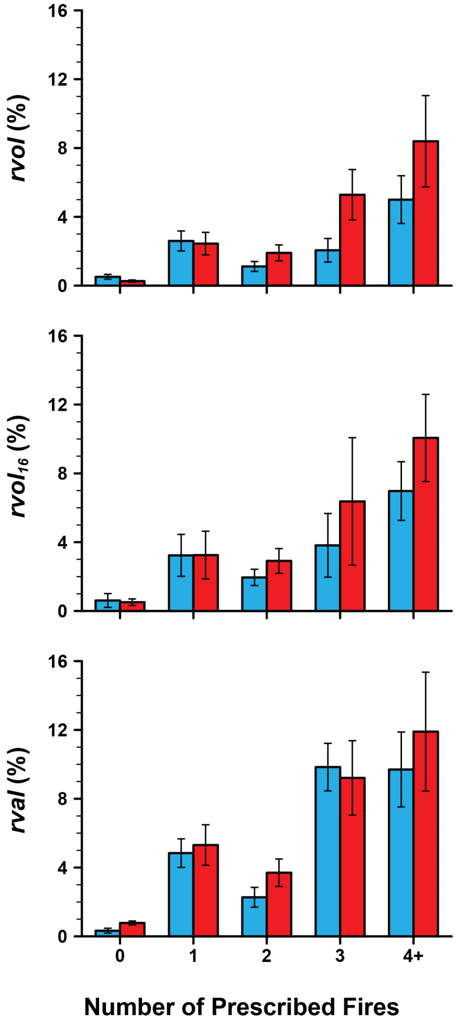

Figure 2. Mean (±standard error) relative total volume (rvol, top), relative butt-log volume (rvol$_{16}$, middle), and relative value (rval, bottom) losses as affected by the number of prescribed fires received in the past 25 years (0, 1, 2, 3, 4+) and predominant aspect (blue = north-facing; red = south-facing) for 139 hardwood-dominated stands across four national forests in the Central Hardwood Region.

Species Effects

Volume and value loss were not uniform across all species groups. Stand-level volume loss was highest for the red oak group, with rvol and rvol$_{16}$ of 5.0 percent and 13.4 percent, respectively, in stands receiving at least one prescribed fire treatment. Volume loss was also high for sugar maple, with rvol and rvol$_{16}$ of 4.7 percent and 9.6 percent, respectively. White oak exhibited a significantly lower volume loss than red oak, with an rvol of 1.6 percent and rvol$_{16}$ of 2.1 percent in stands receiving prescribed fire. Species differences became more pronounced as the number of prescribed fires increased. In stands with four or more prescribed fires, white oak, for example, had the lowest rvol and rvol$_{16}$ of any species group at 2.6 percent and 3.6 percent, respectively (Figure 3).

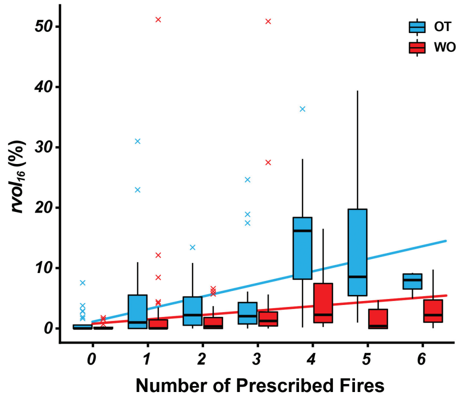

Figure 3. Relative butt-log volume loss (rvol$_{16}$) with increasing numbers of prescribed fires over the past 25 years for the white oak species group (WO; red) and all other merchantable species combined (OT; blue). Box plots were derived from estimates of rvol$_{16}$ for each stand (n = 139), partitioned into white oaks and other merchantable species (i.e., two values per stand, one white oak and one for all other). Linear trendlines are shown for each subset of data.

Value losses were low for most species groups (Table 4). White oaks and tulip poplar had notably small rvals, 4.5 ± 1.0 percent and 4.4 ± 2.0 percent, respectively. Red oaks had the highest rval by a wide margin, exceeding 13 percent. That species group, however, generally had a higher background incidence of damage, as indicated by a high rval, 0.5 ± 0.2 percent, in the control stands, nearly double that of white oak. Sugar maple also had a notably high rval, 9.6 ± 2.6 percent (Table 4).

Regional Differences

Location within the CHR had a highly significant effect on both the volume and value loss caused by prescribed fire; inclusion of random effects for location significantly improved R^2 and lowered AIC for all models (all tests: $P < .001$; Table 3). Average rval ranged from less than 1.0 ± 0.2 percent in the WNF to 15.5 ± 2.8 percent in the MTNF (Table 5). Notably, however, the HNF, WNF, and DBNF were not significantly different from one another, whereas the MTNF was different from all (all pairwise comparisons: $P < .001$). These differences were partially due to a much higher background rval observed in control (0-burn) stands, averaging 1.7 percent in the MTNF compared to 0.2 percent in all other forests measured. These different background rates, and the notably high rvals observed in 3-burn sites on the MTNF, resulted

Table 4. Mean ± standard error of absolute butt-log volume and relative value loss by species group as measured across all inventoried stands receiving prescribed fire (*n* = 111) in four national forests in the Central Hardwood Region.

Species group	Absolute butt-log volume (bdft ac^{-1})	Relative value loss (percent)
White oaks	2,506 ± 171	4.5 ± 1.0a
Other white oaks	860 ± 75	7.1 ± 1.4a
Red oaks	915 ± 64	13.4 ± 2.2b
Hickories	514 ± 49	6.7 ± 1.8a
Tulip poplar	329 ± 57	4.4 ± 2.0a
Sugar maple	213 ± 32	9.6 ± 2.6ab

Note: For relative value loss, means with the same letter are not significantly different from one another as tested with a Tukey honestly significant difference mean comparison test at α = 0.05.

Table 5. Mean ± standard error (range) of relative butt-log volume loss and relative value loss by national forest and for all merchantable species.

National Forest	Relative butt-log volume loss (percent)	Relative value loss (percent)
Mark Twain	10.1 ± 1.7b (0–46.5)	15.5 ± 2.8b (0–57.2)
Hoosier	2.1 ± 0.4a (0–15.2)	2.8 ± 0.5a (0–16.6)
Wayne	0.9 ± 0.2a (0–4.5)	1.0 ± 0.2a (0–4.1)
Daniel Boone	1.9 ± 0.6a (0–8.6)	2.4 ± 0.9a (0–12.2)

Note: Means with the same letter are not significantly different from one another as tested with a Tukey honestly significant difference mean comparison test at α = 0.05.

in different predictive models among the four national forests (Table 3, Figure 4). Responses for rvol$_{16}$ mirrored rval closely for all forests, except those for rvol$_{16}$ are slightly lower than those for rval (Table 5).

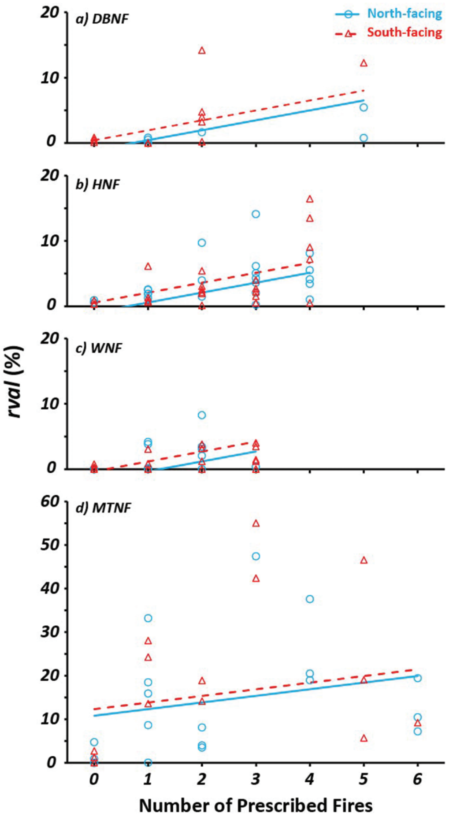

Figure 4. Models of relative value loss (rval) by number of prescribed fires in the last 25 years and predominant aspect (blue = north-facing; red = south-facing) for the Daniel Boone National Forest (a), Hoosier National Forest (b), Wayne National Forest (c), and Mark Twain National Forest (d). Linear models only differ by *y*-intercept and are specified in Table 3 for rval.

Discussion

We found that prescribed fire, as implemented across the CHR, negatively affected residual timber volume, but that effect was relatively minor. Absolute sawtimber butt log volume losses (avol$_{16}$) averaged less than 250 bdft ac^{-1} across all stands receiving fire; rvol$_{16}$ averaged less than 5 percent. Total absolute (avol) and relative (rvol) sawtimber volume losses were even less, largely because damage from prescribed fire was isolated to the butt log. Most observed fire-related volume loss was associated with cull sections, generally caused by a large catface or an oval. Cull sections were rarely associated with seams, multiple seams, bark slough, and basal wounds, a finding supported by Wiedenbeck and Schuler (2014). Only in extreme cases (n < 10) did the cull section extend beyond the butt log and cause the entire tree to become cull. In case of the cull sections, the realized loss could be far less than that which we report here, as careful bucking by a skilled logger could leave most cull in the forest and optimize grade on the remaining merchantable section of the stem (Sessions 1988). Likewise, in the case of more minor wounds, particularly those which are shallow, the realized loss could be less, as the damaged wood might be removed in the slab while forming the cant during milling into sawtimber (Marschall et al. 2014, Wiedenbeck and Schuler 2014).

Prescribed fire also did not change average stand-level USFS tree grade considerably, less than 6 percent. Trees mostly declined by one grade, although 31 percent of these trees (132 of 432) declined by two or more grades. These rates are slightly lower than those reported elsewhere; Wiedenbeck and Schuler (2014) reported 13 percent in their small study (n = 79). However, these rates of grade loss are not surprising, given that the grading face is the second worst face of the best 12 ft section of the butt log (Miller and Wiant 1986). Fire damage would have to extend above 4 ft and/or cause the grading face to shift to another face in order to cause grade loss. Since the USFS tree grade is largely determined by tree diameter, it can be insensitive to many surface defects (although it is linked closely to lumber recovery by grade; Hanks 1976). Furthermore, USFS tree grades fail to resolve the highest-quality material (prime sawlogs and veneer) from within Grade 1; this small fraction of stems in a stand can comprise a majority of the value, yet can be damaged readily by fire. Our methods did not capture changes to these highest-quality stems well.

Fire History

As hypothesized, an increasing number of prescribed fires increased sawtimber volume and value loss. This would be expected, as damage could accumulate on fire-wounded trees over successive burns and with time that allows advanced wood decay (Stambaugh et al. 2017), and by chance, different trees could be damaged with each successive burn (Stanis et al. 2019). However, the low rate of accumulation was surprising, increasing +0.9 percent per burn in terms of rvol and +1.1 percent in terms of rvol_{16} (Table 3). Furthermore, with the potential exception of the MTNF, we found no evidence of a nonlinear response; each fire seemed to have a similar average impact on stand volume and value (Figure 4). This linear relation might emerge when wounding from fire roughly equals the healing and compartmentalization that occurs in the periods between fires. For example, Stambaugh et al. (2017) estimated that larger fire scars (i.e., 4–8 in.) on white oak species in Missouri took approximately 8–17 years to heal after formation. Many of our more frequently burned sites had fire-return intervals of 4–10 years, indicating that many larger wounds were only partially healed and, potentially, leading to a gradual increase in damage as margins of old wounds expand in successive fires.

Alternatively, an acceleration in damage may be expected as trees experienced more fire. This would occur when stands are dominated with species with poor healing, such as red oaks, and repeated wounding leads to significantly more decay. Over time, that could lead to whole trees becoming cull and/or eventually succumbing to mortality (a very rare event in sawtimber-sized trees with prescribed fire used for regeneration purposes; Dey and Schweitzer 2018). We observed very few instances of whole-tree cull (n < 10).

Nevertheless, it is very difficult to disentangle the damage accumulation with increasing number of prescribed fires given the highly variable effects of prescribed fire, even between applications on the same site. Most sawtimber-sized trees, instead, had no measurable wounding associated with prescribed fire. This could be associated with the variable coverage within a prescribed fire. Furthermore, even if a tree stem receives direct flame, the fire does not always cause a visible wound (Hengst and Dawson 1994, Smith and Sutherland 1999, Stanis and Saunders 2018). Therefore, future research should track damage on the same sites and trees over multiple fires and over multiple decades, and/or use dendrochonological techniques on destructively sampled stems to deconstruct wounding response, similar to Stambaugh et al. (2017).

Aspect

Prescribed fires on drier, south-facing aspects increased volume and value losses by, on average, 1–2 percent compared to north-facing slopes (Table 3). Loss differences between aspects were most pronounced in stands that had three or more prescribed fires (Figure 2). However, impacts of aspect were highly variable and much weaker than the effects of fire history on volume and value loss, despite well-replicated observations that fire intensity is higher on south-facing slopes (Pyne et al. 1996) and that wounding occurs at a higher rate (Stevenson et al. 2008, Kinkead et al. 2017). We suspect that burn personnel help to mask aspect differences both by burning at higher humidity and/or fuel moistures and by modifying firing techniques. For example, midslope strip fires are commonly used by fire practitioners on south-facing slopes to control fire intensity (M. Saunders, pers. obs.). Over multiple burns, aspect influences on damage become more apparent, but still highly variable, as different burn crews differentially control fire intensity.

Species Differences

White oak is the most economically important species throughout much of the CHR and possesses bark and life history characteristics indicative of a species tolerant to fire (Lorimer 1985, Abrams 2003). If prescribed fire causes less damage to white oak than to other species as suggested by Wiedenbeck and Schuler (2014) and Stanis et al. (2019), this has potential to limit prescribed-fire-related damage in many areas of the CHR. We did not find white oaks significantly less prone to damage than most other species groups in this regional study; white oaks had approximately the same average likelihood of having fire-associated damage and, correspondingly, roughly the same relative volume and value losses (Table 4). Red oaks, on the other hand, had a significantly higher $rvol_{16}$ and rval than all other species groups, a pattern also seen by Stanis et al. (2019). Notably, red oaks have thinner bark at any given tree size than most white oaks (Hengst and Dawson 1994) and have higher damage rates from fire than many other fire-tolerant species groups (Nelson et al. 1933, Kinkead et al. 2017, Knapp et al. 2017).

Differences among species groups did become more pronounced as stands received more fires. For example, white oaks did not accumulate damage with increasing application of prescribed fire at the same rate as other groups (Figure 3), presumably because of thicker bark, better compartmentalization, and higher heartwood decay resistance than other species (Smith and Sutherland 1999, Dey and Schweitzer 2018). Since white oak accounted for nearly half of the trees sampled in the study (44 percent) and an even larger proportion of total value prior to fire damage (58 percent), we likely observed lower rvol, $rvol_{16}$, and rval values than would occur on sites with fewer white oaks.

Regional Differences

Prescribed fire impacts varied considerably across the Central Hardwood Region. By every metric, the MTNF experienced a much greater rate of sawtimber volume and value loss than the HNF, WNF, and DBNF, ranging from 6 to 15 times greater depending on the comparison (Table 5). Variability was also quite high in the MTNF compared to the other three forests, and nearly one-half of the MTNF stands experienced greater than 10 percent rval loss (Figure 4). Only two stands in the HNF and one stand in the DBNF exceeded that threshold.

However, the higher levels of relative value and volume loss in the MTNF are not wholly unexpected. Prescribed fire is often used as a woodland-management tool in the MTNF, so a reduction in overstory densities and restoration of shortleaf pine are often of higher priority during operations (Kabrick et al. 2007, Kinkead et al. 2017). This leads to application of more intense prescribed fire, causing increased tree mortality in some cases (Kinkead 2013); in our MTNF study stands, we observed a significantly higher rate of wounding and significantly larger average wound size (by surface area) than the other national forests (Mann 2019), both suggesting higher fire intensities. The WNF, DBNF, and HNF, on the other hand, are more representative of mesic and submesic communities where prescribed fire is used at lower intensities primarily to promote oak regeneration (Homoya et al. 1985, Hutchinson et al. 2005, Keyser et al. 2017). Lastly, there were much higher levels of background tree damage found in the MTNF than in other forests. For example, rval in unburnt, control stands in the MTNF was nearly five times greater than rval measured in control stands in other national forests (Figure 4). This may be due to a combination of edaphic factors, past harvesting practices, and incomplete wildfire records for some sites.

Besides the MTNF, we found no significant differences in relative losses among the other national forests. Site productivities, climate, and soils were quite similar among the HNF, WNF, and DBNF sites. For mesic areas of the CHR outside these national forests, predictions of expected volume and value losses from prescribed fires used to promote oak regeneration could largely ignore location effects and use regression coefficients averaged from the non-MTNF random effects (Table 3). We would caution, however, that this estimation may be inaccurate for many areas in the Appalachian Mountains and foothills, as forests of that region experience many more arson-caused wildfires that would lead to higher background incidences of fire damage (Reeves and Stringer 2011).

Conclusion

Prescribed fire is one of the most versatile tools available to forest managers in the Central Hardwood Region. Fire can prepare seed beds, reduce fuels, control understory competition, thin midstories, and release nutrients locked up in the forest floor (Brose et al. 2014, Dey and Schweitzer 2018). In advance of overstory harvest, a growing body of literature, including this study, demonstrates that prescribed fire can have minimal impact on residual timber volume and value when used to prepare sites for successful oak regeneration and recruitment (Marschall et al. 2014, Wiedenbeck and Schuler 2014, Stanis et al. 2019). Validation of modeled estimates of economic loss from prescribed fire in standing timber is still needed, likely using more expansive lumber recovery studies of harvested, prescribed fire-damaged timber.

Unlike previous studies, we evaluated prescribed fire damage on a regional scale and evaluated the effect of a known number of prescribed fire treatments in conjunction with aspect. There were clear differences in the average rate of value and volume loss that should be expected between the western portion of the CHR in Missouri and forests further east. This study also found a high amount of variability in sawtimber volume and value losses, suggesting that practitioners need to be quite careful in application of fire in stands with highly valuable sawtimber and, particularly, veneer (Stanis et al. 2019).

Supplementary Materials

Supplementary data are available at *Journal of Forestry* online.

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