EFFECTS OF PRESCRIBED FIRE ON TREE QUALITY AND VALUE IN THE CENTRAL HARDWOOD REGION

by

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A Thesis

Submitted to the Faculty of Purdue University

In Partial Fulfillment of the Requirements for the degree of

Master of Science

Department of Forestry and Natural Resources

West Lafayette, Indiana

December 2019

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ACKNOWLEDGMENTS

I have so many people to thank for helping me complete this process. My family (Allen, Laura, and Daniel) have supported me throughout the tough moments in this program and introduced me to the outdoors and a love of the natural world. I would never have been in this position if it were not for the many professors and graduate students who supported me during undergrad at the University of Missouri. I'd like to thank Ben Knapp for sparking my interest in natural resources broadly and silviculture specifically, and always challenging me to be better. I would have never pursued this program without the assistance of Carter Kinkead, who introduced me to the field of prescribed fire and forestry research. Carter not only had an excessive amount of patience with me as I learned on the job, but was a great friend, and encouraged me to take the leap and pursue this opportunity. I am also very grateful for the support of my advisor, Mike Saunders, and committee members, Dan Dey and Rick Meilan, throughout this process. I would like to thank my predecessor, Shannon Stanis, for doing the legwork to get a project of this scale off the ground, and various members of the United States Forest Service (particularly Bennie Terrell, Scottie Kizer, Josh Kocher, Jan Wiedenbeck, and Chris Thornton, but so many others) for providing critical logistical support. I would like to thank my friend and former roommate, Logan Wells, for being my first and best friend in the Department of Forestry and Natural Resources, and always being there for me to discuss problems and concerns about graduate school over a beer and a game of Wisconsin basketball. Thank you to Sarah Cuprewich for helping me complete my data collection in Daniel Boone National Forest and continuing this project with your own amazing work, and to my labmates Skye Greenler, Molly Barrett, and David Ralston for being incredibly helpful. Finally, I would like to thank my field crew members: Sera Holland, Katie Rasche, Jesse Cone, and Sam Slowikowski. I couldn't have gotten here with your help, and I appreciate you consistently going above and beyond. I know you all will be very successful in this field.

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ABSTRACT

Prescribed fire is one of the most useful tools available to forest managers attempting to maintain oak-hickory forests in the Central Hardwood Region. Prescribed fire can be useful in promoting regeneration of desirable species groups like oak (*Quercus* spp.) and hickory (*Carya* spp.) by preparing the seedbed, managing competition, and creating canopy gaps. The use of prescribed fire has been limited by concerns regarding the effect of the practice on standing timber. A perception of strong negative effects to tree-quality and tree-value from fire originated largely from sometimes deleterious effects of wildfire on timber. Less research exists demonstrating the potential effects of controlled, prescribed burning on timber quality and value. Furthermore, most research that exists focuses on individual tree characteristics, and is often focused on a relatively small geographic areas.

I conducted a regional study on the effects of prescribed fire on timber quality across a gradient of the Central Hardwood Region, ranging from the Missouri Ozarks to the Appalachian foothills. I studied 139 stands in selected prescribed fire units and control sites in Mark Twain National Forest (MO), Hoosier National Forest (IN), Wayne National Forest (OH) and Daniel Boone National Forest (KY). Selected stands were dominated by hardwoods species and had variable prescribed fire histories, ranging from 0 to 6 prescribed fires.

Measurements were taken concurrently across this plot network for two studies. First, we assessed the estimated effect of prescribed fire on stumpage value, and secondly, we assessed wounding patterns and effects of prescribed fire on tree-quality. Loss in estimated stumpage value from prescribed fire averaged approximately 4.2% across all measured stands. Estimated loss in stumpage value varied significantly by the number of prescribed fires in the last 30 years, with increasing numbers of prescribed fires leading to higher estimated losses in stumpage value. Further, stands in Mark Twain National Forest exhibited higher estimated loss in stumpage value, exceeding 10% on average. Stands in Hoosier, Wayne, and Daniel Boone National Forest only rarely exceed 5% losses in estimated stumpage value, and averaged less than 3%.

Approximately 25% of trees had at least one wound associated with prescribed fire across all study sites, while approximately 5% of trees experienced a reduction in tree quality (as measured by United States Forest Service tree grade) from prescribed fire. Both the rate of wounding and rate of tree grade reduction increased with increasing numbers of prescribed fires.

Stands in the western portion of the Central Hardwood Region (Hoosier and Mark Twain National Forest) exhibiting higher rates of wounding from fire compared to eastern sites (Wayne and Daniel Boone National Forest.)

Effects of wounding varied significantly by type of wound. Catfaces accounted for far more volume loss and reduction in tree grade than any other wound type. Alternatively, some wound types, like seams and bark slough, caused minimal tree-quality and tree-volume effects. Effects also varied by species, with higher wounding effects on sugar maple and red oak, and relatively low effects on white oak and yellow-poplar.

CHAPTER 1. INTRODUCTION

1.1 Importance of Fire in the Central Hardwood Region

Fire has been a critically important disturbance agent in the central and eastern United States for thousands of years. Forest fires have been a key driver of natural communities in the central hardwood region since the conclusion of the last ice age (Van Lear and Harlow 2002). Most historic wildfires in the region are believed to have been caused by native Americans, although natural ignition from lightning also occurred historically (Olson 1996). Prior to European settlement, fire was relatively frequent throughout most of the central and eastern United States, with return intervals ranging from 1 to 20 years throughout most of the region (Dey et al. 2015).

Fire suppression over the past century has dramatically altered forest dynamics. Fire has been excluded from many areas entirely due to effective suppression efforts, and in almost all cases fire return intervals have increased (Van Lear and Harlow 2002). Large-scale exclusion of fire from the region has led to a trend towards the gradual replacement of oak (*Quercus* spp.) and oak-hickory forests with less fire-tolerant genera, particularly *Acer* and *Fagus*. This trend has been exacerbated by the tendency of land managers to adopt uneven-aged forestry techniques that often favor more shade-tolerant, non-oak species. The transition from oak forests to forests dominated by fire-intolerant species, known as “mesophication” has a wide range of ecological consequences, ranging from changes in understory composition to effects on wildlife (Nowacki and Abrams 2008).

Fire suppression and management decisions favoring fire-intolerant species have led to widespread oak regeneration failures across much of the central hardwood region. Between 1980 and 2008, 60% of the eastern United States suffered declines in oak density, with some of the highest losses occurring among high-value white oak (Fei et al. 2011). Due to the widespread economic and ecological benefits provided by oak, mitigating or reversing the widespread trend toward fire-intolerant, mesic species has become a major focus of land-managers in the central hardwood region. Many potential solutions to these oak regeneration failures have been proposed, and the reintroduction of fire onto the landscape through prescribed burning is one method to combat mesophication.

Prescribed fire as a stand-alone treatment has shown mixed results in terms of promoting oak competitiveness (Vander Yacht et al. 2018, Barnes and Van Lear 1998). Prescribed fire in conjunction with other silvicultural techniques (e.g., the shelterwood-burn method) can often be effective for promoting oak competitiveness (Lanham et al. 2002). Implementing prescribed fire shortly before the stand initiation stage and combining prescribed fire with shelterwood silviculture can be an effective method for promoting oak competitiveness (Van Lear and Watt 1993, Brose et al. 1999). As oak tends to sprout more prolifically than many competitors following disturbance events, oak can increase competitive status following the application of prescribed fire, in conjunction with proper silvicultural techniques (Van Lear and Harlow 2002).

Prescribed fire is far from a universal solution to oak regeneration failures in the central hardwood region. Still, the practice can be a crucial tool for land managers to prevent the transition from oak forests to fire-intolerant species. Continued reluctance to utilize prescribed fire in some areas of the central hardwood region (partially due to concerns over potential economic impacts) could limit opportunities to maintain or increase oak dominance.

1.2 Importance of *Quercus* in the Central Hardwood Region

Oaks are a major component of over half of the forested land in the eastern United States (Dey et. al. 2015) and is critically important in the region. The oak-hickory complex accounts for approximately 60% of forested area in Illinois, Indiana, Iowa, Missouri, and Ohio (Schmidt and McWilliams 2003). Oak's importance is two-fold, arising from both high economic and ecological value.

Oaks are among the most economically important woody genera in the United States. Throughout much of the central hardwood region, price per board foot of white oak, and to a lesser extent, red oak (*Q. rubra*), is much higher than most other upland timber species (Smith and Mehmoud 2018, Missouri Timber Price Trends 2018). As of the Spring 2018 Ohio Timber Price Report, the mean price per board foot for #1 Common white oak lumber in Ohio was 37% greater than hard maple lumber of the same grade, and 88% and 94% greater than soft maple and yellow-poplar (*Liriodendron tulipifera*), respectively (Smith and Mehmoud 2018). Sugar maple (*Acer saccharum*), red maple (*A. rubrum*), and yellow-poplar are among the primary species replacing oak throughout much of the central hardwood region, so the economic importance of maintaining oak abundance in the region is clear.

Oak is equally important ecologically in the central hardwood region and beyond. Nixon (1997) classified oaks as "the most important woody genus in the northern hemisphere." Forest Inventory and Analysis data shows that oaks account for more biomass in North America than any other genus (Cavender-Bares 2016). Oak is foundational to many ecosystems in eastern North America, due largely to the reliance of many wildlife species on its mast production (Ellison et al. 2005, McShea et al. 2007). The consequences of continued reduction in oak dominance in the region are significant enough to be described as "an impending crisis" (McShea et al. 2007).

Oak forests (and the associated mast production) are important to wildlife communities ranging from birds to mammals and amphibians. Rodewald and Abrams (2002) found avian species richness to be significantly greater in oak-dominated forests compared to those dominated by maples. Rubbo and Kiesecker (2004) found that amphibian survival is greater in oak-dominated forests compared to maple-dominated forests due to more favorable leaf-litter characteristics. In addition, oaks are critically important to game species such as whitetail deer. During times of high mast production, acorns can comprise as much as 76% of the stomach contents of whitetail deer (*Odocoileus virginianus*) (Harlow et al. 1975). The continuation of the prevailing successional trend from oak-hickory forests to forests dominated by maple, beech, and yellow poplar is likely to have significant consequences for ecosystems and wildlife communities.

1.3 History of Research on Effects of Prescribed Fire on Timber Quality

There is a relatively short history of substantive research on the effects of prescribed fire on the value of timber and wood products. Loomis (1974) developed a model which attempted to predict quality and volume loss to oak and hickory from fire, based on the dimensions of fire-related wounds and other characteristics. The study found that wound height and time between fire and harvest are important determiners of quality and volume loss (Loomis 1974). Loomis' study, however, does not distinguish between effects of wildfire and prescribed fire, and does not discriminate between oak species groups. Guyette (2008) evaluated the effect of prescribed fire on grade changes in tree and log grade of oaks, finding that prescribed fire had relatively few effects on these metrics. This was particularly true in forests with low overall tree quality (Guyette et al. 2008). None of the sites utilized in this study had a prescribed fire history of greater than six years.

Therefore, this project builds on these and several other foundational studies evaluating the effects of prescribed fire on timber quality. Marschall et al. (2014) found that measurable external fire damage can be positively correlated with value loss to lumber from measured red oaks. Marschall's work in the Missouri Ozarks indicated that value loss to wood products from prescribed fire is relatively low, but only for wounds less than 50 cm in height, and for trees harvested 14 years or less after prescribed fire treatment (Marschall et al. 2014). Marshall's study also found that value loss to oak logs was positively related to time since the first prescribed fire occurred on the site, with a maximum time since the first prescribed fire of 14 years.

Wiedenbeck et al. (2014) evaluated the effects of prescribed fire on hardwood timber of several merchantable species. While most white oak and red oak removed in the study showed visual evidence of fire damage, only a small percentage (3 of 37 sampled) possessed defects that resulted in reduction of tree grade or volume loss (Wiedenbeck et al. 2014). This supports the conclusion of previous studies that external fire damage is not always associated with value or scaling losses to wood products. Knapp et al. (2017) evaluated the value effects of prescribed fire in sites with long prescribed fire histories in the Ozark region (>60 years), and it was found that the value effects were relatively low. Stanis et al. (2019) evaluated the effects of prescribed fire on tree quality and standing timber volume and found low to moderate effects on most sites.

No previous research has evaluated the effect of prescribed fire on timber quality and wood products at a region-wide scale. This study will add to existing research by evaluating the effects of prescribed fire on timber quality across the central hardwood region, ranging from its western extreme in the Missouri Ozarks east to the Appalachian Foothills in southern Ohio and eastern Kentucky. This allows evaluation of prescribed fire impacts on timber value to be assessed on a region-wide scale, while accounting for ecological and site differences across the central hardwood region.

1.4 Thesis Objectives

The primary objective of this thesis is to provide a greater understanding of the effects of prescribed fire on timber value and volume across the central hardwood region. While some previous research evaluated the economic impacts of prescribed fire, these effects never been evaluated on a region-wide scale. Prescribed fire is can be avoided as a management practice due to concerns about effects on timber value. More precise knowledge of the economic impacts of prescribed fire on standing timber will allow managers to make more informed, data-based decisions regarding the use of the practice. This study seeks to add to the existing body of research by:

1. Establishing a region-wide plot network with a wide range of fire histories, site conditions, and forest characteristics;
2. Evaluating the effects of fire history and site characteristics potential economic effects of prescribed fire from damage to overstory trees;
3. Evaluating the effects of fire history and site characteristics on wounding and quality reduction of standing trees;
4. Evaluating whether location within the central hardwood region affects wounding, damage, and quality reduction of standing trees; and
5. Evaluating the effect of species group on wounding, damage, and tree-quality effects of prescribed fire.

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CHAPTER 2. EVALUATING ECONOMIC IMPACTS OF PRESCRIBED FIRE IN THE CENTRAL HARDWOOD REGION

2.1 Abstract

This study evaluates the potential economic effects of prescribed fire on timber value in the central hardwood region. Control stands without a prescribed fire history and stands with a history of one to six prescribed fires (n =139) were inventoried in Hoosier, Mark Twain, Wayne, and Daniel Boone National Forests. Stands were chosen so approximately one-half occurred on north-facing and one-half on south-facing aspects in each national forest. All trees of merchantable size (i.e., > 25.4 cm DBH) were evaluated for prescribed fire-related damage. Pooled across all stands, 26.7% of trees experienced at least some damage associated with prescribed fire, but potential value loss only averaged about 4.2% at the stand level. Value loss varied significantly by the number of prescribed burns at a stand, with loss occurring at a much higher rate in stands receiving four or more prescribed fires. Value loss rates associated with prescribed fire were quite variable across the region, ranging from nearly 12% in the Mark Twain National Forest to less than 1% in the Wayne National Forest. Predictive equations were created to model percent value loss and percent volume loss at the stand level by number of burns, stand aspect, and national forest. In models, percent value loss was positively affected by increasing burn numbers and south-facing stand aspects. Species group also had important effects on value loss, with fire-adapted white oaks experiencing lower rates of wounding and value loss associated with prescribed fire compared to other species groups.

2.2 Introduction

Prescribed fire is widely recognized as an important tool for promoting oak (*Quercus* spp.) regeneration (Brose et al. 2013), reducing competition from fire-intolerant species, and maintaining certain desired forest structures and habitat types (Dey and Schweitzer 2018). Historically, the practice has been limited due, in part, to concerns regarding the effects of the practice on tree quality and value (Brose et al. 2014, Knapp et al. 2017). Early research on the effects of fire on timber quality largely focused on sites that experienced wildfire events; 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, due to differences in fire intensity and duration. On average, prescribed fire tends to be less intense and severe than wildfire (Hunter et al. 2010; Malone et. al. 2011), partially due to the tendency to conduct prescribed fires in conditions in which they can be controlled (Nesmith et al. 2011). Within the central hardwood region (CHR), Reeves and Stringer (2011) estimated value loss from multiple wildfire events in Kentucky to be as high as 38%, while Marschall et al. (2014) only reported an approximately 10% value loss to red oaks on sites in Missouri receiving prescribed fire. Stanis et al. (2019) found that relative volume loss in oak-dominated stands in southern Indiana did not exceed 8.0%.

The paucity of research on prescribed fire-caused timber damage also shows highly variable effects. For example, Marschall et al. (2014) found value loss rates to be approximately 10% in the Missouri Ozarks, while a study in West Virginia (Wiedenbeck and Schuler 2014) found that percent value loss did not exceed 1% for any species. While this can be expected given the wide range of edaphic factors, stand structural conditions, and fire parameters (e.g., number of fires, firing patterns, seasonality of burns, flame heights, etc.), there is a notable absence of research evaluating these effects across a wide range of sites and management objectives. Instead, most studies evaluate fire in a binary sense, (i.e., the stand received prescribed fire or not), and related the damage to the time since the last fire (e.g., Marshall et al. 2014). Stanis et al. (2019) is a notable exception; they reported a significant effect of the number of prescribed fires of wounding and volume loss, with sites receiving four or more prescribed fires over the past 25 years having the highest rates of damage. However, that study was limited to the Hoosier National Forest and may not allow for generalization to other areas of the CHR. To my knowledge, there is no research that evaluates the effects of prescribed fire on a region-wide scale in hardwood forests. More detailed information on rates of volume and value loss to standing timber from prescribed fire are necessary to allow managers to make informed decisions regarding the potential economic impact of the practice.

The primary objective of this study is to estimate "potential economic value loss" to standing timber from late-rotation prescribed fire in hardwood stands. In this study, I define potential economic value loss as a reduction in merchantable timber volume and grade due to wounds caused by prescribed fire; this is akin to an estimated reduction in stumpage value, and not equivalent to the realized economic value loss after harvesting and milling. Merchantable timber volume and value loss will be examined at a stand-level by evaluating the effects of: i) fire history (number of prescribed fires), ii) aspect, iii) species group, and iii) location within the CHR. I hypothesize stands with more prescribed fires and stands on south-facing slopes will be associated with higher degrees of value loss associated with prescribed fire. I also hypothesize that value loss will vary by species group, with white oak (*Q. alba*) experiencing less value loss than other species groups because of its fire-adapted traits. Finally, I hypothesize that value loss will vary across the CHR, with highest rates of value loss occurring in the more xeric, western portion of the region and generally decreasing in forests in the eastern portion of the region.

A secondary objective of this study is to create predictive models for percent volume loss and percent value loss at the stand level. This is not the first attempt to create a predictive model for volume or value loss associated with fire; Loomis (1974) modeled the effects of tree-level measurements and wounding on value and volume loss. Marschall et al. (2014) also presented a model specific to prescribed fire to predict percent value loss at the tree-level, largely based on wounding and individual tree data. No model currently exists to predict potential stand-level value effects of prescribed fire based on burn history and site factors, representing a significant knowledge gap as this is the level at which most management actions are focused.

2.3 Methods

2.3.1 Study Sites

Sites for this study were within four national forests: 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 2.1). The MTNF lies near the western extent of the region and is dominated by relatively xeric community types, while the DBNF and WNF are located in the Appalachian foothills near the eastern boundary of the region and dominated by submesic and mesic community types. Prescribed fire has been used extensively as a management tool in all four forests for at least two decades. Collectively, these forests represent a wide range of site conditions and forest management objectives representative of conditions across the entire CHR.

Mark Twain National Forest (MTNF)

The MTNF is located with the Ozark Highlands section of the southern half of Missouri. The Ozark Highland region of southeastern Missouri is characterized by rugged hills and karst topography. Historically, the Ozark Highlands consisted of a mosaic of prairie, savannah, glades, woodlands, and closed-canopy forests maintained by fire and other disturbance agents (Nelson 2012). Prior to European settlement, fire was frequent in the Missouri Ozarks, with return intervals of less than three years in many areas (Cutter and Guyette 2006). The presence of these historic land-type characteristics was largely due to the Ozark Highlands location in the transition zone between the tallgrass prairie and the more mesic forests of the eastern United States (Hanberry et al. 2014). Fire suppression led to widespread conversion of savannas and open woodlands to closed-canopy forests over the past century (Dey and Hartman 2005).

The overstory in the MTNF forests and woodlands 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. Prescribed fire and other treatments are often not required to achieve successful oak regeneration (Larsen et al. 2011). This often leads to burn prescriptions for purposes other than promoting oak regeneration, including maintenance or establishment of woodland communities (Kinkead 2013) or promoting shortleaf pine regeneration. These purposes all tend to require higher burn intensities than is needed solely for oak regeneration.

Hoosier National Forest (HNF)

The HNF is located in the unglaciated region of southern Indiana. Sites for this study are located in the Shawnee Hills Natural Region, which is primarily characterized by steep slopes and a predominance of sandstone geology, with some areas of karst topography (Homoya et al. 1985). The overstory in HNF is largely dominated by oaks, hickories, and tulip poplar (*Liriodendron tulipifera*) (Woodall et al. 2007). 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*), while lower slope positions tend to be dominated by mesic species such as American beech (*Fagus grandifolia*), tulip poplar, northern red oak (*Q. rubra*) and sugar maple (*Acer saccharum*) (Homoya et al. 1985). Because very low levels of timber harvesting have occurred in the recent past, compared to similar forestland in Indiana, the HNF consists largely of mature, large-diameter forest. (Woodall et al. 2007). Promoting oak and hickory regeneration is an important management goal in HNF, and this is a primary objective of prescribed fire in the forest, although fire can also be used to reduce fuel loads and maintain barren habitat in some areas (Hoosier National Forest-Bedford Office 2019).

Wayne National Forest (WNF)

The WNF lies in the hills of the southern half of Ohio and within the southern Allegheny Plateau region (McNab et al. 2007). This highly dissected, unglaciated region consists of a mixture of relatively xeric uplands and more mesic lowland sites underlain primarily by sandstone and shale (Hutchinson et al. 2005). Historically, fire was a major disturbance agent in southern Ohio, with a mean fire return interval of approximately 5 years in the late 19th and early 20th century (Hutchinson et al. 2008). The overstory of the WNF is largely dominated by oaks (predominately white, northern red, chestnut [*Q. montana*] and black), an assortment of hickory species, as well more mesic species, such as beech and tulip poplar (Iverson et al. 2017). The regeneration layer in most sites in the region tends to be dominated by red maple (*A. rubrum*), sassafras (*Sassafras albidum*) and ash species (*Fraxinus* spp.), while only more xeric sites tend to have significant quantities of oak regeneration (Hutchinson et al. 2005). One of the primary purposes for utilizing prescribed fire in the WNF is to promote oak competitiveness in the regeneration layer.

Daniel Boone National Forest (DBNF)

DBNF lies in the Appalachian foothills of eastern Kentucky, split between the Allegheny and Cumberland Plateau. Study sites for this project were isolated to the Cumberland Ranger District near the town of Morehead, KY. This district is characterized by rugged, highly dissected terrain, with slopes that sometimes exceed 50%. Soils tend to be relatively deep and well-drained, dominated by silt-loam texture, with high site indices for white oak (Keyser et al. 2017). The overstory of the Cumberland Ranger District of the DBNF is dominated by mixed oaks, as well as hickory and tulip-poplar. There is a strong component of red maple in the midstory and the regeneration layer tends to be dominated by non-oak species such as red and sugar maple, blackgum (*Nyssa sylvatica*) and serviceberry (*Amelanchier arborea*) (Keyser et al. 2017). Wildfire has historically been a major disturbance agent in the DBNF and the rest of the Kentucky Appalachians. Frequent, low-intensity fires remain characteristic of the area, with arson-caused wildfires still occurring relatively frequently (Maingi and Henry 2007).

Most stands selected for this project were placed within burn units originally implemented for a cooperative research project between the United States Forest Service (USFS) and the University of Kentucky (Arthur et al. 2015), but a smaller number of stands were associated with several burn units delineated by the DBNF personnel with the intended purpose of reducing risk of wildfire and improving forest health. Several stands have extensive history of harvest, resulting in relatively low overall basal area compared to other national forests included in the study.

2.3.2 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, usually ranging in size from 4 to 13 ha (10-50 ac). A total of 139 stands were sampled: 54 stands in the HNF, 33 in the MTNF, 34 in the WNF, and 18 in the DBNF. Selected stands were stratified both by primary stand aspect and by number of prescribed burns that had occurred on a site over the past 25 years. Aspect was classified as either "xeric" or "mesic"; xeric stands had a majority of sampling points facing south, southeast, southwest or west, whereas mesic stands had a majority of sampling points had aspects facing northeast, northeast, northwest, or east. These classifications were made due to the established effect of aspect on fire intensity (Estes et al. 2017, Lecina-Diaz et al. 2014, Pyne et al. 1984). Stands were further stratified by number of prescribed fires, including control stands that had not received prescribed fire treatments, and stands that received 1, 2, 3, 4, 5, or 6 prescribed fire treatments.

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 >3 prescribed fires.

Consistent with a focus on merchantable timber, only stands with an average diameter at breast height (DBH; 1.37 m) of greater than 25.4 cm (10 inches) were selected. Selected stands were dominated by hardwood species, with a strong preference given during selection toward stands with oak and hickory dominance (i.e., >50% of basal area in oak or hickory) because these stand structures were typically chosen by the national forester managers for prescribed fire treatments. Stands with upland oak site indices$_{50}$ of < 18.3 m (60 ft; Carmean et al. 1989.) were generally excluded from the study; management goals for these stands were often not timber production (due to slow growth and low productive potential), and instead open woodland restoration. Areas with extensive wildfire history were also avoided wherever possible. However, on the MTNF, large-scale wildfires have been relatively frequent, although sites with known wildfire in the last 20 years were avoided.

2.3.3 Field Measurements

Each stand was sampled using 15 randomly placed, variable-radius 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 >25.4 cm (10 inches) DBH for measurement. The following data were recorded for each "in" tree: species, DBH, merchantable height to 20.3 cm (8 inches) diameter inside bark (DIB), and presence or absence of fire-related damage. Following the protocol developed by Marschall et al. (2014), two USFS hardwood tree grades (Hanks 1976, Miller and Wiant 1986) were assigned. Initially, a tree was graded considering all wounds associated with fire. Subsequently, the tree was re-graded ignoring the presence of any fire-related damage. The difference between these two grades was assumed to be the effect of prescribed fire on tree grade for that tree.

Any wounding assumed associated with fire was also quantified. 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 (Appendix A). Catfaces were defined as open, roughly triangular wounds near the base of the tree with a measurable depth and visible wound ribs; ovals were similarly defined as open wounds with visible wound ribs, but were generally oval in shape and often present above stump-height. Seams were defined as cracks in the bark and/or cambium with noticeable wound ribs, and bark slough was defined as any chipped, peeling, or missing bark associated with fire damage.

The dimensions of all wounds (i.e. length, width, and depth) were measured to the nearest 0.1 cm. The height of the top of each wound and the bottom of each wound, relative to the uphill side of the tree, was 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. Sections of wound below stump-height (determined to be 15.2 cm above ground-level on the uphill side of the tree) were ignored for dimensional measurements as that portion of the wound did not affect butt log volumes. Similarly, dimensions of wounds entirely below stump-height were not measured at all, although the wounds were noted and categorized when present.

2.3.4 Analysis

Data Summaries

The volume of each individual tree in board feet (bf) was calculated in International ¼" log scale first by converting each tree's merchantable height to the nearest half log, based on 16-ft logs, and then utilizing the following formula (Eq. 1; Wiant, 1986):

$$\text{Volume} = (1.52968L^2 + 9.58615L - 13.35212) + (1.79620 - 0.27465L^2 - 2.59995L)D + (0.04482 - 0.00961L^2 + 0.45997L)D^2 \quad \text{[Eq. 1]}$$

where D= DBH (in inches) and L=number of 16-ft logs.

Value loss to trees associated with prescribed fire could arise from two sources: 1) a reduction in volume, and/or 2) a loss of tree quality (i.e., reductions in USFS tree grade associated with wounding). Volume loss from wounding was calculated for each individual tree, as well as the reduction in USFS tree grade, if any.

To calculate the first source of value loss, each tree in the study was assigned two separate volumes: one volume ignoring any volume loss associated with prescribed fire, and another volume accounting for fire-related wounding and damage. Volume losses associated with specific fire-related wounds were calculated based on the measured dimensions and geometric characteristics of each specific wound type. Any fire-related cull regions were also measured and may result in further volume loss. The difference between these two tree-level volumes allows calculation of both total and percent volume loss resulting from fire-related damage.

Reduction in individual tree quality is also an important source of fire-related value loss. In this study, tree quality was evaluated using the USFS tree grading system. Most fire-related wounds measured in this study would be considered "defects" for the purposes of the USFS tree grading system (Miller and Wiant 1986). In some, but not all cases, these defects were sufficient to result in a reduction of a tree's overall grade. Tree grade is intended to serve as an estimate of a tree's quality and potential lumber-yield (Hanks 1976), so this can be highly important from a tree-value standpoint.

Sawtimber values for merchantable species were calculated based on using best-fit equations developed by Hanks (1976) allowing estimation of volume in each National Hardwood Lumber Association (NHLA) lumber grade based on species, tree grade, and DBH. Board-foot estimates for each species and NHLA lumber grade were divided by 1000 and multiplied by the price per thousand board feet (MBF) calculated from an average lumber price from past timber price reports for the relevant region. To produce the average price estimates, lumber prices from timber price reports across the region for relevant species groups were averaged over a 5-year period (2014-2018) (see Appendix B).

Two tree-level sawtimber value estimates were made for each tree: one estimate ignoring tree grade and volume reductions associated with fire-related damage, and another estimate accounting for fire-related grade and volume reductions. The difference between the value estimates ignoring the effects of fire damage and the estimate accounting for fire damage, is regarded as the value loss associated with prescribed fire. Value loss estimates were only made for the first 16-ft log (hereafter referred to as the butt log) because USFS tree grade is based only on the butt log, allowing for accurate value estimates for only that section.

Tree-level data were then aggregated for the stand-level analysis. The appropriate BAF expansion factor for each tree was applied to convert individual tree volumes to per-acre volume and value estimates; the number of trees per acre represented by each measured stem is equal to the expansion constant for a 20 BAF prism (244.46) divided by squared DBH in inches. Once expanded to per-acre values, these tree-level data were aggregated to the stand-level. Estimates of volume and value loss can be applied on a per-acre basis for each stand, ultimately allowing us to calculate value loss in dollars/acre, as well as percent value loss (PVL).

Merchantable species were divided into the following groups for analysis, based on prevailing timber-market structures in the Central Hardwood Region: a) 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; f) yellow poplar; and g) other species. Species classified as "other species" either did not have viable markets across the region or were not represented in a large enough sample size in our study for robust analysis. Examples of these species include shortleaf pine, white pine, and Virginia pine (*P. echinata*, *P. strobus,* and *P. virginiana*), eastern hemlock (*Tsuga canadensis*), red maple, blackjack oak (*Q. maralandica*), beech, blackgum, American sycamore (*Platanus occidentalis*) and black cherry (*Prunus serotina*).

Statistical Approach

We used mixed-effect, multiple linear regression to test for relationships between number of prescribed fires, aspect, and location (i.e., national forest) on total sawtimber volume, butt-log volume, and percent value loss. Although these three independent variables are percentages and normally assessed using logistic or similar regression approaches, the data was approximately normally distributed. The number of prescribed fires and aspect class (i.e., north-facing vs. 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 (REML) using an unstructured covariance structure. Nonlinearity in each model was assessed first 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-Wilkes Test. Each model's Akaike information criterion (AIC) and conditional R^2 were used to assess fit, with the best-fit model deemed to have the minimum AIC and maximized conditional R^2.

We used Tukey HSD multiple comparison tests to evaluate the average effect of prescribed fire on different species groups for relative volume loss and relative value loss. All hypothesis tests in this study used 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 $\alpha = 0.05$.

2.4 Results

2.4.1 Sample Profile

Although I attempted to provide relatively equal representation across prescribed burn categories, there was a variable numbers of appropriate sites in each forest leading to an unequal distribution of stands across national forests (Table 2.1). In total, 8,093 trees were measured in 139 stands across the MTNF, HNF, WNF, and DBNF. Approximately 92% (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% of the sample (n = 6,151), and white oak was the most common species at 44% (n = 3,591).

At least one wound associated with fire was observed in 27% (n = 2,160) of trees in the sample and a reduction of USFS tree grade was observed in only 5.4% (n = 434) of trees sampled. Excluding 0-burn (control) stands, 31% of trees had at least one wound, and 7% of trees experienced a grade reduction associated with fire.

2.4.2 Effect of Burn Class and Stand Aspect

The number of prescribed burns on a site had a significant effect on percent volume loss ($p < 0.01$). Stand aspect, on the other hand, did not have a significant effect on percent volume loss independent of burn number, although the positive effect of south-facing stands on percent volume loss was narrowly insignificant ($p=0.088$). The highest stand-level volume loss occurred in stands subjected to four or more prescribed burns. (Table 2.3). Stand-level sawtimber volume loss in stands receiving four or more prescribed burn treatments was approximately triple that of stands receiving 0 to 3 prescribed burns. At the stand-level, volume loss was highly variable even excluding control sites. Percent volume loss to the butt log ranged from 0% to 46.5% in stands with 1 to 6 prescribed fire treatments. Absolute volume loss in board feet (bf) per acre was also highly variable. Volume loss to the butt-log averaged 178 bf per acre, but ranged from 0 bf per acre to 1684 bf per acre.

Value loss trends followed an almost identical pattern to volume loss trends, with the primary difference being that relative value loss was slightly higher than relative volume loss across all burn categories. Similar to volume loss, burn number had a significant linear effect on percent value loss ($p<0.001$). Stands with 4 or more prescribed fires on average had nearly three times as much relative value loss as stands receiving 0 to 3 prescribed burns (Table 2.4). Among stands receiving at least one prescribed fire treatment, value loss was highly variable, ranging from 0 to 55.8%. Potential value loss at the stand level ranged from $0 per acre to $601.84 per acre. Value loss in dollars per acre was highest in stands with four or more prescribed fires, averaging $172.35 per acre. Average value loss did not exceed $100 per acre for any other burn classification.

Aspect did not have a significant effect on percent value loss, although the positive effect of south-facing aspects on percent value loss was near the significance threshold ($p=0.058$). South-facing stands that had received four or more prescribed fire treatments were the only classification of sites included in our study with percent value loss >10% (10.9%, compared to 7.9% value loss for north-facing stands with a history of four or more prescribed fires). Volume loss was also highest in south-facing stands receiving four or more prescribed burn treatments (10.1% volume loss to the butt log.)

Percent value loss was highly correlated with volume loss. Percent value loss was particularly closely correlated with percent volume loss to the butt-log (adjusted $R^2=0.98$, $p<0.001$). Percent value loss also exhibited a strong relationship with absolute volume loss to the butt-log in BF per acre (adjusted $R^2=0.89$, $p<0.001$).

2.4.3 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 a relative sawtimber volume loss and relative butt-log volume loss of 5.0% and 6.2%, respectively in stands receiving at least one prescribed fire treatment. Volume loss was also high for sugar maple, with a relative sawtimber volume loss and relative butt-log volume loss of 4.7% and 5.5%, respectively. White oak exhibited significantly lower volume loss compared to red oak, with a relative sawtimber volume loss of 1.6% and and relative butt-log volume loss of 2.1% in stands receiving at least one prescribed fire. The effect became more pronounced as the number of prescribed fires increased (Figure 2.6). In stands with four or more prescribed fires, white oak had the lowest relative sawtimber volume loss and relative butt-log volume loss of any species group at 2.6% and 3.6%, respectively.

Relative value losses were relatively low for most species groups (Table 2.6). White oak, other white oak, and tulip-poplar had notably small relative value losses, 3.6 ± 0.8% (mean ± standard error), 3.6 ± 0.6% and 2.2 ± 1.0%, respectively. Red oak had the highest relative value loss by a wide margin, exceeding 10%. The species in that group, however, generally had much higher background incidence of damage as indicated by relatively high relative value loss, 1.2 ± 0.4%, even in control stands, double that of all other species groups. Sugar maple also had notably high relative value loss, 7.0 ± 1.8%.

2.4.4 Regional Differences

Location within the CHR has a highly significant effect on both the volume and value loss effects caused by prescribed fire ($p<0.01$). Relative value loss at the stand level ranged from an average of less than 1% in the WNF to nearly 12% in the MTNF (Table 2.4). Value loss trends are relatively uniform between HNF, WNF, and DBNF with much higher rates occurring in MTNF. This is partially due to a much higher base value loss rate with control (0-burn) stands in the MTNF averaging 1.2% percent value loss, compared to 0.2% for control stands in all other forests measured. Volume loss trends follow value loss trends closely for all forests, except volume loss rates are slightly lower than value loss rates for all forests. A general trend exists towards a reduction in relative volume loss and relative value loss rates as one moves east across the Central Hardwood Region from the Ozark Highlands toward the Appalachian foothills.

2.4.5 Modeling Volume and Value Effects of Prescribed Fire

Although stand aspect was narrowly insignificant as an individual effect for both volume ($p=0.088$) and value loss ($p=0.058$), inclusion of aspect improved model fit for both percent volume loss and percent value loss. In volume-loss models, inclusion of aspect slightly reduced AIC from 858.7 to 857.8 and increased conditional R^2 from 0.41 to 0.44. Similarly, in value loss models, inclusion of aspect slightly reduced AIC (from 908.7 to 907.2) and increased conditional R^2 from 0.41 to 0.44.

Predictive equations were created for percent volume loss to the whole tree, percent volume loss to the butt log, and percent value loss in the butt log, respectively (Table 2.7). In models for percent volume loss and percent value loss to the butt log, the coefficient for burn number signifies the increase in expected relative losses in percent with each additional prescribed fire. Percent volume loss is expected to increase by approximately 1.1% on average for each additional prescribed fire, and percent value loss is expected to increase by 1.3% with each additional prescribed fire. On average, percent volume loss to the butt-log is expected to be 1.5% greater on mesic stands compared to xeric stands, and percent value loss is expected to be 1.9% higher on south-facing stands compared to north facing stands. Location by national forest explained a large amount of variability in all models. The greatest differences observed were between MTNF and the other three national forests in the study (HNF, DBNF, and WNF). The intercept value for MTNF was much higher for all models compared to any other national forest in the study.

2.5 Discussion

2.5.1 Tree-Level Data

Most trees sampled in the study had no measurable wounding associated with prescribed fire. In some cases, this could be associated with the patchy nature of prescribed fire, but it also suggests that prescribed fire does not always cause noticeable damage to overstory trees. The majority of fire-related volume loss was associated with cull sections associated with wounds. These cull sections were generally caused by catface and (much more rarely) oval wound types, and only occasionally associated with seams, multiple seams, bark slough, and basal wounds, a finding supported by Wiedenbeck and Schuler (2014) and Stanis et al. (2019).

2.5.2 Stand-Level Data

Average sawtimber volume loss at the stand level was relatively low across the study. Stand-level volume and value loss effects both averaged approximately 4%, with less than 3% volume loss to the whole merchantable tree. These trends track closely with Marschall (2014), who found 3.9% volume loss from prescribed fire in red oaks in the Missouri Ozarks. The most common cause of fire-related volume loss was a cull area associated with a catface near the base of the tree, some of which may be removed in the felling and bucking process.

Only sawtimber-size trees were measured in this study. This, in effect, excluded a large proportion of trees in species groups generally considered to be fire-intolerant, including red maple, sugar maple, and American beech. These species were common on many sites, but tended to occur primarily in the midstory, and were often of insufficient diameter to be included in our measurements. It is possible that rates of wounding and volume loss would be higher if smaller trees were included. Further, wounding and volume-loss patterns, even among more fire-tolerant species, such as white oak, may have been different for this smaller size class.

Finally, a very high degree of correlation was found between volume loss to the buttlog and percent value loss. This indicates that while quality reduction certainly plays a role, volume loss accounts for a significant majority of value loss from prescribed fire.

2.5.3 Effect of Burn Class and Aspect

All measures associated with fire-related damage generally increased as the number of prescribed fires on a site increased. Both value loss and volume loss significantly increased between sites receiving 0-3 burns and sites receiving 4 or more burns. This finding, supported by Stanis et al. (2019), was unsurprising for several reasons. A number of sites in our study receiving 4 or more prescribed burn treatments had a management focus more oriented towards woodland management than traditional forest management. This can in some cases impact prescriptions used on these sites, and lead to more intense fires. Finally, there were no sites with 4 or more burns available in Wayne National Forest, where volume and value loss tended to be lowest of all national forests measured for all other burn classes.

2.5.4 Effect of Species Group

White oak is the most economically important species throughout much of the Central Hardwood Region, and possesses bark and life history characteristics indicative of a species tolerant to fire (Abrams 2006; Lorimer 1985) If prescribed fire causes less damage to white oak compared to other species as suggested by Stanis et al. (2019) and Wiedenbeck and Schuler (2014), this has potential to limit prescribed-fire related damage in many areas of the Central Hardwood Region. In our study, white oak had approximately the same likelihood of having at least one wound associated with fire as other species groups, but every other fire damage metric was lower for white oak compared to other merchantable species.

White oaks on average were subject to less than half the amount of volume loss in the butt log compared to other merchantable species, and this effect was especially strong in stands with four or more prescribed fire treatments (Figure 2.8). Value loss for the butt log, similarly for white oak was less than half of that for other merchantable species (Table 2.6, Figure 2.9). This is due to both lower relative volume loss and a low rate of tree grade reduction (2.2%) among white oaks. Since white oak accounted for nearly half of the trees sampled in the study (44%) and an even larger proportion of total value prior to fire damage (58%), this significantly reduced the overall rate of volume and value loss across the study.

2.5.5 Regional Effect

Prescribed fire effects appear to vary considerably across the Central Hardwood Region. Each national forest within the region has unique topographic, management, climactic conditions that could cause a difference in the effects of prescribed fire on timber. The MTNF experienced a much greater rate of relative volume loss and relative value loss compared to Hoosier, Wayne, and Daniel Boone National Forest. Relative value loss was 12 times greater in Mark Twain National Forest (the forest with the highest relative value loss) than Wayne National Forest (the forest measured with the lowest relative value loss). Volume loss closely followed this trend, as well, with losses in MTNF greatly exceeding losses in the other three national forests measured. A clear trend existed towards a decrease in both relative volume loss and relative value loss moving east from MTNF in the Missouri Ozarks to DBNF and WNF in the Appalachian Foothill region. HNF had intermediate volume and value loss levels, although levels were more comparable to those found in WNF and DBNF than the much higher levels found in MTNF.

The higher levels of relative value and volume loss in MTNF are not wholly unexpected. Prescribed fire has a much longer history in the Missouri Ozarks, in comparison to other study sites, with prescribed fire having a history of use as a management tool for at least 60 years (Knapp et al. 2017). Further, in many cases there were longer temporal gaps between prescribed fire events in the MTNF compared to other forests, which could lead to greater fuel build-up, and potentially more intense fire events. Much higher levels of base value and volume loss were found in the MTNF compared other forests. Percent value loss in control (0-burn) stands in the MTNF was nearly five times greater than percent value loss in other national forests. This may be due to wildfire history on some sites, or other causes of higher base damage rates.

The general trend towards lower levels of volume loss in forests further to the east (and especially DBNF and WNF) can partially be explained by the more mesic character of those forests, particularly in comparison to MTNF. Further, promoting oak regeneration is a primary management goal for many prescribed fires in HNF, WNF, and DBNF. These prescribed fires tend to follow prescriptions that lead to lower intensity fires, compared to woodland management-centric fires, which are much more common in MTNF.

2.5.6 Modeling Volume and Value Effects of Prescribed Fire

Value-loss and volume-loss models both indicate that a high number of prescribed fires and xeric aspects are factors that are associated with higher percent volume and value loss. Location is a major factor in the model, and the intercept of the model varies greatly between national forests. This indicates that value loss effects from prescribed fire are not uniform across the CHR. The MTNF had a much higher intercept for all models than any other national forest, leading to higher predicted volume and value loss for all burn classifications.

These models allow managers estimate percent value loss from prescribed fire at a stand level if several easily attainable pieces of information are known: the number of prescribed burns a stand has received, primary slope direction of the stand, and regional location. Research sites were placed over a west-east gradient of the CHR to allow these models to be as broadly applicable as possible. While effect of location in models are specific to each national forest, the broad range represented by MTNF, HNF, WNF, and DBNF allows some broader inferences to be made using the model within the CHR. The MTNF is largely representative of more western xeric sites within the region (Hanberry et al 2014), while WNF, DBNF, and HNF are more representative of mesic and submesic communities where prescribed fire is often used primarily to promote oak regeneration (Homoya et al. 1985, Hutchinson et al. 2005; Keyser et al. 2017). Generally, the model indicates that predictors of high rates of value loss from prescribed fire include stands with a high numbers of past prescribed fires, stands with primarily south or west facing aspects, and location within the western portion of the CHR. Predictors of lower rates of value loss from prescribed fire include stands with a lower number of past prescribed fires, stands with primarily north or east facing aspects, and location within the central or eastern portion of the central hardwood region.

While these models are significant, there is a meaningful amount of variability they do not explain. Adjusted R^2 for all models were 0.40 for percent volume loss to the whole tree and 0.43 for both percent volume and percent value loss to the butt log. There are several potential sources of variability that the limitations of a retrospective study did not allow us to estimate; for example, fire intensity and fuel-loading data were usually not available and estimated percent coverage of the site by each prescribed fire was only occasionally known. Furthermore, not all stands had uniform aspects, although variability of aspect within the stand was reduced as much as possible during stand delineation. Although the models are significant, it is important to understand that other effects, besides burn number and primary stand aspect, may be important in predicting volume and value loss effects at the stand level.

2.6 Conclusion

The results of this study, combined with previous research by Marschall (2014), Wiedenbeck and Schuler (2014), and Stanis et al. (2019) provide a greater understanding of the extent of value and volume loss associated with prescribed fire. This study evaluates prescribed fire damage on a regional scale, and, along with Stanis et al. (2019), are the first to evaluate the effect of the number of prescribed fire treatments in conjunction with aspect. A higher degree of understanding regarding the effects of the practice based on number of prescribed fires, stand aspect, and location within the region allow managers to more precisely understand the possible effects of the practice in more specific contexts. This study suggests that there are clear differences in the rate of value and volume loss that should be expected between the western portion of the Central Hardwood Region in Missouri and forests further east. It further suggests that sites receiving four or more prescribed fire treatments are far more likely to exhibit high rates of relative value loss.

This research will be supported by an ongoing lumber recovery study associated with this project. Lumber recovery studies in HNF (implemented in July 2017) as well as MTNF, WNF, and DBNF will provide a more specific understanding of the economic impact of prescribed fire on actual wood products. This will further provide an opportunity to correlate realized value loss in processed logs and lumber with wounding measured in the field.

Prescribed fire is one of the most versatile tools available to forest managers in the Central Hardwood Region. The goal of this study is to provide a clearer understanding of the economic effects of the practice. In conjunction with past research and ongoing work, this study will provide managers the opportunity to make more informed, data-based decisions regarding the economic effect of prescribed fire.

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2.8 Tables and Figures

Table 2-1 Number of stands and trees sampled within each national forest

National Forest	Stands	Trees
Mark Twain	33	1721
Hoosier	54	3657
Wayne	34	1832
Daniel Boone	18	883
Total	139	8093

Table 2-2 Mean (SE) percent relative volume loss to the whole merchantable tree and butt-log at the stand level by number of prescribed burns in the past 30 years (merchantable species only).

Burn Category	Percent Volume Loss (whole merchantable tree) (SE)	Percent Volume Loss (butt-log only) (SE)
0	0.47 (0.20)	0.56 (0.21)
1	2.53 (0.75)	3.24 (0.90)
2	1.53 (0.34)	2.46 (0.44)
3	3.96 (2.03)	5.33(2.29)
4+	6.48 (1.28)	8.31 (1.46)
Total	2.75 (0.46)	3.69 (0.54)

Table 2-3 Mean ± standard error [SE] value loss/acre in dollars, and percent relative stand-level value loss to butt logs as affected by the number of prescribed burns received (# Rx) in the last 30 years (merchantable species only). Stands with 4, 5, and 6 prescribed fires pooled due to small sample size in each

# Rx	Value Loss/Acre (SE)	Percent Relative Value Loss (SE)	# Stands
0	8.48 (2.87)	0.47 (0.17)	28
1	53.29 (12.86)	4.00 (1.18)	34
2	47.18 (8.48)	2.79 (0.52)	32
3	96.20 (29.60)	6.30 (2.76)	22
4+	172.36 (29.98)	9.19 (1.65)	23
Total	69.35 (8.88)	4.23 (0.64)	139

Table 2-4 Mean, standard error (SE) and range of relative percent value loss to the butt log at the stand level by national forest (merchantable species only).

National Forest	Percent Value Loss (SE)	Range
Mark Twain	11.92 (2.09)	0-55.82
Hoosier	2.29 (0.40)	0-15.29
Wayne	0.98 (0.22)	0-4.19
Daniel Boone	2.11 (0.74)	0-11.19
Total	4.23 (0.64)	0-55.82

Table 2-5 Mean (SE) percent relative volume loss to the butt log at the stand level by national forest (merchantable species only).

Burn Category	Percent Value Loss (SE)
Mark Twain	10.07 (1.73)
Hoosier	2.13 (0.38)
Wayne	0.92 (0.21)
Daniel Boone	1.89 (0.61)
Total	3.69 (0.54)

Table 2-6 Coefficients for models of effect of burn number, stand aspect, and location by national forest on relative percent volume and value loss. VLT=percent volume loss to the whole merchantable tree, VL16=percent volume loss to the butt log, and PVL=percent v

	Random Effect by NF (b_0)				b_1	b_2	Model Fit	
Response	MTNF	HNF	WNF	DBNF	Burn Number	Stand Aspect (S)	Main Effects R^2	Conditional R^2
VLT	5.09	-0.94	-1.29	-1.36	0.86	1.44	0.07	0.40
VL16	6.46	-0.85	-1.39	-0.95	1.14	1.46	0.09	0.43
PVL	7.79	-1.15	-1.73	-1.19	1.27	1.90	0.08	0.44

Table 2-7 Mean (SE) percent relative value loss to the butt log by species group at the stand level, and average trees per acre and pre-fire volume in board feet per acre for each species

Species Group	Percent Value Loss (SE)	TPA	Average Butt-log Volume/Acre (BF)
Sugar maple	5.74 (1.51)	4.93	364.34
Hickory	3.62 (1.00)	6.08	538.72
Tulip poplar	1.79 (0.78)	6.19	653.26
White oak	2.90 (0.65)	22.83	2600.74
Red oak	8.54 (1.44)	7.48	952.21
Other white oak	3.01 (0.50)	10.47	983.04

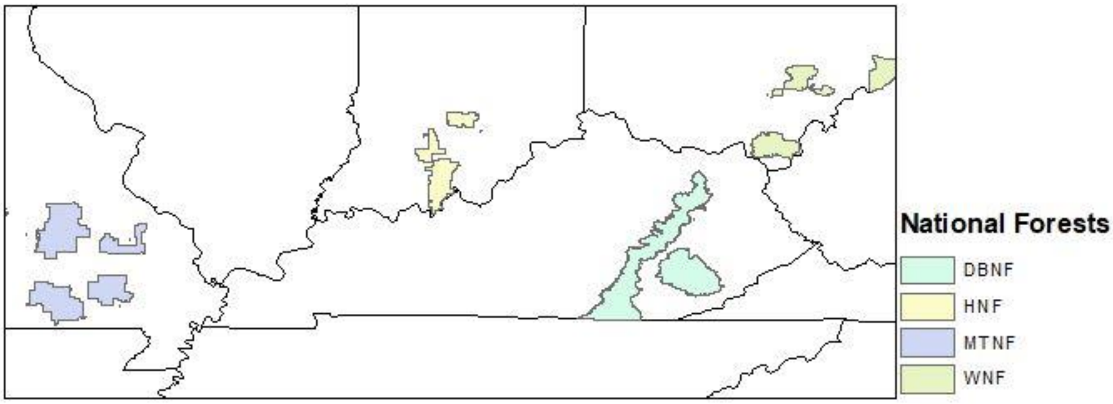

Figure 2-1 Map of the central hardwood region with all national forests included in the study (MTNF, HNF, DBNF, and WNF).

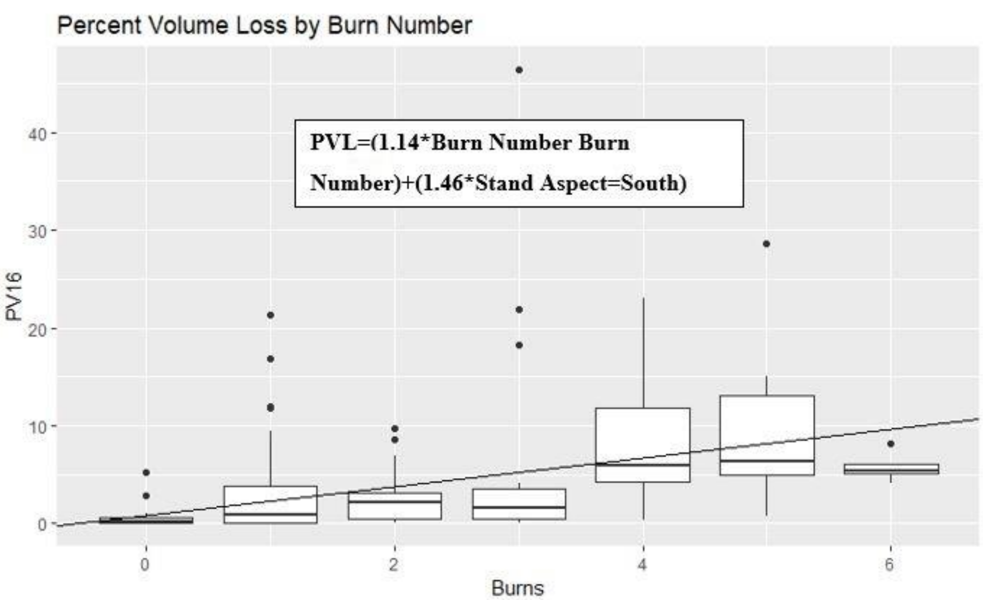

Figure 2-2Boxplot of relative percent volume loss to the butt log by number of prescribed fires in the last 30 years (t=4.16, p<0.01) with equation of predictive model for effect of number of burns and stand aspect.

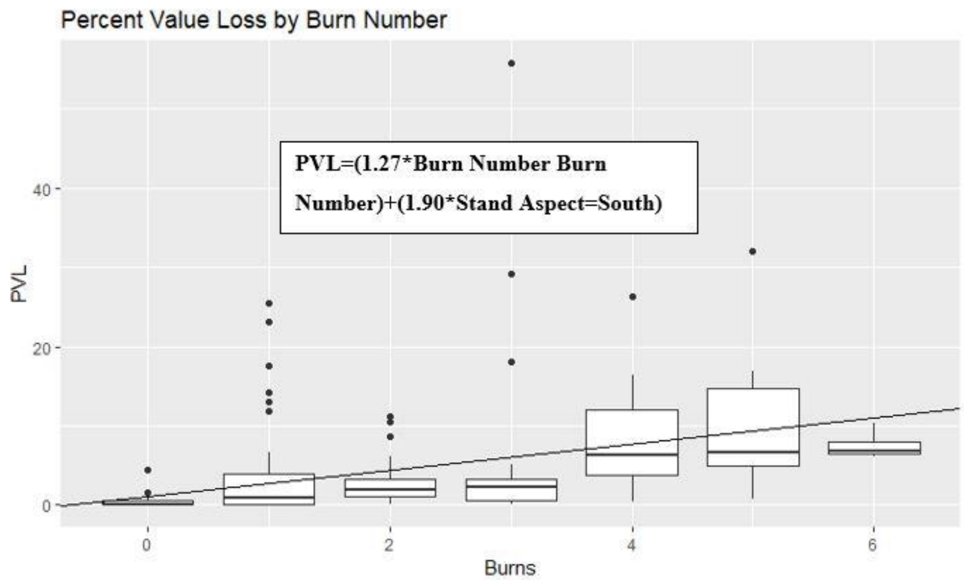

Figure 2-3 Boxplot of relative percent value loss to the butt log by number of prescribed fires in the last 30 years (t=3.87, p<0.01) with equation for predictive model for effect of aspect and burn number.

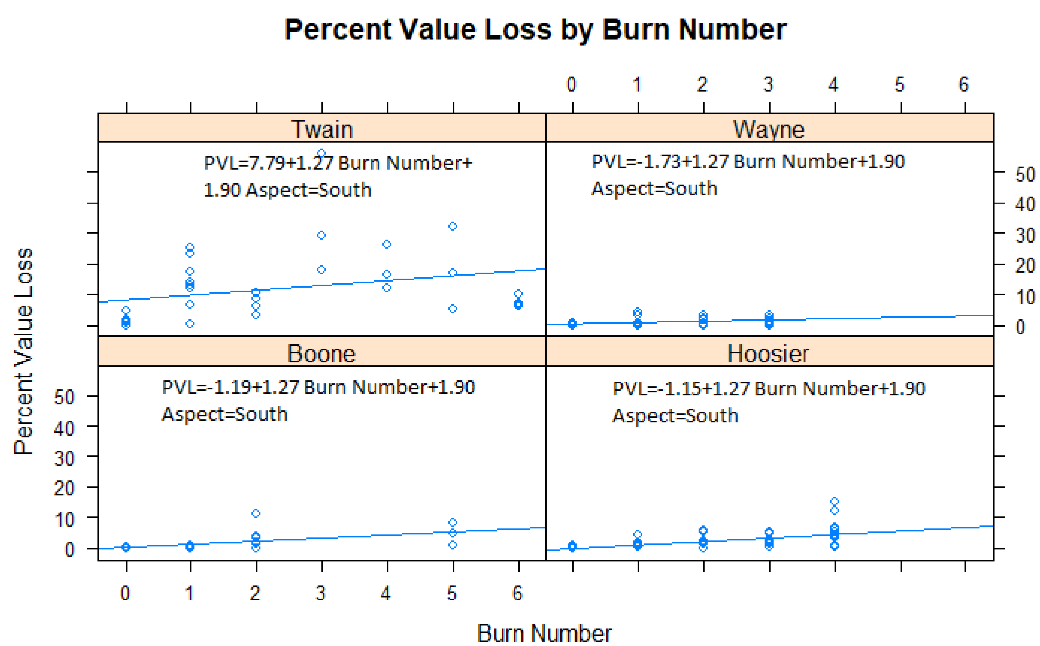

Figure 2-4 Linear regression plot of relative percent value loss to the butt log by number of prescribed fires in the last 30 years (t=3.87, p<0.01) with formula for full linear regression model for each national forest.

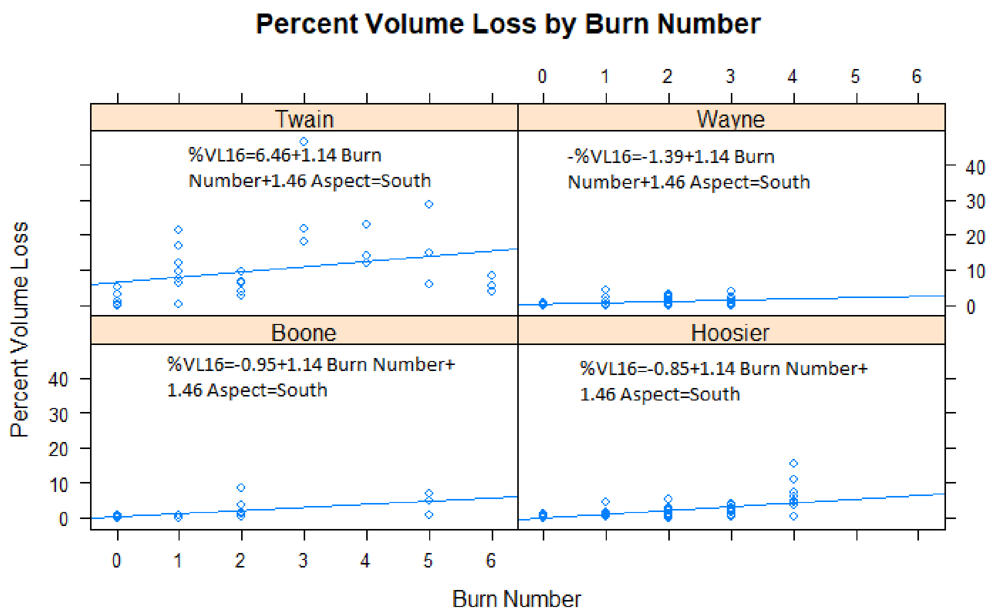

Figure 2-5 Linear regression plot of relative percent volume loss to the butt log across by number of prescribed fires in the last 30 years (t=4.16, p<0.01) with formula for full linear regression model for each national forest.

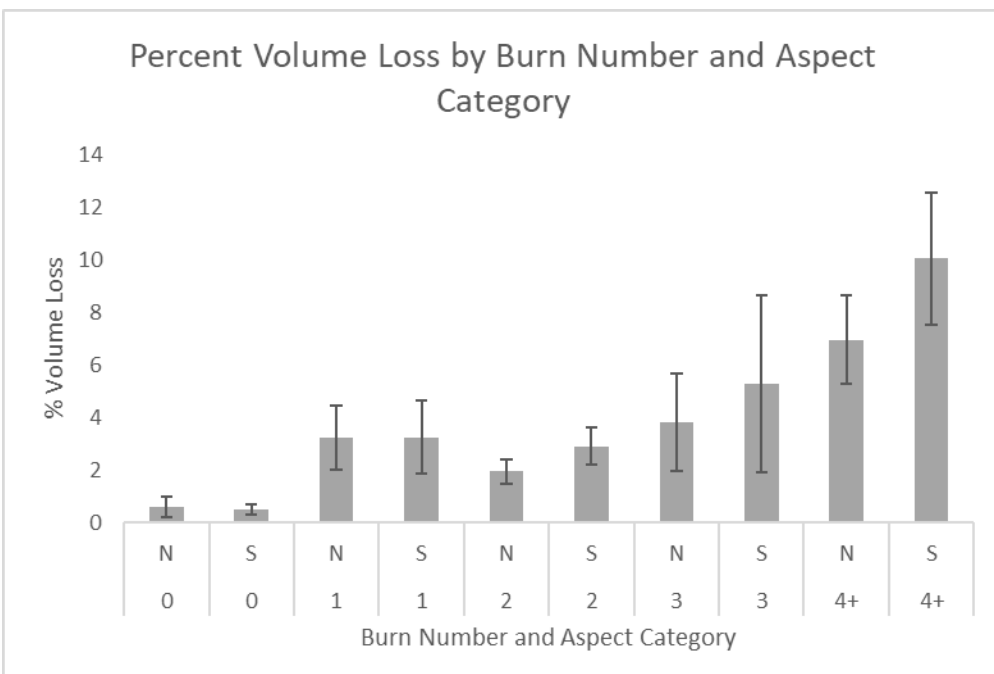

Figure 2-6 Mean and standard error (bars) of relative percent volume loss to the butt log by number of prescribed fires (1,2,3,4+) in the past 30 years and aspect class (north, south).

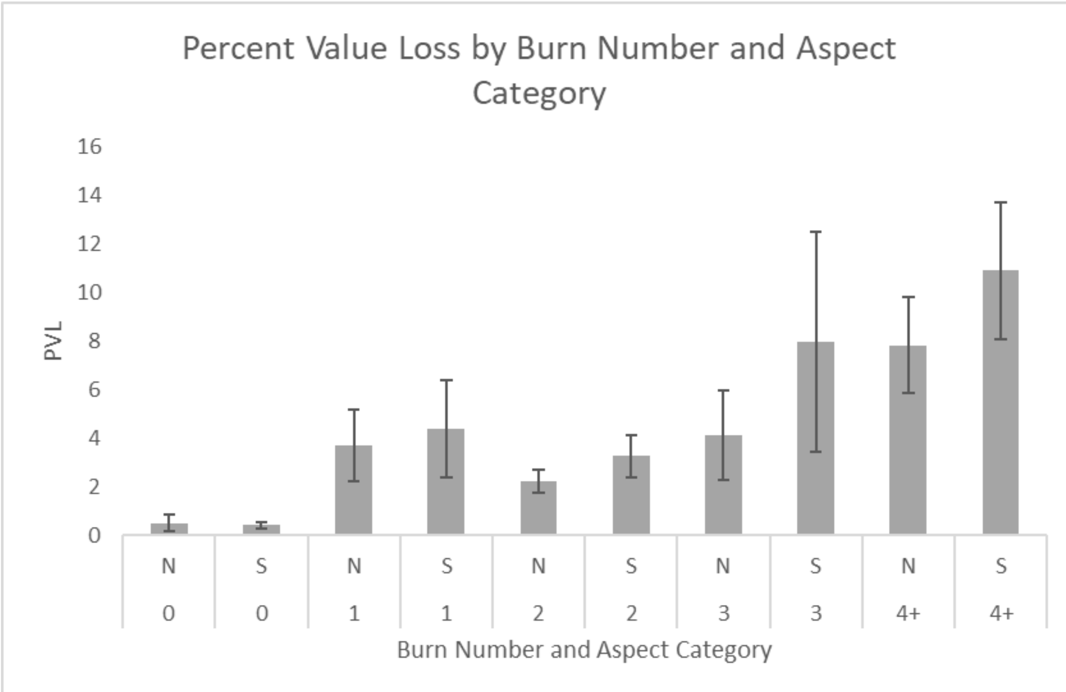

Figure 2-7 Mean and standard error (bars) of relative percent value loss (PVL) to the butt log by number of prescribed fires (1,2,3,4+) in the last 30 years and aspect class (north, south).

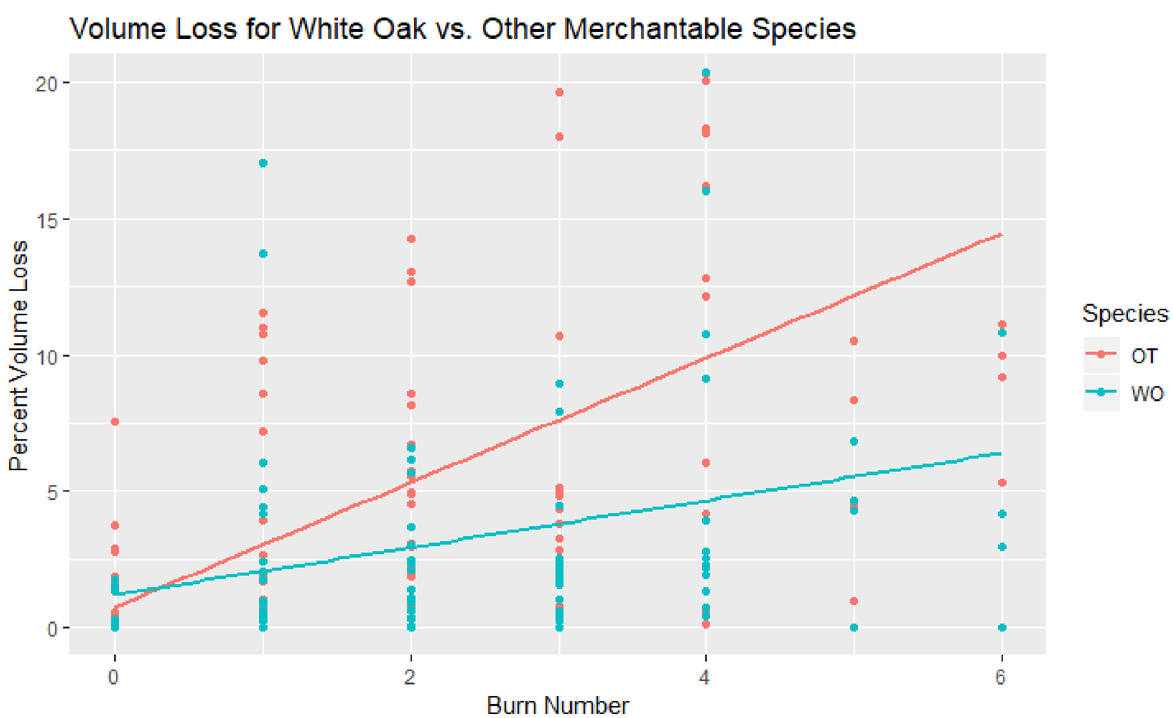

Figure 2-8 Comparison of relative percent volume loss to the butt log by burn number for white oak (WO) and all other merchantable species (OT). ($t=3.64$, $p<0.01$).

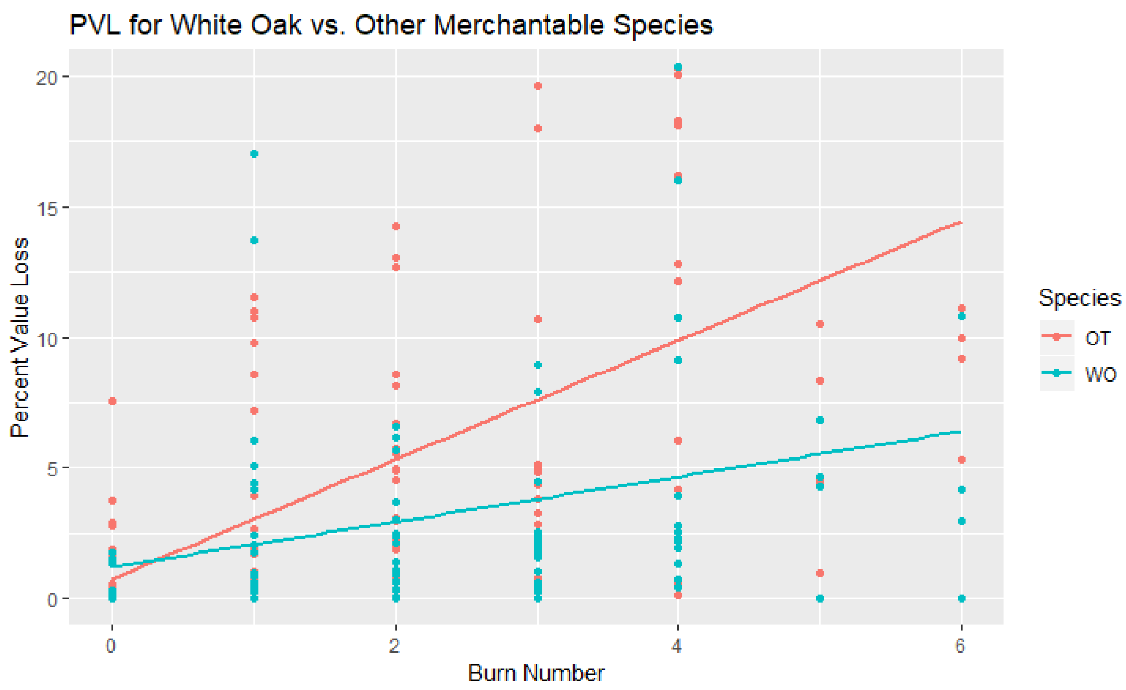

Figure 2-9 Comparison of percent value loss to the butt log by burn number for white oak (WO) and all other merchantable species (OT). ($t=3.29$, $p<0.01$).

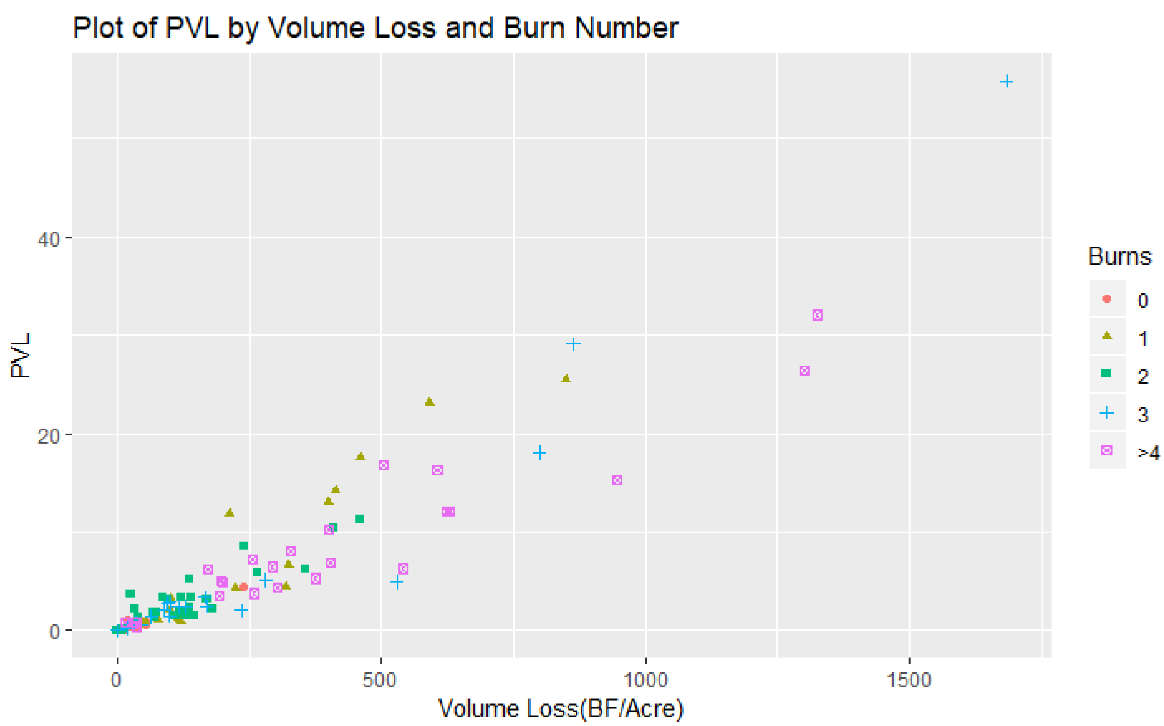

Figure 2-10 Percent value loss at the stand level by volume loss in board feet/acre to the butt-log grouped by number of prescribed fires in the last 30 years (stands with 4 or more prescribed fires pooled for purpose of illustration). Adjusted $R^2=0.89$ ($t=83.32$, $p<0.01$).

CHAPTER 3. EVALUATING WOUNDING AND TREE QUALITY EFFECTS OF PRESCRIBED FIRE IN THE CENTRAL HARDWOOD REGION

3.1 Abstract

Prescribed fire is commonly used by public land managers in eastern North America's oak-dominated (*Quercus* spp.) forests, but concerns about wounding standing trees and damaging timber value have been a barrier to fire's use on industrial and private lands. We quantified fire-caused wounds in 139 oak-dominated stands across the Mark Twain (MTNF), Hoosier (HNF), Wayne (WNF), and Daniel Boone (DBNF) National Forests, each with a history of 0-6 prescribed fires within the last 30 years. In each stand, overstory (>25.4 cm DBH) plot trees were measured (n=8,093) and all wounds related to prescribed fire were categorized by type and measured for size. Trees were then graded both ignoring the effects of prescribed fire, and accounting for the effects of prescribed fire, to detect reduction in tree quality. At a stand level, approximately 25% of all trees sampled had at least one wound associated with fire, and just over 5% of trees in the study exhibited a reduction in United States Forest Service (USFS) tree grade from prescribed fire. The number of prescribed fires on a site had a significant linear effect on the likelihood of wounding, with stands receiving more prescribed burns generally having higher rates of wounding and rates of tree quality reduction. Effects of fire were variable across species groups, with white oak (Quercus alba) exhibiting grade reduction associated with fire at a significantly lower rate than other species. Finally, wounding patterns varied significantly across the region, with much higher wounding rates in HNF and MTNF as compared to WNF and DBNF. All wounds (n=3,403) were categorized by wound type (catface, seam, bark slough, and basal flutes). On average, catfaces were both the most common wound type (n=1,106) and were responsible for more volume loss than other wound types. Seams and bark slough were also very common, but on average accounted for lower amounts of volume loss.

3.2 Introduction

Prescribed fire is recognized as a versatile forest management tool. The practice is often used in the Central Hardwood Region (CHR) to promote oak regeneration (Brose et al. 2013) but can also be used to control midstory competition (Dey and Schweizer 2018), improve wildlife habitat, and achieve woodland management outcomes (Kinkead 2013). Concerns about the effects of the practice on standing timber have limited the use of prescribed fire, particularly in the central and eastern United States (Knapp et al. 2017). Further, public perceptions about the risks associated with fire, and a lack of understanding of the benefits of the practice have limited prescribed fire usage (Nehoda et al. 1995).

There is a long history of research on the effects of wildland fire on timber quality. Early research included attempts to model damage and value loss to timber based on measurements of wounding associated with fire. Much of the research on wounding effects of fire have focused on wildfire, often reporting severe damage. Loomis (1974) evaluated effects of wounding from wildfire on Pennsylvania sites, and Reeves and Stringer (2011) found losses in value from wounding related to wildfire averaged approximately 38%. Research specific to prescribed fire tends to show much lower levels of damage. Stanis et al. (2019) found less than 40% of trees on prescribed fire sites in southern Indiana had any wounding associated with fire, and approximately 3% had a reduction in tree quality (measured by USFS tree grade). Wiedenbeck and Schuler (2014) found that a majority of trees in a prescribed fire site in West Virginia exhibited some wounding associated with fire, but less than 13% of trees exhibited wounding severe enough to affect value. These studies additionally found that white oak display wounding effects from prescribed fire at relatively low rates; Stanis et al. (2019) reported that just 1.8% of white oaks (mostly *Quercus alba*) in the study changed grade as a result of fire-related wounds.

Little previous research exists evaluating the wounding patterns associated with prescribed fire across sites with a variety of fire-history and site characteristics; Stanis (2019) studied wounding patterns across stands in southern Indiana with a history of 0-4+ prescribed fires, and found that wounding rates and grade change tends to increase with increasing numbers of prescribed fires. Until now, no studies have evaluated wounding and grade-change patterns across a regional scale. This study will evaluate effects of wounding across a gradient of edaphic factors within the CHR, allowing the effect of region and variable management practices to be evaluated.

The purpose of this study is to evaluate wounding and tree-quality trends associated with prescribed fire across the CHR. Study objectives include evaluating the effect(s) of: i) number of prescribed burns and aspect on wounding rates; ii) number of prescribed burns and aspect on tree-quality reduction; iii) species on wounding rate and tree quality reduction; iv) e tree diameter on wounding and tree quality reduction patterns; v) location within the CHR on wounding and tree-quality reduction patterns; and vi) burn number and wound type on average volume loss per wound. I hypothesize that wounding rates and tree quality reduction will generally increase with increasing numbers of prescribed burns and south-facing aspects. White oak is hypothesized to have lower wounding rates and tree-quality reduction effects from prescribed fire relative to other commercial tree species. It is further hypothesized that trees with smaller diameters are more likely to experience wounding and tree quality effects from prescribed fire compared to larger stems. Finally, xeric portions of the CHR are hypothesized to exhibit higher wounding rates and levels of tree quality reduction compared to other portions, and it expected that wounding from prescribed fire will generally be less in national forests in the eastern portion of the CHR compared to sites in the western portion of the CHR.

3.3 Methods

3.3.1 Study Sites

Research sites for this study were placed in four national forests, representing a moisture and edaphic gradient that occurs across the CHR: Mark Twain National Forest (MTNF) in southern Missouri; Hoosier National Forest (HNF) in southern Indiana; Wayne National Forest (WNF) in southern Ohio; and Daniel Boone National Forest (DBNF) in eastern Kentucky (Figure 2.1). The stands measured in this study were the same measured in the study detailed in Chapter 2, and data for both projects were collected concurrently. Brief descriptions of study sites are below; a more comprehensive description of study sites can be found in Section 2.3.1.

Mark Twain National Forest

The MTNF is located with the Ozark Highlands section of the southern half of Missouri. Prior to European settlement, fire was frequent in the Missouri Ozarks, with return intervals of less than three years in many areas (Cutter and Guyette 2006). Fire suppression led to widespread conversion of savannas and open woodlands to closed-canopy forest in the region in the past century (Dey and Hartman 2005). The overstory in Ozark forests and woodlands is primarily a mixture of oak (*Quercus* spp.), hickory (*Carya* spp.), and shortleaf pine (*Pinus echinata*) (Kinkead 2013). Competitors to oaks in the regeneration layer tend to be weak and transient. Prescribed fire and other treatments are often not required to achieve successful oak regeneration (Larsen et al. 2011).

Hoosier National Forest (HNF)

Research sites on the HNF are located in the Shawnee Hills Natural Region of southern Indiana (Homoya et al. 1985). This region is primarily characterized by steep slopes and a predominance of sandstone geology, with some areas of karst topography (Homoya et al. 1985). The overstory in HNF is largely dominated by oaks, hickories, and tulip-poplar (*Liriodendron tulipifera*) (Woodall et al. 2007). Promoting oak and hickory regeneration is an important management goal in HNF, and this is a primary objective of prescribed fire in the forest (Hoosier National Forest-Bedford Office 2019).

Wayne National Forest (WNF)

The WNF lies in the hills of the southern half of Ohio and within the southern Allegheny Plateau region (McNab et al. 2007). Historically, fire was a major disturbance agent in southern Ohio, with a mean fire return interval of approximately 5 years in the late 19th and early 20th century (Hutchinson et al. 2008). The overstory of the WNF is largely dominated by oaks (predominately white, northern red, chestnut [*Q. montana*] and black), an assortment of hickory species, as well more mesic species such as beech and tulip poplar (Iverson et al., 2017). One of the primary purposes for utilizing prescribed fire in the WNF is to promote oak competitiveness in the regeneration layer.

Daniel Boone National Forest (DBNF)

Daniel Boone National Forest lies in the Appalachian foothills of eastern Kentucky, split between the Allegheny and Cumberland Plateau. Wildfire has historically been a major disturbance agent in the DBNF and the rest of the Kentucky Appalachians. Frequent, low-intensity fires are characteristic of the area, with arson-caused wildfires still occurring relatively frequently (Maingi and Henry 2007). Most stands selected for this project were placed within burn units originally designated for a cooperative research project between the USFS and the University of Kentucky (Arthur et al. 2015), but a smaller number of stands were associated with several units on which burns were conducted by the DBNF personnel, with the intended purpose of reducing risk of wildfire and improving forest health.

3.3.2 Stand selection

Stands were the primary sampling unit for this study and defined as a contiguous area of forest with relatively homogenous species composition, age structure, and topographic aspect, usually ranging from 10-50 acres. A total of 139 stands were sampled: 54 stands in the HNF, 33 in the MTNF, 34 in the WNF, and 18 in the DBNF. Selected stands were stratified both by primary stand aspect and by number of prescribed burns that had occurred on a site over the past 30 years. Aspect was classified as either "xeric" or "mesic"; xeric stands had a majority of sampling points with aspects facing south, southeast, southwest or west, whereas mesic stands had a majority of sampling points with aspects facing northeast, northeast, northwest, or east. The stands selected for this study are the same is in Chapter 2; a more detailed description of stand selection procedures can be found in Section 2.3.2.

3.3.3 Field measurements

Each stand was sampled using 15 randomly placed, 20 Basal Area Factor Variable Radius plots. Sampling was conducted concurrently with the study detailed in Chapter 2; a more detailed description of field sampling methods can be found in Section 2.3.3.

Any wounding assumed associated with fire was also quantified. A wound was defined as any visible disruption of the bark or cambium that appeared to be directly related to the effects of fire. Following Marschall et al. (2014) and Stanis et al. (2019), wounds were classified into one of four categories: catface, oval, seam, and bark slough/multiple seam (Appendix A). These categories classify the approximate geometric shape of the wound, and were used to determine formulas used to calculated volume associated with each wound. The presence of char or discolored bark was insufficient for classification as a wound, due to the inconsistent relationship of char to physical injury (Smith and Sutherland 1999).

Width, depth, and height of all wounds were measured to the nearest 0.1 cm. 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. Sections of wound below stump-height (determined to be 6 in, or 15.2 cm above ground on the uphill side of the tree) were not measured, and wounds that did not reach above stump height were not measured at all (although they were noted when present). Three height measurements are recorded for each wound: total height, start height, and end height. Total height was defined as the linear distance from the lowest point of the wound to the highest point on the wound. Start height is defined as the linear distance between the top of the stump and the lowest point of the wound. End height was defined as the linear distance from start height to the highest point of the wound. For each wound, it was further noted whether the wound caused an area of cull (i.e., rendered a portion of the log unusable for merchantable lumber) and whether the wound was sufficient to result in a reduction in tree grade for the face of the tree where it was measured.

3.3.4 Analysis

Data Summary

Wounding patterns and most tree-level patterns were evaluated at the individual tree level. For the purpose of species-level analyses, merchantable species were divided into the following groups, based on prevailing timber-market structures in the Central Hardwood Region: 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; f) yellow poplar; and g) other species. Species classified as "other species" either did not have viable markets across the region or were not represented in a large enough sample size in our study for robust analysis. Examples of these species include several pine species (*Pinus echinata*, *P. strobus*, and *P. virginiana*), eastern hemlock (*Tsuga canadensis*), red maple, blackjack oak (*Q. maralandica*), beech, blackgum (*Nyssa sylvatica*), American sycamore (*Platanus occidentalis*) and black cherry (*Prunus serotina*). For the purposes of data summary, DBH was divided into four-inch diameter classifications: >12", 12-16, 16-20", 20-24", 24-28", 28"+.

Some tree-level variables, such as likelihood of wounding and likelihood of tree grade-reduction were expanded to the stand-level for analysis. Tree data from each variable point plot were aggregated to a per-acre basis. The expansion constant for a 20 BAF prism is 244.46. This fixed expansion factor was divided by the squared diameter at breast height (DBH to the nearest

10^{th} of an inch) of each tree to determine the number of trees per acre (TPA) represented by each stem. Data were further aggregated to the stand-level, and summarized by average trees per acre.

Wound-level Variables

Wound dimensions (total height, width, and depth) were used to calculate volume loss associated with wounds. Volume loss in cubic feet was calculated specific to the approximate shape of each wound type. Volume loss in board feet (bf) for each wound was calculated as [Volume in cubic feet (V. ft^3)*12]. We evaluated the effect of burn number and aspect on average volume loss associated with wounds. Further, we evaluated the effect of wound type on average volume loss per wound. The effect of burn number, aspect, and wound type was also evaluated with respect to the likelihood of a wound being associated with grade change and cull areas. Slope at plot center was evaluated for all analyses as a potential random effect.

Marschall et al. (2014) found that wound height is an important predictor of value loss associated with fire, and is an important indicator of the degree of damage caused by prescribed fire. For the purposes of analysis, end height (start height+total height) in feet to the nearest 10^{th} of a foot was utilized. We evaluated the effect of burn number and aspect on average wound height, and also tested whether percent slope had a significant effect on average wound height.

For all aspect-based analysis at the tree and wound level, plot-level aspect (hereafter referred to as neighborhood aspect, and categorized as north-facing or south-facing) was used, as opposed to the stand-level aspect. While neighborhood aspect and stand aspect were the same in most cases, in stands with variable aspects, use of the plot-level data allowed for more precise analyses of the effect of aspect.

Tree-level Variables

The effect of DBH on wounding patterns was evaluated, with the hypothesis that both wounding and grade change rates will be lower for trees in larger diameter classes. Secondly, we evaluated the effect of species group (white oak, red oak, tulip poplar, sugar maple, and hickory) on likelihood of wounding and grade change, with the hypothesis that white oak would have lower likelihood of wounding and grade change compared to other species groups. I further hypothesized that species with thinner bark (e.g., sugar maple would have higher likelihoods of both grade reduction and wounding compared to thicker bark species like white oak.

Stand-level Variables

The percentage of trees per acre with in each stand with at least one wound was calculated as [($TPA_{wounded}/TPA_{total}$)*100]. The percentage of trees per acre in each stand exhibiting grade reduction from fire was calculated as [($TPA_{grade\ change}/TPA_{total}$)*100]. We evaluated the effect of burn number and stand aspect on the percentage of trees per acre with at least one wound from fire, as well as the effect of burn number and aspect on the percentage of trees per acre with a reduction in USFS tree grade.

Statistical approach

I used a linear regression to evaluate whether there was an effect of wound type (bark slough/multiple seams, catface, seams, ovals, and basal flutes) on average volume loss per wound. I used logistic regression to evaluate the effect of wound type on the likelihood of the wound being associated with a cull region, as well as to evaluate the likelihood of the wound causing grade change. I used Tukey's test of Honestly Significant Difference (HSD) (Tukey 1949). to further evaluate differences in average volume loss between wound types. I also used a Tukey Test of HSD to further evaluate differences between wound types in likelihood of grade change and being associated with a cull area. I used a chi-square test to evaluate whether there was a relationship between species group and wound type. For the purpose of chi-square tests, I grouped all “open” wound type (catfaces, ovals, and basal flutes) and “closed” wound types (seams and bark slough). This was necessary in order to meet assumptions for this test for adequate representation in all categorizations, due in part to the low number of wounds classified as basal flutes and ovals. Multiple regression was utilized to evaluate the effects of burn number and aspect on average wound height and average wound volume. Slope percentage at plot center was also evaluated to determine whether it should be included in wound-level models as a random effect.

At the tree level, I used separate logistic regressions to evaluate the effect of DBH on the likelihood of wounding as well as likelihood of reduction in USFS tree grade as a result of fire. I used chi-square tests to determine whether there was a relationship between species group and likelihood of wounding and likelihood of USFS tree grade reduction. At the stand level, I used mixed multiple regression to evaluate the effects of burn number, stand aspect, and location by national forest on the percent of trees wounded and the percent of trees with a reduction in USFS tree grade from prescribed fire.

I assessed linearity of all linear models by inspection of Pearson residual plots to detect any non-linear pattern of residuals. I evaluated heteroscedasticity using the Breusch-Pagan test (Breusch and Pagan 1979), and I evaluated normality using the Shapiro-Wilkes Test. All statistical analyses for this study were run in R 3.5.3 (R Core Team 2019) and I used the LME4 package to conduct mixed-effects regression (Bates et al. 2015). Differences were deemed significant at α = 0.05.

3.4 Results

3.4.1 Sample Profile

A total of 8,093 trees across 139 stands were included in the sample. The sample was dominated by oaks, with the genus accounting for 76% of the sample (n=6,151). Roughly equal numbers of stands were sampled on north-facing (n=70) and south-facing aspects (n=69). Due to variation in the number of suitable sites, both numbers of trees and stands sampled were uneven between national forests. Each classification of number of burns (0-6) were represented by a minimum of four stands.

White oak was the most abundant species, accounting for 44% of the sampled trees. Merchantable species accounted for a vast majority of the sample (92%). A total of 3,403 wounds were measured. Wounding was relatively evenly distributed between catfaces, seams, and bark slough, which in aggregate composed the vast majority of wounds (Table 3.2). Ovals and basal flutes were much less common, accounting for less than 7% of the sample combined.

3.4.2 Wound-level and Tree-level Effects

Average volume loss varied significantly by wound type (F=49.16; Table 3.2). Average volume loss per wound did not vary significantly between bark slough, seams, ovals, or basal flutes, but was significantly higher for catfaces. Catfaces averaged 9.90 bf of volume loss, compared to just 1.93 bf for all other wound types. The likelihood of causing grade change was statistically the same for catfaces, basal flutes, and ovals, but was significantly lower for bark slough and seams (F=34.06, Table 3.3). Catfaces, basal flutes, and ovals caused a grade change on at least one face of the tree 83.4% of the time, compared to just 25.1% for seam and bark-slough wounds. The effect of wound type on likelihood of being associated with a cull region was similar; bark slough and seams were associated with lower likelihood of cull, while catfaces, ovals, and basal flutes were associated with higher likelihoods of cull (F=112.9, Table 3.3). A cull area was associated with 93.0% of catfaces, basal flutes, and ovals, but just 62.5% of seams and bark-slough wounds.

Species group had a significant relationship wound type (χ^2=159.13, p<0.001). White oak had one of the lowest percentages of wounds classified as open (catfaces, ovals, and basal flutes) at 31%. Conversely, sugar maple had the highest percentage of open wounds (68%). The species with the lowest percentage of open wound types was tulip-poplar, at 22%.

Local aspect had a significant effect on the average volume loss associated with wounds, with trees on south-facing sites exhibiting higher average volume loss (T=2.26, p=0.024). Average volume loss for wounds in south-facing points was 5.20 bf, compared to 3.95 bf for north-facing points. Burn number and local aspect had a significant interaction effect on average volume loss associated with wounding, with average volume loss per wound generally increasing on south-sites and sites with higher numbers of prescribed fires (T=2.39, p=0.016). Number of prescribed burns did not have a significant effect on average volume loss from wounds in models that did not include aspect. The effect of slope was evaluated for possible inclusion in the model, but there was no significant effect on average volume loss.

Wound height did not vary as expected based on burn number and aspect. Increasing numbers of burns and south-facing aspects actually had slightly negative correlations with average wound height, although these correlations were extremely weak and likely spurious (conditional R^2 =0.08). Percent slope did not have any significant effect on average wound height.

There was not any significant relationship between DBH and the likelihood of wounding (T=-0.479, p=0.63). Tree diameter did have a significant effect on the likelihood of USFS tree grade reduction associated with fire (T=-2.77, p=0.006). Generally, smaller diameter trees exhibited a higher probability of exhibiting a reduction in tree grade compared to larger diameter trees. Trees less than 20 inch DBH experienced a reduction in tree grade in 5.8% of cases, compared to 4.2% for trees greater than 20 inch DBH.

Species group had a significant effect on both likelihood of wounding and likelihood of reduction in USFS tree grade (χ^2=76.77, p<0.001). Among species groups evaluated, the red oak group had both the highest likelihood of wounding (34%) and the highest likelihood of grade reduction (9%). Tulip-poplar exhibited the lowest rate of wounding (18%) and grade reduction (<2%). White oak exhibited wounding at a rate similar to the sample as a whole (27%) but the likelihood of grade reduction was low (3%).

3.4.3 Stand level effects

Across all forests and numbers of prescribed fires, an average of 25.1% of trees per acre had at least one wound associated with prescribed fire, and 5.7% trees per acre had a reduction of at least one USFS tree grade as a result of fire damage. Location by national forest had a significant effect on both percentage of trees per acre wounded and percentage of trees per acre with grade reduction (p<0.001). MTNF and HNF had the highest percentages of trees per acre wounded of the national forests sampled (32.2% and 35.1% respectively). Neither DBNR nor WNF had more than 13% trees per acre wounded (Table 3.4). Percent of trees per acre with grade change was low and relatively consistent in HNF, DBNF, and WNF (<4%) but was more than four times higher in Mark Twain National Forest (16.0%) (Table 3.5). Since the effect of location by national forest was significant for both percent of trees per acre wounded and percent of trees per acre with grade change, it was included as a random effect in all stand-level models.

The number of prescribed fires in the past 30 years had a significant linear effect on percentage of trees per acre wounded (p<0.001, T=7.15). In control (0-burn) stands, 9.3% of trees per acre were wounded, compared to 29.1% in stands with a history of 1-6 prescribed fires. Generally, the percentage of trees per acre wounded increased as the number of prescribed fires increased (Table 3.8, Figure 3.2). The greatest change in percentage of trees wounded occurred in stands receiving 0-2 prescribed fires (17.3% TPA wounded) and stands receiving 3-6 prescribed fires (41.4% TPA wounded). The percentage of trees per acre wounded increased steadily from 0 to 4 prescribed fires, before leveling off.

Number of burns also had a significant linear effect on percentage of trees per acre experiencing grade change (p<0.001, T=4.86). Increasing numbers of prescribed fires was generally associated with a higher percentage of trees per acre exhibiting grade change associated with fire (Table 3.9, Figure 3.3). Just 3.0% of trees in control sites experienced grade reduction, compared to 7.0% in stands with 1-6 prescribed fires. Percentage of trees with grade reduction increased relatively steadily from 0-5 burns, although there was a slight reduction in average percent of trees with grade reduction per acre from 5-burn stands to 6-burn stands.

South-facing aspects were not associated with higher percentages of trees per acre wounded. On south-facing stands, an average of 24.1% of trees per acre were wounded, compared to 26.1% of trees per acre on north-facing stands, although this effect was not significant. South-facing stands displayed a grade reduction in an average of 6.1% of TPA, compared to 5.2% of TPA in north-facing stands, but again, the effect was not significant (T=1.30, p=0.195).

3.5 Discussion

3.5.1 Wound- and Tree-level Effects

Catfaces were generally associated with more extensive volume loss and higher rates of grade change than "closed" wound types (seams, bark slough). This supports previous research (Smith and Sutherland 1999, Stanis et al. 2019) showing that wounds that either never open or rapidly closed are less likely to lead to serious damage to the tree. Catfaces were responsible, on average, for far more volume loss than all other wound types. Catfaces were associated with much higher likelihood of both grade change and cull areas being associated with the wound. This indicates that not all wound types should be considered the same with respect to impacting tree quality, volume, and value. Bark slough and seams generally did not cause grade reduction, and were less likely to be associated with cull regions. In general, catfaces were the wound type associated with the greatest negative effects from wounding, with respect to volume loss, grade change, and likelihood of being associated with a cull region, while bark slough and seams were generally associated with the least negative effects.

White oak were less likely than most other species groups to exhibit open wound types (catfaces and ovals), which consistently were associated with more volume loss, quality reduction, and cull sections. The majority (69.6%) of wounds on white oak were seams and bark slough, which were generally associated with lower rates of grade reduction and culling compared to ovals and particularly catfaces. The predominance of generally less damaging wound types may have the potential to limit value loss effects to white oaks, which could be an important economic consideration. Sugar maple exhibited extremely high rates of open wounds, particularly catfaces.

The predominance of more damaging wounds in sugar maple is consistent with the species' thin bark (Edward et al. 2014) and low level of fire resistance, especially in comparison to oaks (Starker 1934). Tulip-poplar had the lowest proportion of open wounds. While this might be indicative of thick bark found in mature members of the species (Edward et. al. 2014), it may also be that tulip-poplar with more serious effects from fire are not being measured due to prior mortality (Brose and Van Lear 1998).

Sites with south-facing aspects generally had higher average volume losses associated with wounds than north-facing stands. Increased volume loss on south-facing sites consistent with the assertion that fire intensity is generally greater on south-facing aspects compared to north-facing aspects (Estes et al. 2017). There was a significant positive interaction effect between south-facing aspect and burn number, indicating that the positive effect of south-facing aspects on volume loss per wound is exacerbated with increasing numbers of prescribed fires. Burn number does not appear to have a significant effect on average wound volume when aspect is not included in the model, indicating that the effect is dependent on aspect.

No explanatory variables (aspect, burn number, or slope) measured in this study had a significant positive effect on wound height. This may indicate that fire behavior factors such as fire intensity and flame height may be more strongly associated with wound height than physiographic or fire-history characteristics of the site. Further research accounting for fire intensity and flame height is needed to understand their effects on wound height.

While diameter had no effect on likelihood of wounding, effects on likelihood of grade reduction varied as hypothesized. Smaller diameter trees were significantly more likely to exhibit grade reduction than larger-diameter trees. This is likely due, at least in part, to the process used in determining tree grade; according to diameter-specific specifications, a relatively minor defect is more likely to result in grade reduction in a small-diameter tree compared to a large diameter tree. This is due to the fact that more individual cuttings are often allowed within each grade for trees with large diameters (Miller and Wiant 1986). Previous research indicates that stem size is positively correlated with fire resistance (Brose and Van Lear 2004), so it is not surprising that tree quality effects from prescribed fire are generally less for larger diameter trees.

Wounding patterns were not uniform for all species. Red oak exhibited high rates of both wounding and tree-grade reduction from fire. This is consistent with previous research indicating that red oak has relatively low resistance to fire compared to other oak species and exhibits wounding at higher rates (Starker 1934, Stanis et al. 2019). White oak had intermediate rates of wounding associated with prescribed fire, but low rates of grade reduction. This finding matches white oak's fire-tolerant characteristics (Abrams 2006, Lorimer 1985). Further, relatively low levels of tree-quality effects in white oaks is consistent with the low rates of value and volume loss generally found to occur in white oak as a result of prescribed fire (Stanis et al. 2019; Wiedenbeck and Schuler 2014).

Among species groups sampled, tulip-poplar was found to have the lowest rates of both wounding and tree grade reduction. The low rates of wounding and tree grade reduction in tulip-poplar are likely due to two reasons: tulip-poplar often exhibits relatively high mortality from fire in comparison to hardwoods species (Brose and Van Lear 1998), but also has been shown to exhibit low likelihood of wounding to mature trees from fire due to bark characteristics (Starker 1934). It is possible that tulip-poplar are exhibiting greater effects from fire than was observed in this study, and that these effects were not recorded due to mortality prior to sampling.

3.5.2 Stand level Effects

At the stand-level, the strongest predictor of both percent trees per acre wounded and percent trees per acre with a grade reduction appears to be the number of prescribed burns in the last 30 years. This supports previous research indicating that increasing frequency of prescribed fire is generally associated with higher levels of fire damage (Knapp et al. 2017, Stanis et. al 2019). Generally, higher numbers of prescribed fires were associated with higher rates of wounding and grade change, but these trends were somewhat variable. The percent of trees wounded per acre steadily increased from unburned control sites to those with four prescribed fires, before leveling off. The clearest demarcation (excluding control stands) comes between stands with a history of one to two prescribed fires and stands with a history of three or more prescribed fires. The percent of trees per acre wounded in stands with a history of 3 to 6 prescribed fires was almost exactly double that of stands with a history of 1 to 2 prescribed fires. This roughly mirrors research from Stanis et al. (2019), who found that the greatest difference in damage patterns comes between stands with a history of three or more prescribed burns and stands with a history 0-2 prescribed burns. This is indicates that, in general, repeated fires are likely associated with a higher rate of wounding, but that after three prescribed fires, the likelihood of wounding may not always continue to increase.

The effect of number of prescribed fires on grade change is even more clear. Rates of grade change steadily increase with increasing number of prescribed fires, with the trend only beginning to level off on 6-burn sites (a slight reduction in percent trees with grade reduction per acre from 5-burn sites). The slight reduction between 5-burn and 6-burn stands is possibly due to a much lower number of 6-burn stands available for sampling (n=4), compared to other burn categories. The positive association between burn number and rates of grade change is consistent with research indicating that increasing fire frequency is related to higher tree value effects (Knapp et al. 2017, Stanis et al. 2019). In general, the steady increase in tree grade reduction rates with increasing burn number is indicative of both increased wounding rates from 0 to 3 prescribed burns, and the effect of reburn and increased injury of existing wounds. This indicates that while rates of trees per acre wounded does not appear to increase after three prescribed burns, potential economic effects from the practice may occur beyond this point due to tree-grade reduction.

3.6 Conclusion

This study indicates that wounding and tree quality effects from prescribed fire to merchantable-sized trees were generally low. Consistent with previous research (Wiedenbeck et. al. 2014, Stanis et al. 2019), this study indicates that a majority of trees do not exhibit any measurable effects from prescribed fire, and even a smaller minority exhibit quantifiable tree-quality effects. White oaks were subject to even lower rates of tree grade reduction from prescribed fire than the sample as a whole, indicating that stands dominated by this species may be less likely to exhibit severe effects from the practice. The present study further found that only open catfaces tended to be associated with high levels of volume loss, and that closed wound types (seams and bark slough) tend to have minor volume loss and tree quality effects.

Overall, this research indicates that late rotation prescribed fire can be utilized in hardwood forests without deleterious wounding and tree quality effects to standing timber. In general, sites with a history of 1-2 prescribed fires had extremely low wounding and tree quality rates, while rates were somewhat higher in sites with a history of 3-6 prescribed burns. Still, no burn number category exceeded 17% tree grade reduction. This indicates that even in stands subject to repeated burning, tree quality effects remain relatively limited. Finally, tree quality and wounding effects tended to decrease moving west to east throughout the central hardwood region. MTNF had much higher rates of grade reduction than other forest included in the study, and MTNF and HNF collectively had much higher rates of wounding than DBNF or WNF. This may be indicative of an overall west-east gradient of prescribed fire effects.

3.7 References

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3.8 Tables and Figures

Table 3-1 Number of stands and trees sampled within each national forest

			Species Group[1]						
National Forest	# Stands	# Trees	WO	RO	OW	HI	SM	TP	OT
MTNF	33	1,721	669	320	421	90	0	0	221
HNF	54	3,657	2060	470	330	354	142	172	129
WNF	34	1,832	675	349	262	150	139	115	151
DBNF	18	833	184	171	186	88	25	106	123
Total	139	8,093							

1. **WO**: *Quercus. alba*, *Q. muehlenbergii*; **RO:** *Q. rubra*, *Q. velutina*, *Q. coccinea*, *Q. falcata*; **OW:** *Q. stellata*, *Q. montana*; **HI:** *Carya ovata*, *C. tomentosa*, *C. cordiformis*, *C. glabra*; **SM**: *Acer saccharum*; TP: *Liriodendron tulipifera*; **OT:** *Acer rubrum*, *Fagus grandifolia*, *Fraxinus* spp., *Nyssa sylvatica*, *Pinus echinata*, *Platanus occidentalis*, *Q. maralandica*

Table 3-2 Mean (SE) and range in volume loss (board feet) by wound type classification. Average volume loss (BD FT) varies significantly by wound type (f=49.16, p<0.001). Wound types that are not statistically different than each other denoted by same letter (A,B)

Wound Category	# Wounds	Volume (BD FT)	Range (bd ft)
Seam	1,024	1.85 (0.39) [A]	0.01 – 192.00
Bark Slough/mult. seams	1,038	1.55 (0.12) [A]	0.01 – 59.50
Catface	1,106	9.90 (0.72) [B]	0.01 – 339.59
Oval	202	3.84 (0.72) [A]	0.01 – 124.86
Basal/Flutes	33	4.61 (1.20) [A]	0.09 – 27.47
All types	3403	4.52 (0.28)	0.01 – 339.59

Table 3-3 Likelihood of wound causing grade reduction to at least one face of the tree, and likelihood of wound being associated with cull region by wound type classification. Wound types that are not statistically different in likelihood or grade reduction than e ach other denoted by same letter (A,B)

Wound Category	n	Percent Grade (SE)	Percent Cull (SE)
Seam	1,024	21.58 (1.29) A	63.20 (1.50)
Bark Slough/Mult. seams	1,038	28.61 (1.40) A	63.20 (1.49)
Catface	1,106	83.82 (1.11) B	92.86 (0.77)
Oval	202	81.19 (2.76) A	93.56 (1.73)
Basal/Flutes	33	84.85 (6.34) A	93.94 (4.21)
All types	3403	48.10 (0.86)	74.49 (0.75)

Table 3-4 Mean and standard error (SE) of percent of trees per acre at the stand level with at least one wound from fire, by national forest. ($p<0.001$).

National Forest	Percent TPA Wounded (SE)
Mark Twain	31.20 (3.77)
Hoosier	35.14 (2.93)
Wayne	8.72 (1.58)
Daniel Boone	12.83 (2.55)
Total	25.09 (1.82)

Table 3-5 Mean and standard (SE) error of percent of trees per acre at the stand level with a reduction of at least one USFS tree grade as a result of fire, by national forest. (p<0.001.)

National Forest	Percent TPA Grade Reduction (SE)
Mark Twain	15.90 (2.67)
Hoosier	2.74 (0.56)
Wayne	1.33 (0.42)
Daniel Boone	3.76 (1.42)
Total	5.67 (0.85)

Table 3-6 Mean and standard error (SE) percent of sample trees wounded from prescribed fire and percent of trees with a reduction of at least one USFS tree grade as a result of prescribed fire by species group. (Chi-squared=76.77, p<0.001).

Species Group	Percent Wounded (SE)	Percent Grade (SE)
White oak	26.64 (0.74)	3.40 (0.30)
Red oak	34.20 (1.31)	8.63 (0.78)
Other white oak	27.36 (1.29)	8.51 (0.81)
Yellow-poplar	17.81 (1.93)	1.78 (0.67)
Sugar maple	28.62 (2.63)	7.41 (1.52)
Hickory	20.97 (1.56)	3.67 (0.72)
Other	20.83 (1.63)	6.89 (1.01)

Table 3-7 Mean (SE) percent of sample trees wounded from prescribed fire and percent of trees with a reduction of at least one USFS tree grade as a result of prescribed fire by diameter class (DBH in inches).

DBH Class	Percent Wounded (SE)	Percent Grade Reduction (SE)
<12	23.16 (1.62)	5.01 (0.84)
12-16	26.16 (0.87)	6.89 (0.50)
16-20	28.70 (0.88)	5.00 (0.43)
20-24	27.39 (1.15)	4.24 (0.52)
24-28	25.28 (1.89)	4.53 (0.90)
>28	18.70 (2.58)	3.04 (1.14)

Table 3-8 Stand-level mean and standard error (SE) of percentage of trees per acre with at least one wound resulting from fire by number of prescribed fires in the last 30 years. ($p<0.001$, $t=7.15$).

Burn Number	Percent TPA Wounded (SE)
0	9.19 (1.87)
1	17.68 (2.69)
2	23.89 (2.84)
3	40.32 (5.72)
4	48.91 (5.54)
5	30.61 (7.92)
6	39.43 (4.28)
Total	25.09 (1.82)

Table 3-9 Stand-level mean and standard error (SE) of percentage of trees per acre with a reduction of at least one United States Forest Service tree grade resulting from fire, by number of prescribed fires in the last 30 years. ($t=4.86$, $p<0.001$).

Burn Number	Percent TPA Grade Reduction (SE)
0	0.30 (0.15)
1	4.52 (1.40)
2	4.62 (0.95)
3	7.89 (3.13)
4	11.40 (3.02)
5	16.92 (8.70)
6	13.62 (3.85)
Total	5.67 (0.85)

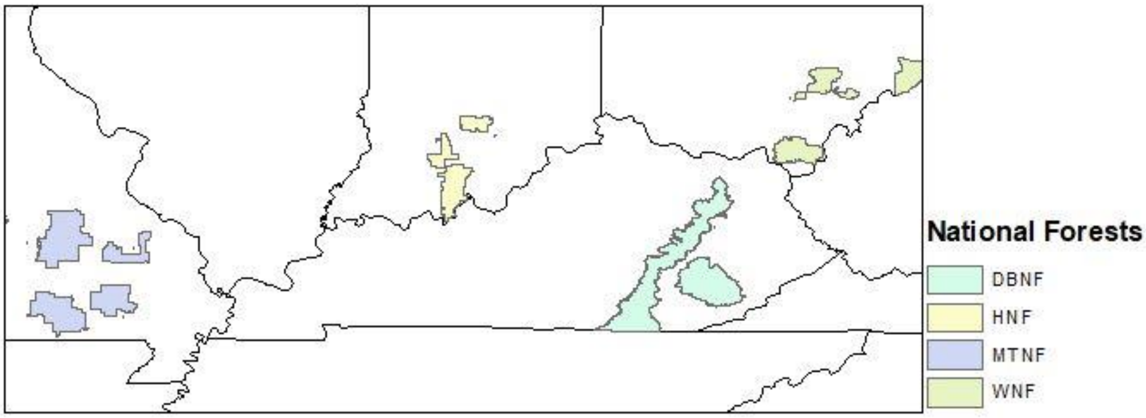

Figure 3-1 Map of the central hardwood region with all national forests included in the study (MTNF, HNF, DBNF, and WNF).

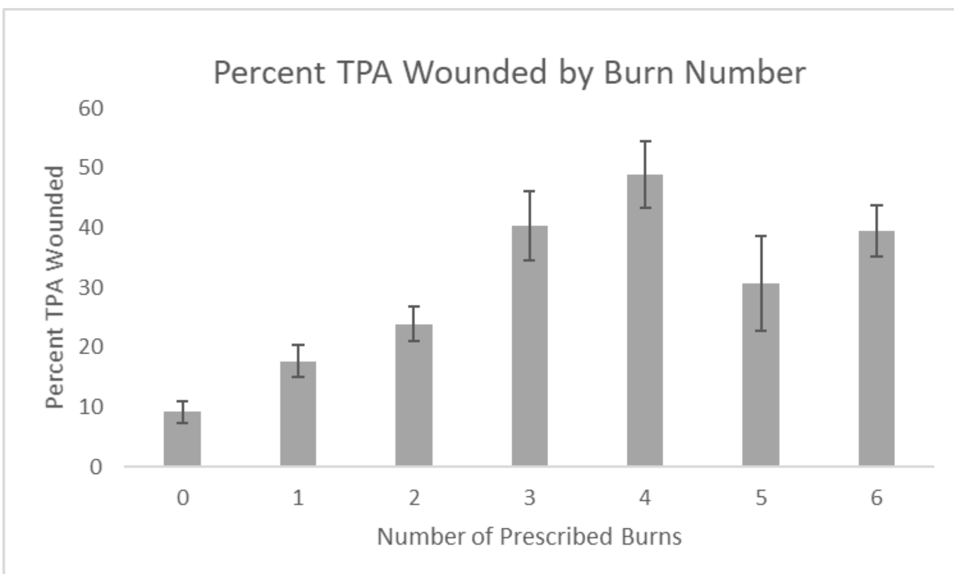

Figure 3-2 Percent of trees per acre wounded from fire by number of prescribed burns across all national forests.

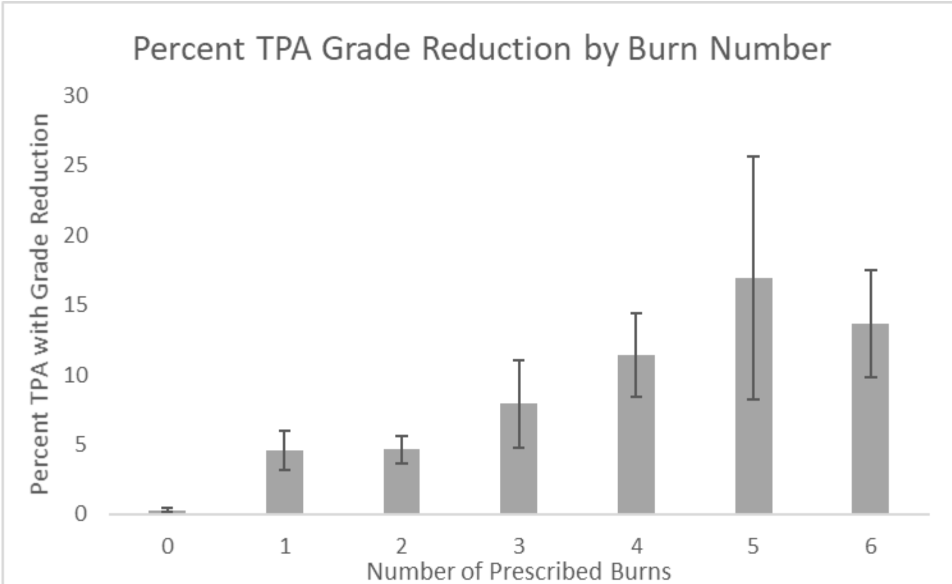

Figure 3-3 Percent of trees per acre with a reduction of at least one United States Forest Service tree grade due to fire by number of prescribed burns across all national forests.

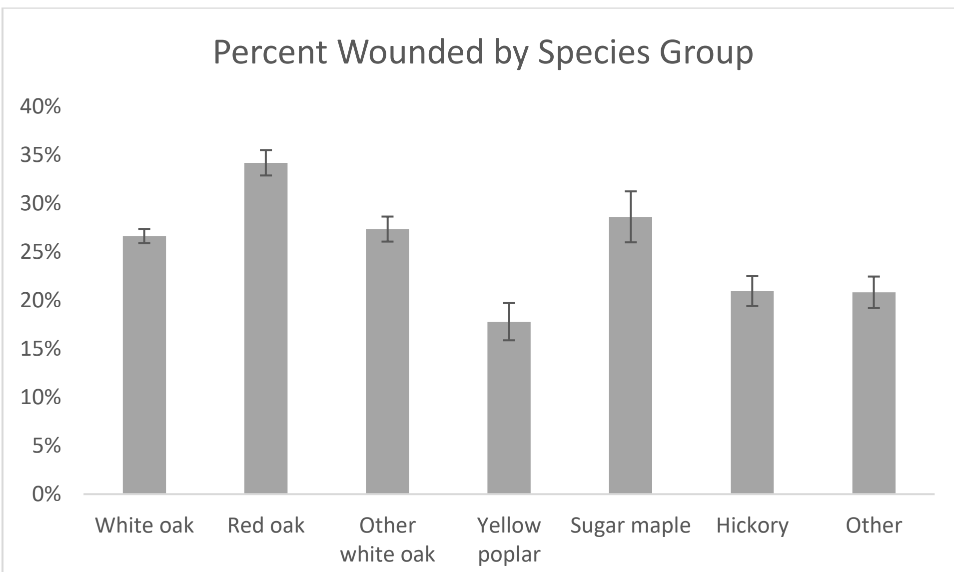

Figure 3-4 Mean and standard error of percent of all sample trees by species group with at least one measurable wound resulting from fire

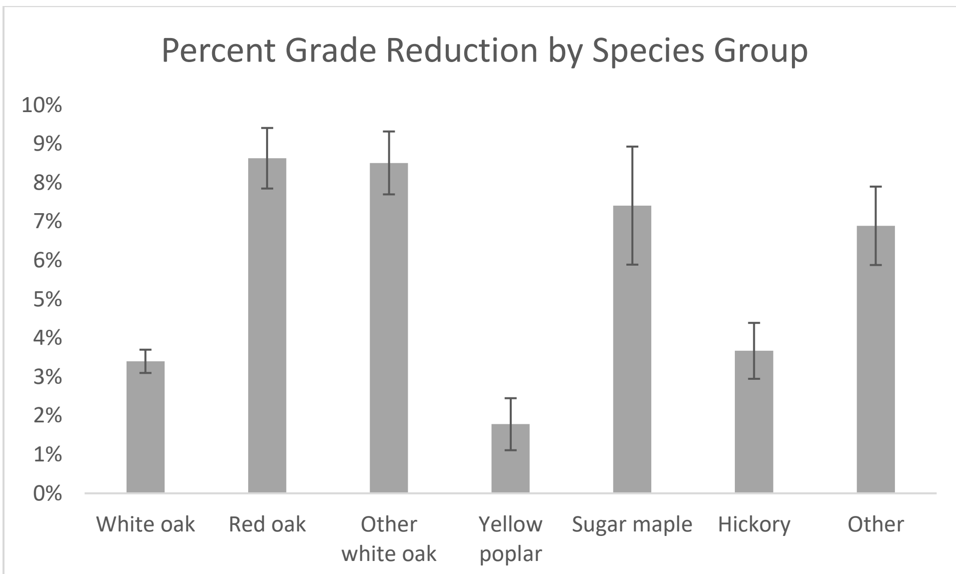

Figure 3-5 Mean (SE) percent of all sample trees by species group with a reduction of at least one USFS tree grade as the result of fire

CHAPTER 4. CONCLUSIONS

Concerns associated with prescribed fire greatly limit the use of one of the most versatile tools available to land managers. Use of prescribed fire can be problematic as concerns about fire escape, smoke control, and other societal factors can impede use (McCaffrey 2006, Knapp et al. 2009). One of the most pervasive questions about prescribed fire in the United States, however, is related to potential value and quality effects to standing timber (Marschall et al. 2014, Wiedenbeck and Schuler 2014, Stanis et al. 2019). This thesis address this concern with a two-pronged approach that evaluated monetary effects of prescribed fire on potential stumpage value, and separately evaluating wounding patterns associated with various prescribed fire regimes, species groups, and diameter classes.

In Chapter 2, I modeled the effects of prescribed fire on stumpage value at the level of the stand, the most common management unit for land managers. While previous research had modeled monetary effects of prescribed fire at the level of the individual tree (Marschall et al. 2014), and volume effects at the stand level (Stanis et al. 2019), there was a striking paucity of research evaluating monetary effects of prescribed fire at the level of the stand. In this chapter, I attempted to address this research gap by modeling effects of prescribed fire based on fire history, site characteristics, and location within the broader Central Hardwood Region (CHR). The goal of this portion of my thesis was to allow land managers to gain a better understanding of potential effects of prescribed fire on stumpage value based on stand-level factors that are generally quite easy to determine; modeling potential stumpage effects based on this method only requires knowing the number of past prescribed fires, primary stand aspect, and regional location of the site. As expected, and also based on work by Knapp et al. (2017), increasing numbers of prescribed fires and south-facing or west-facing aspects were generally associated with higher value effects from prescribed fire.

One major conclusion of Chapter 2 was the strong effect of location within the CHR on potential stumpage value effects. Stands located within the central and eastern portion of the CHR exhibited much lower rates of potential value loss from prescribed fire compared to sites in the western portion of the region. Specifically, potential value effects were much higher in the Mark Twain National Forest, located near the western boundary of the region, compared to the Hoosier National Forest, the Wayne National Forest, or the Daniel Boone National Forest. While this is likely reflective of more xeric site conditions in Mark Twain National Forest, compared to other sites included in the study, I believe this is largely indicative that management goals associated with prescribed fire are important in understanding potential value effects. Woodland restoration, maintaining wildlife habitat, and promoting shortleaf pine (*Pinus echinata*) regeneration are primary management goals of prescribed fire on the Mark Twain National Forest (Blake 2004, Kinkead 2013), while the practice is more often used specifically to promote oak regeneration in the other national forests included in the study (Bowden 2009, Merritt and Pope 1991). In woodland management settings, preserving value of standing timber may be less important than on sites where maintaining and regenerating high-value oak forests is the primary management goal.

In Chapter 3, I evaluated wounding patterns on sites with variable prescribed fire histories. There were two primary goals of this chapter. First I wanted to evaluate how fire history and site characteristics effect wounding patterns; and second, I wanted to evaluate how tree characteristics (species and diameter) affected wounding patterns. A primary finding in this chapter was that most tangible effects from wounding were caused by open wound types (usually catfaces). Catfaces were the only common wound type that generally caused significant volume loss or a high likelihood of tree grade reduction. Closed wound types such as seams and bark slough generally had very limited effects tree volume and quality.

Fire history and regional location had effects on wounding patterns that largely reflect the findings in Chapter 2. Increasing numbers of prescribed fires were associated with higher likelihoods of wounding and tree quality reduction, and sites on the Mark Twain National Forest generally exhibited much higher tree quality effects from wounding compared to sites on Hoosier, Wayne, or Daniel Boone National Forests. This further supports the notion that higher numbers of prescribed fires and a focus on woodland management are associated with greater effects on tree quality from prescribed fire.

Chapter 3 also demonstrated that wounding patterns were not uniform among all tree species and size classes. Trees with smaller diameters and species with thinner bark were generally associated with higher rates of volume loss and tree quality reduction. Effects of species and tree diameter were often reflected more in tree quality effects than overall likelihood of wounding; fire-adapted species, such as white oak, did not exhibit a particularly low likelihood of wounding, but they did not exhibit any reduction in overall tree quality. Moreover, larger diameter trees were not significantly less likely to exhibit wounding from fire, but they were much less likely to have a reduction in tree grade from fire damage. Often wounding and damage from fire is evaluated as binary; either a tree exhibits evidence of wounding from fire, or it does not. Chapter 3 indicates than an understanding of damage from fire cannot be derived solely from the presence or absence of a wound, as wounding does not have uniform effects on tree quality for all species and size classes, and often does not cause a reduction in tree quality.

The regional scale of the study and the emphasis on stand-level effects from prescribed fire (particularly in Chapter 2) address major holes in existing research, but the retrospective nature of this work carries clear limitations. While we knew the number of past, recorded prescribed fires for each site sampled, there were some variables we could not account for. Fire intensity data were not available for the fires on any of our sites in this study, and data on fuel loading, percent coverage, and details of the burn prescription were only occasionally known. Simply knowing the number of past prescribed fires does not provide a full understanding of the stand's fire history (Knapp 2009). Further, the presence of past wildfire was detected on some sites, although we attempted to avoid sites with recent wildfire history whenever possible. To the greatest degree possible, we attempted to discriminate between damage caused by past wildfire and damage associated with prescribed fire, but in some cases this was quite challenging. There is much need for future research to build upon these findings. A controlled study utilizing thermocouples, temperature-sensitive paint-tags, or other fire-monitoring methods would allow many fire-related variables to be addressed that could not be included in this study. A long term study is currently underway to address these concerns (Stanis and Saunders 2018). We are also currently in the process of implementing lumber recovery studies on selected sites associated with this project to determine effects of prescribed fire on lumber and other wood products, in addition to the effects on potential stumpage value as done in the present study. This will refine our understanding on how wounding and perceived losses in stumpage value measured in the field correlate to actual losses in realized value at the sawmill.

Education and outreach efforts are critical to inform stakeholders about the effects of prescribed fire on timber quality. Shaping perceptions of the effects of prescribed fire to reflect scientific findings remains a challenge. This study and several others (Marschall et al 2014, Wiedenbeck and Schuler 2014, Stanis et al. 2019) find tree-value and tree-quality effects from prescribed fire to be relatively low, but from a management perspective, this may mean little if landowners, timber buyers, and managers perceive more serious effects. Potential loss in timber value is one of the greatest concerns of landowners interested in using prescribed fire (Gerald 2010), and many landowners may perceive the practice to be undesirable if they believe it to cause significant loss in timber value. Aditionally, the amount paid for timber is entirely reliant on timber buyers' willingness to bid. If timber buyers expect prescribed fire to cause a high level of damage to timber, they may bid significantly less (or choose not to bid at all) regardless of actual effects on timber quality and volume. Extension and outreach activities can help bridge the gap between perceived effects of prescribed fire on timber and the results of research on the tree-quality and tree-value effects of the practice. Outreach activities could include workshops and field visits to sites with a history of prescribed fire. Results from upcoming lumber recovery studies, including demonstrations of logs and timber products from trees impacted by prescribed fire will be extremely useful in these outreach activities. While quantitative research on the tree-quality and tree-value of prescribed fire is extremely important for increasing understanding, it may have no tangible effect if it does nothing to shape the attitudes and behaviors of stakeholders. Working to increase the knowledge of landowners, land managers, and timber buyers about the effects of prescribed fire may be the most important task going forward to make this research meaningful.

It is my hope that this thesis provides greater clarity to land managers and landowners on the effects of prescribed fire on standing timber. The benefits of prescribed fire in promoting regeneration of desired species must be carefully weighed against potential negative effects to existing timber resources. This study provides a framework for a more data-based approach to making these important management decisions.

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APPENDIX A. ILLUSTRATIONS OF WOUND TYPE CATEGORIES

Figure A.1-A catface wound on a chestnut oak in the Pine Creek burn unit in the Wayne National Forest.

Figure A. 2-An oval wound on a white oak in the Bull Hollow burn unit in Hoosier National Forest. Tree selected and later felled for lumber recovery study associated with this project. Pink paint roughly outlines wound region.

Figure A. 3-Multiple seams from fire in the Bull Hollow burn unit in the Hoosier National Forest. Tree selected and later felled for lumber recovery study associated with this project. Pink paint roughly outlines wound regions.

Figure A. 4-A seam on a black oak in the Bull Hollow burn unit in the Hoosier National Forest. Tree selected and later felled for lumber recovery study associated with this project. Pink paint roughly outlines wound region.

Figure A. 5-An example of chipping and sloughing bark in the Bull Hollow burn unit in the Hoosier National Forest. Tree selected and later felled for lumber recovery study associated with this project. Pink paint roughly outlines wound region.

APPENDIX B. STUMPAGE PRICE ANALYSIS FOR HARDWOOD TIMBER IN THE CENTRAL HARDWOOD REGION

Table B-1 Mean values per state for sawtimber of each species and grade from 2014-2018.

Species		USFS Grade	IN 5 YR Mean ($/MBF)[1]	MO 5 YR Mean ($/MBF)	OH 5 YR Mean ($/MBF)[5]	5 YR Mean ($/MBF)
HI[2]		1	$398.00	$192.60	$307.80	**$299.47**
HI		2	$320.80	$192.60	$307.80	**$273.73**
HI		3	$277.60	$192.60	$268.79	**$246.33**
SM [3]		1	$613.60	No Data	$558.12	**$585.86**
SM		2	$443.20	No Data	$416.07	**$429.64**
SM		3	$296.40	No Data	$317.58	**$306.99**
WO		1	$640.00	$230.60	$590.78	**$487.13**
WO		2	$467.60	$230.60	$438.74	**$378.98**
WO		3	$310.00	$230.60	$335.25	**$291.95**
RO		1	$550.00	$213.80	$550.14	**$437.98**
RO		2	$418.00	$213.80	$434.37	**$355.39**
RO		3	$312.60	$213.80	$330.51	**$285.64**
TP		1	$400.00	No Data	$324.50	**$362.25**
TP		2	$305.00	No Data	$297.43	**$301.21**
TP		3	$255.00	No Data	$372.82	**$263.91**
OW [4]		1	No Data	$150.20	No Data	**$150.20**
OW		2	No Data	$150.20	No Data	**$150.20**
OW		3	No Data	$150.20	No Data	**$150.20**

1. Mean reported stumpage price in dollars/1000 board feet (International Scale) over 5-year period (2014-2018)
2. HI=black hickory/mockernut hickory/pignut hickory/shellbark hickory/shagbark hickory; SM=sugar maple; WO=white oak/chinkapin oak; RO=northern red oak/black oak/scarlet oak/southern red oak; TP=tulip poplar; OW=post oak/chesnut oak
3. No data on sugar maple or tulip poplar available for Missouri; neither species measured in MTNF sites
4. No data for post oak/chesnut oak stumpage prices available in Ohio or Indiana
5. All board footage values for Ohio were originally reported in Doyle Scale, and converted to International Scale prior to analysis

Appendix B. References

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APPENDIX C. STUDY SITES IN HOOSIER (HNF), MARK TWAIN (MTNF), WAYNE (WNF), AND DANIEL BOONE (DBNF) NATIONAL FOREST

Forest	Unit	Burn #	Aspect	Dom. Species1	Stand Basal Area (ft^2ac^{-1})	Trees per acre2	Mean DBH	Butt-log Volume (bf/ac^{-1})3	Merch. Volume (bf/ac^{-1})4	Percent Volume Loss (Butt-log)	Percent Volume Loss (Merchantable)	$/Acre (pre-fire)5	$ loss/ Acre6	Percent Value Loss/ Acre
DBNF	Buck Creek (DBNF)	2	S	RO	39	35	15.9	2519	5599	1.0	0.4	911	33	3.7
DBNF	Buck Creek (DBNF)	2	N	YP	68	48	19.3	4176	10756	1.6	0.4	1419	25	1.8
DBNF	Buck Creek (DBNF)	2	S	RO	72	46	19.1	5326	12907	8.6	4.5	1947	218	11.2
DBNF	Buck Creek (DBNF)	5	N	YP	59	36	19.0	4395	11170	0.8	0.2	1590	13	0.8
DBNF	Buck Creek (DBNF)	5	S	WO, RO	63	42	18.7	4681	11376	7.0	3.8	1658	134	8.1
DBNF	Buck Creek (DBNF)	5	N	OW	59	53	15.7	4218	9421	4.7	1.5	1184	58	4.9
DBNF	Cave Run	1	S	OW	81	64	17.2	5825	12262	0.0	0.0	1597	0	0.0
DBNF	Cave Run	1	N	OW	64	54	17.0	3889	8930	0.0	0.0	1001	0	0.0
DBNF	Cave Run	1	S	WO, YP	73	50	18.6	3963	10647	0.0	0.0	1498	0	0.0
DBNF	Cave Run	1	N	WO, YP	76	59	17.9	4959	11910	0.9	0.3	1738	17	1.0
DBNF	Cave Run	1	N	OW	79	48	19.2	5868	13621	0.0	0.0	1499	0	0.0
DBNF	Cave Run	1	N	OW, YP	59	56	15.9	3598	6960	0.6	0.3	875	3	0.4

Forest	Unit	Burn #	Aspect	Dom. Species[1]	Stand Basal Area (ft^2ac^{-1})	Trees per acre[2]	Mean DBH	Butt-log Volume (bf/ac^{-1})[3]	Merch. Volume (bf/ac^{-1})[4]	Percent Volume Loss (Butt-log)	Percent Volume Loss (Merchantable)	$/Acre (pre-fire)[5]	$ loss/ Acre[6]	Percent Value Loss/ Acre
DBNF	Chesnut Cliffs	2	S	WO	63	38	19.9	4718	11475	0.2	0.1	1986	1	0.1
DBNF	Control	0	S	WO	63	41	18.4	4479	11205	0.5	0.1	1599	9	0.5
DBNF	Control	0	S	WO	65	40	19.1	4618	11697	0.9	0.2	1920	12	0.6
DBNF	Control	0	S	WO	67	57	16.0	4373	10393	0.1	0.1	1732	2	0.1
DBNF	Wolf-Pen Hollow	2	S	YP, WO	56	42	17.3	3219	7534	3.4	3.3	1078	16	1.5
DBNF	Wolf-Pen Hollow	2	S	WO	73	66	15.9	2531	5683	3.5	1.4	837	28	3.3
HNF	Birdseye	1	S	WO	117	73	18.7	8994	19346	1.3	0.6	3681	42	1.1
HNF	Birdseye	4	S	WO	96	56	18.6	7327	17482	7.4	6.5	3178	200	6.3
HNF	Birdseye	4	S	WO	95	54	19.0	6762	16101	6.0	4.9	2889	202	7.0
HNF	Birdseye	1	S	WO	84	71	15.6	6131	13659	0.6	0.3	2619	17	0.6
HNF	Birdseye	1	S	WO	103	78	16.5	7638	17204	0.3	0.1	3147	19	0.6
HNF	Birdseye	4	S	WO	92	54	18.8	5617	13446	11.1	9.6	2204	267	12.1
HNF	Buck Creek	3	N	WO	108	81	16.9	8055	18440	2.9	1.3	3240	92	2.8
HNF	Buck Creek (HNF)	3	N	WO	80	56	17.1	14232	32692	3.7	1.6	5939	318	5.3
HNF	Buck Creek (HNF)	3	N	WO	91	66	17.4	6926	15620	4.1	3.2	2822	145	5.1
HNF	Bull Hollow	3	N	WO	79	63	16.2	5700	10371	1.7	0.9	1971	55	2.8
HNF	Bull Hollow	3	N	WO	81	57	17.7	6287	14174	1.8	0.8	2794	68	2.4

Forest	Unit	Burn #	Aspect	Dom. Species[1]	Stand Basal Area (ft^2ac^{-1})	Trees per acre[2]	Mean DBH	Butt-log Volume (bf/ac^{-1})[3]	Merch. Volume (bf/ac^{-1})[4]	Percent Volume Loss (Butt-log)	Percent Volume Loss (Merchantable)	$/Acre (pre-fire)[5]	$ loss/ Acre[6]	Percent Value Loss/ Acre
HNF	Bull Hollow	3	S	WO	97	77	16.4	7337	16204	2.3	1.0	2945	73	2.5
HNF	Bull Hollow	3	S	WO, OW	73	56	16.1	5284	9226	0.5	0.3	1723	9	0.5
HNF	Bull Hollow	3	N	WO	93	58	18.6	7194	16117	1.4	0.6	3150	46	1.5
HNF	Bull Hollow	3	N	WO	103	61	19.0	7742	17940	0.2	0.1	3307	7	0.2
HNF	Bull Hollow	3	S	WO	81	62	16.7	6205	13441	1.6	0.7	2631	76	2.9
HNF	Bull Hollow	3	S	WO	97	70	17.4	7287	14471	0.6	0.3	2552	13	0.5
HNF	Bull Hollow	3	S	WO	83	58	17.8	6183	14259	1.4	0.6	2527	52	2.1
HNF	Clover Lick	4	N	WO	81	43	20.1	5379	12270	0.3	0.1	2276	17	0.8
HNF	Clover Lick	4	S	WO	93	54	19.0	6224	13983	15.2	14.8	2759	445	16.1
HNF	Clover Lick	4	N	WO	105	77	16.8	7763	14158	4.8	4.3	2803	148	5.3
HNF	Clover Lick	4	N	WO	93	63	18.2	7036	14856	4.3	2.8	3046	132	4.3
HNF	Clover Lick	4	N	WO, RO	75	53	17.5	5258	10868	3.7	1.8	2007	69	3.5
HNF	Clover Lick	4	S	WO	93	63	17.3	7202	16977	0.5	0.2	3285	15	0.4

Forest	Unit	Burn #	Aspect	Dom. Species[1]	Stand Basal Area ($ft^2 ac^{-1}$)	Trees per acre[2]	Mean DBH	Butt-log Volume (bf/ac^{-1})[3]	Merch. Volume (bf/ac^{-1})[4]	Percent Volume Loss (Butt-log)	Percent Volume Loss (Merchantable)	$/Acre (pre-fire)[5]	$ loss/ Acre[6]	Percent Value Loss/ Acre
HNF	Clover Lick	4	N	WO	79	57	17.3	6062	12648	4.3	2.2	2333	107	4.6
HNF	Control	0	S	WO, OW	76	46	18.2	5411	11931	0.4	0.2	1715	6	0.4
HNF	Control	0	N	WO	99	64	18.1	6375	14220	0.0	0.0	2466	0	0.0
HNF	Control	0	S	WO	95	55	19.6	6118	14300	0.0	0.0	2604	1	0.0
HNF	Control	0	S	WO	89	89	14.3	6240	12312	0.0	0.0	2564	1	0.0
HNF	Control	0	S	WO	73	58	16.4	5417	12173	1.0	0.4	2281	19	0.9
HNF	Control	0	N	RO	96	66	18.2	6172	14006	0.5	0.2	2489	13	0.5
HNF	Control	0	N	WO	81	45	19.6	5403	14125	0.2	0.1	2344	4	0.2
HNF	Control	0	S	WO	109	72	17.9	7665	17526	0.4	0.2	3331	11	0.3
HNF	Control	0	N	WO	73	58	16.3	5591	12205	0.9	0.4	2151	11	0.5
HNF	Diamond	1	N	WO	103	51	20.6	7238	18442	1.4	1.3	2718	57	2.1
HNF	Diamond	2	N	WO, OW	73	32	21.6	5788	15881	0.7	0.3	2051	27	1.3
HNF	Fork Ridge	2	N	OW	95	49	20.7	6245	18091	0.0	0.0	1739	0	0.0
HNF	Fork Ridge	2	N	WO, RO	92	68	17.6	6809	15197	1.9	0.9	2609	54	2.1
HNF	Krausch	2	S	WO	88	66	16.9	5841	13388	2.5	1.8	2160	34	1.6
HNF	Krausch	2	S	SM	76	54	17.9	5073	9712	5.2	3.4	1736	105	6.0

Forest	**Unit**	**Burn #**	**Aspect**	**Dom. Species**[1]	**Stand Basal Area (ft^2ac^{-1})**	**Trees per acre**[2]	**Mean DBH**	**Butt-log Volume (bf/ac^{-1})**[3]	**Merch. Volume (bf/ac^{-1})**[4]	**Percent Volume Loss (Butt-log)**	**Percent Volume Loss (Merchantable)**	**$/Acre (pre-fire)**[5]	**$ loss/ Acre**[6]	**Percent Value Loss/ Acre**
HNF	Long Run	2	N	YP	91	69	16.8	6932	15205	0.0	0.0	2386	0	0.0
HNF	Long Run	2	S	YP	79	42	20.5	5814	16004	2.0	2.0	2085	36	1.7
HNF	Ogala	2	N	WO, OW	83	59	17.3	5319	11728	2.6	1.2	1920	100	5.2
HNF	Ogala	2	N	WO	116	88	17.0	7832	20007	0.1	0.0	3083	3	0.1
HNF	Rock House	1	S	WO	95	49	21.3	7228	18561	4.4	2.9	2956	129	4.4
HNF	Rock House	1	S	WO, OW	84	50	19.5	6412	15609	0.6	0.3	2333	16	0.7
HNF	Tally	2	S	WO	85	58	17.7	6503	14597	1.1	0.5	2702	36	1.3
HNF	Tally	2	S	WO	105	72	17.6	7558	15764	0.1	0.1	3041	3	0.1
HNF	Tally	2	S	WO	89	73	15.8	6204	11005	2.2	1.3	2297	53	2.3
HNF	Wolf	1	N	WO, RO	91	64	17.9	5937	12282	1.3	0.6	2244	24	1.1
HNF	Wolf	1	N	YP	113	91	16.5	7020	16990	1.6	1.2	2399	37	1.5
HNF	Wolf	1	N	YP, SM	88	66	16.9	5381	13458	1.0	0.4	1949	18	0.9
HNF	Wolf	1	N	YP	77	50	18.5	5234	13227	0.9	0.3	1849	33	1.8
MTNF	Cane Ridge	1	N	WO	65	50	16.4	4241	6857	7.6	6.4	1403	93	6.6
MTNF	Cane Ridge	1	N	RO, OW	68	49	17.5	3995	6781	21.3	16.3	1238	315	25.4

Forest	Unit	Burn #	Aspect	Dom. Species[1]	Stand Basal Area (ft^2ac^{-1})	Trees per acre[2]	Mean DBH	Butt-log Volume (bf/ac^{-1})[3]	Merch. Volume (bf/ac^{-1})[4]	Percent Volume Loss (Butt-log)	Percent Volume Loss (Merchantable)	$/Acre (pre-fire)[5]	$ loss/ Acre[6]	Percent Value Loss/ Acre
MTNF	Cane Ridge	1	S	OW	61	56	14.5	3498	5328	16.9	13.8	679	157	23.1
MTNF	Cane Ridge	1	S	WO, OW	68	56	15.6	3835	5706	12.0	9.4	1040	182	17.5
MTNF	Cane Ridge	1	S	OW	63	49	16.1	3339	5208	6.4	4.1	839	99	11.8
MTNF	Cane Ridge	3	S	WO	65	59	14.9	3625	5359	46.5	42.3	1078	602	55.8
MTNF	Cane Ridge	1	N	WO	65	51	16.4	3780	6221	0.0	0.0	1410	0	0.0
MTNF	Cane Ridge	2	S	OW, WO	61	55	14.8	3746	5554	6.4	3.4	978	79	8.1
MTNF	Cane Ridge	3	N	OW	68	61	14.9	4392	6981	18.2	9.8	854	154	18.1
MTNF	Cane Ridge	2	N	RO, WO	75	68	14.9	4303	6682	2.8	1.4	1447	48	3.3
MTNF	Cane Ridge	3	S	OW	64	53	15.8	3939	5938	21.9	18.4	852	248	29.1
MTNF	Cane Ridge	2	N	WO	63	50	16.2	4538	7174	3.7	2.0	1639	52	3.2
MTNF	Cane Ridge	1	N	WO	68	51	16.9	3479	5648	11.9	11.9	1295	183	14.1
MTNF	Cane Ridge	4	N	WO	87	72	15.5	5652	8830	23.0	17.4	1634	431	26.4
MTNF	Cane Ridge	4	N	WO	79	71	15.0	5334	8635	11.8	8.9	1525	184	12.1
MTNF	Cane Ridge	4	N	WO	75	60	15.9	4342	6333	14.0	11.1	1437	235	16.3
MTNF	Cane Ridge	1	N	WO	68	61	15.0	4213	6379	9.5	5.8	1467	190	13.0

Forest	Unit	Burn #	Aspect	Dom. Species[1]	Stand Basal Area (ft^2ac^{-1})	Trees per acre[2]	Mean DBH	Butt-log Volume (bf/ac^{-1})[3]	Merch. Volume (bf/ac^{-1})[4]	Percent Volume Loss (Butt-log)	Percent Volume Loss (Merchantable)	$/Acre (pre-fire)[5]	$ loss/ Acre[6]	Percent Value Loss/ Acre
MTNF	Control	0	S	WO	71	51	17.2	3320	5644	0.0	0.0	1212	0	0.0
MTNF	Wolf Hollow	6	N	WO, OW	75	55	16.8	4687	7449	5.5	4.5	1654	120	7.2
MTNF	Wolf Hollow	0	S	OW, WO	71	73	14.2	4929	7239	2.9	2.1	1299	21	1.6
MTNF	Wolf Hollow	0	N	WO	72	54	16.8	5013	8387	0.0	0.0	1662	0	0.0
MTNF	Wolf Hollow	6	N	WO	71	55	16.5	4886	8201	8.2	6.0	1669	171	10.3
MTNF	Wolf Hollow	6	N	WO	87	73	15.9	5461	8752	5.4	4.1	1760	114	6.5
MTNF	Wolf Hollow	2	S	WO, OW	73	61	16.0	4226	6574	9.7	7.8	1299	136	10.5
MTNF	Wolf Hollow	5	S	RO, WO	60	33	19.4	4627	7584	28.6	24.0	1792	574	32.0
MTNF	Wolf Hollow	0	S	WO	69	53	16.4	5208	8268	0.4	0.2	1812	19	1.1
MTNF	Wolf Hollow	6	S	OW	73	52	17.2	4187	6440	4.1	2.2	1103	68	6.2
MTNF	Wolf Hollow	5	S	WO	76	59	16.1	3358	5494	15.0	13.8	1219	205	16.9
MTNF	Wolf Hollow	5	S	WO	64	55	15.3	3436	5434	5.7	4.2	1088	55	5.1
MTNF	Wolf Hollow	2	N	WO	73	55	16.4	5201	8400	6.9	6.9	2022	125	6.2
MTNF	Wolf Hollow	0	N	WO, RO	65	44	17.5	4539	7709	5.2	5.5	1718	77	4.5
MTNF	Wolf Hollow	0	N	WO	68	46	17.0	4318	7071	0.0	0.0	1492	0	0.0

Forest	Unit	Burn #	Aspect	Dom. Species[1]	Stand Basal Area (ft^2ac^{-1})	Trees per acre[2]	Mean DBH	Butt-log Volume (bf/ac^{-1})[3]	Merch. Volume (bf/ac^{-1})[4]	Percent Volume Loss (Butt-log)	Percent Volume Loss (Merchantable)	$/Acre (pre-fire)[5]	$ loss/ Acre[6]	Percent Value Loss/ Acre
WNF	Big Bailey	3	S	WO, SM	61	51	16.4	3620	6795	0.0	0.0	1357	0	0.0
WNF	Big Bailey	3	S	RO	69	61	15.5	4522	8336	0.0	0.0	1674	0	0.0
WNF	Big Bailey	3	S	RO, OW	71	48	17.4	5373	12091	2.4	1.9	1825	45	2.4
WNF	Big Bailey	3	S	RO, WO	65	52	16.6	4276	9212	3.9	2.6	1610	54	3.3
WNF	Bluegrass	1	N	WO	64	54	16.4	4679	10157	0.2	0.0	1846	2	0.1
WNF	Bluegrass	1	S	WO	76	53	17.6	5861	12144	2.1	2.5	2155	18	0.8
WNF	Bluegrass	1	N	WO	63	38	19.2	4914	12475	2.1	0.6	1847	59	3.2
WNF	Bluegrass	1	N	WO	56	34	20.3	4095	10449	0.0	0.0	1646	0	0.0
WNF	Bluegrass	1	N	WO	69	45	19.8	5015	12271	4.5	6.5	1937	81	4.2
WNF	Bluegrass	1	S	WO	69	43	19.1	5320	12751	0.8	0.3	1891	17	0.9
WNF	Buckhorn	2	N	WO	71	50	17.9	5272	12414	1.4	0.4	1903	35	1.9
WNF	Buckhorn	2	S	WO	59	40	18.7	4451	9754	0.0	0.0	1527	0	0.0
WNF	Buckhorn	2	N	WO, OW	76	45	18.7	5756	14667	3.1	1.8	1948	43	2.2
WNF	Buckhorn	2	S	WO	71	49	17.8	5266	12470	2.5	2.2	2128	34	1.6

Forest	Unit	Burn #	Aspect	Dom. Species[1]	Stand Basal Area (ft^2ac^{-1})	Trees per acre[2]	Mean DBH	Butt-log Volume (bf/ac^{-1})[3]	Merch. Volume (bf/ac^{-1})[4]	Percent Volume Loss (Butt-log)	Percent Volume Loss (Merchantable)	$/Acre (pre-fire)[5]	$ loss/ Acre[6]	Percent Value Loss/ Acre
WNF	Buckhorn	2	N	WO, YP	71	52	18	4758	11411	0.0	0.0	1711	0	0.0
WNF	Buckhorn	2	S	WO	71	48	18	5156	11516	0.4	0.1	1922	8	0.4
WNF	Buckhorn	2	N	WO, OW	71	58	18	4447	10363	2.1	0.7	1505	47	3.1
WNF	Control	0	N	WO, OW	79	50	20	6076	14743	0.0	0.0	2176	0	0.0
WNF	Control	0	S	WO	63	38	20	4817	11701	0.3	0.1	2020	2	0.1
WNF	Control	0	S	WO	60	40	19	3874	9504	0.8	0.2	1564	15	1.0
WNF	Control	0	S	WO, OW	73	53	18	5370	11723	0.0	0.0	1784	0	0.0
WNF	Control	0	N	WO	65	32	21	5018	12761	0.0	0.0	1977	0	0.0
WNF	Control	0	N	WO	65	38	19	4537	10881	0.0	0.0	1901	0	0.0
WNF	Control	0	S	WO	93	59	18	7051	16279	0.0	0.0	2618	0	0.0
WNF	Control	0	N	WO, OW	59	38	19	4457	10813	0.0	0.0	1640	0	0.0
WNF	Pine Creek	1	N	YP	59	44	19	3607	9042	0.0	0.0	1248	0	0.0
WNF	Pine Creek	1	S	RO, WO	84	48	21	4808	12479	0.0	0.0	1739	0	0.0
WNF	Pine Creek	1	N	OW	69	30	23	5260	14842	0.0	0.0	1714	0	0.0

Forest	Unit	Burn #	Aspect	Dom. Species[1]	Stand Basal Area ($ft^2 ac^{-1}$)	Trees per acre[2]	Mean DBH	Butt-log Volume (bf/ac^{-1})[3]	Merch. Volume (bf/ac^{-1})[4]	Percent Volume Loss (Butt-log)	Percent Volume Loss (Merchantable)	$/Acre (pre-fire)[5]	$ loss/ Acre[6]	Percent Value Loss/ Acre
WNF	Pine Creek	2	S	WO, SM	80	44	20.3	5712	14296	0.6	0.2	2103	47	2.2
WNF	Pine Creek	3	S	WO	105	62	19.6	7080	17562	0.5	0.1	3100	25	0.8
WNF	Pine Creek	3	S	WO	75	47	18.6	5092	12973	1.3	0.3	2034	29	1.4
WNF	Pine Creek	3	N	WO	77	49	18.7	5653	14789	0.3	0.1	2415	6	0.2

1. Dominant overstory species group by basal area. WO: *Quercus. alba*, *Q. muehlenbergii*; RO**:** *Q. rubra*, *Q. velutina*, *Q. coccinea*, *Q. falcata*; OW**:** *Q. stellata*, *Q. montana*; YP: *Liriodendron tulipifera*, SM: *Acer saccharum*
2. Trees per acre as estimated by 20 BAF prism plots. Only accounts for trees>10 in. diameter at breast height.
3. Estimated per-acre volume of first 16-ft. butt-log only, in International ¼ bd ft
4. Estimated per-acre volume of merchantable tree up to 9 in top, in International ¼ bd ft
5. Estimated per-acre pre-fire stumpage value of stand
6. Estimated stumpage value lost on a per-acre basis