Prescribed Fire Effects on Tree Grades and Wounds on the Monongahela National Forest, WV

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ABSTRACT

Species traits, including but not exclusive to bark thickness and texture, sprouting ability, and litter bulk density and chemistry, may be related to a stem's potential to withstand potential heating from wildland fire. Trees exhibiting similarities for these properties and others may be classified into two broad functional groups: pyrophytes and pyrophobes. To our knowledge, few research studies have been conducted to determine how prescribed fires may affect wood quality of merchantable tree species in the Appalachian Mountains. Understanding potential relationships between wounding and fire tolerance may assist prescribed fire managers as they seek to promote and expand the use of prescribed fire for management purposes.

To investigate this issue, six locations on the Monongahela National Forest, West Virginia, that had been subjected to one or two mixed intensity and severity prescribed fires since 2012 were selected for stand inventory in 2021. Overstory trees within these burned locations and adjacent, unburned locations were measured and graded using variable radius sampling, and additional landscape features and physiographic factors, such as aspect, elevation, and slope percentage, were also recorded at each variable radius sampling location. The most common, commercially valuable deciduous species encountered were red maple (*Acer rubrum*) (17.5%), white oak (*Quercus alba*) (9.8%), chestnut oak (*Quercus montana*) (32.8%), and northern red oak (*Quercus rubra*) (39.9%). Using field measurements and tree grades, the total number and types of wounds, potential volume loss, charring, basal area, and diameters at breast

height (DBH) were compared by species, burn status (burn or control), and the number of burns. Overall, *A. rubrum* and *Q. rubra* comprised 93% of the total trees exhibiting volume loss from wounds in the burned locations. However, total volume loss only constituted about 3% of the merchantable timber. Trees in the burned locations experiencing volume loss differed significantly between species (p=0.0294) with *Q. rubra* constituting 60% of volume loss trees. In burned and control plots, *A. rubrum* was the most commonly wounded tree with 43.5% of trees having at least one wound. Cat face and oval wounds were the only wound types resulting in volume loss.

Felling and milling stems identified in this study as having potential volume loss from any fire-influenced wounds would be valuable. Furthermore, assessing the potential impact of outer bark char resulting from prescribed fires would be desired to better understand if charring constitutes any potential internal damage to stems. Deploying a similar, field-scale experiment on areas with varying fire frequencies and intensities would be useful to determine how wood quality may be affected after several prescribed burns.

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GENERAL AUDIENCE ABSTRACT

Prescribed fire is a cultural land management practice used historically and currently in many locations around the world. These burns have been and are currently conducted for many reasons, including wildlife habitat management, hazardous fuel reduction, and vegetation control. Trees have innate characteristics that increase potential resistance and resilience to fire damage, however, these characteristics can vary depending on tree species and tree age. These characteristics may include, but are not limited to, bark thickness and texture, litter chemistry, leaf shape, and a species' resprouting strategy.

Prescribed fire is often used in conjunction with other forest management techniques (i.e. herbicides, thinning) in locations where timber value is a management priority, therefore it is important to understand how prescribed fire may affect the growth and quality of merchantable timber species. Few studies have focused on potential wood quality issues posed by the use of prescribed fire in the Appalachian Mountains. Determining if prescribed fires affect wood quality may provide land managers, in many locations, with information that may aid their selection of desired management practices and priorities.

To help address this knowledge gap, a research study was designed and conducted to investigate these issues for the following merchantable timber species in six burned and adjacent, unburned locations of the Monongahela National Forest, West Virginia: red maple (*Acer rubrum*), white oak (*Quercus alba*), chestnut oak (*Q. montana*), and northern red oak (*Q. rubra*).

The results show that one or two mixed intensity and severity prescribed fires, implemented since 2012, resulted in an overall volume loss of 3% from the bottom logs, therefore prescribed fire did not cause a significant reduction in total volume. Two main species, *A. rubrum* and *Q. rubra*, comprised 93% of the trees with wounds resulting in volume loss. However, *Q. rubra* alone constituted 60% of trees with volume loss wounds. The results also show that *A. rubrum* was the most commonly wounded tree with 43.5% having at least one wound. Additional research is warranted to more fully understand these dynamics, including sampling locations that have experienced more prescribed fires and fires with different intensities and milling wounded trees and charred trees located in burned locations.

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Chapter 1. Introduction

Wildland fire has been part of the global landscape for millenia (Pyne, 2010; Ryan et al., 2013; Van Lear and Waldrop, 1989). The frequency and patchiness of fire has often determined the vegetative successional states present in a given location at a specific point in time (Dey and Schweitzer, 2018; Greenberg et al., 2012; Knapp et al., 2015; Knapp et al., 2017; Stambaugh et al., 2017; Waldrop et al., 2012). Each vegetative species may respond differently to wildland fire. Some species have unique properties and varying levels of traits that make them more resistant to fire, such as bark thickness and texture, resprouting strategy, and root-fungal associations (Dey and Schweitzer, 2018; Keyser et al., 2018; Kreye et al., 2013; Smith and Sutherland, 2006; Stambaugh et al., 2017; Stanis et al., 2019; Waldrop et al., 2012; Van Lear and Waldrop, 1989; Varner et al., 2015). Following a disturbance, such as prescribed fire, vegetative competition may be influenced by these differences in traits and properties among species (Waldrop et al., 2012; Van Lear and Waldrop, 1989).

To date, little is known about how prescribed fire affects wood quality of merchantable timber species in the Appalachian Mountains. This region, like many others in the eastern United States, are experiencing an increased use of prescribed fire to achieve long-term restoration and management goals (Carter and Foster, 2004; Coates et al., 2020; Greenberg et al., 2012; Keyser et al., 2018; Kinkead et al., 2017; Knapp et al., 2015; Mann et al., 2020; Pyne, 2010; Ryan et al., 2013; Van Lear and Waldrop, 1989; Waldrop et al., 2012; Wiedenbeck and Schuler, 2014). Additional information about the potential impacts of prescribed fire on wood quality may assist land managers as they anticipate potential fire effects while planning prescribed fire operations.

In this thesis, Chapter 2 highlights current knowledge regarding prescribed fire and wood quality in merchantable hardwood species. Chapter 3 describes how prescribed fires affected wounding and potential volume and value losses of four hardwood species within the Monongahela National Forest in West Virginia. Chapter 4 highlights what was learned from the prescribed fire and wood quality experiment and how additional research may be utilized to derive more broad-scale conclusions regarding potential wood quality impacts resulting from prescribed fire operations.

Chapter 2. Literature Review

2.1 The phenomenon of wildland fire

Prescribed fire is one of the oldest land management practices used in North America today. It was originally used by Native Americans for hunting, clearing land, and warfare (Pyne, 2010; Ryan et al., 2013; Van Lear and Waldrop, 1989). Later, Europeans primarily used fire as a tool to clear agricultural land and promote grazing conditions (Pyne 2010; Waldrop et al., 2012; Van Lear and Waldrop, 1989). Today, people commonly use prescribed fire to mitigate hazardous fuel accumulation, restore fire-dependent ecosystems, and prepare sites for regeneration (Carter and Foster, 2004; Coates et al., 2020; Greenberg et al., 2012; Keyser et al., 2018; Kinkead et al., 2017; Knapp et al., 2015; Mann et al., 2020; Pyne, 2010; Ryan et al., 2013; Waldrop et al., 2012; Wiedenbeck and Schuler, 2014; Van Lear and Waldrop, 1989). Several wildlife species, such as red-cockaded woodpeckers (*Leuconotopicus borealis*) and gopher tortoises (*Gopherus polyphemus*), also depend on fire to maintain their desired habitat conditions (Ryan et al., 2013; Waldrop et al., 2012).

2.2 Prescribed fire as a silvicultural tool

Repeated fire, started by lightning and Native Americans, led to the development and proliferation of forests dominated by fire-tolerant and dependent species, such as many oaks (*Quercus* spp.), hickories (*Carya* spp.), and pines (*Pinus* spp.) (Ryan et al., 2013; Pyne, 2010; Stanis et al., 2019; Waldrop et al., 2012). Where they once thrived in fire-sculpted environments, their regeneration now struggles to compete with regeneration of more mesophytic species (Izbicki et al., 2020; Ryan et al., 2013). These fire-sensitive species, such as maples (*Acer* spp.), American beech (*Fagus grandifolia*.), and yellow-poplar (*Liriodendron tulipifera*), have the ability to change forest composition, structure, and function (Izbicki et al., 2020; Reilly et al., 2016; Ryan et al., 2013). Fire not only alters the way an area looks, but it can have significant impacts on the composition of species present, how they are structurally arranged, and the growth responses of residual stems, which may influence some functions of that forest or ecosystem (Knapp et al., 2015; Knapp et al., 2017; Reilly et al., 2016; Ryan et al., 2013; Schweitzer et al., 2018). With the frequent and persistent use of fire, we tend to see more open and diverse understories, reduced midstories, and a less dense overstory, which are characteristics commonly used to describe woodlands or savannas (Izbicki et al., 2020; Knapp et al., 2015; Knapp et al., 2017; Reilly et al., 2016; Schweitzer et al., 2018; Stanis et al., 2019). Repeated prescribed fire can halt succession by hindering regeneration (Dey and Schweitzer, 2018; Greenberg et al., 2012; Knapp et al., 2015; Knapp et al., 2017; Stambaugh et al., 2017; Waldrop et al., 2012). Changes in forest structure and composition also potentially impact wildlife communities that inhabit those ecosystems by altering nesting sites, food availability, and cover types (Coates et al., 2020; Ryan et al., 2013; Waldrop et al., 2012).

2.3 Prescribed fire intensity and frequency

Most prescribed fires in the eastern United States are conducted in order to achieve low fire intensity and severity (Keyser et al., 2018; Mann et al., 2020; Ryan et al., 2013). These types of fires are often implemented during the dormant season, and generally consume forest floor materials, top-killing only the smallest seedlings and saplings (Dey and Schweitzer, 2018; Schweitzer et al., 2018). Burning during the growing season is much more likely to damage meristematic tissues in trees and reduce the density of smaller diameter stems (Reilly et al., 2016; Waldrop et al., 2012). Forests burned annually do not have time to reaccumulate a reliable surface fuel load, whereas periodically burned (i.e. mean fire return interval of 4-5 years) forests do (Dey and Schweitzer, 2018; Knapp et al., 2015). This increase in surface fuels may increase fire intensity and therefore the likelihood of damage followed by mortality (Coates et al., 2020; Knapp et al., 2015; Ryan et al., 2013). Among fire-adapted species, as tree diameter increases, the likelihood of mortality from prescribed fire decreases (Dey and Schweitzer, 2018; Keyser et al., 2018; Knapp et al., 2017; Kinkead et al., 2017; Wiedenbeck and Schuler, 2014). Most larger diameter trees, except for thin barked species such as American beech (*Fagus grandifolia),* are not as susceptible to direct stem heating from fire, however, prescribed fires can still induce mortality through feeder root mortality with duff consumption, direct stem heating from severe fires, and delayed mortality from fire-influenced wounds that lead to decay or attract insects (Dey and Schweitzer, 2018; Smith and Sutherland, 2001; Stephens et al., 2018; Waldrop et al., 2012; Weidenbeck and Smith, 2018; Van Lear and Waldrop, 1989). Indirect effects of prescribed fires on overstory trees can include decreased competition and increased soil nutrient availability (Waldrop et al., 2012; Van Lear and Waldrop, 1989).

2.4 Tree wounding from prescribed fire

Direct stem heating is one of the ways wildland fires may impact overstory trees through cambial tissue injury or death (Keyser et al., 2018; Stambaugh et al., 2017). Most plant cells experience mortality when heated to 50-65°C (Stambaugh et al., 2017; Waldrop et al., 2012). Tissue may be damaged by temperatures in the lower part of the aforementioned range through exposure over an extended period of time (Stambaugh et al., 2017; Waldrop et al., 2012). Trees killed by fire (snags) play an important ecological role by providing wildlife with areas to rear their young, protect themselves from the elements, and store food (Smith and Sutherland, 2001; Stambaugh et al., 2017).

A common type of fire damage to trees is wounding, or scarring. Wound wood is an important component to consider when managing for wood quality (Stambaugh et al., 2017).

Types of fire scars, or fire-wounds, include catfaces, seams, and bark sloughs (Kinkead et al., 2017; Dey and Schweitzer, 2018; Stanis et al., 2019). However, damage may not be visible immediately post-fire (Kinkead et al., 2017; Wiedenbeck and Smith, 2018). It may take several years after a fire for the bark to fall off and reveal cambial injuries (Kinkead et al., 2017; Smith and Sutherland, 2001; Wiedenbeck and Smith, 2018). Some of the main factors that may determine whether stems will be injured as a result of wildland fire are fire behavior, stem size, and species characteristics, such as bark thickness and texture (Kinkead et al., 2017; Dey and Schweitzer, 2018; Smith and Sutherland, 2001; Wiedenbeck and Smith, 2018). More intense and severe fire behavior, like that of wildfires, often results in more scarring, damage, and potential mortality. However, larger diameter trees with thicker bark have been shown to be less prone to overall wounding (Dey and Schweitzer, 2018; Stanis et al., 2019; Wiedenbeck and Smith, 2018).

Some specific studies have been conducted that focused on trees wounded by prescribed fire. These include the study by Stanis et al. (2019), which was conducted in southern Indiana and looked at species such as white oak (*Q.s alba*), northern red oak (*Q. rubra*), *Carya* spp., and sugar maple (*A. saccharum*). Prescribed fire histories between the 54 study sites varied based on 1, 2, 3, or 4+ prescribed fires over a 25-year period. They found that wounding led to a decrease in grade for 2.8% of the 3,654 total trees samples. However, these grade changes were not evaluated to determine potential differences between species. Another study by Kinkead et al. (2017) was conducted in Missouri and looked at southern red oak (*Q. falcata*), *Carya* spp., and *Q. alba* after two burns conducted in 2003 and 2005/2006. They found that *Q. falcata* had a greater percentage of wounded trees than *Q. alba*. However, they lumped all other species, including *A. rubrum*, into an 'other' species category. These 'other' species were the most susceptible to fire-influenced wounding. <insert concluding statement>

A large multi-state study was conducted by Mann et al. (2020) in Missouri, Indiana, Ohio, and Kentucky after 1, 2, 3, or 4+ prescribed burns had been conducted over the course of a 25 year period. Species of interest included *Q. alba*, chestnut oak (*Q. montana*), *A. saccharum,* and *Q. rubra*. They found *Q. rubra* exhibited higher volume and value losses from wounding than other oak species. Similar conclusions were found by Knapp et al. (2017) in Missouri where they investigated white oak species, red oak species, *Carya spp.,* and others. They found that fire-influenced wounds resulted in less than 3% value loss in stands that had been burned approximately 15-60 times over the course of 60 years.

2.5 How trees protect themselves

A tree's first line of defense against fire is its outer bark. Thicker, less heat-conductive bark is commonly seen in fire-tolerant species and helps to slow stem heating and prevent cambial injury and death (Dey and Schweitzer, 2018; Kinkead et al., 2017; Keyser et al., 2018; Stambaugh et al., 2017; Stanis et al., 2019; Waldrop et al., 2012; Wiedenbeck and Schuler, 2014). If a tree is damaged by fire, it immediately begins to compartmentalize the wound and the surviving tissue works to grow over it (Smith and Sutherland, 2001). This enables wounded trees to ward off fungus, infections, and decay (Dey and Schweitzer, 2018; Smith and Sutherland, 2001). However, closed wounds have the potential to hide pockets of decay which can lead to reduced wood volume and value (Stanis et al., 2019). Wounds which result in cambial damage trigger induced defenses, such as column boundary layers (compartmentalization), barrier zones, and wound wood ribs (Dey and Schweitzer, 2018; Smith and Sutherland, 2001; Wiedenbeck and Smith, 2018). When the bark sloughs off to reveal a wound, the exposed wood is at a higher risk for damage, such as additional charring and disease (Wiedenbeck and Smith, 2018). Compartmentalization of wounded tissue allows trees to prevent cell dehydration and helps ward off infections (Dey and Schweitzer, 2018; Wiedenbeck and Smith, 2018). When the ribs meet, this junction decreases the amount of oxygen available to any fungus in the wound, which can slow decay (Wiedenbeck and Smith, 2018).

2.6 Tree grading

Fire scars and other damage can result in decreased wood quality and value (Mann et al., 2020). The first indication of a tree's quality is perceived by grading the best 3.7 m out of the first 4.9 m, or merchantable stem. This grade accounts for all visible defects of a merchantable stem in order to determine its quality, and thus its value (Mann et al., 2020). Since tree grading ignores the side with the most defects, and fire commonly only damages one side of a stem, most fire damaged trees retain their grade (Mann et al., 2020; Stanis et al., 2019). Studies on wood quality conducted soon after burning may not yield accurate results, as trees have not had time to display total damages and decay that occurred in the incipient stage (Kinkead et al., 2017; Stanis et al., 2019; Wiedenbeck and Schuler, 2014; Wiedenbeck and Smith, 2018). Generally, the larger a wound is, the more likely it will have a significant impact on wood quality (Dey and Schweitzer, 2018). The more damage, decay, and discoloration a tree has the greater the reduction in wood quality (Stanis et al., 2019; Wiedenbeck and Smith, 2018).

2.7 Management Implications

Most wounds caused by prescribed fires tend to seal within ten years (Stambaugh et al., 2017; Wiedenbeck and Smith, 2018). Scars are more likely to be found in areas burned with prescribed fire periodically (every 4-5 years) than those burned very frequently (every 1-2 years) (Dey and Schweitzer, 2018; Stambaugh et al., 2017). This is due to the fact that areas burned every year, or every other year, have a lighter fuel load which is more characteristic of lower intensity fire (Knapp et al., 2015). Therefore, frequent burning would be an important management practice if the main objective was to improve timber quality by reducing scarring and scar size (Stambaugh et al., 2017). Managers should be especially careful with first-entry burns, specifically when they plan to follow it up with more frequent burning (Kinkead et al., 2017; Stambaugh et al., 2017). According to Dey and Schweitzer (2018), harvesting injured trees within 5 years of damage can limit value losses (Stanis et al., 2019; Wiedenbeck and Schuler, 2014).

Chapter 3. Hardwood Tree Grades, Wounds, Volume Losses, and Charring Following Prescribed Fires on the Monongahela National Forest, West Virginia, USA

3.1 Introduction

It has been documented that trees exhibit species-specific, fire-adapted traits (Babl et al., 2020; Smith and Sutherland, 2006). These include, but are not limited to, bark thickness and texture (Dey and Schweitzer, 2018; Keyser et al., 2018; Smith and Sutherland, 2006; Stambaugh et al., 2017; Stanis et al., 2019; Wiedenbeck and Schuler, 2014), resprouting ability (Waldrop et al., 2012; Van Lear and Waldrop, 1989), and leaf physical and chemical properties (Kreye et al., 2013; Varner et al., 2015). Bark thickness, in particular, helps trees to resist potential heat-induced damage arising from wildland fires and capitalizes on the input of nutrients that typically follows low intensity and severity prescribed surface fires (Schweitzer et al., 2018; Waldrop et al., 2012; Van Lear and Waldrop, 1989). The main factors that determine whether stems will be injured or not are fire behavior, time since fire, stem size, and the aforementioned species-specific characteristics, such as bark thickness and texture (Dey and Schweitzer, 2018; Kinkead et al., 2017; Marschall et al. 2014; Smith and Sutherland, 2001; Wiedenbeck and Smith, 2018). Species that possess traits which help them withstand and propagate fire are labeled pyrophytes. Species that possess opposing traits are generally labeled pyrophobes (Blackhall et al., 2017).

Wounds are often noted in stems following wildland fires. Types of wounds include catfaces, seams, and bark sloughs (Kinkead et al., 2017; Dey and Schweitzer, 2018; Stanis et al., 2019). However, fire-influenced damage may not be visible immediately post-fire (Kinkead et al., 2017; Wiedenbeck and Smith, 2018). It may take several years after a fire for the bark to fall off and reveal cambial injuries and wounds, or “scars” (Kinkead et al., 2017; Smith and Sutherland, 2001; Wiedenbeck and Smith, 2018). The location, position, and size of wounds is critically important when considering potential prescribed fire effects. Determining if wounds resulting in volume loss may be related to fire tolerance designations could be helpful for prescribed fire managers, especially when targeting specific burn parameters to maximize silvicultural objectives associated with fire. These objectives include controlling undesired vegetation in the understory and mid-story (Carter and Foster, 2004; Dey and Schweitzer, 2018).

A study by Wiedenbeck and Schuler (2014), in a mesic, mixed oak forest in northeastern West Virginia, looked at wood quality impacts from prescribed fire on red maple (*Acer rubrum*), northern red oak (*Quercus rubra*), white oak (*Q. alba*), and yellow-poplar (*Liriodendron tulipifera).* Trees were harvested five to eight years following two prescribed fires. Minimal fire effects were noted on lumber produced from those trees; with the exception of *Q. rubra*, the second board sawn under the fire-damaged face was clear of defects. Furthermore, Wiedenbeck and Schuler (2014) determined that char, bark slough, small cat faces, and butt scar were superficial in terms of the quality of the underlying wood. Dey and Schweitzer (2018) in their study of oak-dominated systems in North America, concluded that harvesting injured trees within five years of damage may limit volume and value losses (Stanis et al., 2019; Wiedenbeck and Schuler, 2014).

Another study by Stanis et al. (2019) was conducted in various oak-dominated stands in southern Indiana, and the authors determined that prescribed fire did not significantly affect relative volume loss or grade at the stand-level. Another study conducted by Kinkead et al. (2017) in Missouri consisted of a group of red oak species, including southern red oak (*Q. falcata*), a group of white oak species, including *Q. alba*, and hickories (*Carya* spp.). Trees were evaluated after two burns had been conducted in 2003 and 2005/2006. The authors hypothesized that red oak species would have a higher percentage of wounded stems than those in the white oak group due to differences in bark thickness. However, they lumped all other species, including fire-intolerant species, such as *A. rubrum*, into an ‘other’ species category. These ‘other’ species were the most susceptible to fire damage.

To investigate potential tree wounding from prescribed fire in the Appalachian Mountains, a field experiment was conducted on the Monongahela National Forest in West Virginia. One hundred thirty study plots (104 burned; 26 unburned control) were established at six units where one or two mixed intensity and severity prescribed fires had been conducted since 2012 to either promote forest health or increase the quality of wildlife habitat (J. Fry, personal communication, 2021). Four commercially valuable hardwood species were inventoried in the study: *A. rubrum*, *Q. alba*, chestnut oak (*Q. montana)*, and *Q. rubra*. The study hypotheses were:

1. Tree grades will not be affected by the mixed intensity and severity prescribed fires conducted on the Monongahela National Forest since 2012.
2. Wounding will differ by species, with *A. rubrum* and *Q. rubra* exhibiting more wounds than *Q. alba* or *Q. montana*.
3. Significant volume and value losses will not be associated with overstory trees found in the burned locations.

3.2 Methods

3.2.1 Study site

The Monongahela National Forest (MNF) is located within the Allegheny Mountains, part of the broad Appalachian Mountain range, along the eastern edge of West Virginia (Figure 1). The mean annual temperature range is 4℃ to 17℃ and mean precipitation is 116.7 cm (US Climate Data, 2020). Soils within the MNF generally arise from acidic sandstone, shale, and siltstone (Fowler, 2021). Ultisols are the dominant soil order, with the occasional Inceptisol

(USDA Web Soil Survey, 2022). A wide variety of tree species are present on the MNF, including, but not limited to, *A. rubrum*, sugar maple (*A. saccharum*), *Q. rubra*, mockernut hickory (*Carya tomentosa*), *Q. montana*, and yellow birch (*Betula alleghaniensis*).

3.2.2 Unit selection

Six locations within the MNF were selected for assessments of tree grades and measurements of tree wounds. These locations had been burned one or two times since 2012. Burn histories for these locations were obtained solely from management records, and there were no records of burn day parameters or postburn conditions. All units, except one, were burned using hand ignitions; the other burn unit, Big Mountain Unit 6, was ignited aerially using a plastic sphere dispenser (PSD). Adjacent, unburned, or control, locations were located in close proximity to the prescribed burn units. To our knowledge, these control locations had not been exposed to any wildland fires for at least the last 20 years. In total, 130 variable radius plots were established using a prism (basal area factor (BAF) 20). The number of plots was composed of 104 plots within burn units and 26 control plots located adjacent to burn units. The specific location of the variable radius plots were randomly established using the fishnet tool in ArcGIS Pro (ESRI Company, Redlands, CA, USA).

3.2.3 Field Measurements and Assessments

All standing stems greater than or equal to 25.4 cm diameter at breast height (DBH) were inventoried in the BAF 20 variable radius plots. A minimum DBH of 25.4 cm was selected because that is the lower threshold for sawtimber tree DBH. Species was recorded and DBH (cm) was measured for each stem. Dead trees were inventoried and measured when species was discernable. At each location where the BAF prism was utilized, aspect (measured using a clinometer), elevation (m), slope percent, and slope position (upper, middle, or low) were also measured or assessed.

3.2.4 Wound appraisal

Additionally, for each inventoried stem, all wounds above stump height (15.2 cm aboveground) were identified. Wounds occurring below stump height were ignored. Wounds were assumed to be fire-influenced on trees within the burn units if there were visible signs of degradation to the bark or cambium around the wound (Figure 2.) Wounds were classified into four categories: catface, oval, seam, and slough. This deviated from previous studies looking at wounding, such as Marschall et al. (2014) and Stanis et al. (2019), in that the wound category of multiple seams was excluded.

Catfaces were defined as measurable, open, triangular-shaped wounds near the base of a tree with distinct depth and wound ribs present (Smith and Sutherland, 2001). Ovals were classified as open wounds with apparent wound ribs. They were typically elliptically-shaped and located greater than 1.37 m on the stem. Seams appeared as cracks in the bark, but looked like the joint of two wound ribs. Bark slough was similar to a seam, but was distinguished by chipped, peeling, and/or missing pieces of bark (Mann et al., 2020). Regardless of wound type, dimensions such as length, height, depth, and width were measured for each wound. Width was measured at the widest point of the wound, and depth was measured at the deepest point (Mann et al., 2020). For wounds such as seams and bark slough, where no measurable depths were present, a depth of 1.3 cm was assigned (Mann et al., 2020; Stanis et al., 2019).

In addition to these, char was noted and measured for trees within the burned locations, but char was not considered a wound due to its suspected, superficial nature (Stanis et al., 2019; Smith and Sutherland, 2006). However, char was specifically monitored in this study due to the hesitancy of timber buyers within the Appalachian Region to place bids on timber sales containing charred trees out of concern that any char is associated with poor wood quality, marketability, and value (A. Coates, personal communication, 2019). Char was considered any blackening of the tree bark from fire.

3.2.5 Tree grading

Based upon the wound assessments noted in section 3.2.4, and any other potential defects such as rot, tree grades were also assessed for each inventoried stem using the USDA Forest Service hardwood tree grading system (Hanks 1976) and the protocols developed by Loomis (1974). This grade accounts for all visible defects on a merchantable stem in order to determine its quality, and thus its value (Mann et al., 2020), and is based on the second worst face out of the best 3.7 m section of the bottom 4.9 m butt log (Miller and Wiant, 1986). When a fire-related wound was suspected for a given tree within a burned location, as mentioned in section 3.2.4 (Figure 2), these trees were reassessed and given a new grade, taking into account any potential fire-influenced wounds. The following grades could be assigned to each tree: 1, 2, 3, or below grade.

3.2.6 Volume and value loss

For each inventoried and graded tree within the sampling locations, potential volume loss and percentage of cull were calculated for wounds. Specific equations were utilized to approximate potential volume loss and followed those used by Mann et al. (2020), Larsen (2017), and Hilt et al. (1983).

3.2.7 Statistical analyses

All statistical analyses were conducted in JMP Pro 16 (SAS Corporation, Cary, NC, USA) and statistical differences were determined at α=0.05. Basal area (m^2 ha^{-1}) was compared between the burned and unburned locations for all inventoried stems using a Wilcoxon test for non-parametric data (Conover, 1971). Subsequently, all non-commercial species and dead stems were excluded from our analyses. Median tree grades and mean DBH for the four, primary commercial species, *A. rubrum*, *Q. alba*, *Q. montana*, and *Q. rubra*, were compared between the burned and control locations using Wilcoxon tests for non-parametric data (Conover, 1971). To assess potential differences in the probability of encountering wounded stems (by wound count, type, and species) between the burned and control locations, models were assessed using Fisher's Exact Test for binomial data with small sample sizes (Ott and Longnecker, 2015). Potential best fit models to assess the probability of encountering a wounded stem in any of the sampled locations were assessed using the full host of physiographic factors (aspect, elevation, slope percent, slope position) assessed at each sampling locations and the measured or assessed variables at each stem using logistic regression (Ott and Longnecker, 2015).

For the burned trees, separate assessments of wounding for charred trees were also conducted using Fisher's Exact Test for binomial data (Ott and Longnecker, 2015). Potential models to assess the probability of encountering a charred tree within the burned locations were assessed using the full host of aforementioned physiographic factors assessed at each sampling location and the measured or assessed variables at each stem using logistic regression (Ott and Longnecker, 2015).

Potential volume and value loss comparisons between the burned and control locations were planned, however, few trees possessed wounds constituting either volume or value losses (see section 3.3.1.3). Therefore, no statistical comparisons were conducted to assess differences between the burned and control locations for these variables.

3.3 Results

3.3.1 Burned and control comparisons

3.3.1.1 Basal area, diameter at breast height, and tree grades

In total, 622 trees were measured within the burned and control locations on the MNF in West Virginia. Four hundred eighty-nine of those trees were in burned locations, and the other 133 trees were in control locations. Total, live, and dead basal area did not differ between the burned and unburned locations (all $p>0.05$) (Table 1). For the four selected commercial species, mean DBH only differed between the burned and control locations for *A. rubrum* ($p=0.0028$) (Table 2). Mean DBH differences between species within the burned and control units were similar, regardless of burn status (both $p<0.0001$): *A. rubrum* was the smallest, followed by *Q. montana*, which was not significantly different than *Q. alba*. *Quercus rubra* stems were the largest, but they did not differ from *Q. montana* (Table 2). Median tree grades did not differ within species between the burned and control locations (all $p>0.1719$) (Table 3). No trees within the burned or control locations contained wounds or defects that altered tree grade.

3.3.1.2 Wounds

A significantly higher probability of finding wounded stems in burned locations than in control locations existed for all species except *Q. alba* (all other $p<0.0019$) (Table 4) and the probability of finding each wound type was greater in burned locations than control locations (all $p<0.0253$) (Table 5). However, according to our visual assessment and determination of fire-influenced wounds on trees located in the burned locations (Figure 2), the probability of encountering a fire-influenced wound did not differ by species within the burned locations ($p=0.3477$) (Table 6). Without regard for whether or not wounds within the burned locations were categorized as fire-influenced wounds, the probability of encountering an oval wound in *A.*

rubrum stems was greater in burned locations than control locations (p=0.0318) (Table 5). The probability of encountering *Q. montana* and *Q. rubra* stems with seams and sloughs was greater in burned locations than control locations (all p<0.0213) (Table 5). Without regard for burn status (burned or control), the likelihood of encountering an oval wound differed by species (p=0.0184) and was greatest for *A. rubrum* (Table 5).

Comprehensive best fit models to determine the probability of encountering a wounded tree in the burned or control locations, without considering whether or not a wound was fire-influenced within the burned locations, were assessed using the following factors: burn status, burn area, number of burns, DBH, species, aspect, elevation, slope percent, and slope position. The best fit model ($r^2=0.08$) included only burn status (burned or control) (p<0.0001) and tree species (p=0.0471). According to the odds ratios for this model, an individual would be:

a. 6.3 times more likely to encounter a wounded tree in a burned location (p<0.0001).
b. 2.6 times more likely to encounter a wounded *A. rubrum* than a wounded *Q. alba* (p=0.0388*)*.
c. 2.7 times more likely to encounter a wounded *Q. rubra* than a wounded *Q. alba*. (p=0.0192)

3.3.1.3 Volume and value losses

Two stems within the control locations possessed wounds that constituted volume losses, one *Q. alba* and one *Q. montana*. Twenty-two stems within the burned locations possessed wounds that constituted volume losses: seven with volume loss not related to fire and fifteen stems with volume loss associated with fire-influenced wounds. The probability of encountering any stems with volume loss wounds in the burned locations did not differ by species (p=0.0891) (Table 7), but the probability of encountering stems with fire-influenced volume loss wounds did differ by species (p=0.0294), with *A. rubrum* possessing the highest percentage of trees with fire-influenced volume loss, followed by *Q. rubra* and *Q. montana* (Table 7).

For all trees sustaining wounds that would result in volume loss, regardless of burn status, all volume losses constituted less than 3% of the first 4.9 m log, therefore value loss was not calculated for any of these stems.

3.3.2 Charred stems

Mean DBH for charred stems differed by species (p<0.0001), with *Q. rubra* stems being significantly larger than *Q. montana* and *A. rubrum*, but not significantly different than *Q. alba* (Table 8). The probability of char presence on stems differed between the six burned locations (p<0.0001) (Table 9), but these differences were not significantly related to the number of prescribed burns (either 1 or 2; p=0.4733) (Table 10). The range of char presence on stems within the burned units was 54.5%-98.6% (Table 9), with both the low and high percentages for that range constituting locations that were burned only once.

Additionally, the probability of charring did not differ by species (p=0.2146) (Table 11). For trees that were both charred and wounded, the probability of encountering stems with oval wounds differed by species (p=0.0299) and was highest for *A. rubrum*, followed by *Q. montana* and *Q. rubra*; no oval wounds were found on charred and wounded *Q. alba* stems (Table 11). Again, the probability of charring on wounded trees did not differ by the number of prescribed fires (p=0.4733) (Table 10), but the probability of charring on wounded stems for *Q. rubra* was greater in locations that were burned twice (p=0.0187) (Table 11).

Based upon the number of burns, burn area, physiographic factors, and tree assessments conducted within the burned locations, the best fit model to determine the probability of encountering a charred stem included only burn area ($p<0.0001$; $r^2=0.24$). According to the odds ratios, an individual would be:

a. 56.7 times more likely to find a charred tree in BMU6 than BMU5 ($p<0.0001$).
b. 17.5 times more likely to find a charred tree in HUAB than BMU5 ($p=0.0003$).
c. 4.0 times more likely to find a charred tree in HUC than BMU5 ($p=0.01$).
d. 14.1 times more likely to find a charred tree in BMU6 than HUC ($p=0.0165$).
e. 51.0 times more likely to find a charred tree in BMU6 than MMS ($p=0.0002$).
f. 15.8 times more likely to find a charred tree in HUAB than MMS ($p=0.0005$).
g. 3.6 times more likely to find a charred tree in HUC than MMS ($p=0.0184$).
h. 17 times more likely to find a charred tree in BMU6 than RAM ($p=0.0269$).

Mean char height range was 0.48 – 2.13 m and both locations at the poles of this range were burned once since 2012. The burn objectives for these locations differed (0.48 m: timber; 2.13 m: wildlife) (Table 9). However, BMU6 had the highest odds ratios from the best fit model, but had only the second greatest mean char height (1.76 m) (Table 9).

3.4 Discussion

3.4.1 Tree grades

In this study, tree grades did not differ when fire-related wounds and defects were considered (Table 3). Similar studies using USDA Forest Service hardwood tree grades documented small percentages of trees with grade changes due to fire-influenced wounding (Mann et al., 2020; Stanis et al., 2019; Wiedenbeck and Schuler, 2014). In a study by Stanis et al. (2019) of *Q. alba*, *Q. rubra*, *Carya* spp., and *A. saccharum* on the Hoosier National Forest in southern Indiana, 54 sites were evaluated that had been burned at least once over the previous 25 years, but included some locations that were burned multiple times (2, 3, or 4+). The authors determined that wounding led to a grade reduction in 2.8% of the 3,654 sampled trees. However, none of these grade changes were attributed to specific species, but were generalized for all species. They also found that grade change increased to 7% for all species except *Q. alba* after four prescribed fires.

A comparable study by Mann et al. (2020) conducted on the Hoosier (Indiana), Mark Twain (Missouri), Wayne (Ohio), and Daniel Boone (Kentucky) National Forests looked at species such as *A. saccharum, Q. alba, Q. montana*, *Q. rubra*. They classified stands into prescribed fire histories of 1, 2, 3, or 4+ prescribed fires in the last 25 years. They found that fire-related wounds led to a grade reduction in 6.6% of the 2,008 hardwood trees sampled. Another study by Wiedenbeck and Schuler (2014) conducted in northeastern West Virginia, looked *A. rubrum*, *Q. alba*, *Q. montana*, *Q. rubra*, and *L. tulipifera*. previous prescribed fires had been conducted in 2002 and 2005 before the study began. They found that 10 out of 79 (12%) trees selected and milled showed a reduction in grade or scale volume due to substantial fire effects. However, 7 of those 10 stems were *A. rubrum*. The authors hypothesized these grade reductions were due to a higher fire intensity and increased fire behavior.

Based upon the comparison of our study on the MNF to the other studies, it may be hypothesized that a larger sample size or a longer period of time since the last fire occurred may lead to potential grade changes on the MNF. In areas burned one year prior to the study, some wounds were likely still hidden underneath the outer bark and were not observed (Kinkead et al., 2017; Smith and Sutherland, 2001; Wiedenbeck and Schuler, 2014; Wiedenbeck and Smith, 2018).

3.4.2 Wounding

In our study, in the burned locations, wounds occurred on 37.6% of trees (Table 6). This is greater than the 19.3% found by Kinkead et al. (2017) in their study of red and white oaks and hickories in Missouri. However, our result was comparable to the percent of wounded trees found in their thin + burn treatment (32.4%). Similar to our study (Table 6), they also found that *A. rubrum*, categorized as an ‘other’ species in their group comparisons, was most susceptible to fire damage. Our study also found that for all species (*A. rubrum*, *Q. alba*, *Q. montana*, and *Q. rubra*) the percent of trees wounded increased after two prescribed fires (Table 10). The actual number of wounded stems increased for *Q. alba* and *Q. rubra* (Table 10). However, a study by Schweitzer et al. (2018) in central Alabama looked at species such as *A. rubrum*, *Q. alba*, *Q. montana*, and various pine (*Pinus* spp.) species. They classified one fire as an infrequent fire regime and three fires as a frequent fire regime, and found that wounding may increase after three dormant season prescribed fires. They also found that thinning along with frequent fire (every 1-2 years) led to the greatest number of bole wounds.

In our study, it often was difficult to assess whether or not a wound had been caused by fire, especially in areas with two fires. If locations had been burned once and a wound was present with char in it, then that wound was not assumed to be fire-influenced (Figure 2). It was difficult to determine if a wound was fire-influenced in locations that had been burned more than once because the wound may have been caused by the first prescribed fire, not the most current prescribed fire. The mean char heights and patchy nature of char being found on individual trees led us to think that most of the burned locations were subjected to mixed intensity and severity prescribed fires. On trees with no char present, it was especially difficult to determine if a wound was caused by fire or not. As mentioned previously in section 4.1, in areas burned one year prior to the study, some wounds may have resided underneath the bark and were therefore unrecorded (Kinkead et al., 2017).

3.4.3 Volume and value losses

In this study, the probability of encountering a stem with fire-influenced wounds resulting in volume loss differed by species. *Acer rubrum* had the most trees with fire-influenced wounds resulting in volume loss, followed by *Q. rubra*, and *Q. montana* (Table 7). Similarly, in the multi-state study conducted by Mann et al. (2020), the authors found that *Q. rubra* experienced higher value loss than other oak species, and that as the number of prescribed burns implemented grew, so did sawtimber volume and value loss. Their study showed that volume and value losses increased by +0.9% and +1.5% per burn over a 25-year period. In our study, for all trees exhibiting wounds that may result in volume loss, all volume losses constituted less than 3% of the first 4.9 m log. Similar conclusions were found by Knapp et al. (2017) in Missouri in their study of white oaks, red oaks, hickories, and other species. They found that fire-influenced wounds resulted in less than 3% value loss in stands following 60 years of prescribed burning. This agrees with our conclusion on the MNF that all volume and value losses appeared to be very minimal following prescribed fires.

In our study, specific value losses were not calculated due to so few trees possessing wounds constituting both volume and value loss. For those few trees that were suspected to contain volume loss, the volume losses were minimal and were confined to locations close to the ground. However, a study by Marschall et al. (2014) conducted in Missouri looked at red oaks (*Q. velutina*, *Q. rubra*, and *Q. coccinea*) following 3-4 prescribed fires over a 10-14 year period, and found that the fire-influenced butt logs of merchantable red oaks only lost approximately 10% of their commercial value after harvesting. Trees were harvested a maximum of 14 years after the fire damage occurred. Assuming this is the same for oak stands throughout the eastern US, the value loss associated with prescribed fire is relatively minor (Kinkead et al., 2017; Smith and Sutherland, 2001; Wiedenbeck and Smith, 2018).

3.4.4 Management implications

It has been shown that harvesting wounded stems 5-10 years after a burn will minimize volume and value losses (Dey and Schweitzer, 2018; Schweitzer et al., 2018; Weidenbeck and Schuler, 2014). A study by Stambaugh et al. (2017) showed that in a periodic prescribed fire regime (mean fire return interval 5 years), wounds would be expected to close prior to the next burn if wounds were small. As time since fire increased, wounds would have a chance to seal before subsequent exposure to the next fire. However, fuels would reaccumulate over this time period, therefore higher fire intensity of any subsequent burns many increase the likelihood of a wounding (Stambaugh et al., 2017). Therefore, selecting a desired fire return interval may benefit from considerations of fuel reaccumulation and time needed for potential wound closures.

It has been shown that conducting a prescribed fire right after thinning can lead to a greater percentage of stems with bole wounds than either of those practices by themselves (Dey and Schweitzer, 2018; Kinkead et al., 2017; Schweitzer et al., 2018). Prescribed fire alone is not likely to accomplish management objectives associated with forest structure in a timely manner, therefore it is recommended that another management practice be used in combination with fire, such as precommercial or commercial thinning (Dey and Schweitzer, 2018; Kinkead et al., 2017). The long-term benefits of thinning and prescribed fire to promote desired structural conditions and species compositions in eastern oak forests were documented by Waldrop et al.

(2016) and Oakman et al. (2019) in western North Carolina. However, wildlife habitat was the primary management objective at this location, not timber management.

The Monongahela National Forest plans to continue the use of prescribed fire in our burned locations. In our study, no direct effects of measurable wood quality were obtained because no stems were felled and milled to evaluate lumber quality and potential defects. Continued research is warranted at this site and others where prescribed fire has been used in Appalachian Mountain forest management to determine the effects of prescribed fire on potential value losses in final products. Char is a concern for timber buyers within this region, therefore precommercial and commercial thinning and final harvest operations will continue to be hampered by this suspicion. Documented evidence of the direct effects of fire on wood quality may further assist land managers as they determine how to accomplish their long-term management objectives in specific locations.

3.5. Conclusions

Comprehensively, our results from an evaluation of six locations subjected to 1 or 2 prescribed burns on the Monongahela National Forest since 2012 suggested that: 1. Median grade was not impacted by these prescribed fires (Table 3); 2. stem wounding, overall, was greater in the burned locations (37.8% of stems) than the control locations (8.7%) (Table 5 and the best fit probability model, section 3.3.1.2), but additional, visual diagnoses of whether or not a wound was fire-influenced in the burned locations suggested that actual fire-influenced wounds accounted for a much smaller percentage of stems (only 13.5% of stems) (Table 6); 3. All volume and value losses appeared minimal within these locations, regardless of burn status; and 4. the probability of charring did not differ by species within the burned locations (Table 11), nor the number of fires (Table 10). Char was not considered a wound for this exercise and no felling, sawing, or milling was conducted to actually assess wood quality. Therefore, continued research is warranted at this site to determine how prescribed fires may impact actual volume and value losses for both wounded and/or charred trees and to determine if char and any of the wounds noted within the burned units constitute additional volume and value losses as time since fire increases or additional burns are conducted. Additional research within this region is justified to determine how differences in fire behavior and time since fire impact responses to heating for these species and additional, commercially marketable species.

3.6 References

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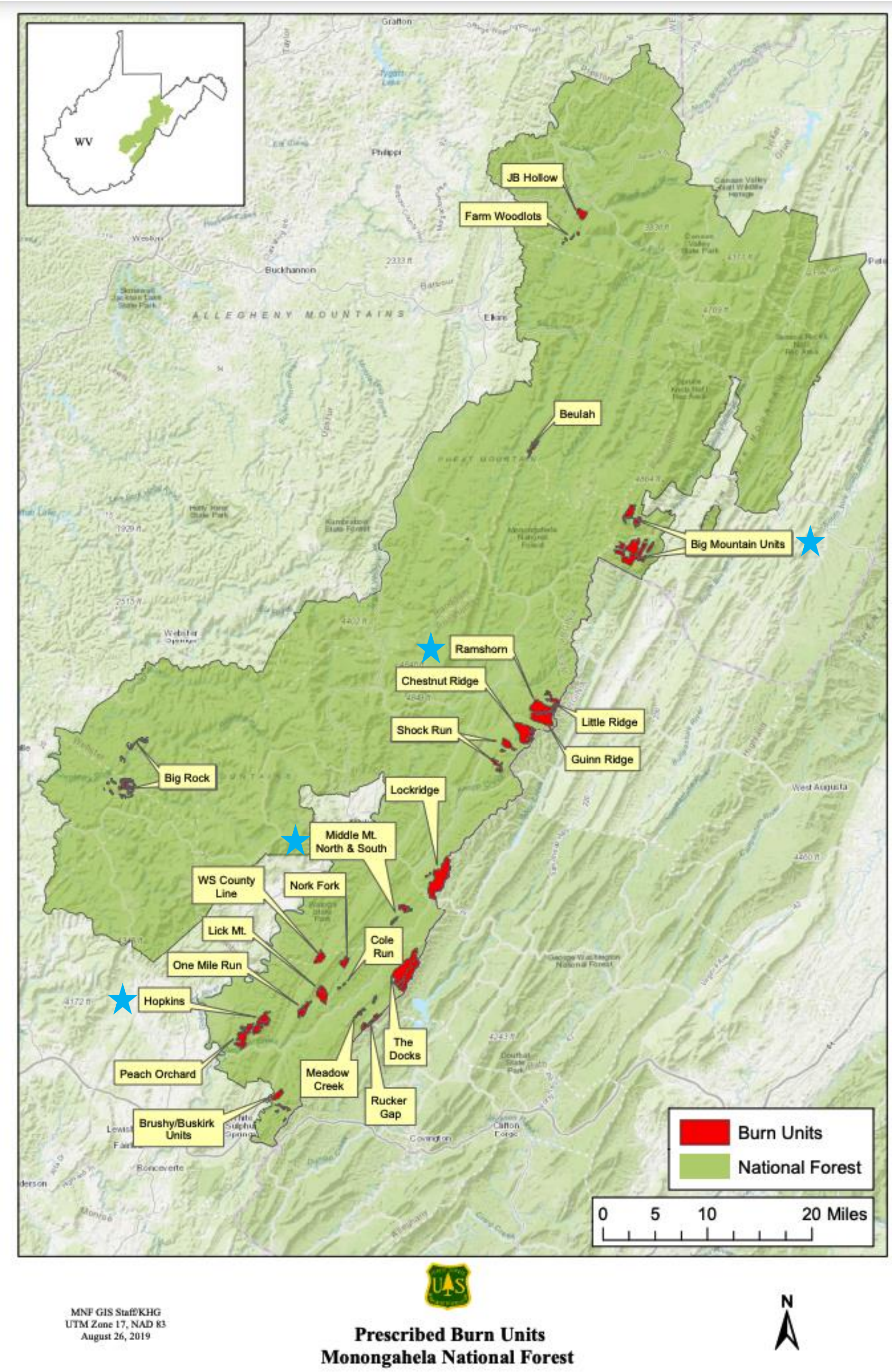

Figure 1. Location of the Monongahela National Forest in West Virginia, USA, and burn units within the Forest. The following were selected for assessment of tree grades, measurements of wounds, and observations of charring: Big Mountain Unit 5 (BMU5), Big Mountain Unit 6 (BMU6), Middle Mountain South (MMS), Hopkins Unit A&B (HUAB), Hopkins Unit C (HUC), and Ramshorn (RAM).

Figure 2. Pictures of tree wounds and char found on the Monongahela National Forest, West Virginia, USA: a. char at base of tree, b. catface, c. oval, d. seam, e. bark sloughing off to reveal a wound, f. tree with char, oval, and bark slough.

Table 1. Total, live, and dead basal area (m^2ha^{-1}) within the burned and control plots measured on the Monongahela National Forest, WV, USA.

<table>
<tr><th colspan="4">Total Basal Area (m^2ha^{-1})</th></tr>
<tr><th>Burn Status</th><th>Mean</th><th>Standard Error of Mean</th><th>p-value</th></tr>
<tr><td>Burn (n=104)</td><td>16.5</td><td>0.8</td><td rowspan="2">0.2227</td></tr>
<tr><td>Control (n=26)</td><td>18.7</td><td>1.5</td></tr>
<tr><th colspan="4">Live Basal Area (m^2ha^{-1})</th></tr>
<tr><th>Burn Status</th><th>Mean</th><th>Standard Error of Mean</th><th>p-value</th></tr>
<tr><td>Burn (n=104)</td><td>15.7</td><td>0.8</td><td rowspan="2">0.2167</td></tr>
<tr><td>Control (n=26)</td><td>18.2</td><td>1.6</td></tr>
<tr><th colspan="4">Dead Basal Area (m^2ha^{-1})</th></tr>
<tr><th>Burn Status</th><th>Mean</th><th>Standard Error of Mean</th><th>p-value</th></tr>
<tr><td>Burn (n=104)</td><td>0.8</td><td>0.3</td><td rowspan="2">0.6933</td></tr>
<tr><td>Control (n=26)</td><td>0.5</td><td>0.3</td></tr>
</table>

Table 2. Mean diameter breast height (DBH) (cm) differences by burn status within and between species for live trees within the burn and control units of the Monongahela National Forest, WV, USA. Letter notations listed with the mean values indicate significant differences between burn status or species.

Differences by burn status within species

Species	**Burn Status**	**Mean DBH (cm)**	**Standard Error of the Mean (cm)**	**Wilcoxon p-value**
Acer rubrum (n=84)	Burn (n=62)	38.3 A	1.5	0.0028
	Control (n=19)	30.5 B	1.1	
Quercus alba (n=47)	Burn (n=35)	46.9	2.3	0.2243
	Control (n=10)	40.9	4.1	
Quercus montana (n=157)	Burn (n=112)	43.6	1.2	0.1818
	Control (n=38)	41.0	2.2	
Quercus rubra (n=191)	Burn (n=147)	54.9	1.4	0.2139
	Control (n=36)	50.8	2.5	

Differences by burn status between species

Species	**Burn Units**			**Control Units**		
	Mean DBH (cm)	**Standard Error of the Mean (cm)**	**Steel-Dwass p-value**	**Mean DBH (cm)**	**Standard Error of the Mean (cm)**	**Steel-Dwass p-value**
Acer rubrum	38.3 C	1.5	<0.0001	30.5 C	1.1	<0.0001
Quercus alba	46.9 AB	2.2		40.9 AB	4.1	
Quercus montana	43.6 B	1.2		41.0 B	2.2	
Quercus rubra	54.9 A	1.3		50.8 A	2.5	

Table 3. Median grade by species for live trees in the burned and control plots measured on the Monongahela National Forest, WV, USA.

Species	**Burn Status**	**Median Tree Grade**	**Wilcoxon Score Mean**	**p-value**
Acer rubrum	Burn (n=62)	2	0.46	0.1719
	Control (n=19)	3	0.61	
Quercus alba	Burn (n=35)	1	0.45	0.2219
	Control (n=10)	2	0.63	
Quercus montana	Burn (n=112)	1	0.48	0.2236
	Control (n=38)	1.5	0.58	
Quercus rubra	Burn (n=147)	1	0.51	0.4661
	Control (n=36)	1	0.47	

Table 4. Number of wounds by species for the live trees in the burned and control plots measured on the Monongahela National Forest, WV, USA.

Species	**Burn Status**	**Number of Wounds per Tree**					**Total Count Wounded**
		0	**1**	**2**	**3**	**4**	
Acer rubrum	**Burn (n=62)**	35 (56.5%)	20 (32.2%)	6 (9.7%)	0 (0.0%)	1 (1.6%)	27 (43.5%)
	Control (n=19)	18 (94.7%)	1 (5.3%)	0 (0.0%)	0 (0.0%)	0 (0.0%)	1 (5.3%)
							p-value 0.0019
Quercus alba	**Burn (n=35)**	28 (80.0%)	6 (17.1%)	1 (2.9%)	0 (0.0%)	0 (0.0%)	7 (20.0%)
	Control (n=10)	9 (90.0%)	1 (10.0%)	0 (0.0%)	0 (0.0%)	0 (0.0%)	1 (10.0%)
							p-value 0.6611
Quercus montana	**Burn (n=112)**	75 (67.0%)	25 (22.3%)	8 (7.1%)	4 (3.6%)	0 (0.0%)	37 (33.0%)
	Control (n=38)	35 (92.1%)	2 (5.3%)	1 (2.6%)	0 (0.0%)	0 (0.0%)	3 (7.9%)
							p-value 0.0025
Quercus rubra	**Burn (n=147)**	84 (57.1%)	49 (33.4%)	11 (7.5%)	3 (2.0%)	0 (0.0%)	63 (42.9%)
	Control (n=36)	32 (88.9%)	3 (8.3%)	1 (2.8%)	0 (0.0%)	0 (0.0%)	4 (11.1%)
							p-value 0.0004
Overall Burn Status	**Burn (n=356)**	222 (62.4%)	100 (28.1%)	26 (7.2%)	7 (2.0%)	1 (0.3%)	134 (37.6%)
	Control (n=103)	94 (91.3%)	7 (6.8%)	2 (1.9%)	0 (0.0%)	0 (0.0%)	9 (8.7%)
							p-value <0.0001

Table 5. Tally of wound type by species for the live trees in the burned and control plots measured on the Monongahela National Forest, WV, USA. Fisher's Exact states the probably of yes for the response variable between the levels.

Wounding by Burn Status within Species					
Species	**Burn Status**	**Catface**	**Oval**	**Seam**	**Slough**
Acer rubrum	**Burn (n=62)**	4 (6.5%)	13 (21.0%)	4 (6.5%)	11 (17.7%)
	Control (n=19)	0 (0.0%)	1 (5.3%)	0 (0.0%)	0 (0.0%)
	Fisher's Exact p-value	0.5681	0.0318	0.5681	0.0590
Quercus alba	**Burn (n=35)**	1 (3%)	1 (2.9%)	4 (11.4%)	2 (5.7%)
	Control (n=10)	0 (0%)	1 (10.0%)	0 (0.0%)	0 (0.0%)
	Fisher's Exact p-value	1.000	1.000	0.5607	1.000
Quercus montana	**Burn (n=112)**	6 (5.4%)	10 (8.9%)	14 (12.5%)	16 (14.3%)
	Control (n=38)	1 (2.6%)	3 (7.9%)	0 (0.0%)	0 (0.05)
	Fisher's Exact p-value	0.6793	0.2914	0.0213	0.0122
Quercus rubra	**Burn (n=147)**	18 (12.2%)	9 (6.1%)	25 (17.0%)	20 (13.6%)
	Control (n=36)	1 (2.8%)	2 (5.6%)	2 (5.6%)	0 (0.0%)
	Fisher's Exact p-value	0.1290	0.6894	0.0051	0.0151
Wounding by Burn Status		**Catface**	**Oval**	**Seam**	**Slough**
	Burn (n=356)	29 (8.1%)	33 (9.3%)	47 (13.2%)	49 (13.8%)
	Control (n=103)	2 (1.9%)	7 (6.8%)	2 (1.9%)	0 (0.0%)
	Fisher's Exact p-value	0.0253	0.0107	<0.0001	<0.0001
Wounding by Species		**Catface**	**Oval**	**Seam**	**Slough**
	***Acer rubrum* (n=81)**	4 (4.9%)	14 (17.2%)	4 (4.9%)	11 (13.6%)
	***Quercus alba* (n=45)**	1 (2.2%)	2 (4.4%)	4 (8.9%)	2 (4.4%)
	***Quercus montana* (n=150)**	7 (4.7%)	13 (8.7%)	14 (9.3%)	16 (10.7%)
	***Quercus rubra* (n=183)**	19 (10.4%)	11 (6.0%)	27 (17.8%)	20 (10.9%)
	Fisher's Exact p-value	0.1109	0.0184	0.1810	0.4695

Table 6. Visual estimation of wounded trees within the burn units of the Monongahela National Forest, WV, USA that possessed fire-influenced wounds (either catface, oval, seam, or slough).

Species	**Wounded Count**	**Fire-influenced Wounds**	
		Count	**Fisher's Exact p-value**
Acer rubrum (n=62)	27 (43.5%)	11 (17.7%)	0.3477
Quercus alba (n=35)	7 (20.0%)	2 (5.7%)	
Quercus montana (n=112)	37 (33.0%)	13 (11.6%)	
Quercus rubra (n=147)	63 (42.9%)	22 (15.0%)	
Total	134 (37.6%)	48 (35.8%)	

Table 7. Volume loss for trees within the burned units of the Monongahela National Forest, WV, USA.

Species	**Any Volume Loss**	**Fire Volume Loss Only**
Acer rubrum (n=62)	7 (11.3%)	5 (8.9%)
Quercus alba (n=35)	0 (0%)	0 (0%)
Quercus montana (n=112)	4 (3.6%)	1 (0.9%)
Quercus rubra (n=147)	11 (7.5%)	9 (6.1%)
Fisher's Exact p-value	0.0891	0.0294

Table 8. Mean diameter breast height (DBH) (cm) by species for charred trees within the burn units of the Monongahela National Forest, WV, USA. Letter notations associated with the mean values indicate significant differences between species.

Species	**Mean DBH (cm)**	**Standard Error of the Mean**	**Wilcoxon p-value**
Acer rubrum* *(n=32)	40.7 B	2.2	<0.0001
Quercus alba* *(n=9)	51.9 AB	4.1	
Quercus montana* *(n=68)	41.6 B	1.3	
Quercus rubra* *(n=86)	55.7 A	1.8	

Table 9. Stem counts for charred stems located within the burn areas evaluated on the Monongahela National Forest, WV, USA.

Burn Unit	**Number of Burns**	**Burn 1**	**Burn 2**	**Burn purpose**	**Mean Char Height (m)**	**Stems in Burn Unit**	**Charred Stems**	
							Count	**Fisher's Exact p-value**
BMU5	1	Apr. 2019	n/a	Timber	0.48	44	24 (54.5%)	p<0.0001
BMU6	1	Apr. 2018	n/a	Timber	1.76	69	68 (98.6%)	
HUAB	2	Apr. 2014	Apr. 2018	Wildlife	1.12	44	42 (95.5%)	
HUC	2	Nov. 2015	Apr. 2018	Wildlife	0.73	35	29 (82.9%)	
MMS	2	Apr. 2012	Mar. 2021	Wildlife	0.75	42	24 (57.1%)	
RAM	1	Mar. 2019	n/a	Wildlife	2.13	10	8 (80.0%)	
					1.16	244		

Table 10. Number of wounds per stem for charred trees by species based upon the number of prescribed fires since 2012 on the Monongahela National Forest, WV, USA.

<table>
<tr><th rowspan="2">Species</th><th rowspan="2">Number of Burns</th><th colspan="5">Number of Wounds per Charred Tree</th><th colspan="2" rowspan="2">Total Count Charred and Wounded</th></tr>
<tr><th>0</th><th>1</th><th>2</th><th>3</th><th>4</th></tr>
<tr><td rowspan="3"><i>Acer rubrum</i>
<i>(n=32)</i></td><td>One
(n=24)</td><td>11
(45.8%)</td><td>10
(41.7%)</td><td>3
(12.5%)</td><td>0</td><td>0</td><td colspan="2">13
(54.2%)</td></tr>
<tr><td>Two
(n=8)</td><td>3
(37.5%)</td><td>2
(25.0%)</td><td>2
(25.0%)</td><td>0</td><td>1
(12.5%)</td><td colspan="2">5
(62.5%)</td></tr>
<tr><td colspan="6"></td><td>p-value</td><td>1.000</td></tr>
<tr><td rowspan="3"><i>Quercus alba</i>
<i>(n=9)</i></td><td>One
(n=0)</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td colspan="2">0</td></tr>
<tr><td>Two
(n=9)</td><td>7
(77.8%)</td><td>1
(11.1%)</td><td>1
(11.1%)</td><td>0</td><td>0</td><td colspan="2">2
(22.2%)</td></tr>
<tr><td colspan="6"></td><td>p-value</td><td>1.000</td></tr>
<tr><td rowspan="3"><i>Quercus montana</i>
<i>(n=68)</i></td><td>One
(n=16)</td><td>10
(62.5%)</td><td>4
(25.0%)</td><td>2
(12.5%)</td><td>0</td><td>0</td><td colspan="2">6
(37.5%)</td></tr>
<tr><td>Two
(n=52)</td><td>32
(61.5%)</td><td>11
(21.2%)</td><td>5
(9.6%)</td><td>4
(7.7%)</td><td>0</td><td colspan="2">20
(38.5%)</td></tr>
<tr><td colspan="6"></td><td>p-value</td><td>1.000</td></tr>
<tr><td rowspan="3"><i>Quercus rubra</i>
<i>(n=86)</i></td><td>One
(n=60)</td><td>38
(63.3%)</td><td>19
(31.7%)</td><td>3
(5.0%)</td><td>0</td><td>0</td><td colspan="2">22
(36.7%)</td></tr>
<tr><td>Two
(n=26)</td><td>9
(34.6%)</td><td>11
(42.4%)</td><td>3
(11.5%)</td><td>3
(11.5%)</td><td>0</td><td colspan="2">17
(65.4%)</td></tr>
<tr><td colspan="6"></td><td>p-value</td><td>0.0187</td></tr>
<tr><td rowspan="3">Cumulative Species</td><td>One
(n=100)</td><td>59
(59.0%)</td><td>33
(33.0%)</td><td>8
(8.0%)</td><td>0</td><td>0</td><td colspan="2">41
(41.0%)</td></tr>
<tr><td>Two
(n=95)</td><td>51
(53.7%)</td><td>25
(26.3%)</td><td>11
(11.6%)</td><td>7
(7.4%)</td><td>1
(1.0%)</td><td colspan="2">44
(46.3%)</td></tr>
<tr><td colspan="6"></td><td>p-value</td><td>0.4733</td></tr>
</table>

Table 11. Charred trees within the burn units possessing additional wounds by species, Monongahela National Forest, WV, USA.

Species	**Number of Charred Trees**	**Charred Trees with Wounds**			
		Catface	**Oval**	**Seam**	**Slough**
Acer rubrum (n=41)	32 (78.0%)	2 (6.3%)	8 (25.0%)	2 (6.3%)	11 (34.3%)
Quercus alba (n=14)	9 (64.3%)	1 (11.1%)	0 (0.0%)	1 (11.1%)	1 (11.1%)
Quercus montana (n=79)	68 (86.1%)	3 (4.4%)	7 (10.3%)	6 (8.8%)	5 (7.4%)
Quercus rubra (n=110)	86 (78.2%)	10 (11.6%)	5 (5.9%)	13 (15.1%)	20 (23.3%)
Fisher's Exact p-value	0.2146	0.3485	0.0299	0.6393	0.4765

Chapter 4. Conclusion

Prescribed fire is an important, and commonly implemented land management practice in the southeastern United States (Carter and Foster, 2004; Coates et al., 2020; Greenberg et al., 2012; Keyser et al., 2018; Kinkead et al., 2017; Knapp et al., 2015; Mann et al., 2020; Pyne, 2010; Ryan et al., 2013; Van Lear and Waldrop, 1989; Waldrop et al., 2012; Wiedenbeck and Schuler, 2014). Species exhibit traits conducive to fire managed environments, such as varying levels of bark thickness and texture, resprouting strategy, and root-fungal associations (Dey and Schweitzer, 2018; Keyser et al., 2018; Kreye et al., 2013; Smith and Sutherland, 2006; Stambaugh et al., 2017; Stanis et al., 2019; Waldrop et al., 2012; Van Lear and Waldrop, 1989; Varner et al., 2015). After a period of fire exclusion, the eastern region of the United States is experiencing an increased interest in and implementation of prescribed fire to achieve restoration and management goals, mitigate hazardous fuel accumulation, and to prepare sites for regeneration (Carter and Foster, 2004; Coates et al., 2020; Greenberg et al., 2012; Keyser et al., 2018; Kinkead et al., 2017; Knapp et al., 2015; Mann et al., 2020; Pyne, 2010; Ryan et al., 2013; Van Lear and Waldrop, 1989; Waldrop et al., 2012; Wiedenbeck and Schuler, 2014). However, little is known about the potential negative effects prescribed fires can have on timber volume and quality. The experiment outlined in Chapter 3 attempted to investigate the potential impacts prescribed fire can have on stem wounding and charring dynamics.

Based upon this experiment, it did not appear that median tree grades differed between burn and control locations. Yet, the probability of encountering a wounded stem was 2.72 times greater in burned locations than control locations. Out of all species, red maple (*Acer rubrum*) possessed the highest percentage of stems with wounds and fire-influenced volume loss wounds. The probability of char being present on any wounded stems was not affected by the number of prescribed fires in that location, but was greatest for northern red oak (*Quercus rubra*) in areas that had been burned twice. However, there did not seem to be a trend relating mean char heights to the number or intent of burns. Regardless of burn status, volume loss averaged around 3% of the first 4.9 m log, resulting in minimal expected value losses. When these results are considered with other studies that have evaluated tree grades, wounds, and potential volume or value losses throughout the United States (Dey and Schweitzer, 2018; Kinkead et al., 2017; Mann et al., 2020; Marschall et al., 2014; Stambaugh et al., 2017; Stanis et al., 2019; Wiedenbeck and Schuler, 2014), it would appear that potential wounding and volume and value losses might be related to: 1). Specific tree species, 2). fire intensity and severity, which might be related to the number of burns conducted in an area and the length of time that has passed since a wildland fire (wildfire or prescribed fire) last occurred, as well as 3) length of time that passed between the last prescribed fire and the investigation of stem and wood quality.

Future investigations of char are warranted on the Monongahela National Forest at our study locations to determine what potential impacts outer bark char has on interior wood quality due to the apprehension most foresters and timber buyers have regarding char. Additionally, felling and milling stems within the burned and control locations to determine the impacts of wounding on actual volume and value losses will more comprehensively address the actual volume and value losses that can be measured following the prescribed fires that have been documented at these locations since 2012.

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