EFFECTS OF PRESCRIBED BURNING IN MISSOURI OZARK UPLAND FORESTS

A Thesis
presented to
the Faculty of the Graduate School
at the University of Missouri-Columbia

In Partial Fulfillment
of the Requirements for the Degree

Master of Science

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by
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DECEMBER 2007

The undersigned, appointed by the dean of the Graduate School, have examined the thesis entitled:

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a candidate for the degree of Master of Science, and hereby certify that, in their opinion, it is worthy of acceptance.

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DEDICATION

For Grandpa Al and Grandpa Jim

ACKNOWLEDGEMENTS

I would like to thank Dr. Rose-Marie Muzika and Dr. Richard Guyette for guiding me throughout my research project. They both offered help and insight that made my project much more meaningful. I would also like to thank Rose-Marie for being a great advisor, not only on issues of academia, but also on greater issues of life.

Many thanks go to all the professors that have helped me with my project, most importantly Dr. Mark Ellersieck and Dr. John Fresen. I would also like to thank all those that assisted me throughout my project, including the Missouri Department of Conservation, the University of Missouri Tree-Ring Lab, and the Forest Ecology Lab. I thank Joe Marschall, Jeremy Kolaks, and Kim Houf for contributing time and energy to help with my project. Without the help from these people and many more this project would not have been possible.

I acknowledge everyone that has encouraged me through the years, especially my friends and family. Special thanks go to Rachel for supporting me through the final stages of my research. The most important thanks goes to my mom and dad, because without their love and encouragement I never would have made it this far.

This project was funded by the Missouri Department of Conservation and the U.S Forest Service Forest Health Monitoring Program, Northeastern Area, St. Paul, MN.

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ABSTRACT

Prescribed fire is used in Missouri to achieve various silvicultural goals, but the use of burning in upland Ozark forests raises many questions that research has yet to answer. The purpose of this study is to examine the effects of prescribed burning on fire scars, overstory tree vigor, and ground flora vegetation. Data were collected from 22 burn units in five counties in the Missouri Ozark. Fire scar data were collected for *Quercus alba* L., *Quercus coccinea* Muench., *Quercus shumardii* Buckl., *Quercus stellata* Waengh., *Quercus velutina* Lam., *Carya* spp. Nutt., and *Pinus echinata* Mill. *Pinus echinata* was the most resistant to fire scarring, and *Quercus coccinea* and *Quercus shumardii* were the least resistant. Regression analysis reveals that stem bark char height, a proxy for fire intensity, is the most effective postfire predictor of percentage of trees scarred and extent of scarring. Landscape features such as aspect, fetch, and slope steepness were also important predictors of extent of scarring for some species. Tree vigor in *Quercus coccinea* was negatively correlated with fire injury, but there was no difference in tree vigor in burned and unburned stands. Tree vigor of *Quercus velutina* was higher in burned stands, although the difference may not be biologically significant. Grass cover was highest in burned stands, and tree seedling cover was highest in stands burned one year before sampling. Models developed from this study can aid managers in assessment of potential injury to trees based on landscape features and fire intensity.

CHAPTER 1: INTRODUCTION

Before EuroAmerican settlement, landscapes of the Ozark Highlands were greatly influenced by anthropogenic fires. In the uplands, periodic surface fires created an open woodland mosaic characterized by variable canopy cover and diverse ground flora (Nigh 1992). *Pinus echinata* Mill. was a major overstory component across many areas of the Ozark uplands (Nelson 1997, Batek et al. 1999, Harlan 2007), but frequent fires and widespread logging of seed trees removed most *Pinus echinata* by 1909 (Guyette and Dey 1997, Flader 2004). Woodland livestock grazing and frequent fires in the late 1800s and early 1900s provided additional disturbances that altered the landscape structure of the Ozarks (Benac and Flader 2004). Fire suppression starting in the 1930s converted the upland Ozark landscape from the woodland mosaic found during pre-EuroAmerican settlement to the more homogenous, closed-canopy forests that exist today (Nigh 2004). Currently the upland Ozark forests are dominated by *Quercus alba* L., *Quercus velutina* Lamb, and *Quercus coccinea* Muench., with minor representations from *Pinus echinata*, *Carya* spp. Nutt., and other hardwoods (Hahn and Spencer 1991, Nigh and Schroeder 2002).

Prescribed fire on Missouri public lands first started in the late 1950s and early 1960s, when glades and woodland areas at Caney Mountain Conservation Area in Ozark County were burned by the Missouri Department of Conservation (MDC) to promote forage for the wild turkey (*Meleagris gallopovo* L.) and other wildlife (Lewis et al. 1964). Prescribed burning did not continue in Missouri until the mid 1980s, when wildlife biologists from MDC started burning Long Bald Mountain at Caney Mountain to reduce woody undergrowth and promote herbaceous vegetation in glades and woodlands. By the early 1990s public agencies across the Ozarks were implementing prescribed burning plans. Agencies that currently burn upland forests in the Ozarks include MDC, Missouri Department of Natural Resources, Ozark National Scenic Riverways, U.S. Forest Service, and The Nature Conservancy.

The primary goal of prescribed fire in Missouri Ozark uplands is the restoration of woodland, savanna, and glade communities. To achieve those goals, the burn objectives include topkilling saplings, increasing cover of conservative native herbaceous species, reducing fuel loads, and creating a mosaic of fire intensities across the landscape. Other areas in Missouri, such as study sites established for the Joint Fire Science Program and The Nature Conservancy's Chilton Creek Management Area, have similar prescription goals but also include research goals that evaluate the effects of fire on fuel loading, vegetation, and timber resources. While prescribed fire may be the solution for some restoration goals, the use of burning in upland Ozark forests raises many questions that research has yet to answer.

Research Goals

The purpose of this study is to answer some questions that arise from the use of prescribed fire in upland forests of the Missouri Ozarks. Many public agencies in Missouri manage forests for multiple resources, and the effects of fire on those resources needs to be fully explored. The impacts of fire on commercial timber resources is a major concern for forest managers across Missouri, but no quantifiable information exists to address those concerns. Overstory tree vigor may also be impacted by fire-related scarring, but few studies have linked fire scars with tree vigor in eastern hardwoods. Increased herbaceous cover is often a goal of prescribed burning, but no studies have examined fire effects across the Ozarks to assess the success of this burning objective. The value of this study is to determine prescribed fire effects in the Ozarks and provide forest managers with results that may help guide future management directions.

Chapter 2 examines landscapes currently managed with prescribed fire and provides an assessment of fire-caused scars, mortality, and basal cavities in the Missouri Ozarks. Chapter 2 also presents models that predict fire-caused scarring of Ozark hardwoods using a postfire assessor of fire intensity (stem bark char) and landscape features.

Chapter 3 compares tree vigor of two common upland oak species, *Quercus coccinea* and *Quercus velutina*, in burned and unburned areas of the Ozarks. It also examines the relationship between fire-caused scarring and tree vigor in burned areas.

Chapter 4 addresses the response of physiognomic plant groups to fire across the Ozarks by examining cover of herbaceous and woody understory species in burned and unburned areas.

Chapter 5 provides a summary of findings from the three previous chapters, and provides land managers guidelines about the effects of prescribed fire in upland Ozark forests.

CHAPTER 2: FIRE SCARS FROM PRESCRIBED BURNING

Introduction

Fire in Missouri

For centuries fire has influenced the composition and structure of eastern oak-dominated forests (Abrams 1992, Abrams 2000, Johnson et al. 2002). In Missouri where lightning-caused fires are rare (Westin 1992, Missouri Department of Conservation 2007), anthropogenic ignitions were the primary source of historic fires (Pyne et al. 1996, Guyette et al. 2006). Fire regimes in the Missouri Ozarks have been linked with human population densities and topographic roughness (Guyette and Cutter 1997, Guyette et al. 2002). Although some people have questioned the impact of anthropogenic fires in the Missouri Ozarks (Steyermark 1959), others have concluded that the Ozarks were dominated historically by open woodlands, savannas, and glades maintained by anthropogenic fires (Nigh 1992, Hartman 2005, Nelson 2005).

Before EuroAmerican settlement, the flora of the Ozark Highlands was influenced by anthropogenic fires. Low intensity surface fires created open woodlands with diverse ground flora composed of grasses and forbs (Nigh 1992, Nelson 2005). *Pinus echinata* Mill. once dominated areas of the Ozark Highlands (Nelson 1997, Batek et al. 1999), but widespread logging following EuroAmerican settlement removed most *P. echinata* by 1909 (Flader 2004). Overgrazing and frequent fires in the late 1800s and early 1900s, followed by decades of fire suppression starting in the 1930s, converted the Ozark landscape from an open woodland mosaic to the more homogenous, closed-canopy forest that exist today (Nigh 2004). Currently, the forests of the Ozark Highlands are dominated by *Quercus alba* L., *Quercus velutina* Lamb., and *Quercus coccinea* Muench. with minor representations from *P. echinata*, *Carya* Nutt., and other hardwoods (Hahn and Spencer 1991, Nigh and Schroeder 2002).

Prescribed Burning and Fire-Caused Scars

Prescribed burning is often a necessary tool to achieve certain ecosystem goals and manage fire-dependent natural communities (Vose 2000, Nelson 2005). In Missouri, prescribed fire is currently being used to increase herbaceous diversity, reduce fuel loads, and restore natural communities. A major concern about using prescribed fire is the likelihood of fire injury to commercial timber resources (Hartman 2005).

Fire scars form when excessive heat from fire kills the vascular cambium and woundwood is formed to cover the killed area (Gill 1974, Guyette and Stambaugh 2004). In forests managed with prescribed fire, fire scars represent an important factor that can affect timber quality and volume (Toole 1959, Berry and Beaton 1972, Loomis 1974, Wendel and Smith 1986). Fire scars serve as an entryway for insect and fungal pathogens that cause extensive decay and reduce the quality of the butt log (Hepting 1941, Toole and Furnival 1957, Berry and Beaton 1972, Hepting and Shigo 1972, Wendel and Smith 1986).

Oaks respond to fire injuries by compartmentalizing the wound and thereby resisting the spread of decay (Shigo 1984, Smith and Sutherland 1999), but examinations of fire scars in oaks have shown that 99-100% of open fire scars lead to decay (Kaufert 1933, Berry and Beaton 1972). Volume losses can reach up to 14% or 25 board feet of cull per tree for an average sized wound (Kaufert 1933, Hepting and Shigo 1972). Basal scars on oaks have also shown to be an effective predictor of sawtimber volume and quality losses from fires (Loomis 1974, Loomis 1989).

Stem Bark Char Height, Fire Intensity, and Fire Injury

Since heating from fire causes cambium injury, the intensity of a prescribed burn is a useful predictor for the number and size of fire-caused scars in a burned area. Unfortunately the intensity of a prescribed burn is rarely noted or difficult to quantify. Loomis (1973) stated that bark blackening, including bark char, was a good indicator of temperature and exposure time of a fire. In northern hardwoods, bark char has been linked with percent circumference killed of overstory trees (Simard et al. 1986).

Bark char height has been related to tree mortality in conifers (Dixon et al. 1984, Regelbrugge and Conrad 1993, Menges and Deyrup 2001, Beverly and Martell 2003, Keyser et al. 2006) and eastern hardwoods (Loomis 1973, Regelbrugge and Smith 1994), and therefore is a good proxy for fire intensity. Bark char does not necessarily indicate a fire-related injury (Smith and Sutherland 2001), but it can be a useful postfire predictor of scar sizes for hardwoods (Loomis 1973, Simard et al. 1986).

Fire Behavior and Landscape Features

Landscape features can influence fire intensity and therefore directly affect the extent of fire-caused stem scars (Pyne et al. 1996, Jenkins et al. 1997). Aspect and slope steepness are two landscape features that determine solar radiation exposure on a slope and therefore directly affect air temperature and fuel moisture levels. These factors contribute to fire intensity, which causes higher fire temperatures on southwest-facing slopes and relatively intense fires on very steep slopes (Pyne et al. 1996, Schwemlein and Williams 2006). Studying a wildfire in the Arkansas Ozarks, Jenkins et al. (1997) found a higher percentage of trees scarred on steeper slopes and on south- and west-facing slopes. Following a wildfire in an Appalachian forest, steeper slopes were linked with higher fire intensities and higher rates of overstory mortality (McCarthy 1928).

Upper slope positions are more xeric than lower slope positions (Parker 1982), and therefore fire may have a relatively higher intensity at upper slope positions. The distance to the bottom of a hill, or fetch, is a useful variable for describing slope position on the landscape. Jenkins et al. (1997) used fetch as a predictor of percentage trees scarred, and he found a positive relationship between scarring and fetch. Following a prescribed fire in the southern Appalachians, Elliott et al. (1999) related high fire intensities on ridge tops with relatively high overstory mortality.

Other factors that contribute to fire intensity include fuel loads and wind currents (Hare 1965, Gill 1973, Van Lear and Waldrop 1989), but these variables are of little use in a postfire fire assessment of fire damage. Season of burning also affects fire intensity and subsequent heat-related tree injuries (Brose and Van Lear 1999). In Missouri, public agencies typically used a prescribed burning window from November thru mid-April for burning of forest uplands, and therefore season of burn for most areas is categorized simply as dormant season.

Fire Intensity, Ignition Pattern, and Management Objectives

Prescribed fire intensity can be controlled through prescription, fuel preparation, and ignition patterns (Pyne et al. 1996). In Missouri, most prescribed burns are ignited using the ring-head fire technique (Missouri Natural Resources Conservation Service 2004). For this ignition technique, fire is lit in a ring around a burn unit. The burn unit is typically a knob or hillside, and the fire is ignited in the lower slopes. The fire increases in intensity as it moves upslope and draws inward, which may cause dangerous convection currents that cause flare-ups and could injure trees (Wade and Lunsford 1989, Pyne et al. 1996). Managers in Missouri utilize the ring-head fire technique because it is relatively simple to implement, can be used over a large area, and results in a moderately intense fire that may reduce woody understory vegetation in accordance with prescribed fire goals.

Other ignition techniques that may be suitable for the topographically rough Ozarks include backfiring, strip head firing, spot firing, or delayed aerial ignition devices (DAID or ping-pong ball system). Backfiring results in low intensity fires that move slowly against the wind or slope, but the technique is relatively more expensive to implement then other ignition patterns (Pyne 1996). Strip head firing results in a relatively rapid flame spread as successive strips are lit, and fire intensity can be adjusted with the strip widths. Spot firing is similar to strip head firing, except spots are lit in predetermined locations within the burn unit, and spot spacing is used to adjust the fire intensity (Pyne 1996). Ignition with DAID allows for rapid firing with the use of a helicopter and creates a mosaic pattern of ignition across the landscape (Wade and Lunsford 1989). Although ring-head fires are currently the ignition technique of choice in Missouri, future prescription goals that depend on controlling fire intensity may require use of alternative ignition techniques.

Bark, Tree Size, and Fire-Caused Scars

Fire intensity and flame residence time are both correlated with cambial tissue necrosis (Bova and Dickinson 2005), but bark can insulate the cambium from lethal temperatures (Hare 1965, Hengst and Dawson 1994). Thickness is one attribute of bark that has been linked with resistance to fire, although other bark properties also contribute to protection from fire (Hare 1965, Harmon 1984, Hengst and Dawson 1994, Gignoux et al. 1997). Bark characteristics vary among species and can account for differences in resistance to fire injury among tree species (Hare 1965, Harmon 1984).

Tree diameter is positively correlated with bark thickness and has shown to have a positive relationship with resistance to fire injury (Paulsell 1957, Loomis 1973, Harmon 1984, Guyette and Stambaugh 2004). Many studies have shown that mortality following fire is highest in the small diameter classes, both due to thinner bark and higher percentage of cambium killed (McCarthy 1928, McCarthy and Sims 1935, Paulsell 1957, Scowcraft 1966, Godsey 1988, Huddle and Pallardy 1996, Blake and Schuette 2000, Elliott and Vose 2005, Hutchinson et al. 2005).

Prescribed Fire and Percentage Trees Scarred

Low-intensity surface fires such as those used in prescribed burning typically do not scar all trees. At Turkey Mountain in Arkansas, Jenkins et al. (1997) reported 37-52% of trees scarred following a wildfire. At University Forest in southeastern Missouri, Paulsell (1957) found that on periodically burned plots 34% of surviving trees had scars, while on annually burned plots 27% of surviving trees had scars. A study also conducted at University Forest found that scarring of surviving trees was 53% and 69% on annually and periodically burned plots (Scowcraft 1966)   Following a single prescribed fire in an Appalachian oak-hickory forest, 66% of overstory trees showed signs of fire injury (Wendel and Smith 1986).

Fire Scar Type, Scar Size, and Decay

Scars may be classified according to the tree response to injury. Following a fire-caused injury, trees will form woundwood that arises from the edges of the fire scar. Several years post-fire injury, some trees may completely close the wound and thereby protect the wood from insects and fungal pathogens. These “closed” fire scars are characterized by a vertical seam formed when the woundwood ribs have grown so as to close the scar (Smith and Sutherland 2001).

Fire scars too wide for woundwood to completely compartmentalize the injury leave an exposed, “open” wood face. Most open fire scars are dubbed “cat-face” scars, a term used to denote an open, triangular shaped scar (Mathews 2003). The term cat-face is derived from the turpentine industry, where v-shaped carvings used to gather turpentine resemble the whiskers on a cat’s face (Florida Division of Forestry 2007). Other types of open scars include oval- or irregularly-shaped scars.

In oaks, fire scars are associated with cull and extensive decay (Burns 1955, Toole 1959, Berry and Beaton 1972, Hepting and Shigo 1972). Examination of oaks in the central hardwood region revealed that 99% of open scars and 64% of closed scars led to decay (Berry and Beaton 1972). Rates of decay often differ among species (Toole 1959, Berry and Beaton 1972, Hepting and Shigo 1972, Wendel and Smith 1986), and characterizing scar type by species may provide insight into future decay following fire.

The size of a fire scar has been shown to be directly linked to the extent of damage from decay insects and fungi (Hepting 1941, Toole and Furnival 1957). Thus large fire scars and subsequent decay can cause significant degradation to timber logs (Loomis 1973). Fire scars from *Quercus velutina*, *Quercus coccinea, Quercus stellata* Waengh., and *Quercus alba* have been used to predict the loss of quality and volume in oak sawtimber (Loomis 1974, 1989).

Basal Cavities Formed From Fire Scars

Prescribed fire has both a positive and negative impact on wildlife habitat. Fire creates basal scars that eventually lead to cavities that may be used by wildlife (Van Lear and Harlow 2002, Keyser and Ford 2006) and may also create habitat more suitable for cavity-dwelling species (Boyles and Aubrey 2006). But fire also consumes cavity trees, snags, and coarse woody debris utilized by wildlife (Horton and Mannan 1988, Conner et al. 1991). Repeated use of prescribed fire can create more open forest conditions that may be detrimental to certain wildlife species (Tiedemann et al. 2000).

Project Goals

The goal of this project was to characterize basal scars caused by prescribed fire in the Missouri Ozarks. Specific goals for this project include 1) to determine the relationship between scarring and fire intensity; 2) to examine the influence of landscape features on scarring; 3) to establish the fire sensitivity of the most abundant and economically important upland Ozark species, including *Q. alba, Q. coccinea, Q. stellata, Q. velutina, Carya* spp., and *P. echinata*; and 4) to determine the percentage of fire-caused scars that form basal cavities. The results from this study will provide managers insight into the potential impacts of using prescribed fire in areas managed for timber and wildlife resources.

Methods

Study Area

The study areas were located in forest uplands across the Missouri Ozark Highlands (Figure 2.1). Twenty-two burn units currently managed with prescribed fire were selected for sampling: one in the Meramec River Hills Ecological Subsection, three in the White River Hills Ecological Subsection, and eighteen in the Current River Hills Ecological Subsection (Nigh and Schroeder 2002). All areas are managed by public agencies, with the exception of The Nature Conservancy's Chilton Creek Management Area. A summary of fire history and primary burn objectives for each burn unit is provided in Table 2.1 and Table 2.2.

The study area in the Meramec River Hills is part of the Pea Ridge Conservation Area (CA) managed by the Missouri Department of Conservation (MDC). The 37 ha burn unit is located in the East Meramec Oak Woodland/Forest Hills Ecological Landtype Association (LTA). Prescribed burning occurred in the unit in March of 1995, 1997, 1999, and 2004. Primary management objectives in the area include using prescribed fire to restore a pine-oak woodland by reducing woody undergrowth and encouraging growth of grasses and forbs.

All study areas in the White River Hills are part of the Caney Mountain CA managed by MDC. The area is within the Gainesville Dolomite Glade/Oak Woodland

Knobs LTA. In the 1950s and 1960s, selected glades on Caney Mountain CA were burned to promote forage for wildlife and create habitat more suitable for wild turkeys (*Meleagris gallopovo* L.) (Lewis et al. 1964). Prescribed fire ceased at Caney Mountain CA until the 1980s, when wildlife biologists began landscape level burning throughout portions of the area. Current prescribed fire objectives include restoration and enhancement of wildlife habitat, including reducing woody undergrowth in glade and woodland areas, increasing cover of early successional native grasses and forbs, and reducing leaf litter. Fires are conducted during the dormant season at an interval of two to five years.

The Current River Hills contain the greatest number of study sites because of large areas of publicly owned forests, including Peck Ranch CA, Clearwater CA, Logan Creek CA, Mule Mountain at Rocky Creek CA, and Ozark National Scenic Riverways (ONSR) managed by National Park Service (NPS). A large, privately owned tract in the Current River Hills includes The Nature Conservancy's (TNC) Chilton Creek Management Area, a 1012 ha forested area currently managed with prescribed fire and accessible to researchers.

Study areas in the Ozark National Scenic Riverways (ONSR), the northern section of Peck Ranch CA (including Stegall Mountain), and Mule Mountain are located in the Eminence Igneous Glade/Oak Forest Knobs LTA. Study areas in the southern section of Peck Ranch CA are located in the Current River Oak-Pine Woodland/Forest Hills LTA. Burn units in Peck Ranch CA range in size from 95 ha to 660 ha. The first year of prescribed burning for each unit ranges from 1989 to 2001. The Mill Mountain burn unit is 181 ha in size and was first burned in 1997. The Mule Mountain burn unit is 128 ha in size and was first burned in 2001. Prescribed fire intervals for all burn units in this area range from 2-6 years and are implemented during the dormant season. For MDC and NPS, the primary management goal for using prescribed fire is the restoration of woodland and glade communities by eliminating woody undergrowth, increasing vigor of ground flora, and reducing litter depths.

Chilton Creek Management Area is located east of Peck Ranch CA in the Current River Oak Forest Breaks. The area is subdivided into five burn unit that range in size from 150 ha to 271 ha. Four units are burned at 1-4 year intervals, except for one unit that is burned annually. TNC uses Chilton Creek as an "outdoor laboratory" to assess the effects of large-scale fires on timber and wildlife resources (The Nature Conservancy 2007).

Burn units sampled in the Logan Creek CA and the Clearwater Lake CA are part of a project associated with the Joint Fire Science Program (JFSP), an interagency partnership devoted to fire research. The current project implemented by MDC and U.S. Forest Service examines the effect of timber harvest and prescribed fire on fuel loading in upland forests. Joint Fire Science Block 1 and Block 3 are located in Clearwater CA in the Black River Oak-Pine Woodland/Forest Hills LTA. Joint Fire Science Block 2 is located in Logan Creek CA and is in the Current River Pine-Oak Woodland Dissected Plain LTA. Burn units range in size from 10 ha to 27 ha. Block 1 and 2 were burned in April 2005 and March 2005. Block 3 was burned first in March 2003, and the entire block was burned again following two separate burns in March 2006 and April 2006. In 2006, a portion of JFSB 2 was burned following bud break in April and caused widespread mortality. This area and others with high fire-caused mortality were excluded from this study.

All three Ecological Subsections are within the historic range of *Pinus echinata*. The pre-EuroAmerican settlement vegetation was a mixed oak and pine-oak woodland and forest. The uplands are now primarily closed-canopy forests dominated by *Quercus coccinea*, *Quercus alba*, and *Quercus velutina*, with minor representations from *Carya* spp. and *Pinus echinata*. The range of *Quercus coccinea* does not extend into the White River Hills study area, but *Quercus shumardii* Buckl. was relatively common throughout the area.

Data Collection

In each burn unit, transects were established along the slope of the hill in forested areas with an oak-dominated overstory. The number of transects per burn unit varied according to the size of the burn unit. Transects were stratified by slope position (upper slope, middle slope, lower slope). Plots were systematically located within each slope position and were > 40 m from forest edge and > 75 m from other plots. If a plot location did not contain at least fifteen oaks ≥10 cm dbh then the plot was relocated to the closest point that met this requirement. Plots per transect ranged from two (no middle slope position sampled) to three (all three slope positions sampled) based on the length of the hillside. Open woodlands (30-50% canopy cover), glades, and forests with relatively high fire-caused overstory mortality were not sampled. A total of 100 20-m radius plots were established along transects across the burn units: eight at Pea Ridge CA, 20 plots at

Caney Mountain CA, 12 at ONSR (nine at Mill Mountain and three at Rocky Falls), 24 at Peck Ranch CA, five at Mule Mountain, 19 at Chilton Creek, and 12 at JFSP blocks.

Aspect, slope steepness, slope shape, slope position, number of trees ≥ 10 cm, basal area (BA) per acre of live trees, BA of dead trees, BA of declining trees, and BA of fire-killed trees were determined for each plot. Slope position was coded as three slope positions: 15 = lower, 10 = middle, 5 = upper. For stem bark char measurements, plots were subdivided into one-third sections and a mean maximum bark char height on hardwoods was calculated from at least two char measurements in each one-third subplot. Bark char refers to any blackening of the stem bark due to fire. Leaf litter depth was measured from four points located 5 m from plot center: one point down slope, two points at left and right along the side slope, and one point up slope. The dbh of the largest fire-killed tree was recorded for *Quercus* and for "other" species.

For trees ≥10 cm dbh, the proportion of scarred trees was recorded for *Quercus alba*, *Quercus coccinea*, *Quercus shumardii*, *Quercus velutina*, *Quercus stellata*, *Carya* spp., and *Pinus echinata*. Fire scars were examined and the three largest scars for each species were selected for further measurements. Subjective judgment based on scar height, scar width and tree diameter was used to select the largest scars to measure. Scar types were classified as cat-face (triangular in shape), oval, closed (woundwood grew over the fire scar), basal (occurring on trunk fluting or exposed root), or other (irregular shaped). Scar height, scar width at scar midpoint (one-half the distance to total scar height) for oval and cat-face scars, tree diameter at scar midpoint, and dbh of scarred tree were recorded (Figure 2.2). For trees with a scar width measurement, percent cambium killed (PCK) was calculated by dividing the scar width at scar midpoint by tree circumference calculated from the diameter at scar midpoint.

Figure 2.1. Location of study areas across the Ozark Highlands.

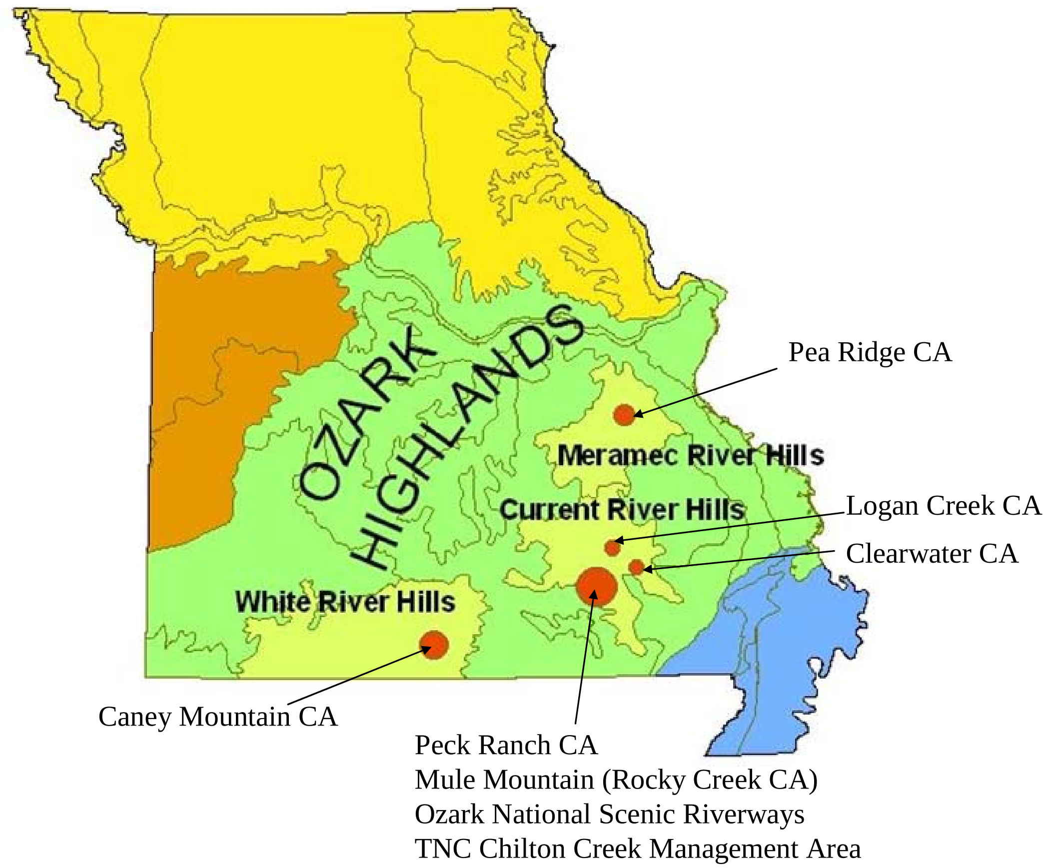


Table 2.1. Summary of information for burn units sampled in fire effects study.

Area / County	Burn unit	Size (ha)	Plots	FBD[1]	No. Rx burns	MFI[2]	GSB[3]
Caney Mountain CA / Ozark Co.	Long Bald	253	8	1985	7	2.4	0
	High Rock	380	9	early 1990s	5	2.33	2
	Morrison Knobs	107	3	early 1990s	4	4	3
Pea Ridge CA / Washington Co.	Pea Ridge	37	8	Mar 1995	4	3	3
The Nature Conservancy's Chilton Creek Management Area/ Shannon Co. and Carter Co.	Chilton North	199	4	3/13/98	3	3	2
	Chilton South	271	4	3/26/98	4	2.25	3
	Chilton East	184	4	4/2/98	4	2.25	0
	Kelly North	233	2	4/5/98	9	1	0
	Kelly South	150	5	4/6/98	4	2.25	2
Clearwater CA & Logan Creek CA / Reynolds Co.	JFSB1	10	4	Apr 2003	2	2	1
	JFSB2	27	4	Apr 2003	2	2	1
	JFSB3	18	4	Mar 2003	2	2	0
Ozark National Scenic Riverways (ONSR) / Shannon Co.	Mill Mountain	181	9	1997	2	5	2
Rocky Creek CA / Shannon Co.	Mule Mountain	128	5	2001	3	2	1
Peck Ranch CA / Carter Co.	Stegall North[4]	423	5	1991	6	2.67	0
	Stegall South	660	4	1989	5	3	1
	Little Thorny Mt.	130	4	1996	3	3.5	2
	Thorny Mt. South	356	2	1997	7	2.57	3
	Mule Hollow	149	2	1992	4	2.4	2
	Compartment 5	196	6	1998	3	4.67	4
	Compartment 17-West	179	2	1996	2	5.5	5
	Compartment 17-East	95	2	2001	1	6	4

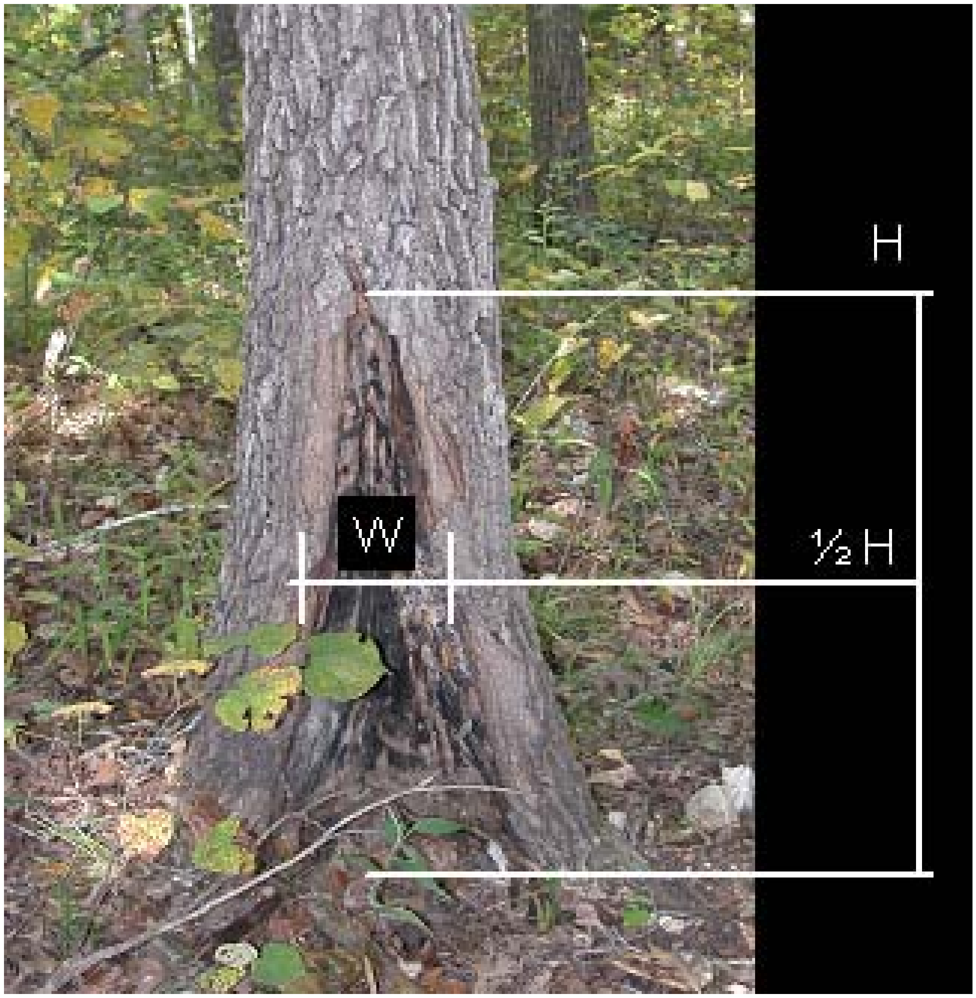
[1]FBD = first burn date
[2]MFI = mean fire interval as of May 2006; MFI for Long Bald, High Rock, and Morrison Knobs based on most recent records
[3]GSB = full growing seasons since last burn as of May 2006
[4]Northern portion of Stegall North extends into ONSR, Shannon Co

Table 2.2. Summary of prescribed fire prescription goals for burn units sampled in fire effects study.

Burn unit	Primary burn objectives
Long Bald High Rock Morrison Knobs	wildlife habitat improvement; control woody encroachment in glade and woodland areas; encourage early successional grasses and forbs; reduce leaf litter
Pea Ridge	pine-oak woodland restoration
Chilton North Chilton South Chilton East Kelly North Kelly South	using large-scale prescribed fire for biodiversity management while studying effects of fire on timber and wildlife resources
JFSB1 JFSB2 JFSB3	study effects of forest management on fuel loading, fire behavior, and vegetation
Mill Mountain	maintenance and expansion of glade/savanna areas and improving woodland and native species assemblages
Stegall North[1]	kill 20-40% of saplings < 4” in uplands; top kill 70-90% and 50-70% of blackjack oak, winged elm, and winged sumac < 2” and >2” on glades and glade margins; moderate intensity over 75-90% of unit; mosaic of different levels of fire severity
Stegall South[2]	burn 65-95% of unit; top kill 20% and 40% of blackjack oak, hickory, and winged elm >2” and <2” on glade margins; increase herbaceous composition by >15%
Little Thorny Mt.[3]	top kill ≥ 10% and ≥ 20% of blackjack oak, winged elm, and hickory > 2” and < 2”on glade and glade margins; burn at least 50-75% of unit with low intensity fire; increase cover of grasses and forbs by 20% by 3 years postburn; reduce litter depth by at least 50%; reduce density of woody understory (2-6”) by 5% in woodlands
Thorny Mt. South[4]	increase vigor and abundance of conservative natives; increase fine fuel species; reduce leaf litter; reduce oak sapling densities to increase light penetration to ground cover; stimulate pine reproduction
Compartment 17-West[5] Compartment 17-East	reduce fuel loading by 25% without deteriorating soil conditions; stimulate native grass and forb composition by increasing vigor and abundance of conservative species
Mule Mountain Mule Hollow Compartment 5	maintain, enhance, and restore woodland and glade communities

[1]Primary burn objectives based on prescription plan for 2002 and 2006
[2]Includes burn dates for Wolf Hollow; primary burn objectives based on prescription plan for 1996
[3]Primary burn objectives based on prescription plan for 2002
[4]Includes burn dates for Mud Spring Glade area; primary burn objectives based on prescription plan for 2003
[5]Primary burn objectives based on prescription plan for 2001

Figure 2.2. Fire scar measurements for a cat-face scar on *Quercus velutina*. "H" is scar height; "½ H" is height to scar midpoint; "W" is scar width at scar midpoint.



Old fire scars (scars formed prior to current prescribed fire management) were identified for each species and counted separately from recently formed scars. Old fire scars are distinct from recently formed scars because decades of growth after the injury cause large ribs to form at the edge of the woundwood. Also, old fire scars have no stem-bark char evident on the tree.

Upland forests across much of the Missouri Ozarks were burned prior to public ownership and subsequent management. Therefore, we sampled unburned areas (control) to assess the distribution of old fire scars across the landscape. Unburned stands chosen for sampling had to meet certain criteria: similar physiognomy (i.e. species composition, forest structure) as burned areas, no current forest management activities, and close proximity to burn units included in the study. Transects were established in control areas in the same manner as in burned areas. Plots were randomly located in areas with at least fifteen oaks with dbh ≥ 10 cm. Forty control plots were sampled across the study area: two from Pea Ridge CA, eight from Caney Mountain CA, two from ONSR, four from JFSP blocks, and 24 from Peck Ranch CA. Old fire scars in control and burned areas were compared to determine the efficacy of distinguishing old fire scars from recently formed fire scars at sites currently managed with prescribed fire.

In burned areas, basal cavities formed from fire-caused scars were measured. Cavity opening width, cavity opening height, within-bole cavity height, dbh, species, and evidence of animal use were recorded. Within-bole cavity height was estimated acoustically using the blunt end of a hatchet. Cavities were classed as either formed from a recent prescribed fire or from a pre-management fire (old fire scar).

For each burn unit, the years in which prescribed fires occurred were obtained from ownership records or from dating fire scars. Scarred trees were selected within sampled burn units but outside of sampling plots, and wedges were cut from scarred trees with a chainsaw. Wedge sections were smoothed by sanding and fire scars were identified by examining callus tissue and cambial injury. Fire scars were dated to the first year of cambial injury.

Plot locations recorded from a GPS unit were converted to shape points using DNR Garmin (Minnesota Department of Natural Resources 2007). ArcView 9.1 was used to determine the fetch (distance to bottom of hill) for each plot. Fetch was calculated as the distance from plot center (indicated by the shape point) to the closest point at the bottom of the hill. Other plot-level variables calculated in the lab include mean stem-bark char height, mean litter depth, and quadratic mean diameter (QMD). Trees per hectare and BA per hectare were calculated from plot measurements.

Quercus coccinea is a major overstory component in the Meramec River Hills and the Current River Hills, but it is replaced by *Quercus shumardii* at Caney Mountain CA in the White River Hills. Initially it was thought that *Quercus coccinea* was a major component in stands across all study areas, and thus *Quercus shumardii* at Caney Mountain were sampled and tallied as *Quercus coccinea*. Due to similar leaf and bark characteristics of the two species, distinction between the two species was difficult and did not occur until near the end of data collection. Bark characteristics between the two species are nearly identical, and therefore both species should respond similarly to fire. Therefore no effort was made to separate out *Quercus coccinea* scar data from *Quercus* *shumardii* scar data, and a separate species group containing both species (red oaks) was used for analysis.

Analysis

The data for percentage of trees scarred forms a binomial distribution, and therefore the percentage of trees scarred was normalized using Bartlett's arcsine transformation (Zar 2004). Stepwise forward regression analysis was used to model the (arcsine transformed) percent trees scarred for each species and all species combined with respect to mean stem bark char height (m), aspect (transformed, Beers et al. 1966), fetch (m), quadratic mean dbh (QMD) (cm), trees per hectare, and basal area (m^2 per ha). Variables retained in the model had to be significant at $\alpha = 0.05$.

Before analysis, predictor variables were visually assessed for normality by examining univariate distributions. Collinearity of predictor variables was assessed using a scatter plot matrix. A test for multicollinearity revealed that trees per hectare, basal area per hectare, and QMD were correlated. Stepwise regression never selected more than one of these variables as a predictor in a regression model, and therefore multicollinearity was not an issue.

For each species, plot-level means were calculated for scar height, scar width, and PCK. Univariate distributions for scar height, scar width, and PCK were visually assessed for data normality. Scar heights were not normally distributed and were transformed by taking the natural logarithm of the scar height measurement. For each species, stepwise forward regression analysis was used to model the scar size variable with respect to the same predictors used in the percent trees scarred models. For scar width and scar height regression analysis, tree diameter (cm) at scar midpoint was added as a predictor. Confidence bands were calculated for models with high coefficients of determination (R^2) and a single selected predictor variable. A separate regression analysis was conducted for sawtimber trees (dbh ≥ 28 cm) for each species. Predicted scar variables versus predictor variables were plotted for each regression model.

Univariate distributions of dbh for largest fire-killed oak and "other" species were visually assessed for normality. Stepwise forward regression analysis was used to model largest fire-killed oak and "other" species with respect to the previously listed predictor variables. Variables retained in the model had to be significant at $\alpha = 0.05$.

All regression analyses were performed using the following statements in SAS 9.1:

```
PROC REG;
MODEL SCAR = PREDICTOR1 PREDICTOR2 … PREDICTOR n /
                SLENTRY = 0.05 SELECTION = FORWARD;
RUN;
```

where *SCAR* = fire scar variable of interest and $PREDICTOR_n$ = predictor variable for specific scar model.

Results

Site Characteristics

Burn and control plots had similar stand density measurements (Table 2.3). Mean trees per hectare was slightly lower in burned plots, but mean basal area per hectare and QMD were nearly identical. Mean litter depth was 5.0 cm in control plots versus 3.2 cm in burn plots. Major species composition of trees ≥ 10 cm dbh varied somewhat between burn and control plots (Table 2.4). Burn plots contained a higher percentage of red oaks, while control plots contained a higher percentage of *Quercus velutina* and *Carya* spp.

Old Fire Scars

For all six species, a total of 3945 trees were examined for fire scars in one hundred burn plots in stands managed with prescribed fire. Of that total, 2255 trees were classified as scarred from recent (last 15 years) prescribed fires. In burned areas, ninety-five plots were sampled for old scars and 66 out of 3754 trees (1.8%) had old fire scars. In unburned areas, 1660 trees were examined for old fire scars, and of that total 43 trees (2.6%) had old fire scars.

The percentage of trees with old fire scars was similar between burn and control plots (Table 2.5). Among species in control plots, the percentage of trees with old fire scars ranged from 0% to 7.3%. In burn plots, the percentage of trees with old scars ranges from 0% to 2.9%. Examining species differences in old scar percentage between control and burn plots reveals that *Carya* spp. has the largest difference, with 7.3% of trees in control plots with old fire scars and 2.9% of trees in burn plots with old fire scars. One control plot had a relatively high percentage (71%) of *Carya* spp. with old scars, and removing the data from this plot lowers the percentage of *Carya* spp. with old scars in control plots to 4.0%.

Table 2.3. Summary of stand characteristics (mean ± standard deviation).

	No. plots	Trees· ha^{-1}	BA (m^2 per ha)	QMD (cm)	Litter depth (cm)
Burn	100	362 ± 74	21.5 ± 6.1	27.6 ± 4.3	3.2 ± 1.4
Control	40	377 ± 64	21.4 ± 5.3	27.0 ± 3.9	5.0 ± 1.2

“BA” is basal area; “QMD” is quadratic mean diameter

Table 2.4. Species composition across all sites for trees ≥ 10 cm dbh.

	% of total	
	Control	Burn
Red oaks[1]	11.5	18.9
Quercus velutina	19.9	15.6
Quercus alba	27.6	27.0
Quercus stellata	8.3	6.6
Carya spp.	18.1	12.7
Pinus echinata	2.5	3.9
Other[2]	12.1	15.3
Total	100	100

[1]red oaks include *Quercus coccinea* and *Quercus shumardii*
[2]Other species include *Acer saccharum* Marsh., *Acer rubrum* L., *Cercis canadensis* L., *Cornus florida* L., *Fraxinus* spp. Marsh., *Juglans nigra* L., *Juniperus virginiana* L., *Nyssa sylvatica* Marsh., and *Ulmus* spp. L.

Table 2.5. Summary of old scars counted in control and burn plots.

Species	Plot type[1]	Trees examined	Old scars	% old scars
Red oaks[2]	Control	218	3	1.4%
	Burn	810	17	2.1%
Quercus velutina	Control	376	8	2.1%
	Burn	719	11	1.5%
Quercus alba	Control	521	6	1.2%
	Burn	1201	14	1.2%
Quercus stellata	Control	157	1	0.6%
	Burn	306	8	2.6%
Carya spp.[3]	Control	341	25	7.3%
	Burn	553	16	2.9%
Pinus echinata	Control	47	0	0.0%
	Burn	165	0	0.0%
All trees combined	Control	1660	43	2.6%
	Burn	3754	66	1.8%

[1]plots sampled: control = 40; burn = 95
[2]red oaks include *Quercus coccinea* and *Quercus shumardii*
[3]one control plot had a relatively high proportion (12 of 17) of *Carya* spp. with old fire scars; omitting this plot yields old fire scar percentages in control plots of 4.0% for *Carya* spp. and 1.9% for all trees combined

Predictor Variables in Regression Models

Plot-level mean maximum stem bark char height (i.e. bark char) on hardwoods was 0.89 m and ranged from 0.083 to 2.33 m (Table 2.6). Mean fetch was 45 m and mean slope was 14°. Trees per ha ranged from 191 to 597, and basal area (BA) ranged from 11.5 to 41.3 m^2 per ha. Distribution of plots by slope position was 43 at the upper slope position, 31 at the lower slope position, and 26 at the middle slope position. Distribution of plots by aspect was nearly identical on northeast- (54) and southwest-facing (46) slopes (Figure 2.3).

Percent Trees Scarred (PTS)

For each species and all species combined, the percentage of trees scarred (PTS) was higher on southwest-facing slopes than on northeast-facing slopes (Figure 2.4). For both southwest- and northeast-facing slopes, red oaks had the highest and *Pinus echinata* had the lowest PTS. On northeast-facing slopes, PTS for *P. echinata* and *Q. stellata* was 12% and 33%. All other species had a range of PTS values from 49% to 59%. On southwest-facing slopes, *P. echinata* had a PTS of 27%, and all other species had a range of PTS values from 60% to 75%. For all species combined, PTS was 64% on southwest-facing slopes and 52% on northeast-facing slopes. Because *P. echinata* had such low PTS values, those values were omitted for a separate calculation made for data collected from hardwoods. PTS for hardwoods was 67% on southwest-facing slopes and 53% on northeast-facing slopes.

Table 2.6. Summary of predictor variables in percent trees scarred model.

	Mean	Min	Max
Bark char (m)	0.89	0.083	2.33
Fetch (m)	45	0	133
Slope (°)	14	2	28
Tree · ha^{-1}	371	191	597
BA (m^2 · ha^{-1})	23.8	11.5	41.3
QMD (cm)	20.3	13.1	27.1

“char” is plot-level mean maximum stem-bark char height on hardwoods; “fetch” is distance to bottom of hill; “BA” is basal area; “QMD” is quadratic mean diameter

Figure 2.3. Distribution of burn plots by slope aspect.

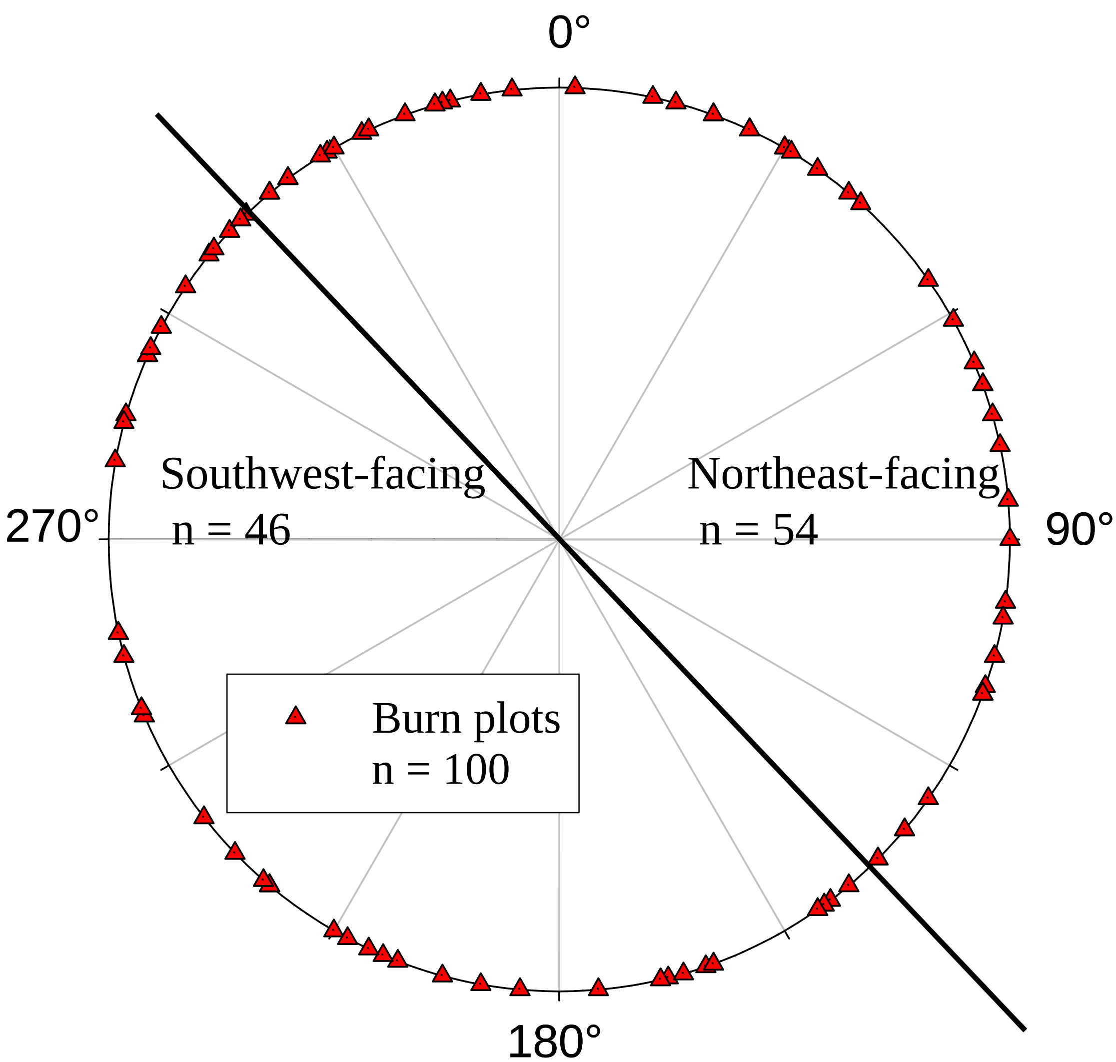
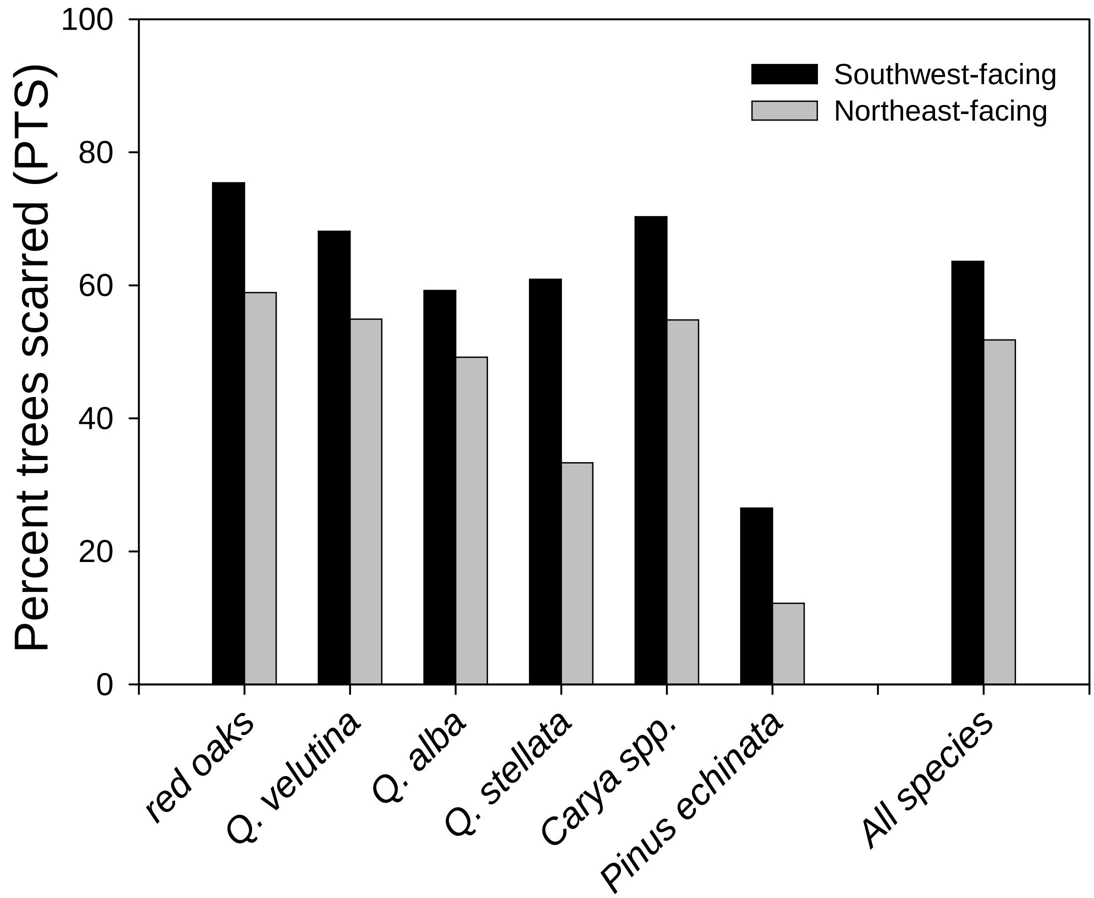


Figure 2.4. Percentage of trees scarred (PTS) by species and aspect.



Bark char was the first variable selected in the PTS model for each species, all species combined, and hardwoods (Table 2.7). Bark char was positively related with PTS for all regression models. Aspect was the second variable selected for red oaks, *Quercus alba*, all species combined, and hardwoods. Aspect was inversely related to PTS, which indicates that as aspect changes from the extreme southwest-facing slope (225°) to the extreme northeast-facing slope (45°), percent trees scarred (PTS) decreases. Basal area (m^2 per ha) was the second variable selected in the *Q. stellata* PTS model, and QMD (cm) was the second variable selected for the *Carya* spp. model. Both basal area and QMD were negatively related with PTS. All PTS models were significant ($p < .001$), and R^2 values ranged from 0.21 to 0.46.

Table 2.7. Multiple regression coefficients and R^2 values for models predicting arcsine transformed percentage of trees scarred (PTS) for five species groups, hardwoods, and all species combined.

Species	n	B_0	B_1	x_1	B_2	x_2	R^2
Red oaks[1]	88	47.53	18.08	char	-8.51	aspect	0.37
Q. velutina	79	37.22	16.61	char	na	na	0.25
Q. alba	97	38.99	15.95	char	-4.56	aspect	0.32
Q. stellata	57	44.17	18.68	char	-0.82	BA	0.35
Carya spp.	73	64.79	13.98	char	-1.33	QMD	0.21
Hardwoods[2]	100	41.48	17.65	char	-5.99	aspect	0.46
All species[3]	100	41.60	10.13	char	-3.12	aspect	0.30

All models are significant at $p < 0.001$. All regression coefficients differ significantly from zero at $p < 0.05$; n is the number of plot-level means in each model; B_0 is the intercept; B_n are model coefficients; x_n are model parameters; “char” is mean maximum stem-bark char height (cm) on hardwoods; “aspect” is transformed to a linear scale following Beers (1966); “BA” is basal area (m^2 per ha); “QMD” is quadratic mean diameter (cm)

[1]red oaks include *Quercus coccinea* and *Quercus shumardii*

[2]hardwoods include all species groups listed

[3]all species includes all species groups listed and *Pinus echinata*

Using bark char as the only predictor in all models allowed for a direct comparison of fire intensity effects on species sensitivity to scarring. At a bark char height of 0.1 m, predicted PTS for *Quercus stellata* is around 20%, followed by 33% for *Quercus alba* and 40% for red oaks, *Quercus velutina*, and *Carya* spp. (Figure 2.5). As char height increases, PTS starts to increase at a rate slightly higher for red oaks than for other species. At a char height of 2.25 m predicted PTS for red oaks is nearly 100%, followed by 93% for *Q. velutina*, 90% for *Quercus alba*, and 87% for *Carya* spp. and *Q. stellata*.

There were differences in predicted PTS for *Quercus alba* and red oaks by aspects and bark char heights. When bark char is 0.1 m, *Quercus alba* has 42% and 27% PTS on southwest- and northeast-facing slopes (Figure 2.6). At the same bark char height, PTS for red oaks is 58% and 29%. As char height increases the difference between PTS on southwest- and northeast-facing slopes decreases. At an extreme char height of 2.33 m, PTS is 94% and 85% for *Q. alba* on southwest- and northeast-facing slopes. For red oaks, the PTS is 100% and 91% on southwest- and northeast-facing slopes.

Regardless of char height, the regression model for *Q. stellata* indicates a substantial difference in PTS between low basal area (BA) sites and high basal area sites. At the lowest char height, PTS ranges from 6% at 39 m^2 per ha to 38% at 10 m^2 per ha, a difference of 32% (Figure 2.7). At the highest char height, PTS ranges from 69% to 96% at 39 and 10 m^2 per ha, a difference of 33%.

Hardwoods had higher predicted PTS values on southwest- versus northeast-facing slopes, although the difference is less at higher char heights (Figure 2.8). For a char height of 0.1 m, predicted PTS ranged from 27% to 47% on northeast- and southwest-facing slopes. At 2.3 m, predicted PTS ranged from 89% to 98% on northeast- and southwest-facing slopes.

The PTS model for *Quercus velutina* had only one predictor variable, and therefore 95% confidence bands were calculated for the regression line. The bands indicate that estimation of the regression model was not very precise near mean char height (0.89 m), and becomes even less precise at the low and high values of char (Figure 1.9). The upper confidence band becomes constrained at the upper PTS values because only 100% of the trees could possibly be scarred.

Figure 2.5. Relationship between bark char height and predicted percent trees scarred (PTS) across all species sampled.

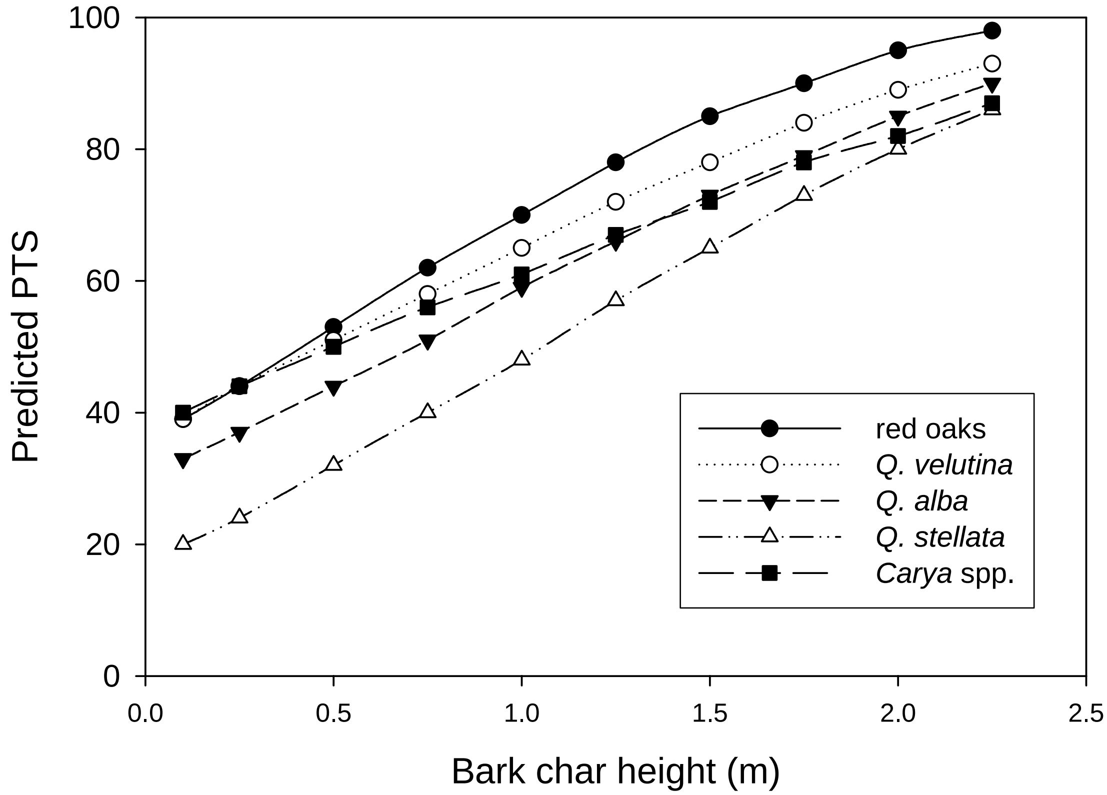


Figure 2.6. Percent trees scarred (PTS) predicted by bark char and aspect for red oaks and *Quercus alba*.

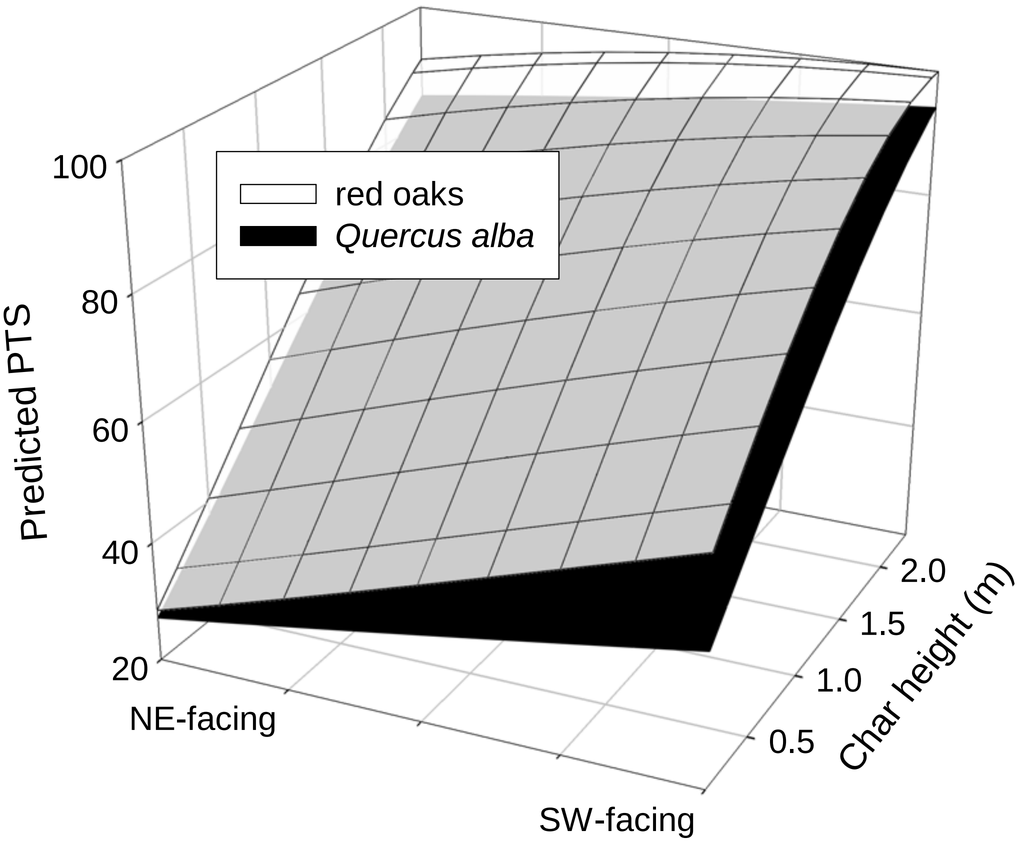


Figure 2.7. Percent trees scarred (PTS) of *Quercus stellata* predicted by basal area (BA) and bark char height.

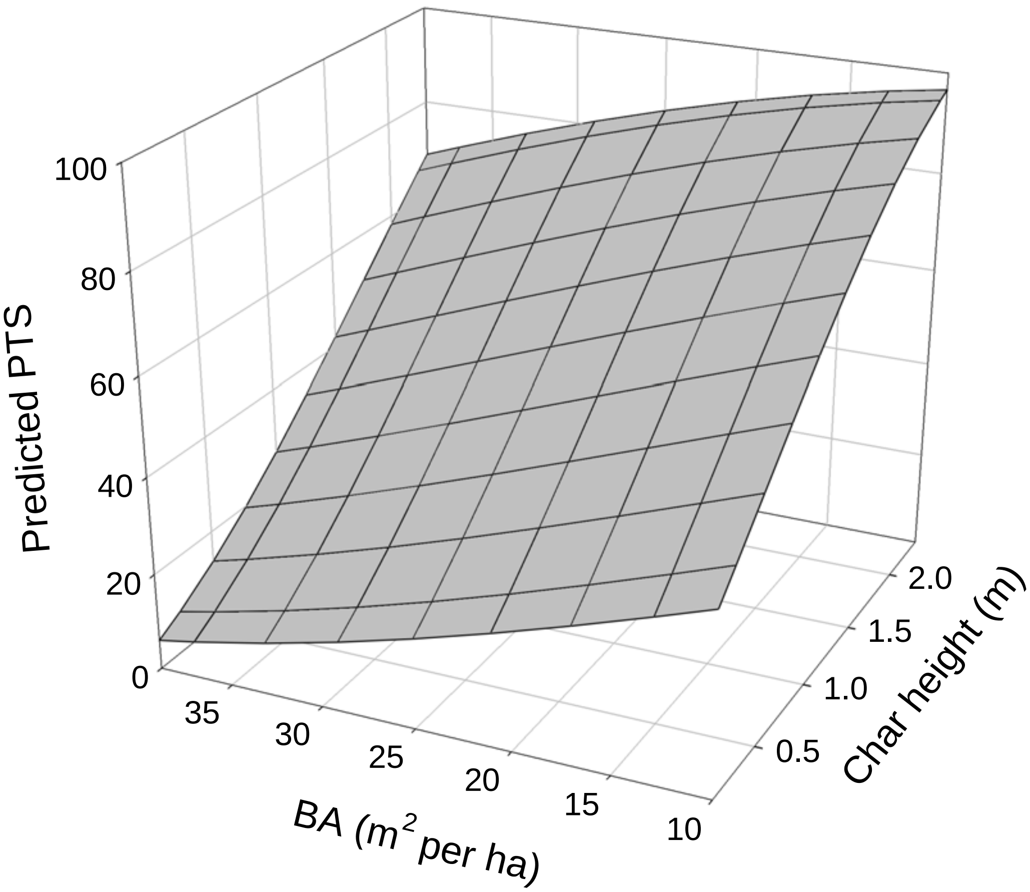


Figure 2.8. Percent trees scarred (PTS) of hardwoods predicted by aspect and bark char height.

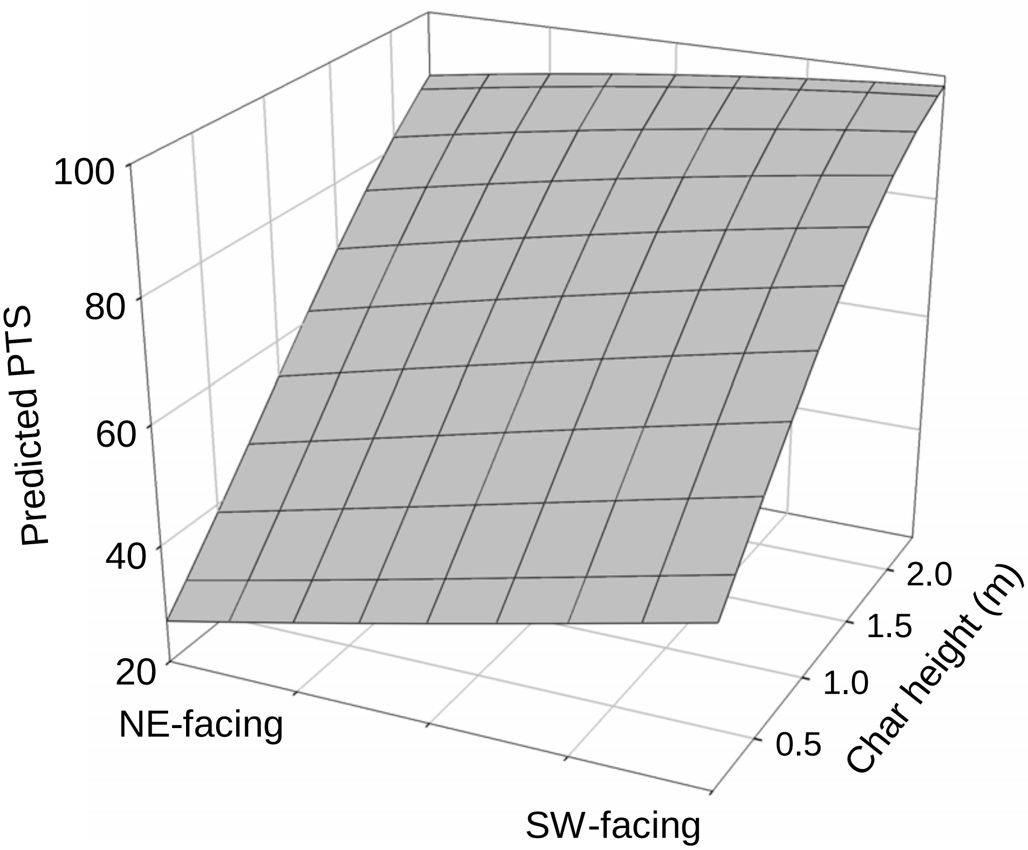
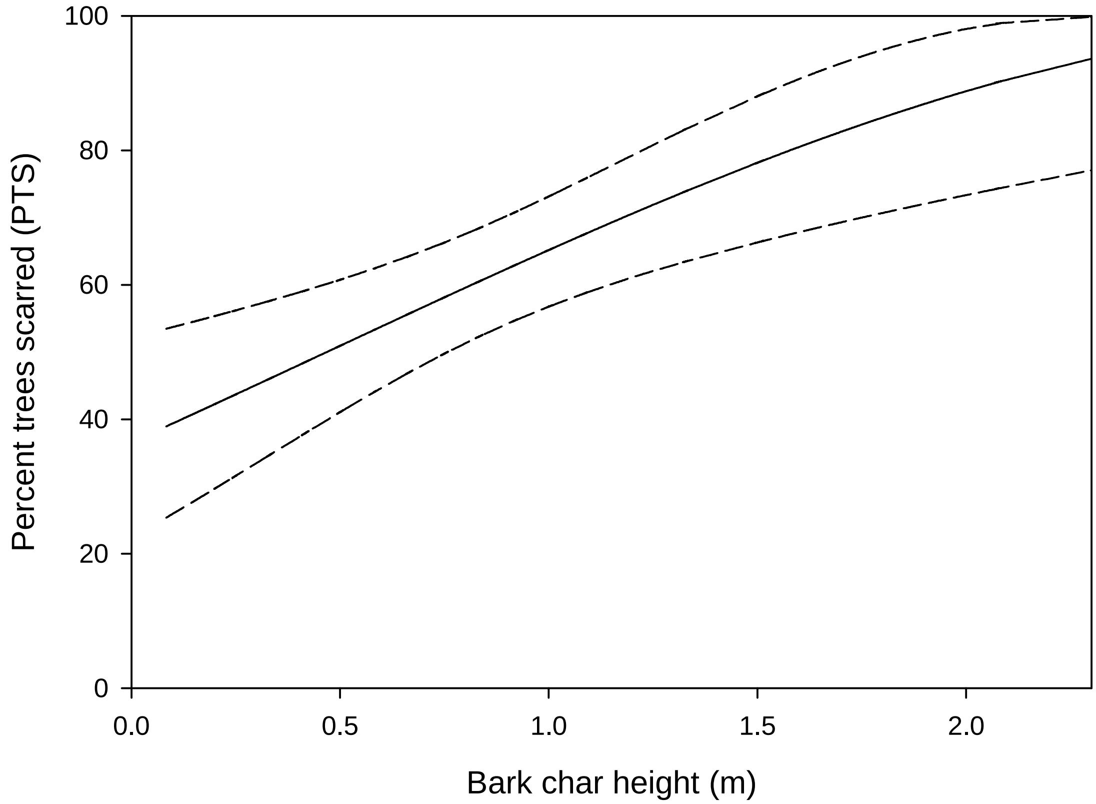


Figure 2.9. Regression line and 95% confidence bands for *Quercus velutina* percent trees scarred (PTS) model.



Scars Measured by Species and Type

Quercus alba had the highest number of scars measured (250), followed by red oaks (202), *Q. velutina* (182), *Carya* spp. (161), *Q. stellata* (84), and *Pinus echinata* (27). The majority of scars measured were cat-face scars (66%), followed by closed (20%), basal (7%) and oval (7%), and other (1%) (Table 2.8). Cat-face scars made up the largest proportion of measured scars for all species and ranged from 56% to 72% of measured scars for *Pinus echinata* and *Quercus alba*. Closed scars were the second most commonly measured scar type for all species.

Table 2.8. Distribution of fire scars measured and the percentage of scars by type and species.

Scar type	Red oaks[1]	*Quercus velutina*	*Quercus alba*	*Quercus stellata*	*Carya* spp.	*Pinus echinata*	All Species
Cat-face	138	110	181	48	110	15	602
	68%	60%	72%	57%	68%	56%	66%
Closed	44	44	43	19	24	7	181
	22%	24%	17%	23%	15%	26%	20%
Basal	11	9	11	10	17	1	59
	5%	5%	4%	12%	6%	4%	7%
Oval	8	18	12	6	10	3	57
	4%	10%	5%	7%	6%	11%	7%
Other	1	1	3	1	0	1	7
	<1%	<1%	1%	1%	0%	4%	1%
Total	202	182	250	84	161	27	906

[1]Red oaks include *Quercus coccinea* and *Quercus shumardii*

Scar Size Models for Trees ≥ 10 cm dbh

Scar Height

There were a total of 906 scar heights measured: 250 for *Q. alba*, 202 for *Q. velutina*, 161 for *Carya* spp., 84 for *Q. stellata*, and 27 for *Pinus echinata*. Trees measured for scar heights ranged from 10 cm to 76 cm dbh (Table 2.9). Mean dbh was lowest for *Carya* spp. and highest for *Q. velutina*. Mean scar height was highest on southwest-facing slopes for all species, although *Carya* spp. had only 1 cm difference between aspects (Figure 2.10). Red oaks had the largest and *Pinus echinata* the smallest scar heights on southwest- and northeast-facing slopes. *Pinus echinata* was excluded from scar height regression analysis because of lack of adequate sample numbers.

Plots had to have at least one scar height measurement to determine a plot-level scar height mean. The number of plots with scar height measurements ranged from 40 for *Q. stellata* to 93 for *Q. alba*. Plot-level mean scar heights ranged from 53 cm for *Carya* spp. to 86 cm for red oaks (Table 2.10). The smallest plot-level mean was 175 cm for *Q. stellata*, and the largest plot-level mean was 350 cm for red oaks.

Figure 2.10. Individual tree level means and standard errors for scar heights by species and aspect.

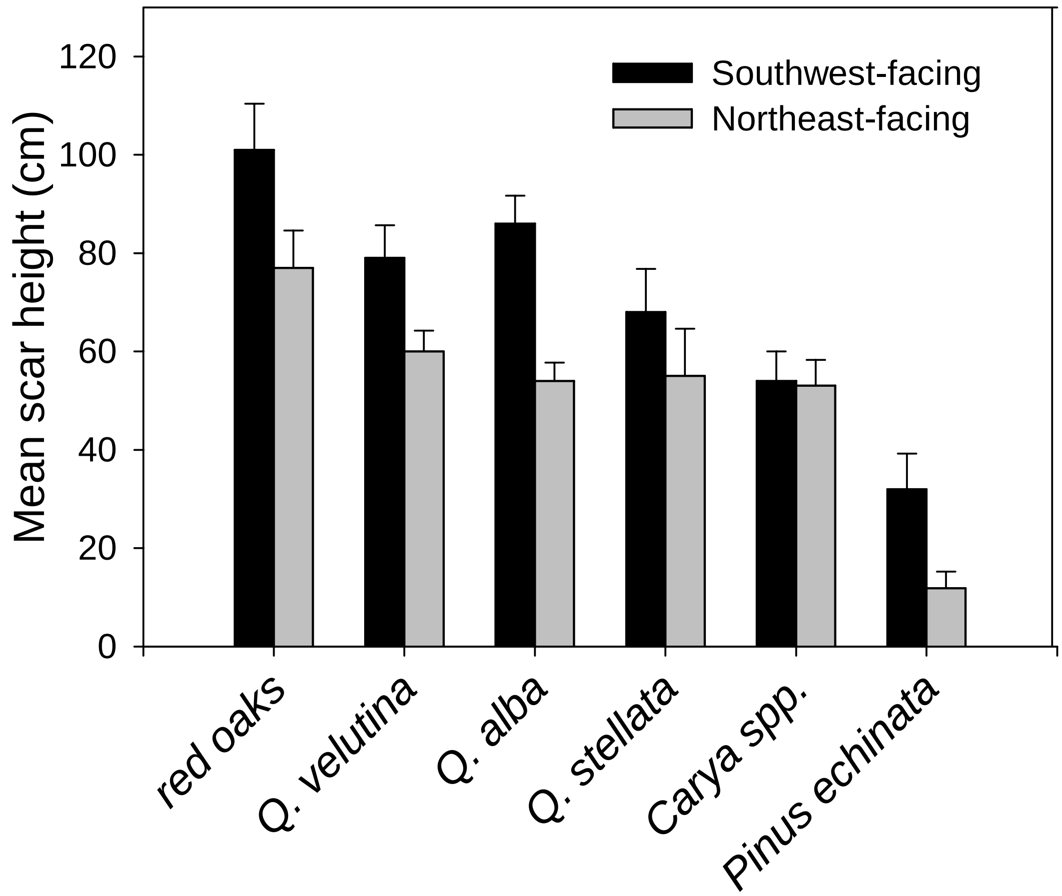


Table 2.9. Summary of diameters for trees dbh ≥ 10 cm used in scar height regression models.

		dbh (cm)		
Species	n	mean ± stdev	min	max
Red oaks[1]	202	29 ± 13	10	76
Q. velutina	182	31 ± 12	10	72
Q. alba	250	23 ± 12	10	66
Q. stellata	84	29 ± 11	10	55
Carya spp.	161	20 ± 9	12	51

[1]Red oaks include *Q. coccinea* and *Q. shumardii*

Bark char was the first variable selected in the scar height regression models for all species (Table 2.11). All scar height models revealed a positive relationship between bark char and scar heights. Aspect was the second variable selected for the *Q. alba* and *Q. stellata* models. The relationship between aspect and scar height was negative, which indicates the models predict that southwest-facing slopes have higher scar heights than northeast-facing slopes. Fetch was the third variable selected for *Q. alba*, and the relationship between fetch and scar height was positive. All models were significant ($p < 0.001$), and R^2 values ranged from 0.17 to 0.45.

At low bark char values, there is little difference in *Q. stellata* predicted scar heights between northeast- and southwest-facing slopes (difference = 9 cm) (Figure 2.11). As char height increases, scar height increases at an exponential rate on southwest-facing slopes. Thus the difference in scar heights between southwest- and northeast-facing slopes increases as char height increases. At a char height of 2.3 m, the difference between scar heights on southwest- and northeast-facing slopes is nearly 1 m.

The scar height of *Quercus alba* is influenced by a three-way interaction of char height, slope aspect, and fetch (Figure 2.12). At the lowest char height and fetch values, there is little difference in predicted scar height on northeast- and southwest-facing slopes (difference = 12 cm). At a constant fetch but a char height of 2.3 m, the difference between scar height rises to 60 cm between NE- and SW-facing slopes. At a char height of 0.1 m and ranging from the lowest to highest fetch value (0 m to 133 m), the difference in scar heights between NE- and SW-facing slopes rises from 12 cm to 31 cm, although the highest predicted scar height is relatively low (55 cm on SW-facing slope; fetch = 133 m). With increasing fetch and char height, the predicted scar height increases at an exponential rate on SW-facing slopes. At a char height of 2.3 m and a fetch of 133 m, the predicted scar height is 2.95 m on SW-facing slopes and 1.75 m for NE-facing slopes.

Using only bark char as a predictor, a direct comparison of predicted scar height can be made for all species. At the lowest char height, predicted scar height for *Q. stellata* is 13 cm and around 24 cm for all other species groups (Figure 2.13). After 1 m char height, predicted scar height for red oaks increases at a rate that differentiates it from other species. *Carya* spp. scar height increases minimally, and is surpassed by *Q. stellata* as char increases to 1.5 m. At the highest rate of bark char (2.3 m), the predicted scar heights range from 79 cm for *Carya* spp. to 231 cm for red oaks.

Regression parameters in the red oak and *Q. velutina* scar height models were very similar. Confidence limits on the regression parameters indicate some overlap in the parameter values between the two models (Figure 2.14). A test of parallelism was performed to ensure the models are actually different. Assuming equal intercepts, the red oak and *Q. velutina* scar height models are significantly different ($\alpha = 0.05$).

The red oak model had the highest coefficient of determination ($R^2 = 0.45$) among scar height models and therefore was selected to have 95% confidence bands calculated. The confidence bands indicate that the regression line for the natural log transformed scar height was estimated fairly precise near the mean char height (0.89 m), but was estimated much less precise at the low and high ends of char height (Figure 2.15a). After retransformation of the values back to actual scar heights (cm), the confidence bands around the regression line reveal that at the low ends of char height, estimation of the regression line is very precise, but as char height increases estimation of the regression line becomes increasingly imprecise (Figure 2.15b). This increasing band width is due to the exponential nature of the natural log transformation of scar height.

Table 2.10. Summary of plot-level scar heights of trees ≥ 10 cm dbh used for stepwise regression models.

		Plot-level scar height (cm)		
Species	Plots	mean ± stdev	min	max
Red oaks[1]	82	86 ± 67	10	350
Q. velutina	69	68 ± 44	8	242
Q. alba	93	69 ± 46	5	252
Q. stellata	40	58 ± 46	3	175
Carya spp.	67	53 ± 39	2	225

[1]Red oaks include *Q. coccinea* and *Q. shumardii*

Table 2.11. Multiple regression coefficients and R^2 values for models predicting natural log of scar height for five tree species groups (dbh ≥ 10 cm).

Species	n	B_0	B_1	x_1	B_2	x_2	B_3	x_3	R^2
Red oaks[1]	82	3.12	1.04	char	na	na	na	na	0.45
Q. velutina	69	3.09	0.89	char	na	na	na	na	0.41
Q. alba	93	3.23	0.75	char	-0.27	aspect	0.0055	fetch	0.37
Q. stellata	40	2.71	1.04	char	-0.41	aspect	na	na	0.44
Carya spp.	67	3.07	0.58	char	na	na	na	na	0.18

All models are significant at $p < 0.001$; All regression coefficients differ significantly from zero at $p < 0.05$; n is the number of plot-level means in each model; B_0 is the intercept; B_n are model coefficients; x_n are model parameters; "char" is mean maximum stem-bark char height (m) on hardwoods; "aspect" is transformed to a linear scale following Beers (1966); "fetch" is distance (m) to bottom of hill.
[1]Red oaks include *Quercus coccinea* and *Quercus shumardii*.

Figure 2.11. Predicted scar height for *Q. stellata* ≥ 10 cm dbh.

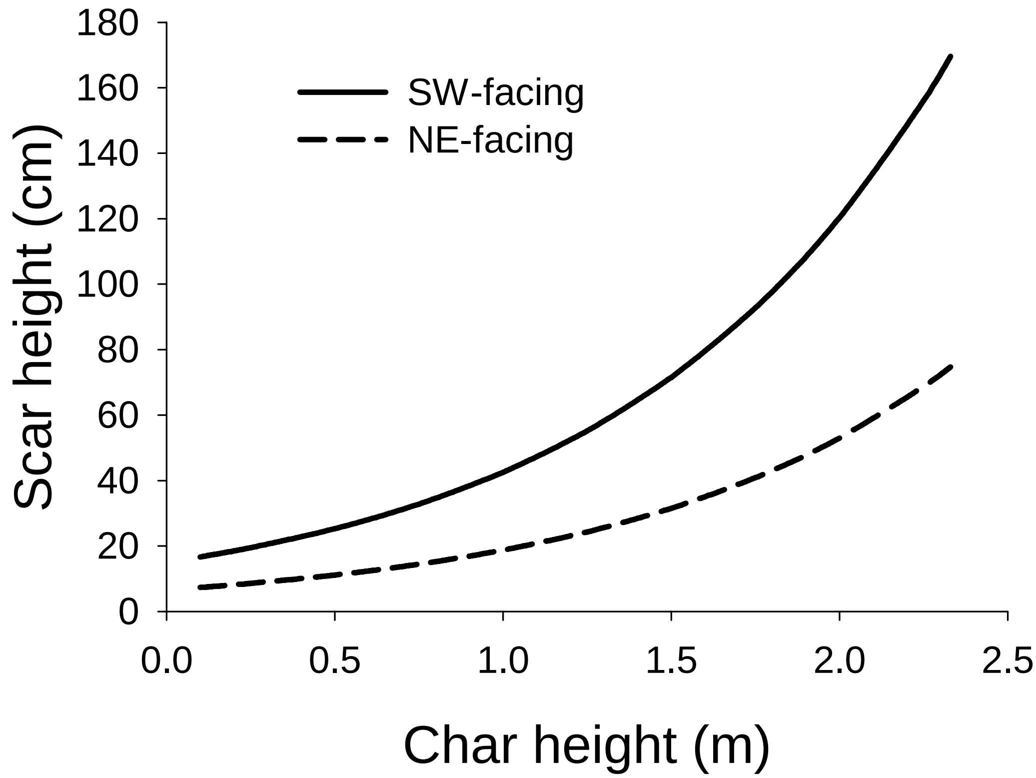


Figure 2.12. Predicted scar height for *Quercus alba* ≥ 10 cm dbh.

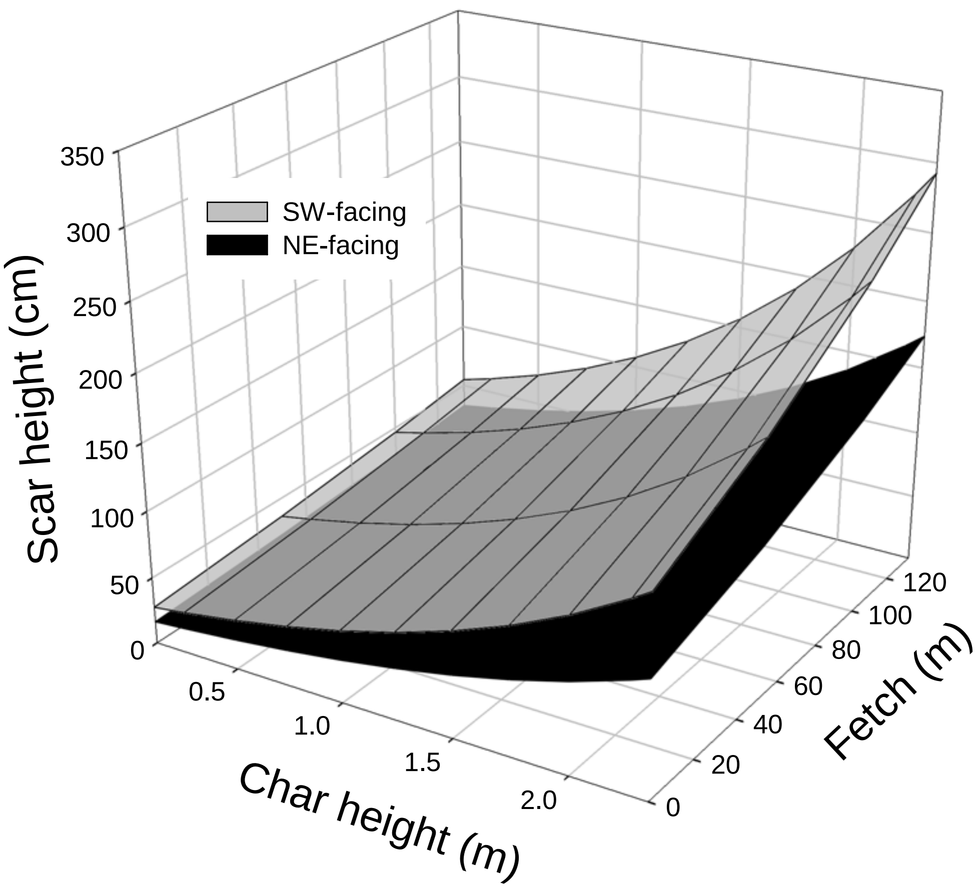


Figure 2.13. Predicted scar heights of trees ≥ 10 cm dbh for five species groups.

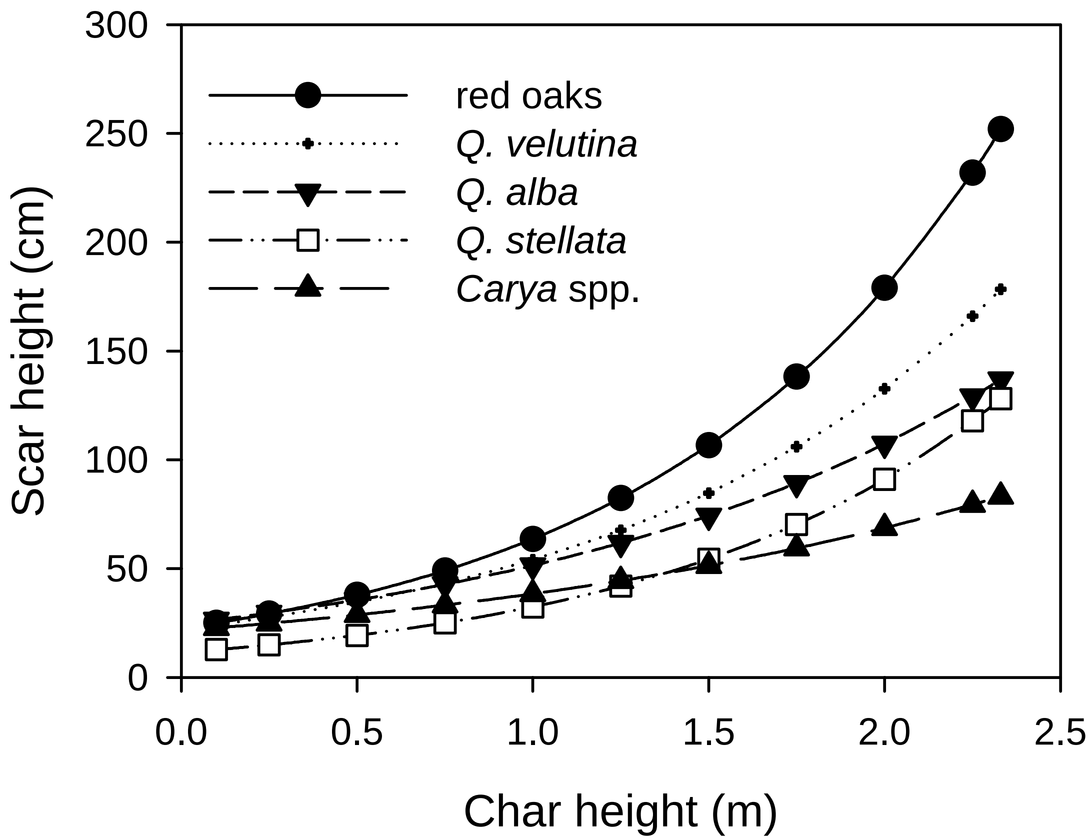


Figure 2.14. Comparison of regression parameters (with standard errors) and scar height models for red oaks and *Quercus velutina* (dbh ≥ 10 cm). Assuming equal intercepts, test of parallelism indicates nonlinear model slopes are significantly different ($\alpha = 0.05$).

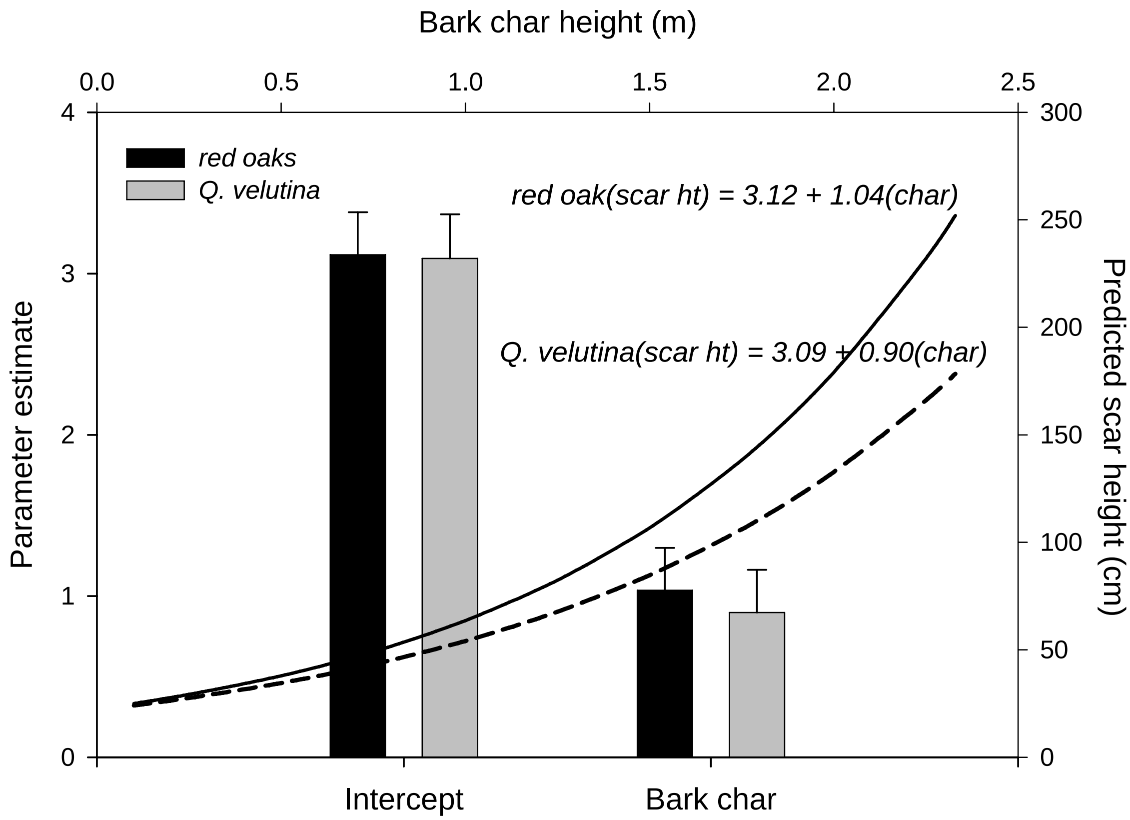


Figure 2.15a. Regression line and 95% confidence bands for a nonlinear model using bark char to predict scar height of red oaks with dbh ≥ 10 cm.

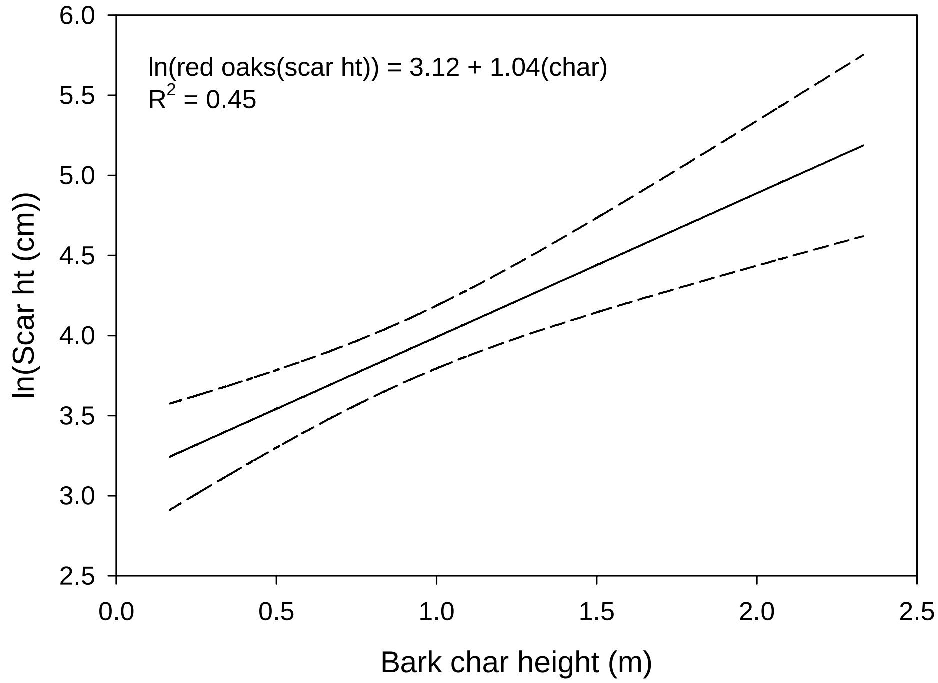
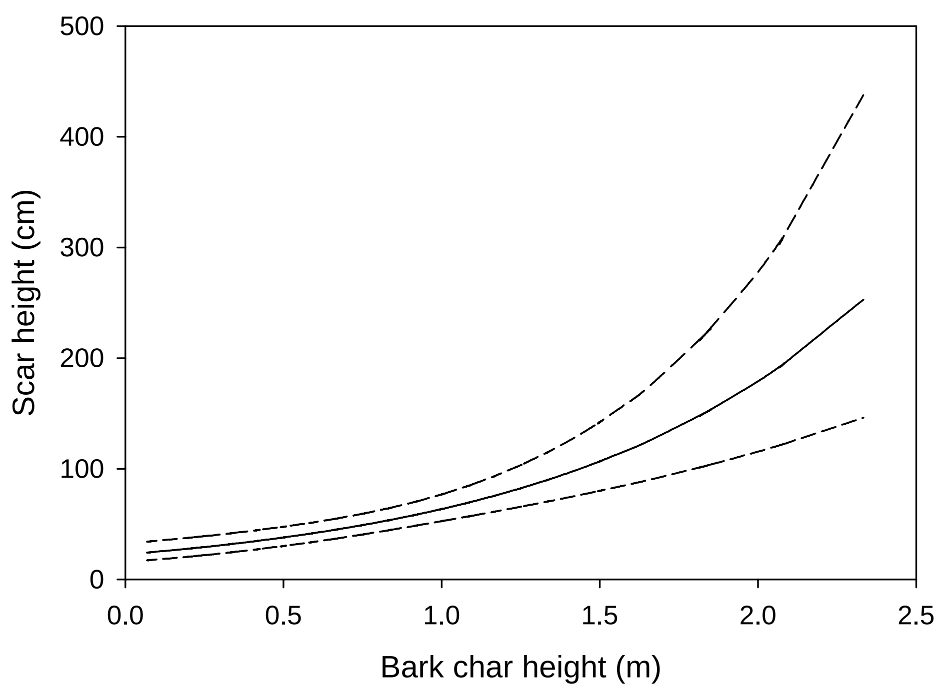


Figure 2.15b. Retransformed regression line and 95% confidence bands for a model using bark char to predict actual scar height of red oaks with dbh ≥ 10 cm.



Scar Width

In total, 671 width measurements were measured for fire scar midpoints: 200 from *Q. alba*, 156 from red oaks, 132 from *Q. velutina*, 125 from *Carya* spp., and 58 from *Q. stellata* (Table 2.12). Mean scar width was highest on southwest-facing slopes for all species (Figure 2.16). On both southwest- and northeast facing slopes, *Q. velutina* had the highest mean scar width, followed by red oaks, *Q. alba*, *Q. stellata*, *Carya* spp., and *Pinus echinata*. Mean dbh of trees measured for scar widths ranged from 19 cm to 31 cm. The smallest tree measured for scar width was a 10 cm dbh *Q. alba*, and the largest was a 76 cm dbh red oak.

A plot-level mean scar width for each species was estimated in each plot with at least one scar width measurement. Mean plot-level scar width ranged from 19 cm for *Carya* spp. to 29 cm for red oaks and *Q. velutina* (Table 2.13). The smallest plot-level scar width was 0.5 cm, and the largest was 74 cm.

Table 2.12. Summary of diameters for trees (dbh ≥ 10 cm) used in scar width regression models.

		dbh (cm)		
Species	n	mean ± stdev	min	max
Red oaks[1]	156	29 ± 17	11	76
Q. velutina	132	31 ± 13	11	72
Q. alba	200	23 ± 12	10	66
Q. stellata	58	29 ± 10	13	55
Carya spp.	125	19 ± 9	10	51

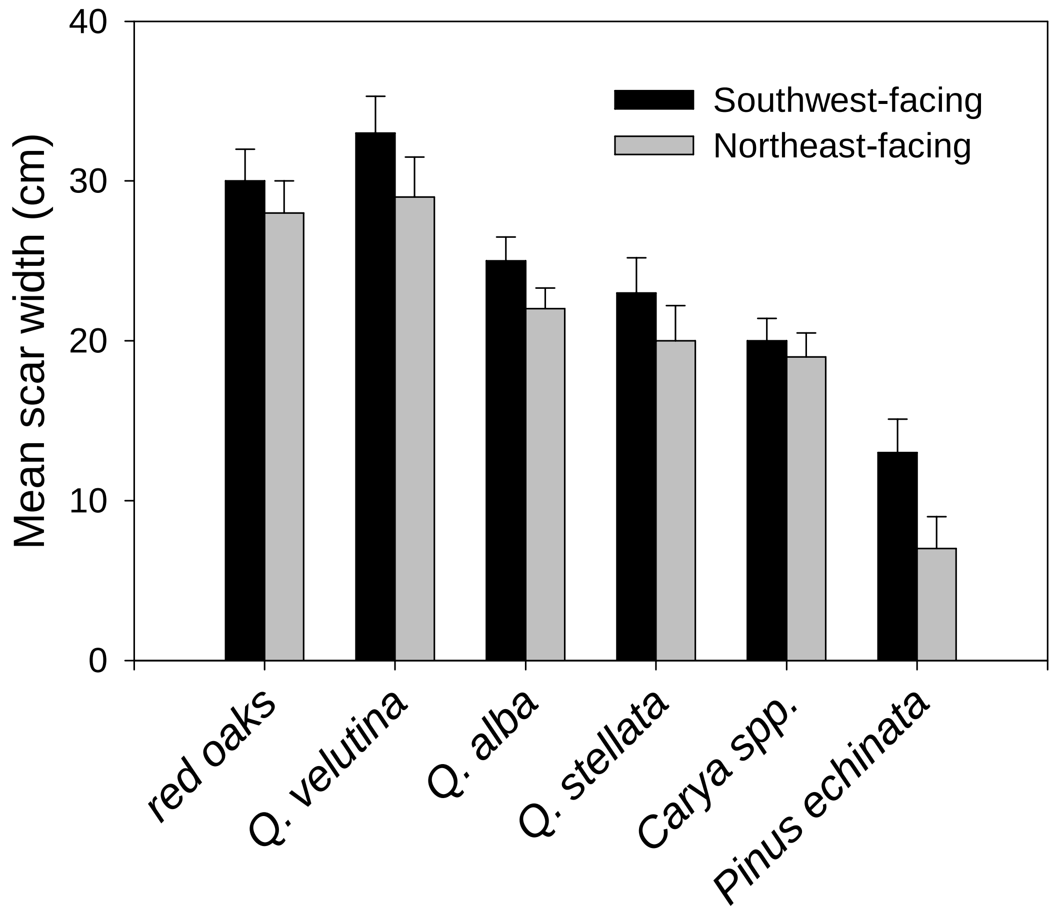
[1]Red oaks include *Q. coccinea* and *Q. shumardii*

Table 2.13. Summary of plot-level scar widths used for stepwise regression models (dbh ≥ 10 cm).

		Plot-level scar width		
Species	Plots	mean ± stdev	min	max
Red oaks[1]	72	29 ± 16	0.5	74
Q. velutina	61	29 ± 14	8	60
Q. alba	85	22 ± 10	5	58
Q. stellata	32	21 ± 10	4	42
Carya spp.	60	19 ± 10	5	60

[1]red oaks include *Q. coccinea* and *Q. shumardii*

Figure 2.16. Individual tree means and standard errors for scar midpoint widths by species and aspect.



For *Q. stellata* and *Carya* spp., there were no significant regression models predicting scar width from the selected predictor variables. Bark char was the first variable selected in the regression model for red oaks, *Q. velutina*, and *Q. stellata* (Table 2.14). Bark char was positively related with scar width in all three models. Slope position was the second variables selected in the *Q. velutina* scar width model. The relationship between slope position and scar width was negative. Slope position was a linear coded variable (5 = upper, 10 = middle, 15 = lower), so a negative relationship indicates that the *Q. velutina* model predicts scar widths to be highest on upper slopes. The white oak model explained little variation in scar width ($R^2 = 0.08$) compared to the red oak ($R^2 = 0.28$) and *Q. velutina* models ($R^2 = 0.30$).

The *Q. velutina* scar width model predicts increasing scar widths with increasing bark char height (Figure 2.17). Although slope position is a significant predictor of *Q. velutina* scar width, changes in slope position cause only minimal changes in scar width. Regardless of char height, the regression model predicts that scar width will increase by 4 cm from lower slope positions to mid-slope positions, and increase another 4 cm from mid-slope to upper slope positions. On upper slope positions, scar width ranges from 21 cm at 0.1 m char height to 49 cm at 2.3 m char height.

The red oak model explained relatively more variation in scar width than the *Q. alba*, and therefore 95% confidence bands were calculated for the red oak model to determine the appropriateness of the fitted regression model. The confidence bands indicate the red oak regression line is not very precise, especially at the smallest and largest char heights (Figure 2.18).

Table 2.14. Multiple regression coefficients, R^2 values, and p-values for models predicting scar width for five tree species groups.

Species	n	B_0	B_1	x_1	B_2	x_2	R^2	p
Red oaks[1]	72	12.84	16.35	char	na	na	0.28	<0.001
Q. velutina	61	24.31	12.56	char	pos	-0.85	0.30	<0.001
Q. alba	85	17.75	4.97	char	na	na	0.08	0.01
Q. stellata	32	-	-	-	-	-	NS	NS
Carya spp.	60	-	-	-	-	-	NS	NS

All regression coefficients differ significantly from zero at $p < 0.05$; n is the number of plot-level means in each model; “NS” mean no significant model; B_0 is the intercept; B_n are model coefficients; x_n are model parameters; “char” is mean maximum stem-bark char height (m) on hardwoods; “pos” is slope position (three classes: 5 = upper slope, 10 = mid-slope, 15 = lower slope)

[1]Red oaks include *Quercus coccinea* and *Quercus shumardii*

Figure 2.17. Predicted width at scar midpoint for *Q. velutina* at different slope positions.

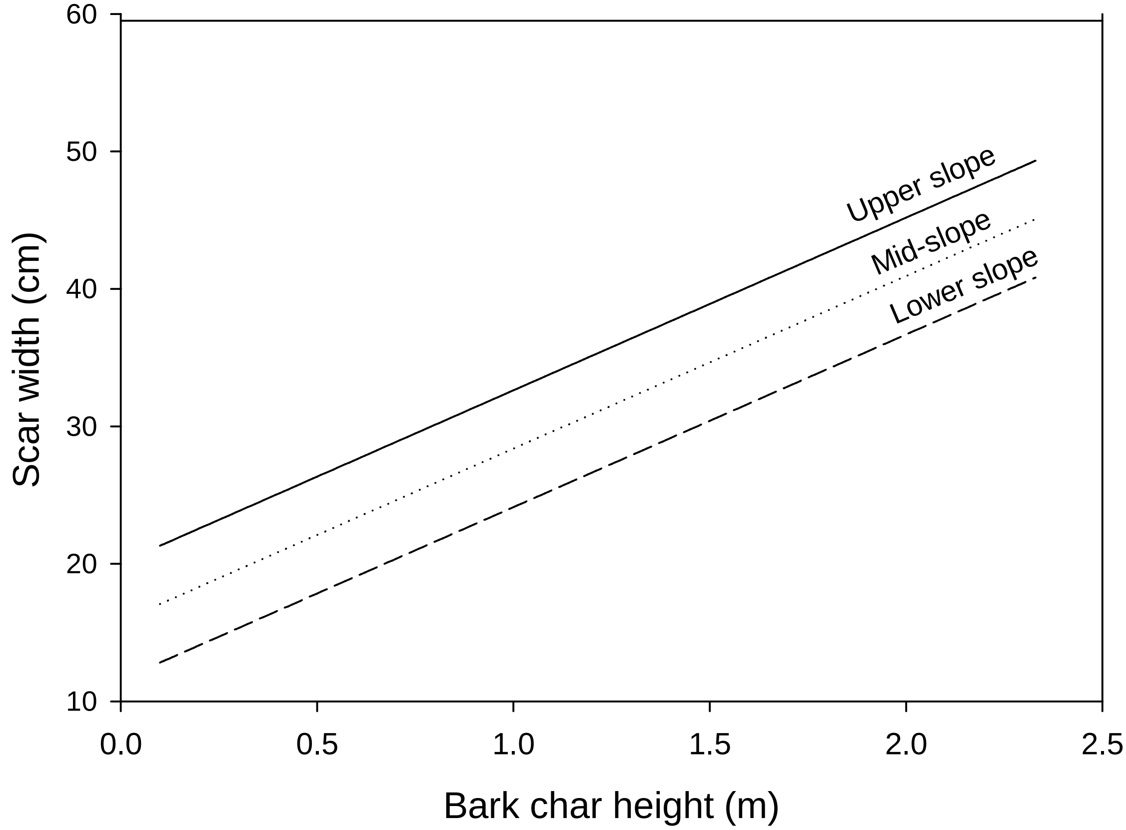
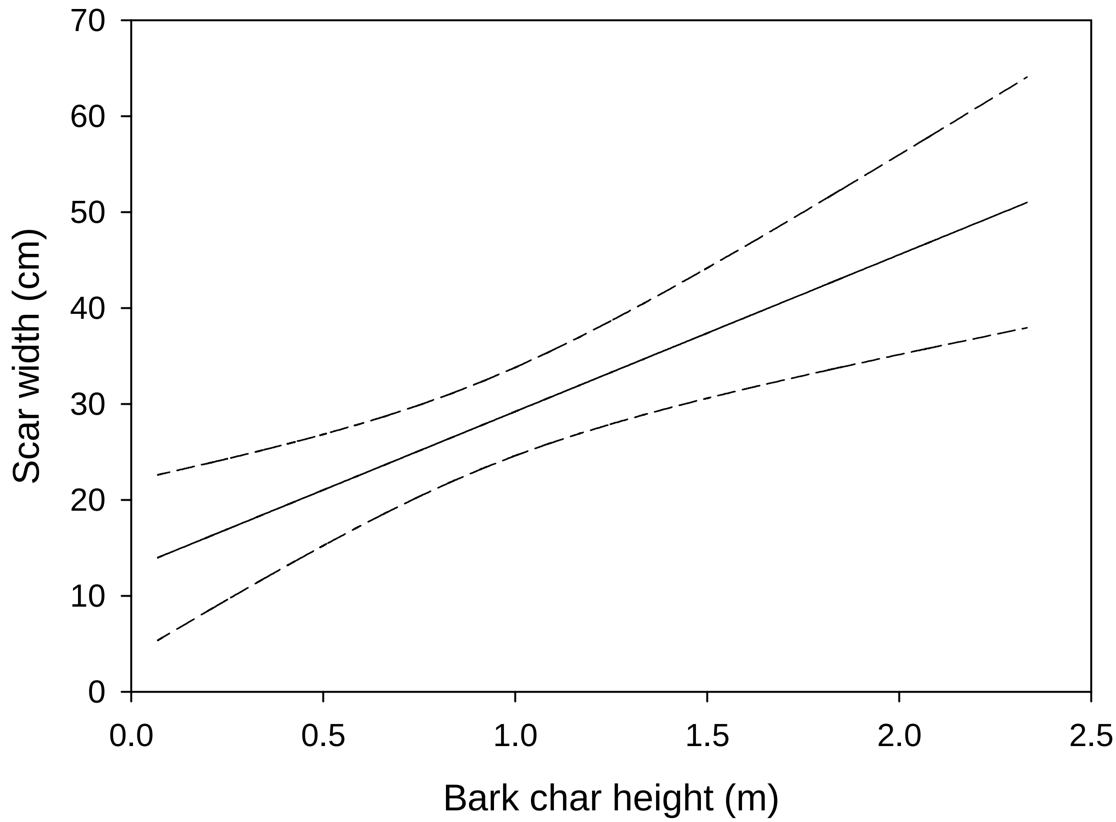


Figure 2.18. Estimated scar width regression line and 95% confidence bands for red oak (dbh ≥ 10 cm).



Percent Cambium Killed

The percent cambium killed (PCK) was calculated from 660 measurements of scar width and tree diameter at scar midpoint (Table 2.15). Mean dbh for trees included in PCK regression analysis ranged from 19 cm for *Carya* spp. to 31 cm for *Q. velutina*. The mean PCK for individual trees ranged from 21% for *Q. stellata* to 29% for *Q. velutina*. Plot-level mean PCK for all species ranged from 20% to 27%, with a minimum mean of <1% and a maximum mean 70% (Table 2.16).

Except for *Carya* spp., PCK was higher on SW- versus NE-facing slopes (Figure 2.19). PCK for *Carya* spp. was 1% higher on northeast-facing slopes. On SW-facing slopes, PCK ranged from 17% for *P. echinata* to 31% for *Q. velutina*. On NE-facing slopes, PCK ranged from 8% for *P. echinata* to 28% for *Carya* spp.

Table 2.15. Individual tree means and standard deviations for PCK of five species groups (dbh ≥ 10 cm).

Species	n	dbh (cm)	Scar width (cm)	Diameter at scar midpoint (cm)	PCK (%)
Red oaks[1]	153	29 ± 12	28 ± 16	38 ± 16	26 ± 12
Q. velutina	130	31 ± 13	29 ± 14	38 ± 15	29 ± 17
Q. alba	198	23 ± 12	22 ± 10	31 ± 16	28 ± 14
Q. stellata	58	29 ± 10	21 ± 10	37 ± 13	21 ± 14
Carya spp.	121	19 ± 9	20 ± 10	26 ± 12	28 ± 10

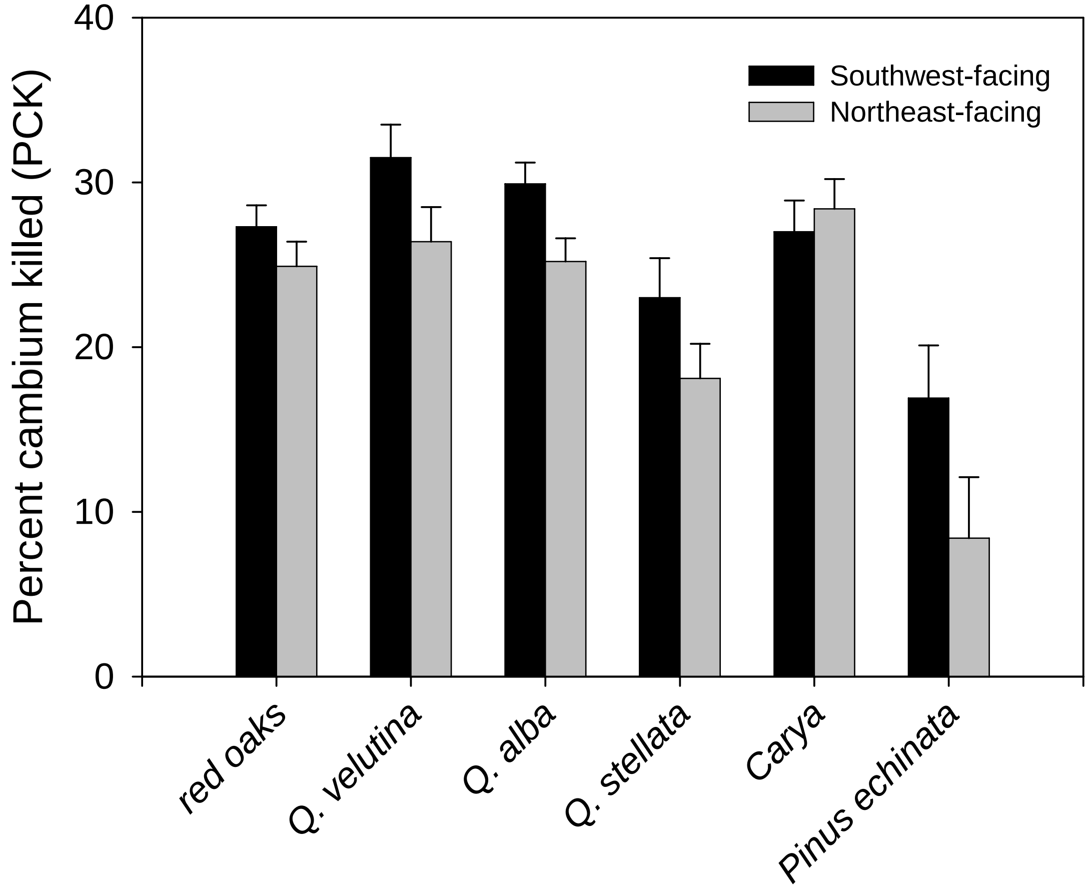
[1]Red oaks include *Q. coccinea and Q. shumardii*

Table 2.16. Plot-level means and standard deviations for PCK of five species groups (dbh ≥ 10 cm).

		Percent cambium killed (PCK)		
Species	n	mean	min	max
Red oaks[1]	72	26 ± 10	<1	51
Q. velutina	61	27 ± 12	9	55
Q. alba	84	27 ± 11	3	52
Q. stellata	32	20 ± 11	4	45
Carya spp.	58	27 ± 11	6	70

[1]Red oaks include *Q. coccinea and Q. shumardii*

Figure 2.19. Individual tree means and standard errors for percent cambium killed (PCK) by species and aspect.



Regression models had R^2 values ranging from 0.07 for red oaks to 0.28 for *Q. stellata* (Table 2.17). For *Carya* spp., slope position (pos) was the only variable selected in the PCK regression model. The relationship between slope position and PCK was negative, indicating higher predicted PCK values at upper versus lower slope position. For all other species, bark char height was the first variable selected in the regression models and was positively related with PCK. For *Q. alba*, BA (m^2 per ha) was the second variable selected and was negatively associated with PCK.

Q. stellata had the highest R^2 value (0.28) for its PCK regression model among all species. Predicted PCK values range from 11% at 0.1 m char height to 32% at 2.3 m char height. To determine the precision of the fitted regression line, 95% confidence bands were calculated on the regression line. The confidence bands indicate that there is considerable wobble in the *Q. stellata* PCK regression line, especially at the high and low values of bark char height (Figure 2.20).

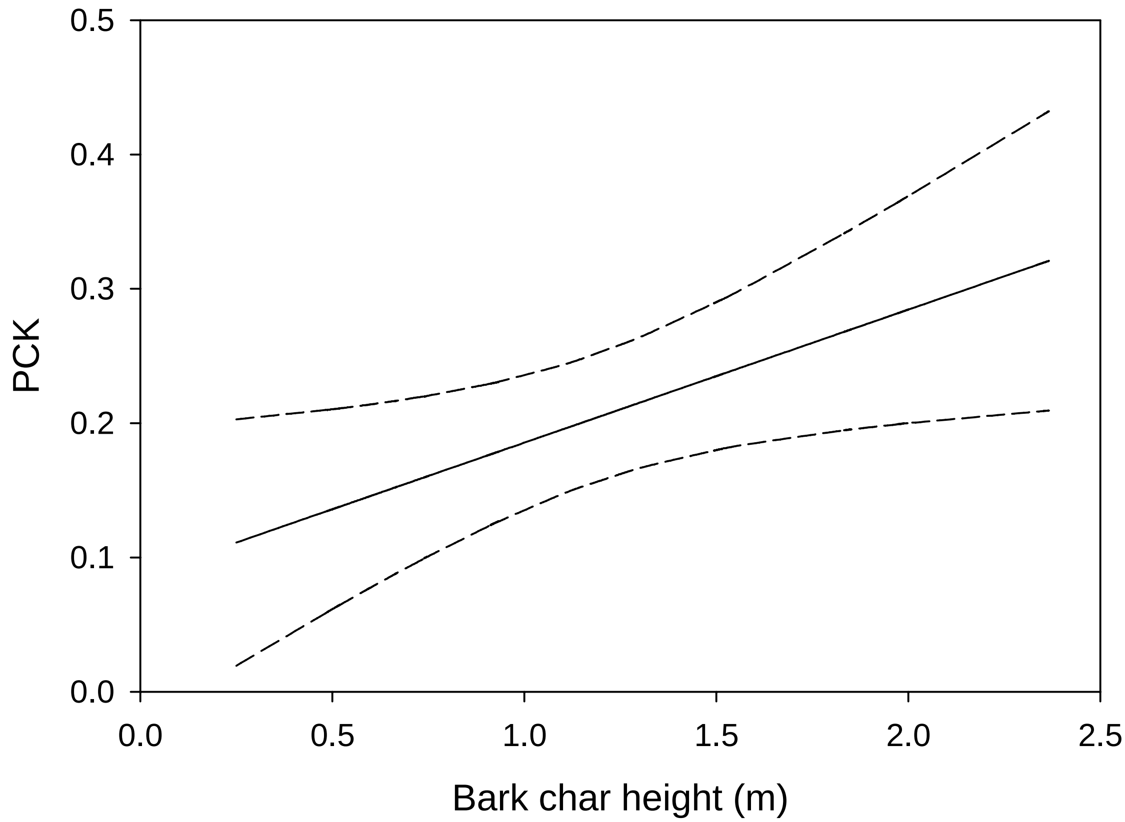
Table 2.17. Multiple regression coefficients, R^2 values, and p-values for models predicting percent cambium killed for five tree species groups.

Species	n	B_0	B_1	x_1	B_2	x_2	R^2	p
Red oaks[1]	72	0.20	0.052	char	na	na	0.07	0.03
Q. velutina	61	0.19	0.078	char	na	na	0.11	<0.01
Q. alba	84	0.31	0.050	char	-0.0039	BA	0.13	<0.01
Q. stellata	32	0.086	0.099	char	na	na	0.28	<0.01
Carya spp.	58	0.34	-0.0078	pos	na	na	0.07	0.03

All regression coefficients differ significantly from zero at $p < 0.05$; n is the number of plot-level means in each model; B_0 is the intercept; B_n are model coefficients; x_n are model parameters; “char” is mean maximum stem-bark char height (m) on hardwoods; “BA” is basal area (m^2 per ha); “pos” is slope position (3 classes: 5 = upper slope, 10 = mid-slope, 15 = lower slope)

[1]Red oaks include *Quercus coccinea* and *Quercus shumardii*

Figure 2.20. Regression line and 95% confidence bands for model predicting percent cambium killed (PCK) for *Quercus stellata*.



Scar Size Models for Sawtimber Trees (dbh ≥ 28 cm)

<u>Scar Height</u>

A total of 340 scar height measurements were recorded from sawtimber trees (dbh ≥ 28 cm) of five species groups: 101 for red oaks, 104 for *Q. velutina*, 68 for *Q. alba*, 44 for *Q. stellata*, and 23 for *Carya* spp. (Table 2.18). Mean dbh ranged from 37 cm to 40 cm, and the largest dbh was a 76 cm red oak. Mean plot-level scar heights ranged from 62 cm for *Carya* spp. and *Q. stellata* to 88 cm for red oaks (Table 2.19). Of the twenty-three *Carya* spp. scar heights recorded for individual trees, only eighteen plot-level means were calculated.

Carya spp. was the only species that did not have a significant regression model. All other species had significant models ($p \leq 0.001$) and R^2 values ranging from 0.29 to 0.46 (Table 2.20). Bark char had a positive relationship with scar height for all significant regression models. Bark char was the first and only predictor selected in the regression model for red oaks and *Q. velutina* . Bark char and slope were the first and second predictors selected in the *Q. stellata* scar height model. Slope had a positive relationship with scar height. For *Q. alba*, diameter at scar midpoint (DIAM) was the first predictor selected, followed by fetch and char. DIAM was negatively related with scar height, and fetch was positively related with scar height.

Table 2.18. Summary of diameters for sawtimber trees (dbh ≥ 28 cm) used in scar height regression models.

Species	n	dbh (cm) mean ± stdev	min	max
Red oaks[1]	101	39 ± 10	28	76
Q. velutina	104	40 ± 9	28	72
Q. alba	68	39 ± 10	28	66
Q. stellata	44	37 ± 7	28	55
Carya spp.	23	37 ± 7	28	51

[1]Red oaks include *Q. coccinea* and *Q. shumardii*

Table 2.19. Summary of plot-level scar heights used for stepwise regression models for sawtimber trees (dbh ≥ 28 cm).

Species	Plots	Plot-level scar height (cm) mean ± stdev	min	max
Red oaks[1]	63	88 ± 70	3	350
Q. velutina	55	79 ± 51	4	242
Q. alba	51	78 ± 55	11	206
Q. stellata	29	62 ± 62	3	310
Carya spp.	18	62 ± 57	2	250

[1]Red oaks include *Q. coccinea* and *Q. shumardii*

Table 2.20. Multiple regression coefficients and R^2 values for models predicting scar height on sawtimber trees (dbh ≥ 28 cm).

Species	n	B_0	B_1	x_1	B_2	x_2	B_3	x_3	R^2
Red oaks[1]	63	2.94	1.16	char	na	na	na	na	0.39
Q. velutina	55	3.25	0.85	char	na	na	na	na	0.29
Q. alba	47	4.66	-0.029	DIAM	0.0089	fetch	0.56	char	0.46
Q. stellata	29	1.34	1.08	char	0.080	slope	na	na	0.40

All models are significant at $p \leq 0.001$; All regression coefficients differ significantly from zero at $p < 0.05$; n is the number of plot-level means in each model; B_0 is the intercept; B_n are model coefficients; x_n are model parameters; “char” is mean maximum stem-bark char height (m) on hardwoods; “DIAM” is tree diameter (cm) at scar midpoint; “fetch” is distance (m) to bottom of hill; “slope” is slope steepness (°).
[1]Red oaks include *Quercus coccinea* and *Quercus shumardii*

Predicted scar heights for red oaks and *Q. velutina* are similar at the lowest char height values (Figure 2.21). At 0.25 meters of char height, red oak predicted scar height is 25 cm and *Q. velutina* scar height is 32 cm. Predicted car heights for both species remain as char height increases to approximately 1.25 m. As char height increases from 1.25 m red oak scar heights start to increase at a higher rate than *Q. velutina*. At 2.3 m char height, predicted scar height for *Q. velutina* and red oaks is 184 cm and 282 cm.

There was high amount of variability in models for trees with dbh ≥ 10 cm (Figure 2.15a, Figure 2.15b), and therefore it is likely that calculation of confidence bands for the red oak and *Q. velutina* regression lines would reveal similar variability. A test of parallelism was used to ensure that the red oak and *Q. velutina* models differ. Assuming equal intercepts, the test of parallelism indicates that the red oak and *Q. velutina* models have slopes significantly different from each other and therefore the species models should be kept separate.

Predicted scar height of *Q. stellata* was most sensitive to slope steepness (Figure 2.22). At the lowest slope value (2°), predicted scar height ranged from 5 cm at 0.2 m char height to 55 cm at 2.3 m char height. At the highest char height value, predicted scar height ranged from 55 cm at 2° of slope to 236 cm at 20° of slope. The rate of increase for scar height is exponential for the highest slope values and almost linear for the lower to medium slope values.

Predicted scar height values for *Q. alba* were dependent on char height and fetch values, and varied according to the diameter at scar midpoint (DIAM). Three DIAM values (30 cm, 50 cm, and 70 cm) were chosen to represent three different size classes (small, medium, and large) of sawtimber-size *Q. alba*. At the lowest char height and fetch values, scar height ranged from 15 cm for large sawtimber trees to 46 cm for small sawtimber trees (Figure 2.23). As char increased and fetch remained low, scar heights increase at a linear rate for all size classes. At the highest char height and lowest fetch values, scar height rangeds from 48 cm for large sawtimber trees to 154 cm for small sawtimber trees. With the exception of small sawtimber trees, predicted scar heights increased at an approximate linear rate with increasing char height and fetch. For small sawtimber trees at the highest fetch, predicted scar heights increased exponentially with increasing char height. Scar heights at the highest fetch and char height values ranged from 145 cm for large sawtimber trees to 465 cm for small sawtimber trees.

Figure 2.21. Predicted scar heights of sawtimber trees (dbh ≥ 28 cm) for red oaks and *Q. velutina*.

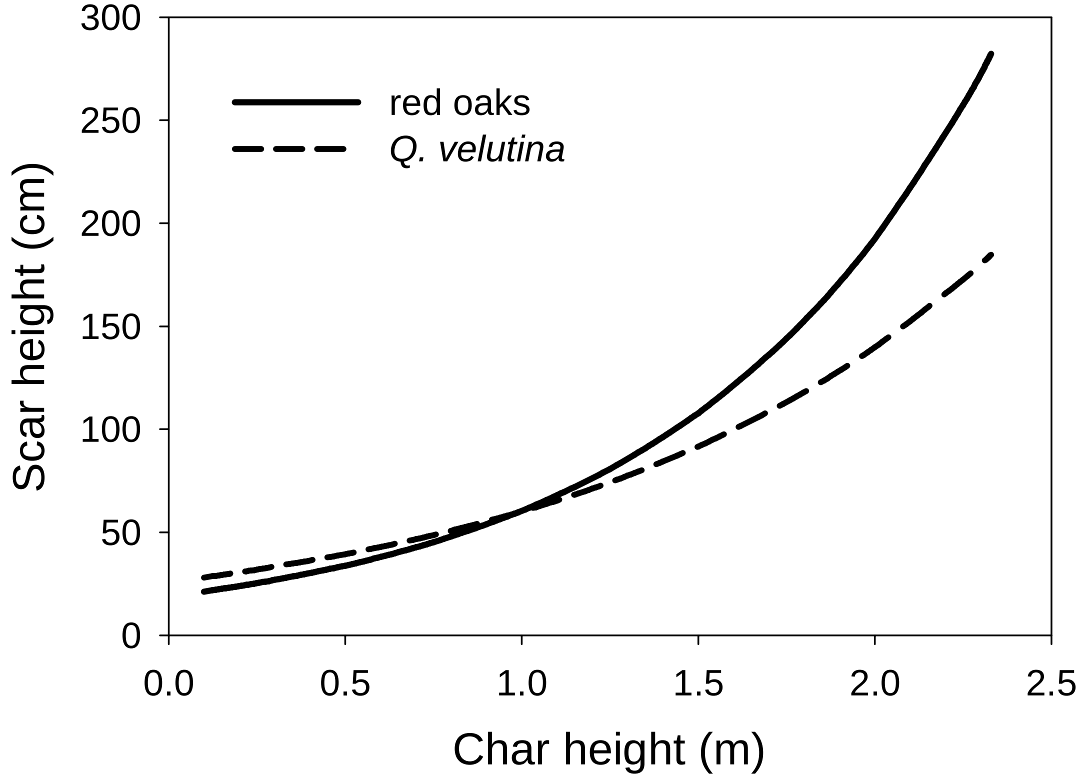


Figure 2.22. Predicted scar heights of sawtimber trees (dbh ≥ 28 cm) for *Q. stellata*. Slope is in degrees.

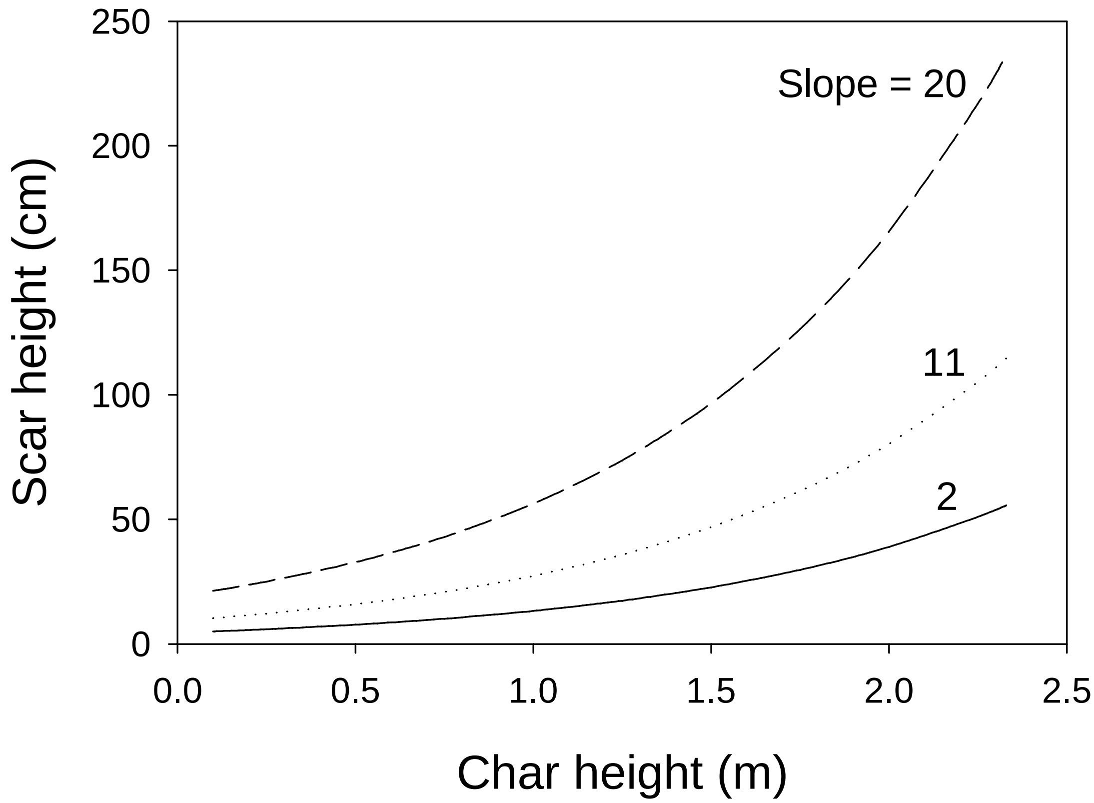
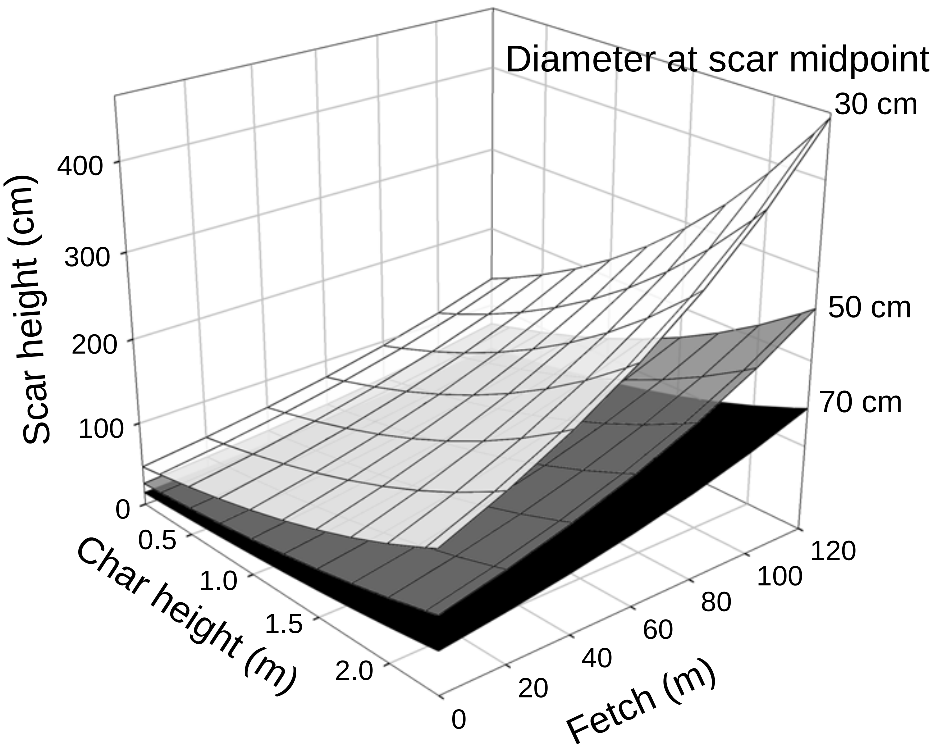


Figure 2.23. Predicted scar height of sawtimber trees (dbh ≥ 28 cm) for *Q. alba* at three diameter classes.



Scar Width

A total of 254 scar width measurements were recorded for cat-face and oval scars on trees of sawtimber size (Table 2.21). Mean dbh of trees measured ranged from 36 cm to 40 cm. Mean plot-level scar widths ranged from 20 cm for *Q. stellata* to 34 cm for red oaks and *Carya* spp. (Table 2.22). The smallest plot-level scar width was 0.5 cm for red oaks, and the largest was 109 cm for *Q. alba*.

There were no significant regression models for *Q. alba*, *Q. stellata*, and *Carya* spp. (Table 2.23). Models for red oaks and *Q. velutina* were both significant ($p < 0.01$). Bark char height was the first predictor selected for both red oaks and *Q. velutina* models. Fetch was the second variable selected for the *Q. velutina* regression model. Both bark char height and fetch had positive relationships with scar width.

Predicted scar heights for *Q. velutina* follow a linear pattern with both char height and fetch (Figure 2.24). At the lowest char height value, predicted scar widths range from 16 cm at 0 m fetch to 33 cm at 120 m fetch. At the highest char height value, predicted scar widths range from 43 cm at 0 m fetch to 60 cm at 120 m fetch.

Table 2.21. Summary of diameters for sawtimber trees (dbh ≥ 28 cm) used in scar width regression models.

		dbh (cm)		
Species	n	mean ± stdev	min	max
Red oaks[1]	80	39 ± 10	28	76
Q. velutina	74	40 ± 9	28	72
Q. alba	54	40 ± 11	28	66
Q. stellata	31	36 ± 7	28	55
Carya spp.	15	38 ± 8	28	51

[1]Red oaks include *Q. coccinea* and *Q. shumardii*

Table 2.22. Summary of plot-level scar widths used for stepwise regression models (trees ≥ 28 cm).

		Plot-level scar width		
Species	Plots	mean ± stdev	min	max
Red oaks[1]	50	34 ± 19	0.5	74
Q. velutina	45	33 ± 16	4	75
Q. alba	43	31 ± 20	5	109
Q. stellata	24	20 ± 10	3	42
Carya spp.	14	34 ± 17	10	70

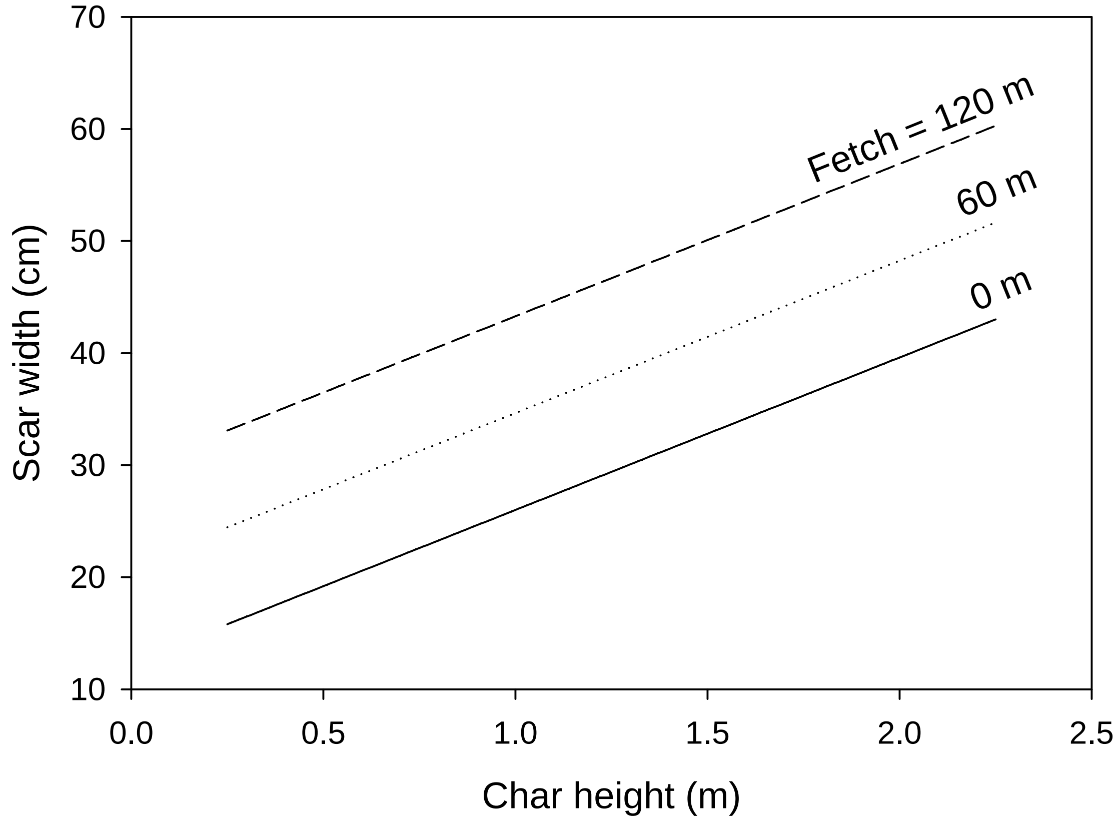
[1]Red oaks include *Q. coccinea* and *Q. shumardii*

Table 2.23. Multiple regression coefficients, R^2 values, and p-values for models predicting scar width for five tree species groups.

	n	B_0	B_1	x_1	B_2	x_2	R^2	p
Red oaks[1]	50	17.73	14.81	char	na	na	0.16	<0.01
Q. velutina	45	12.40	13.60	char	fetch	0.14	0.23	<0.01
Q. alba	43	-	-	-	-	-	NS	NS
Q. stellata	24	-	-	-	-	-	NS	NS
Carya spp.	14	-	-	-	-	-	NS	NS

All regression coefficients differ significantly from zero at $p < 0.05$; n is the number of plot-level means in each model; "NS" mean no significant model; B_0 is the intercept; B_n are model coefficients; x_n are model parameters; "char" is mean maximum stem-bark char height (m) on hardwoods; "fetch" is distance (m) to bottom of hill.
[1]Red oaks include *Quercus coccinea* and *Quercus shumardii*

Figure 2.24. Predicted scar width for sawtimber (dbh ≥ 28 cm) *Q. velutina*.



Percent Cambium Killed (PCK)

Calculations of percent cambium killed (PCK) were made for 250 sawtimber trees. Mean dbh of trees measured ranged from 36 cm to 40 cm (Table 2.24). Mean scar width ranged from 20 cm to 34 cm, and tree diameter at scar midpoint ranged from 40 cm to 51 cm. Plot-level means for PCK ranged from 14% for *Q. stellata* to 27% for *Carya* spp. (Table 2.25).

There were no significant regression models for *Q. stellata* and *Carya* spp. Bark char height was the first predictor selected for the red oak, *Q. velutina*, and *Q. alba* model (Table 2.26). Fetch was the second variable selected for the *Q. velutina* model. Fetch had a positive relationship with PCK in the *Q. velutina* model, and bark char had a positive relationship with PCK in all significant models. The *Q. velutina* model explained the most variation in PCK (R^2 = 0.35), followed by the red oak model (R^2 = 0.12) and the *Q. alba* model (R^2 = 0.10).

Predicted values for PCK of *Q. velutina* have the same linear relationship with char height and fetch as for predicted scar widths of *Q. velutina* (Figure 2.24). At the lowest char height values, PCK ranges from 3% at 0 m fetch to 21% at 120 m fetch. At the highest char height values, PCK ranges from 31% at 0 m fetch and 48% at 120 m fetch.

Table 2.24. Individual tree means and standard deviations for PCK of five species groups (dbh ≥ 28 cm).

Species	n	dbh (cm)	Scar width (cm)	Tree diameter at scar midpoint (cm)	PCK
Red oaks[1]	77	38 ± 9	34 ± 19	49 ± 12	24 ± 12
Q. velutina	73	40 ± 9	33 ± 16	40 ± 12	26 ± 14
Q. alba	54	40 ± 11	31 ± 20	51 ± 14	20 ± 14
Q. stellata	31	36 ± 7	20 ± 10	46 ± 8	15 ± 8
Carya spp.	15	38 ± 8	34 ± 18	47 ± 14	26 ± 18

[1]Red oaks include *Q. coccinea and Q. shumardii*

Table 2.25. Plot-level means and standard deviations for PCK of five species groups (dbh ≥ 28 cm).

		Percent cambium killed (PCK)		
Species	n	mean	min	max
Red oaks[1]	49	23 ± 12	< 1	50
Q. velutina	45	24 ± 13	3	52
Q. alba	54	20 ± 12	2	54
Q. stellata	24	14 ± 8	2	29
Carya spp.	14	27 ± 18	5	67

[1]Red oaks include *Q. coccinea and Q. shumardii*

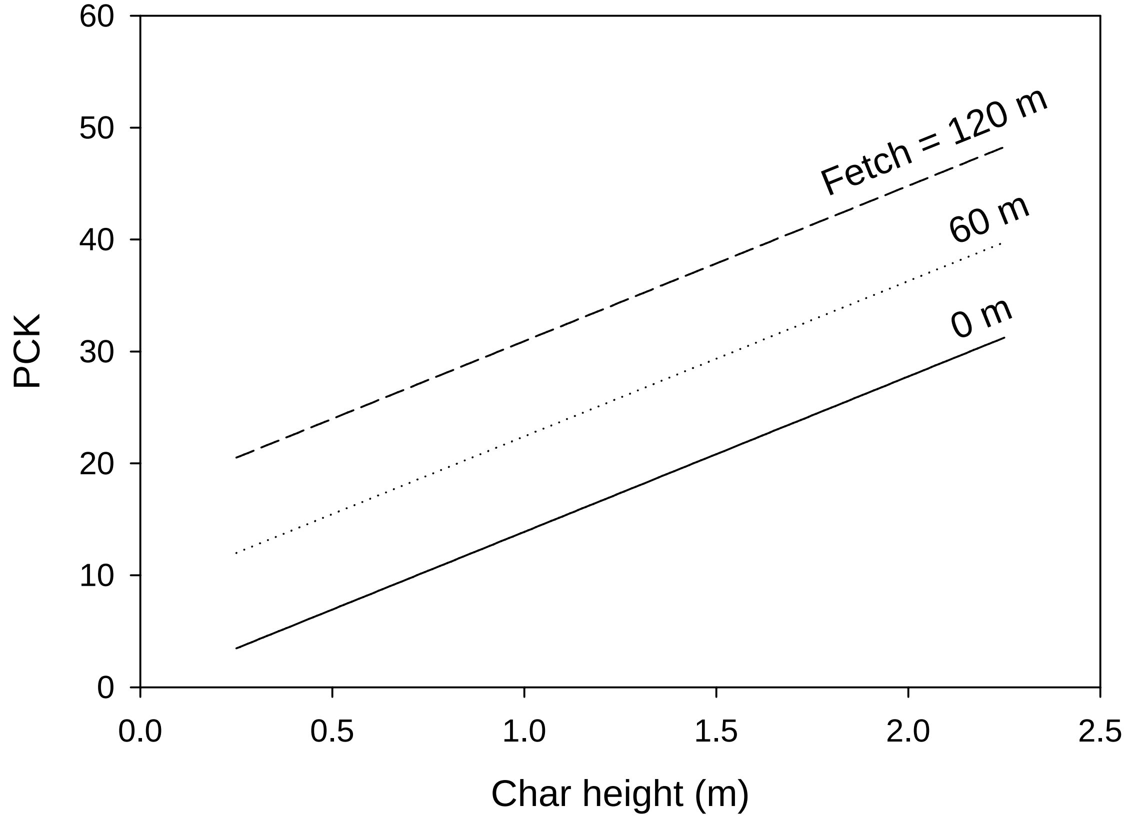
Table 2.26. Multiple regression coefficients, R^2 values, and p-values for models predicting percent cambium killed of sawtimber trees (dbh ≥ 28 cm).

Species	n	B_0	B_1	x_1	B_2	x_2	R^2	p
Red oaks[1]	49	0.15	0.080	char	na	na	0.12	0.01
Q. velutina	45	-	0.14	char	fetch	0.0014	0.35	<0.001
Q. alba	43	0.13	0.069	char	-	-	0.10	0.04
Q. stellata	24	-	-	-	-	-	NS	NS
Carya spp.	14	-	-	-	-	-	NS	NS

NS indicates non-significant models. All regression coefficients differ significantly from zero at $p < 0.05$ except B_0 for *Q. velutina*; n is the number of plot-level means in each model; B_0 is the intercept; B_n are model coefficients; x_n are model parameters; “char” is mean maximum stem-bark char height (m) on hardwoods; “fetch” is distance (m) to bottom of hill.

[1]Red oaks include *Quercus coccinea* and *Quercus shumardii*

Figure 2.25. Predicted percent cambium killed (PCK) for sawtimber *Q. velutina*.



Largest Fire-Killed Quercus *and "Other" Species*

The dbh of 94 fire-killed *Quercus* and 92 fire-killed "other" species were recorded in the burn plots (Table 2.27). Six burn plots had no fire-killed *Quercus*, and eight plots had no fire-killed "other" species. Mean dbh of fire-killed trees was 13 cm and 8 cm for *Quercus* and "other" species.

Models predicting dbh of largest killed trees were significant for both *Quercus* and "other" species ($p < 0.001$) (Table 2.28). Bark char was the first and only predictor selected for both models, and bark char had a positive relationship with dbh. Predicted values of dbh indicate that at low char height values, dbh of largest fire-killed tree is approximately 8 cm for *Quercus* and 7 cm for "other" species (Figure 2.26). The slope of the *Quercus* regression line is much steeper than for "other" species, and at the highest char height values dbh of largest fire-killed tree is approximately 21 cm for *Quercus* and 11 cm for "other" species.

Table 2.27. Summary for largest fire-killed trees used in regression analysis.

		dbh (cm)		
Species	n	mean	minimum	maximum
Quercus spp.	94	13	1	43
"other"[1]	92	8	2	24

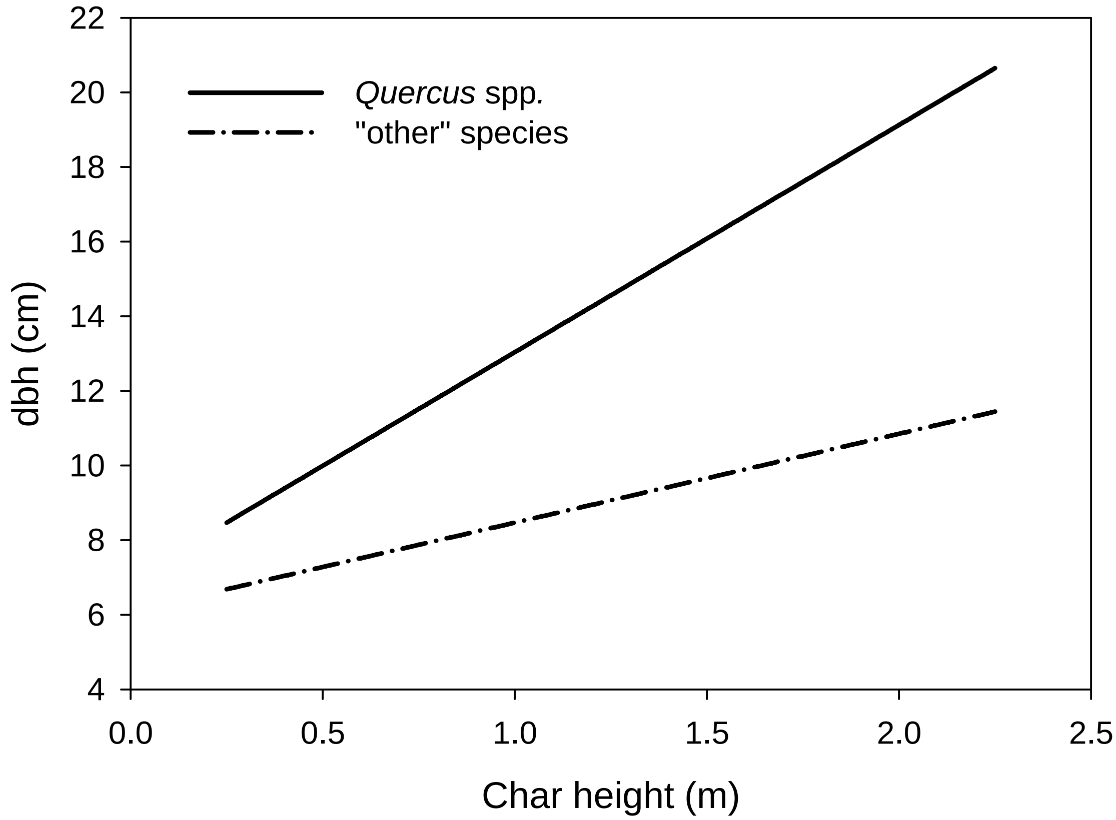
[1] "other" includes *Carya* spp. (33), *Cornus florida* (27), *Sassafras albidum* (15), *Acer rubrum* (6), *Pinus echinata* (3), *Nyssa sylvatica* (2), *Amerlanchier arborea* Michx. (1), *Juniperus virginiana* (1), and unknown (4)

Table 2.28. Multiple regression coefficients and R^2 values for models predicting dbh (cm) of largest fire-killed tree.

Species	n	B_0	B_1	x_1	R^2
Quercus spp.	94	6.95	6.09	char	0.23
"other"[1]	92	6.08	2.38	char	0.11

All models are significant at $p < 0.001$. All regression coefficients differ significantly from zero at $p < 0.05$; n is the number of plot-level means in each model; B_0 is the intercept; B_n are model coefficients; x_n are model parameters; "char" is mean maximum stem-bark char height (cm) on hardwoods.
1 "other" includes *Carya* spp. (33), *Cornus florida* (27), *Sassafras albidum* (15), *Acer rubrum* (6), *Pinus echinata* (3), *Nyssa sylvatica* (2), *Amerlanchier arboreum* Michx. (1), *Juniperus virginiana* (1), and unknown (4)

Figure 2.26. Predicted dbh of largest fire-killed tree for *Quercus* and “other” species.



Basal Cavities Formed From Fire Scars

A total of nineteen fire-caused basal cavities were found at all burn plots. Fourteen cavities were formed from scars caused by recent prescribed fires, and five were formed from old fire scars formed from pre-management fires (Table 2.29 and Table 2.30). Mean cavity dimensions for cavities from recently formed fire scars were 31 cm in width, 157 cm in height, and 33 cm in depth. Mean cavity dimensions for basal cavities from old fires cars were 17 cm in width, 217 in height, and 21 cm in depth. Species with fire-caused basal cavities included red oaks, *Q. abla, Q. stellata, Q. velutina, Carya* spp., and *Nyssa sylvatica*. Evidence of animal use in the cavities included acorn hulls, nesting material, feathers, sawdust excavation, salamander presence, and woodpecker damage to bole (Table 2.31). A total of 37% of basal cavities showed some animal evidence.

Table 2.29. Summary of measurements for trees (n = 14) with basal cavities formed from scars from recent prescribed fires.

	Mean	Minimum	Maximum
dbh (cm)	37	18	56
Scar height (cm)	96	9	190
Scar width (cm)	31	6	70
Cavity height (cm)	157	20	> 300
Cavity depth (cm)	33	11	40

Cavities by species: *Q. alba* (3), red oaks (*Q. coccinea* and *Q. shumardii*) (3) , *Q. stellata* (3), *Carya* spp. (3), *Q. velutina* (1), and *Nyssa sylvatica* (1); Cavities by scar type: cat-face (11), oval (2), not recorded (1); Animal evidence recorded in cavity trees: acorn hulls in cavity (3), nesting material in cavity (1), woodpecker damage to bole (1), sawdust excavated from cavity (1), blue-tailed salamander in cavity (1), feathers in cavity (1), none (9).

Table 2.30. Summary of measurements for trees (n = 5) with basal cavities formed from scars from pre-management fires (old fire scars).

	Mean	Minimum	Maximum
dbh (cm)	31	21	51
Scar height (cm)	60	19	120
Scar width (cm)	17	10	87
Cavity height (cm)	217	70	> 300
Cavity depth (cm)	21	9	35

Cavities by species: *Carya* spp. (3), *Q. velutina* (1), and *Q. stellata* (1); Cavities by scar type: cat-face (4) and oval (1); Animal evidence recorded in cavity trees: salamander in cavity (1), none (4)

Table 2.31. Summary of cavities found on burn plots.

Cavity formation	n	Cavities per ha	Animal evidence[1]
Recent fire scar	14	0.49	43%
Old fire scar	5	0.17	20%
Total	19	0.66	37%

[1]animal evidence includes acorn hulls in cavity, nesting material in cavity, woodpecker damage to bole, sawdust excavated from cavity, blue-tailed salamander in cavity, nesting material in cavity, and feather in cavity

Discussion

Old Fire Scars

Results indicate that it is possible to discern scars created from “old” fires (pre-management; fires > 15 years prior) from scars created from “current” prescribed fires (fires within last 15 years). There were more old fires scars detected on control sites (2.6% versus 1.8%), but the percentages are nearly identical when one control plot with a relatively high number of old *Carya* spp. fire scars is removed (1.9% versus 1.8%).

Despite examination of 212 *Pinus echinata*, no old fire scars were found. Previous studies have relied on fire scars on *Pinus echinata* stumps and live trees to determine the fire history of areas throughout the Ozarks region (Guyette and Cutter 1991, Guyette and Cutter 1997, Guyette et al. 2002, Guyette and Spetich 2003, Stambaugh and Guyette 2006). Those studies, however, targeted areas with a major *Pinus echinata* overstory component. This study focused on areas with a major *Quercus* component, areas where *Pinus echinata* trees comprised less than 4.0% of trees dbh ≥ 10 cm on control and burn sites.

Species Sensitivity to Scarring

The percentage of trees scarred is a direct measure of the sensitivity to scarring for trees in this study. *Pinus echinata* is clearly the most fire resistant species, with far fewer percent trees scarred (PTS) than other species on northeast- and southwest-facing slopes (Figure 4). Considering the low PTS for *P. echinata* and examining the predicted PTS for all other species (Figure 5), scarring sensitivity could be ranked as follows:

Q. coccinea/*Q. shumardii* > *Q. velutina* > *Q. alba* > *Carya* > *Q. stellata* >> *P. echinata*

Bark characteristics, such as thickness and specific gravity, have been directly linked to likelihood of fire-scarring and fire-caused mortality (Harmon 1984, Hengst and Dawson 1994, Smith and Sutherland 2006). Probability of fire scarring has also been linked with tree diameter, often a reliable indicator of bark thickness (Guyette and Stambaugh 2004). Because of its thin bark, *Q. coccinea* has been recognized as a relatively fire sensitive oak (Johnson 1990). Bark thickness equations from Harmon (1984) (QMD in burned plots = 28 cm) indicate that *P. echinata* has the thickest bark of species in our study, followed by *Q. velutina*, *Carya* spp., *Q. alba*, and *Q. coccinea*. Others have found *Q. alba* has thinner bark than *Q. coccinea* but suggested the bark of *Q. coccinea* is a better conductor of heat (Starker 1932). A study of southern upland oaks found that for small diameter trees, *Q. alba* is relatively thin-barked and *Q. stellata* is relatively thick-barked, while *Q. coccinea*, *Q. velutina*, and *Q. shumardii* have intermediate bark thickness (Howard 1977). If *Q. alba* is thinner barked than *Q. coccinea*, my results support Starker (1932) and suggest the bark of *Q. coccinea* is a better conductor of heat because of higher susceptibility to fire-caused scarring.

At University Forest in southeast Missouri, Burns (1955) found *Q. coccinea* was more frequently damaged by fire than *Q. alba* and *Q. velutina*. An examination of scarring on annually burned plots at University Forest found *Q. coccinea* was most frequently scarred and *Q. stellata* was the least frequently scarred, with *Q. alba*, *Q. velutina*, and *Carya* spp. having intermediate scarring (Paulsell 1957, Scowcraft 1966). In a mixed oak forest in Virginia, *Q. coccinea* was the least fire resistant of all *Quercus* examined (Regelbrugge and Smith 1994). A direct comparison of predicted PTS for red oaks (*Q. coccinea* and *Q. shumardii*) and *Q. alba* (Figure 2.6) shows that for any given aspect or fire intensity (i.e. char height), red oaks are more likely to scar from prescribed fire than *Q. alba*.

Landscape Features and Scarring

Landscape features directly affect wildland fire behavior (Pyne et al. 1996), and therefore determine distribution of fire scarred trees across a fire-burned landscape (Jenkins et al. 1997). Fire damage regression models developed within this study indicate that aspect, fetch, slope position, and slope steepness explain significant amounts of variation in fire-caused damage. Following a wildfire in northern Arkansas, Jenkins et al. (1997) found aspect, slope steepness and fetch were important factors for predicting the percentage of trees scarred.

Aspect and steepness determine solar radiation exposure on a slope, which directly affects air temperature and fuel moisture levels. These factors contribute to fire intensity, which leads to relatively high fire temperatures on southwest-facing slopes and more intense fires on very steep slopes (Pyne et al. 1996, Schwemlein and Williams 2006). The PTS and fire damage models in this study indicated that for some species, there is an increase in scar frequency and scar size on southwest- versus northeast-facing slopes. The predicted scar height of *Q. stellata* increased at an exponential rate on southwest-facing slopes. There was also an increase in scar height of sawtimber *Q. stellata* with increasing slope steepness. Jenkins et al. (1997) found a higher percentage of trees scarred on southwest-facing slopes and indicated a positive relationship between slope steepness and percent trees scarred.

Upper slope positions are more xeric than lower slope positions (Parker 1982), and therefore relatively higher fire intensities could be expected on upper slopes. Our models used fetch (a continuous variable measuring distance to bottom of hill) and slope position (a linear categorical variable) in fire damage regression models, and both fetch or slope position were a significant predictor in at least two models. For both variables, fire damage was highest at larger fetch values or on upper slope positions. Jenkins et al. (1997) also found increasing percent of trees scarred with increasing fetch.

Scar Size by Species and Tree Size

Only the largest scars were measured for this study, and scar heights were greatest on southwest-facing slopes. For both northeast- and southwest-facing slopes, *P. echinata* had much smaller scar heights than all other species (Figure 2.10) and supports the notion that *P. echinata* is the most fire resistant of all Ozark tree species (Nelson 2005). Although *Q. alba* had similar scar heights as *Q. velutina*, the mean dbh of *Q. alba* with large fire scars was lower than all other species except *Carya* spp. (Table 2.9).

It is interesting that for all hardwoods examined, *Carya* spp. had the smallest mean dbh of trees with large fire scars and the lowest mean scar height (Table 2.10). Predicted scar heights following relatively intense fires (i.e. char height $\geq$ 1.5 m) indicate that among hardwoods, red oaks have the highest fire scar heights, followed by *Q. velutina*, *Q. alba*, *Q. stellata*, and *Carya* spp. This would indicate that although *Carya* spp. is more frequently scarred than *Q. stellata*, the extent of damage following fire is less severe.

Tree diameter has been linked with bark thickness (Harmon 1984, Hengst and Dawson 1994), and the probability of scarring may be predicted by using stem diameter (Guyette and Stambaugh 2004). For sawtimber *Q. alba*, this study indicated that trees with smaller diameters were more likely to have higher scar heights, although this was the only model directly linking tree diameter and scar size. Plot-level measurements of tree size and stand density (i.e. basal area (m^2 per ha) and QMD (cm)) were significant predictors in three scar size models. QMD directly represents mean tree size in a plot, but BA may indicate tree size or stand openness. A low BA may indicate more open forest conditions and not smaller trees, and more open forest conditions would lead to increased solar exposure and relatively higher wind speeds, two factors directly linked to fire intensity.

Scarring on Sawtimber Trees

Red oaks, *Q. velutina*, and *Q. stellata* fire scars represented 73% of all scars measured for sawtimber trees (dbh ≥ 28 cm), but only 53% of scars measured for all trees with a dbh ≥ 10 cm. This indicates that either red oaks, *Q. velutina*, and *Q. stellata* do not have increased resistance to scarring with increasing tree size, or large scars on *Q. alba* and *Carya* spp. are usually formed on smaller diameter trees. As noted earlier, the mean dbh of trees (dbh ≥ 10 cm) with large scars was lowest for *Q. alba* and *Carya* spp.

Of the eighty-four *Q. stellata* that had fire scars measured, more than half (44) were sawtimber trees. But among hardwoods, *Q. stellata* had the lowest percentage of cat-face scars and the highest percentage of basal scars (Table 2.8). While examining *Q. stellata* scars in the field it was noted that frequently the largest scars on *Q. stellata* were small basal scars, while other hardwoods had large cat-face or closed scars. Of the forty-four sawtimber *Q. stellata* with large scars, twenty-five of those trees had scars < 20 cm. The mean plot-level scar height for sawtimber *Q. stellata* was 16 cm less than any other oak. So although large diameter *Q. stellata* frequently scarred, the scars were relatively small compared to other species.

The predicted scar height of sawtimber trees of red oaks and *Q. velutina* can be used to directly compare sensitivity of scarring between species. The regression models predict that both species will have scars of similar size at low to medium intense fires (char height < 1.2 m), but as fires become more intense (i.e. char height increases) red oaks will become increasingly sensitive to fire at an exponential rate (Figure 2.21). For *Q. velutina*, the rate of predicted scar height increases only slightly as fires become more intense. In stands with sawtimber-size trees and a relatively intense prescribed fire, red oaks will form larger fire-caused scars than *Q. velutina*.

Stem Bark Char Height, Mortality, and Scarring

Many studies have used stem-bark char height as a postfire predictor of tree mortality in conifers (Dixon et al. 1984, Regelbrugge and Conrad 1993, Menges and Deyrup 2001, Beverly and Martell 2003, Keyser et al. 2006) and eastern hardwoods (Loomis 1973, Regelbrugge and Smith 1994). For this study, char height was the only postfire predictor of dbh for the largest fire-killed *Quercus* or “other” species. Bark char height is therefore the most important indicator of fire intensity and a useful postfire predictor of mortality.

Stem bark char height was the most important predictor in nearly all fire scar models. For percent trees scarred (PTS) and scar height of trees ≥ 10 cm dbh, bark char height was the most important predictor for all models (Table 2.7 and Table 2.11). For PTS, char height was the only predictor selected for all models. Stem bark char has been used to predict scar height and scar width in Missouri oaks and hickories (Loomis 1973) and to predict percent circumference killed in northern hardwoods (Simard et al. 1986). Our findings showed that stem-bark char is the most effective postfire variable for assessing extent of scarring and PTS in Missouri oaks and hickories.

Largest Fire-Killed Trees

For all bark char heights, predicted dbh of largest fire-killed trees was higher for *Quercus* than "other" species. There are several possible explanations for this result: 1) study areas had numerous *Quercus* trees throughout all size classes, and therefore there was a greater likelihood for a large *Quercus* to be killed by fire than a large "other" species; 2) often there were few fire-killed trees in the "other" species group, and the largest fire-killed "other" species were often small diameter understory trees such as *Cornus florida*, *Sassafras albidum*, or *Acer rubrum* (Table 2.27), or 3) *Carya* spp. made up a large portion of trees in small to medium diameter size classes, and this study showed that *Carya* spp. has less fire damage than oaks following prescribed burning; therefore mortality for *Carya* spp. would be restricted to relatively small diameter trees less protected from fire damage.

Comparison of Models with Loomis (1973)

Loomis (1973) developed models predicting damage height and width following wildfires. He measured trees in all size classes, although he suggests his models work best for trees 3 – 41 cm dbh. My study examined only trees with dbh ≥ 10 cm. Loomis (1973) recognized three degrees of bark blackening: burn (blackening of bark ridges), char (charring of bark ridges), and scorch (browned or blackened bark surface). He later combined all into the variable bark blackening for analysis, which is essentially the same variable as stem bark char height used in this study.

Loomis (1973) related bark blackening of a tree to its fire-caused wound. My study utilized a plot-level measure of bark char height and related it to a plot-level measure of scar size for each species. I also used multiple predictor variables and performed stepwise regression analysis to determine significant predictors. For his regression analysis, Loomis (1973) used only bark blackening as the predictor and set the intercept equal to zero. Loomis (1973) used scars at least 5 cm in length or width, whereas scars used in my study represented the largest scars in a plot.

Despite differences in our methods, a direct comparison can be made between Loomis's (1973) wound height prediction models and this study's scar height prediction models. Since most wound measurements were obtained from *Q. velutina* and *Q. alba*, Loomis (1973) developed models for those two species and grouped all other species into those models. All species were kept separate in my models because each model either had different parameters or significantly different parameter estimates indicated by tests of parallelism.

Loomis (1973) reported large standard errors for parameter estimates in his models, but did not report R^2 values. From 0.5 to 2.0 m of char height, predictions based on his wound height equations yield results higher than scar height models developed for this study (Figure 2.27). Differences in predicted heights of fire damage could be attributed to differences of tree sizes used in each study. The mean dbh of trees used in Loomis (1973)'s study ranged from 11 cm for *Carya* spp. to 21 cm for *Q. coccinea*, while the mean dbh of trees used in my study ranged from 20 cm for *Carya* spp. to 31 m for *Q. velutina* (Table 2.32).

Mean height of fire damage was similar between Loomis's (1973) and the current findings. Loomis (1973) reported mean wound heights ranging from 52 cm for *Q. stellata* to 100 cm for *Carya* spp., while my findings showed mean plot-level scar heights ranging from 53 cm for *Carya* spp. to 93 cm for red oaks. The large wound heights for *Carya* spp. reported by Loomis (1973) could be attributed to the small diameter *Carya* spp. he sampled. The minimum and maximum dbh of *Carya* spp. sampled was 5 cm and 37 cm, contrasted with 10 cm and 51 cm for this study. Following fire, small diameter trees are more likely to receive extensive fire damage than large diameter trees.

Despite differences in size of trees measured and data collection, both the Loomis (1973) models and the current models illustrate the importance of using bark char height as a predictor of fire damage. He used individual tree bark blackening as a predictor, which was not feasible for my study because some scarred trees had no noticeable bark char because previously charred bark had been shed and new bark formed since the previous fire. Therefore a plot-level bark char worked best because some trees still had evidence of bark blackening. Another difference in our methods was that Loomis (1973) chose to combine species together for analysis. I chose to use tests of parallelism to determine whether species models should be kept separate.

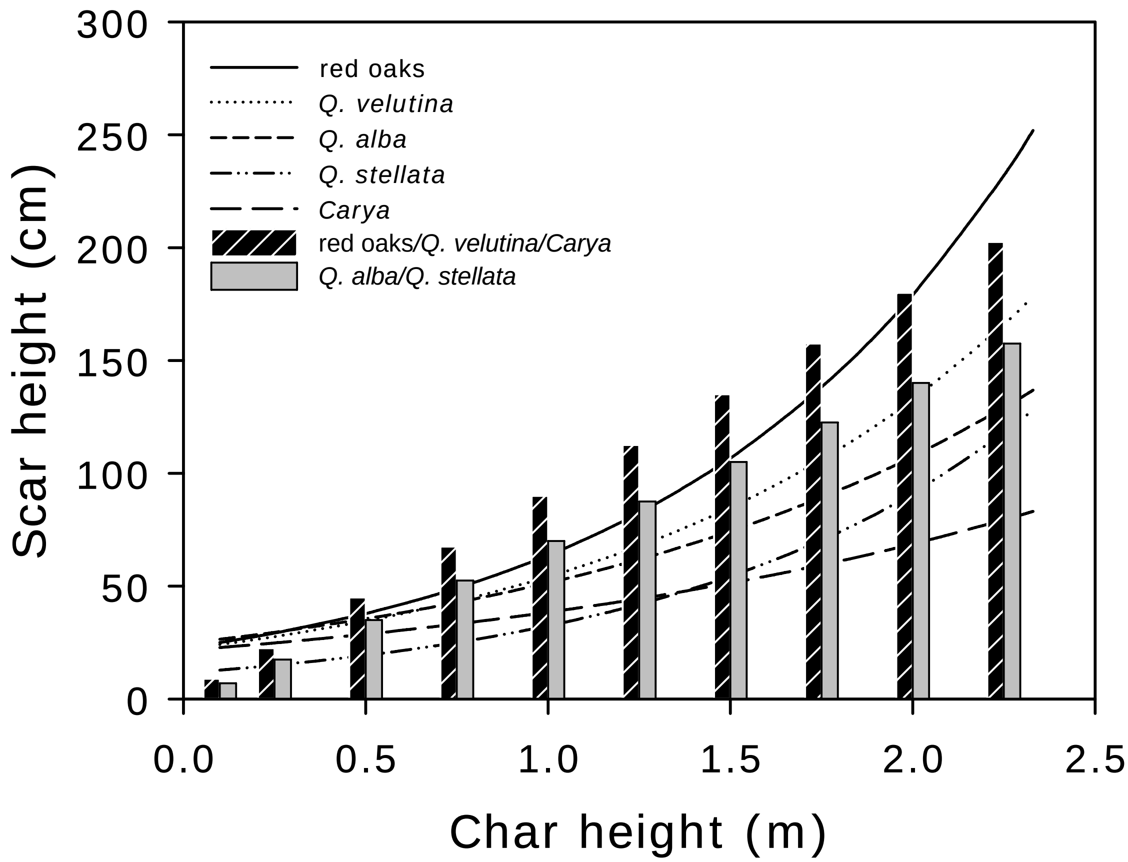
One final difference should be noted between the fire damage height models of Loomis (1973) and my scar height models. Loomis (1973) set intercepts to zero in his models, which allowed prediction of wound heights that approached zero as bark blackening became extremely small. There are three reasons why I chose to keep the intercept in all regression models: 1) other predictors besides bark char height were selected for possible inclusion in the prediction models, and, for example, if aspect had been selected as the only significant predictor, an intercept of zero and a (transformed) aspect value of zero (southwest-facing slope) would have resulted in an erroneous predicted scar height of zero; 2) from my observations, there is a minimum bark char height (0.1 m) following fire, and therefore a minimum scar height value that incorporates the intercept at the minimum char height is reasonable, and 3) the method of analysis I chose did not support removal of the intercept. An option would have been to conduct a post hoc removal of intercepts from models with bark char height as the only predictor, and then rerun the PROC REG statement with NOINT to eliminate the intercept in those models. But the NOINT statement causes SAS to use the uncorrected sums of squares, which grossly inflates the R^2 and F statistic (Uylar and Erdem 1990).

Table 2.32. Summary of diameters for trees included in scar size models for this study and for Loomis (1973).

		dbh (cm)		
Species	Study	mean	minimum	maximum
Q. coccinea[1]	Loomis (1973)	21	12	33
	current study	29	10	76
Q. velutina	Loomis (1973)	20	8	57
	current study	31	10	72
Q. alba	Loomis (1973)	14	5	40
	current study	23	10	66
Q. stellata	Loomis (1973)	14	6	29
	current study	29	10	55
Carya spp.	Loomis (1973)	11	5	37
	current study	20	10	51

[1]*Q. coccinea* includes *Q. coccinea* and *Q. shumardii* for current study.

Figure 2.27. Comparison of predicted scar heights from models developed in this study and models from previous study. Bars represent results from Loomis (1973).



Applicability of Models

Although the fire damage models in this study are highly significant, the highest R^2 was 0.46 for models predicting PTS of hardwoods and for scar height of sawtimber *Q. alba*. Therefore the best models explain less than half of the variation in the data set. For selected models, 95% confidence bands around the fitted regression lines reveal the imprecision of the regression line away from the char height mean. The natural logarithm transformation of scar height coupled with increased “wobble” of the regression line at high bark char values led to imprecision of the fitted regression line for predicting scar height of red oaks at bark char height > 1.5 m, and therefore questions the validity of all scar height models at moderate to high char height values. But the importance of the fire scar models lie in the consistency of the selected predictors and their relationship with scarring, not in precise postfire scarring predictions.

For percent trees scarred (PTS) models, char height was selected as the first predictor for all models, aspect was twice chosen as the second predictor, and QMD and BA were each selected once as the second predictor. For scar size models of trees ≥ 10 cm dbh, char height was selected as the first predictor in all but one model that had slope position selected. Aspect was chosen as a predictor twice, BA and fetch once, and slope position was chosen once as a secondary predictor. For scar size models of sawtimber, char height was chosen as the first predictor in eight models, and diameter at scar was chosen as the first predictor in one model. For secondary predictors, fetch was chosen three times, and slope steepness, char height, and diameter at scar midpoint were chosen once.

Bark char height was consistently and positively related with PTS or scar size. Therefore bark char height is an adequate proxy for fire intensity and the most important postfire indicator of the size and number of scars within a burned area. Aspect was always negatively correlated with PTS or scar size, suggesting that northeast-facing slopes had less scarring than southwest-facing slopes. Fetch and slope position had a positive relationship with scar size, supporting the assumption that fire intensity increases as fires move upslope (Pyne et al. 1996, Jenkins et al. 1997). Measures of tree size (QMD, diameter at scar midpoint, BA) were consistently negatively associated with scar size. This provides further evidence that fires cause more extensive injury to small diameter trees than to large diameter trees (Harmon 1982, Guyette and Stambaugh 2004).

Scar Types

Noting the scar type for the largest fire scars provides insight into future decay among different species. Open fire scars such as cat-face or oval-shaped scars lead to invasion by insect and fungal pathogens which eventually cause extensive volume losses (Berry and Beaton 1972, Loomis 1973). For all species, cat-face scars made up more than half of all large scars, and field observations noted that cat-face scars cause the largest amount of volume loss. Closed scars were the second most frequent large scar type, but even closed scars can lead to extensive decay (Berry and Beaton 1972). *Q. stellata* and *P. echinata* had the lowest percentage of open scars (64% and 67%), a clear reflection of the fire resistance of the two species. *Q. stellata* also had a relatively high number of basal scars that were deemed the “largest” scars for that species in a plot.

Basal Cavities Formed From Fire Scars

Only seventeen trees with basal cavities formed from fire scars were found in burned study areas. Accounting for the size of each plot, that figure translates into an estimated 0.66 basal-cavity trees per ha. Forest Land Management Guidelines from the Missouri Department of Conservation (MDC) recommend a minimum of 17 cavity trees per ha for optimal wildlife habitat (Missouri Department of Conservation 1986). Although the recommendation includes trees with non-basal cavities, a study conducted for the Missouri Forest Ecosystem Project (MOFEP) found that 44% of all cavities were basal cavities, and 58% of all cavity trees had a basal cavity (Jensen et al. 2002).

There are two possible reasons for the low number of basal-cavity trees found at burned sites: 1) while fire scars may eventually become cavities, repeated burning will consume some cavity trees (Conner et al. 1991, Van Lear and Harlow 2002); and 2) before use of prescribed fire, study areas might have been managed for timber resources and cavity trees were removed. A MOFEP study found that all sites had cavity tree densities exceeding the MDC recommendation (Jensen et al. 2002), but MOFEP sites had no previous management and therefore may have had existing remnant cavity trees. Fan et al. (2005) found that the vast majority of plots in second growth forest had zero cavity trees. Monitoring cavity trees in areas with prescribed fire would provide more information about how low-intensity surface fires influence cavity tree abundance.

Management Implications

Models developed from this study should be used as a guide, and resource managers using prescribed fire can consult these models to gain a better understanding of the synergistic effects of fire intensity, landscape features, tree size, and species composition before utilizing prescribed burning. Bark char height on hardwoods can be an effective postfire indicator of fire intensity, but landscape features also determine fire intensity in an area. Trees on southwest-facing slopes will be at higher risk for scarring than trees on northeast-facing slopes. Small diameter sawtimber trees at upper slope positions are extremely vulnerable to large scars due to increasing fire intensity as fire moves upslope. Managers interested in maintaining sawtimber *Q. alba* might consider that small diameter (30 cm) sawtimber trees located at a high fetch and on southwest-facing slope may have scars 3 to 4m tall following a moderate to severe fire. After a relatively intense fire, stands dominated by *Q. coccinea* or *Q. shumardii* will have more large fire scars than stands dominated by *P. echinata* and *Q. stellata*. The relationship between fire intensity, landscape features, tree size, and species composition are important factors to consider when using prescribed fire.

CHAPTER 3: EFFECTS OF PRESCRIBED BURNING ON TREE VIGOR IN *QUERCUS COCCINEA* AND *QUERCUS VELUTINA*

Introduction

Tree crown conditions can be used as indicators of forest health (Oak et al. 2004, U.S. Department of Agriculture 2004, Zarnoch et al. 2004) and individual tree health (Starkey and Guldin 2004). Many studies have used categorical classes to assess crown condition (Nebeker et al. 1992, Biocca et al. 1993, Dwyer et al. 1995, Meadows et al. 2001, Dimov et al. 2004, Starkey et al. 2004), while others directly estimate crown variables (Webster et al. 1996, Hopkin and Howse 1998, Starkey and Guldin 2004). Direct estimation of crown variables can be time consuming and lead to problems with repeatability among observers (Ghosh et al. 1995, Bechtold et al. 2002, Redfern and Boswell 2004), but detailed crown sampling methods such as those provided in the Forest Inventory and Analysis (FIA) field methods allow for more accurate and repeatable measurements (Zarnoch et al. 2004, U.S. Department of Agriculture 2005).

The ratio of crown surface area to stem surface area is an effective measure of relative tree vigor within a species (Voelker et al. 2007). Studies have shown a strong relationship exists between leaf area and sapwood area in *Quercus velutina* Lam. and *Quercus alba* L. (Rogers and Hinkley 1979) as well as in other species (Waring et al. 1977, Waring et al. 1980). Relative measures of tree vigor may be calculated by comparing the ratio of leaf surface area to stem surface area among trees of the same species (Waring et al. 1980, Waring 1983). Stem surface area may be approximated by using diameter at breast height (Whittaker and Woodwell 1967), but calculation of total leaf area for individual trees is time intensive and not feasible in large-scale ecological studies. Measurements of crown diameter and crown length can be used to calculate the three-dimensional surface area of individual tree crowns. Crown surface area represents the outer sheath of the crown where most carbon assimilation occurs, and may be the most important factor when assessing growth potential of individual trees. (Hamilton 1969, Sprinz and Burkhart 1987, Zarnoch et al. 2004).

Several studies have addressed the direct effects of fire on *Quercus* tree vigor. Following a wildfire in southern California, *Quercus agrifolia* Née. had relatively lower tree vigor three years postfire, but vigor improved by the eighth year (Dagit 2002). Prescribed fires in Midwest and Appalachian hardwood forests have shown to reduce overstory tree vigor and cause crown dieback (Anderson and Brown 1983, Wendel and Smith 1986, Loucks and Arthur 2004).   Brose and Van Lear (1999) found a smaller proportion of *Quercus* with healthy crowns following spring and summer burns in a *Quercus*-dominated shelterwood, and fire damage to the boles of other hardwoods caused declining crown conditions.

The purpose of this study was to examine the relationship between repeated prescribed burning and the vigor of two Missouri Ozark upland species. Species chosen for examination include a fire intolerant species, *Quercus coccinea* Muench. (Johnson 1990), and a relatively fire tolerant species, *Quercus velutina* (Lorimer 1985). The formal hypotheses are:

1) H_0: Fire injury is not correlated with tree vigor of *Q. coccinea*
H_A: Fire injury is negatively correlated with tree vigor of *Q. coccinea*

2) H_0: Fire injury is not correlated with tree vigor of *Q. velutina*
H_A: Fire injury is negatively correlated with tree vigor of *Q. velutina*

3) H_0: Prescribed burning does not affect landscape-level tree vigor of *Q. coccinea*
H_A: Prescribed burning does affect landscape-level tree vigor of *Q. coccinea*

4) H_0: Prescribed burning does not affect landscape-level tree vigor of *Q. velutina*
H_A: Prescribed burning does affect landscape-level tree vigor of *Q. velutina*

Methods

Study Area

The study areas are located in upland forests across the Missouri Ozark Highlands (Figure 3.1). Data were collected from public and private lands located in the Current River Hills Ecological Subsection and the White River Hills Ecological Subsection (Nigh and Schroeder 2002). Study sites include burn units at Peck Ranch Conservation Area, Mule Mountain at Rocky Creek CA, Mill Mountain at Ozark National Scenic Riverways, and TNC Chilton Creek Management Area in the Current River Hills; and burn units at Caney Mountain Conservation Area in the White River Hills.

The Ozark Highlands are characterized as hilly to rugged lands with relatively thin, rocky soils. The pre-EuroAmerican settlement vegetation in the uplands was a mosaic of mixed-oak and pine-oak woodlands and forests (Harlan 2007). The current upland forests are dominated by *Quercus alba*, *Quercus coccine*a, and *Quercus velutina*, with minor representations from *Carya* spp. Nutt. and *Pinus echinata* Mill. *Quercus shumardii* Buckl. replaces *Quercus coccinea* on most sites in the White River Hills. Current management objectives in the area include using prescribed fire in upland forests to restore the open understory (10-50% area cover) and variable canopy structure (30-100% closure) of the oak and pine-oak woodlands (Nelson 2005).

Data Collection

Eighteen burn units were sampled from two Ecological Subsections: three units in the White River Hills and fifteen units in the Current River Hills. Each burn unit can be characterized as an upland oak- or pine-oak dominated forest matrix with glade inclusions and woodland intergrades. Burn units ranged in size from 10 ha to 660 ha. As of 2006, each burn unit had at least one dormant season prescribed fire in the last five years, and the number of growing seasons since the last burn ranged from zero to five. A summary of burn unit information can be found in Table 2.1 and Table 2.2. In each burn unit, transects were established along the slope of the hill in forested areas with an oak-dominated overstory. The number of transects per burn unit varied according to the size of the burn unit.

Five unburned areas (control) were also sampled throughout the study area. Areas were selected based on two criteria: 1) similar physiognomy (i.e. overstory species composition, stand structure) as burned areas and 2) close proximity to burned areas. Unburned areas selected for sampling include east of Denning Hollow near Mill Mountain; MOFEP Site 8 in Peck Ranch CA; an area north of Road 13, east of Road 14, and south and west of Boundary Road in Peck Ranch CA (Figure 3.2); north of Road 3 near Sasser's Rock in Caney Mountain CA; and west of Road 3 near Holdman Hollow in Caney Mountain CA (Figure 3.3). Transects were established in control areas in the same manner as in burned area.

Figure 3.1. Location of areas sampled for tree vigor study.

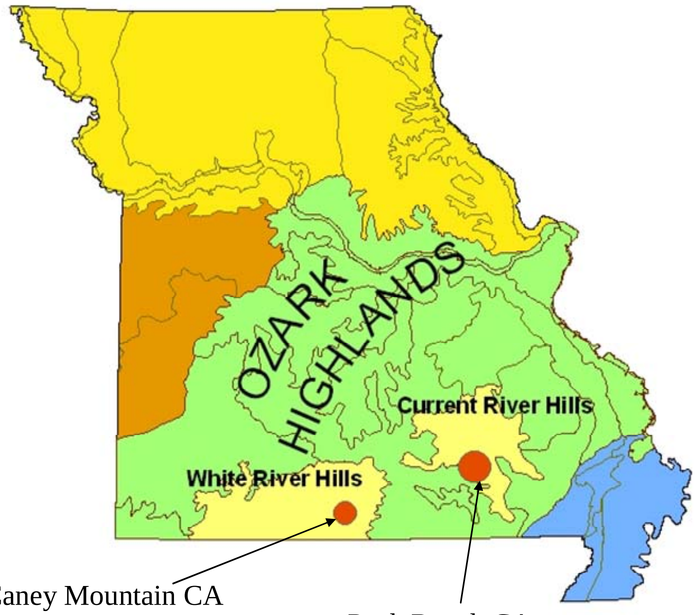


Figure 3.2. Location of sampling areas in the Current River Hills.

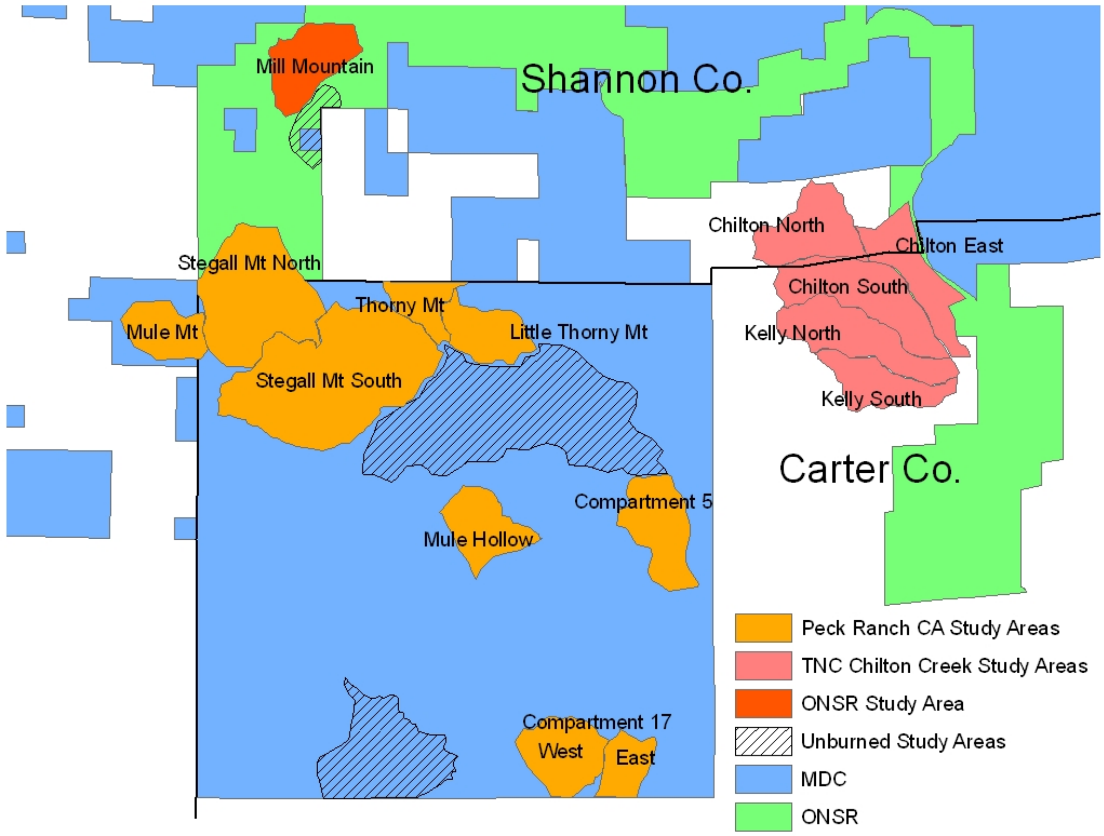
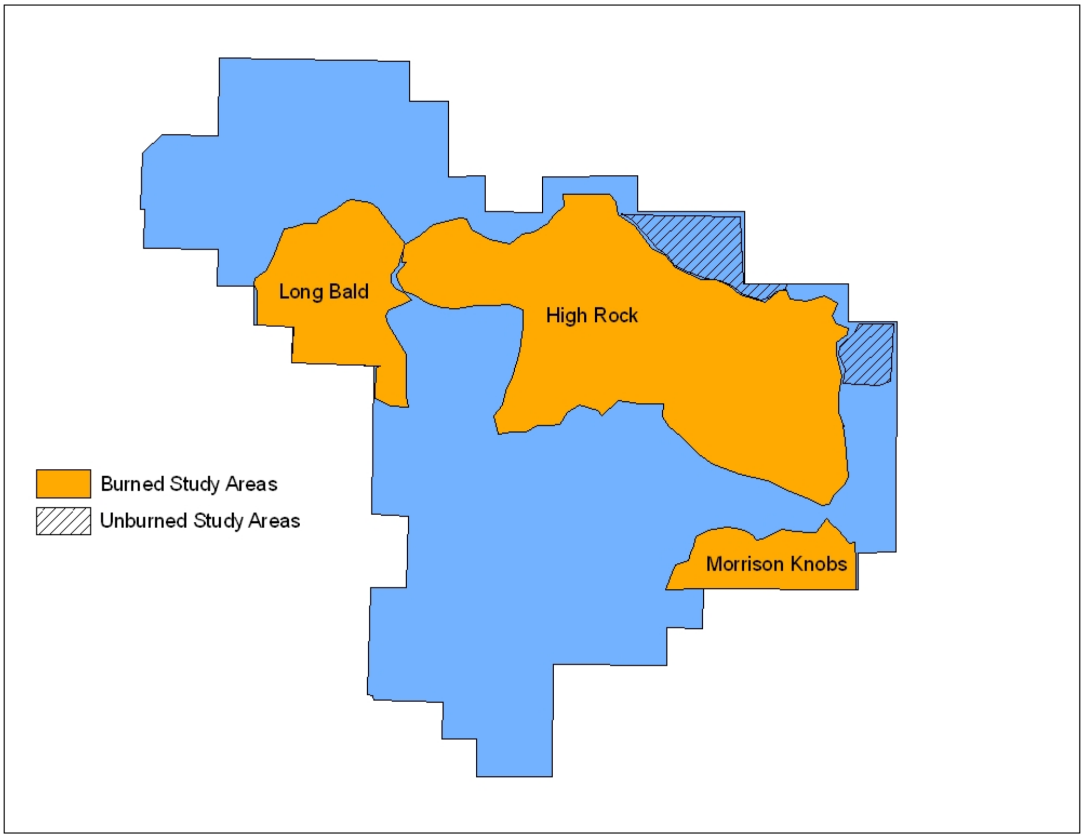


Figure 3.3. Location of sampling areas at Caney Mountain Conservation Area in the White River Hills.



Sampling occurred in 20 m radius plots located along each transect. Transects were stratified by slope position (upper slope, middle slope, lower slope). Plots were systematically located within each slope position and were > 40 m from forest edge and > 75 m from other plots. If a plot location did not contain at least fifteen oaks ≥ 10 cm dbh, then the plot was relocated to the closest point that met this requirement. Plots per transect ranged from two (no middle slope position sampled) to three (all three slope positions sampled) based on the length of the hill. A total of sixty-eight burn plots and thirty-one unburned plots were sampled across the study area. More plots were sampled in burned areas to capture variability that may be present due to burning. Plots were equally sampled on northeast- (316°-135°) and southwest-facing (136°-315°) slopes. Woodlands, glades, and forested areas with relatively high mortality or obvious crown scorch were not sampled. The range of *Quercus coccinea* does not extend into Caney Mountain CA and therefore it was sampled only in the Current River Hills.

Stem bark char height on hardwoods was determined for each plot. Plots were subdivided into one-third sections and a mean maximum bark char height on hardwoods was calculated from at least two char measurements in each one-third subplot. Bark char refers to any blackening of the stem bark due to fire.

Tree height (H), crown diameter, live crown ratio (LCR), crown density (CD), fire injury, and dbh were recorded for up to four randomly selected *Quercus velutina* and *Quercus coccinea* overstory trees in each plot. Tree height was estimated using a clinometer and distance tape. Crown diameter was measured at the widest axis of the crown and perpendicular to that axis. Live crown ratio was estimated by ocular assessment and is defined as the percentage of total tree height occupied by the crown.

Crown density is defined as the amount of crown branches, foliage and reproductive structures that block light through the crown (Zarnoch et al. 2004). Crown density was estimated by ocular assessment using a crown density-foliage transparency card from the 3.0 Phase 3 Field Guide—Crown: Measurements and Sampling (U.S. Department of Agriculture 2005). Fire injury was categorized by the type and height of fire-caused scar:

0 = no scar,
1 = closed scar,
2 = open scar < 25 cm in height,
3 = open scar 25 – 50 cm in height,
4 = open scar 51 – 100 cm in height,
5 = open scar > 100 cm in height.

Fire injury was coded so that the lowest value (0) represents no effect of fire on tree and increasing values represent increasing negative impacts of fire on tree vigor.

Crown length, crown radius, crown surface area, crown volume, and stem surface area were calculated for each tree based on field data. Crown length (CL) was calculated as LCR multiplied by H. Crown radius (R) was calculated as one-half multiplied by the mean of the two crown diameter measurements. Crown surface area (CSA) and crown volume (CV) tree were calculated based on the assumption that the crown surface is approximated by a parabaloid (Eq. 1 and Eq. 2) (Zarnoch et al. 2004). Stem surface area (SSA) was calculated by assuming the bole of the tree was equal to the surface area of a cone using tree height (m), dbh (cm), and an adjustment coefficient (Eq. 3) (Whittaker and Woodwell 1967). The full equations are defined as:

Eq. 1: $CV = (0.5\pi R^2 CL)\times CD$

Eq. 2: $CSA = (4\pi CL/3R^2)[(R^2 + (R^4/4CL^2))^{1.5} - (R^4/4CL^2)^{1.5}]CD$

Eq. 3: $SSA = ((\pi \times dbh \times H) / 2)c$, where R = radius (m), CL = crown length (m), CD = crown density (%), dbh = diameter at breast height (cm), H = tree height (m), and c = 1.268, an adjustment coefficient for *Quercus coccinea* from Whittaker and Woodwell (1967).

Two measures of tree vigor were calculated based on research conducted by Voelker (2004): a crown surface index (CSI) and a tree vigor index (TVI). The CSI was calculated based on two assumptions: 1) less vigorous trees have smaller crowns and lower leaf surface area (Rust and Roloff 2002) and 2) photosynthetic gain per unit of foliage increases towards the top of the crown due to the vertical trend in light intensity (Zeide 2002, Funk and Ledaru 2004). CSI was calculated by weighting the CSA by the LCR:

Eq. 4: CSI = CSA(1 – LCR),

where CSI = crown vigor index, CSA = crown surface area (m^2), and LCR = live crown ratio (%).

A tree vigor index (TVI) was calculated based on the assumption that the ratio of leaf surface area to stem surface area indicates relative tree vigor (Waring et al. 1980, Waring 1983):

Eq. 5: TVI = CSI / SSA,

where TVI = tree vigor index, CSI = crown surface index, and SSA = stem surface area (m^2). For example, a tree with a CSI of 50 and a SSA of 15 m^2 has a TVI of 3.33. A tree with CSI of 50 and a SSA of 10 m^2 has a TVI of 5. So given equal CSI, a tree with a relatively large bole is less vigorous than a tree with a small bole due to higher carbon requirements for maintenance of woody tissue. A list of all variables used in this study can be found in Table 3.1.

Analysis

To assess normality, the univariate distributions of CSI and TVI were examined at both the individual- and plot-level values. For both species, Spearman correlation coefficients ($\alpha = 0.05$) were calculated to determine the relationship of fire injury with bark char height and both tree vigor measures. Spearman correlation coefficients were determined using the PROC CORR SPEARMAN statement in SAS 9.1. To determine differences in tree vigor between burned and unburned areas, a mixed model ANOVA design was used with treatment (burned or unburned) as the fixed effect, unit (burn unit or stand) as the random effect, and $\alpha = 0.05$. SAS 9.1 was used for all ANOVA calculations and separate analyses were conducted for *Quercus velutina* and *Quercus coccinea*:

```
PROC MIXED;
        CLASS   TREATMENT   UNIT   PLOT;
        MODEL CSI   TVI = TREATMENT;
        RANDOM UNIT(TREATMENT)   PLOT(UNIT TREATMENT);
        LSMEANS TREATMENT / PDIFF;
RUN;
```

Table 3.1. List of variables used in tree vigor study.

Abbreviation	Definition
dbh	diameter at breast height
H	tree height
R	crown radius
LCR	live crown ratio
CD	crown density
CV	crown volume
CSA	crown surface area
SSA	stem surface area
CSI	crown surface index
TVI	tree vigor index

Results

Summary of Individual Tree Conditions

For *Quercus coccinea,* individual tree sizes were consistently larger in unburned areas (Table 3.2). Mean dbh, H, and R were all larger in unburned areas, which led to relatively high values of CV, CSA, and SSA. There was little difference in LCR, CD, or TVI between burned and unburned areas, but CSI was much higher in unburned areas. All but two trees in burned plots were assigned fire injury codes of 3 or lower (Table 3.3).

For *Quercus velutina*, dbh and H were greater in unburned areas, but R and LCR was slightly greater in burned areas (Table 3.4). There was little difference in CD between burned and unburned areas. Calculated means for CV and CSA were higher in burned areas, but the associated standard deviations were high for the means in both burned and unburned areas. Mean SSA was slightly higher in unburned areas. Mean CSI was similar between burned and unburned areas, but TVI was slightly higher in burned areas. Over 37% of trees in burned areas had no fire injury, and all but three trees were assigned fire injury codes of 3 or lower (Table 3.5).

Table 3.2. Individual tree means and standard deviations for *Quercus coccinea*.

Variables	Unburned (n = 75)	Burned (n = 178)
dbh (cm)	39 ± 11	32 ± 10
H (m)	24.9 ± 3.7	20.1 ± 3.8
R (m)	4.5 ± 1.6	3.9 ± 1.3
LCR (%)	38 ± 8	41 ± 11
CD (%)	44 ± 5	41 ± 8
CV (m^3)	158 ± 124	105 ± 119
CSA (m^2)	88 ± 46	65 ± 45
SS (m^2)	20 ± 7	13 ± 6
CSI	92 ± 47	64 ± 39
TVI	4.5 ± 1.3	4.6 ± 1.5

"H" = total tree height, "R" = mean crown radius, "LCR" = live crown ratio, "CD" = crown density, "CV" = crown volume, "CSA" = crown surface area, "SS" = stem surface area, "CSI" = crown surface index, "TVI" = tree vigor index

Table 3.3. Summary of fire injury to *Quercus coccinea* in burned areas.

Code	Injury	n
0	no fire scar	49
1	closed scar	33
2	open scar < 25 cm in height	42
3	open scar 25 – 50 cm in height	52
4	open scar 51 – 100 cm in height	1
5	open scar > 100 cm in height	1

Table 3.4. Individual tree means and standard deviations for *Quercus velutina*.

Variables	Unburned (n = 104)	Burned (n = 227)
dbh (cm)	37 ± 11	34 ± 12
H (m)	22.0 ± 3.3	20.2 ± 3.6
radius (m)	3.4 ± 1.2	3.6 ± 1.3
LCR (%)	35 ± 8	40 ± 11
CD (%)	42 ± 6	40 ± 7
CV (m^3)	74 ± 66	83 ± 78
CSA (m^2)	52 ± 31	56 ± 34
SS (m^2)	16 ± 6	14 ± 6
CSI	57 ± 32	56 ± 33
TVI	3.5 ± 1.3	3.9 ± 1.3

"H" = total tree height, "R" = mean crown radius, "LCR" = live crown ratio, "CD" = crown density, "CV" = crown volume, "CSA" = crown surface area, "SS" = stem surface area, "CSI" = crown surface index, "TVI" = tree vigor index

Table 3.5. Summary of fire injury to *Quercus velutina* in burned areas.

Code	Injury	n
0	no fire scar	85
1	closed scar	53
2	open scar < 25 cm in height	36
3	open scar 25 – 50 cm in height	50
4	open scar 51 – 100 cm in height	2
5	open scar > 100 cm in height	1

Correlation Analysis: Fire Injury and Tree Vigor

For both *Quercus coccinea* and *Quercus velutina*, injury values of “4” and “5” were reclassified as “3” because of the low number of trees sampled from those injury classes. Injury class “3” was renamed to represent all “open fire scars > 25 cm in height”, although most trees are in the 25 – 50 cm range.

Bark char height was positively correlated with fire injury for both species. Fire injury was not correlated with CSI for both species (Table 3.6). TVI had a weak negative correlation with fire injury for *Quercus coccinea*. TVI was not correlated with fire injury for *Quercus velutina*.

ANOVA: Differences in Tree Vigor between Burned and Unburned Areas

Examination of univariate distributions revealed that CSI and TVI for both species were normally distributed for burned and unburned areas. For *Quercus coccinea*, CSI was significantly different between burned and unburned areas, but TVI was not significantly different (Table 3.7-3.9, Figure 3.4-3.5). For *Quercus velutina*, CSI was not significantly different in burned and unburned areas, but TVI was significantly different (Table 3.7, Table 3.10-3.11, Figure 3.4-3.5).

Table 3.6. Spearman correlation coefficients and corresponding p-values for relationship between fire injury and tree vigor in two tree species. Values in bold are significant (α = 0.05).

	Species	Bark char height	CSI	TVI
Fire injury	*Quercus coccinea*	**0.63**	-0.10	**-0.17**
	(n = 177)	**(< 0.0001)**	(0.17)	**(0.02)**
	Quercus velutina	**0.39**	-0.07	-0.01
	(n = 227)	**(< 0.0001)**	(0.29)	(0.86)

"CSI" = crown surface index; "TVI" = tree vigor index

Table 3.7. Results of mixed-model ANOVA (α = 0.05) to determine differences in tree vigor in burned and unburned areas.

Vigor Measure	Species	Num df	Den df	F-value	Pr > F
CSI	*Q. coccinea*	1	18	5.58	**0.03**
	Q. velutina	1	27	0.17	0.68
TVI	*Q. coccinea*	1	18	0.16	0.69
	Q. velutina	1	27	5.82	**0.02**

Table 3.8. Results of least square means test to determine difference in CSI for *Q. coccinea*.

Treatment	Estimate	Standard error	t-value	Pr > | t |
Burned	94.3	10.6	8.89	<0.0001
Unburned	66.3	5.3	12.48	<0.0001
Difference	28.0	11.9	2.36	**0.03**

Table 3.9. Results of least square means test to determine difference in TVI for *Q. coccinea.*

Treatment	Estimate	Standard error	t-value	Pr > | t |
Burned	4.53	0.19	23.31	<0.0001
Unburned	4.62	0.13	36.71	<0.0001
Difference	-0.09	0.23	-0.40	0.69

Table 3.10. Results of least square means test to determine difference in CSI for *Q. velutina.*

Treatment	Estimate	Standard error	t-value	Pr > | t |
Burned	57.3	4.4	13.14	<0.0001
Unburned	55.1	2.9	19.16	<0.0001
Difference	2.2	5.2	0.42	0.68

Table 3.11. Results of least square means test to determine difference in TVI for *Q. velutina*.

Treatment	Estimate	Standard error	t-value	Pr > | t |
Burned	3.47	0.15	22.6	<0.0001
Unburned	3.92	0.10	37.7	<0.0001
Difference	-0.45	0.19	-2.41	**0.02**

Figure 3.4. Comparison of crown surface indexes (CSI) in burned and unburned plots for *Quercus velutina* and *Quercus coccinea*. Differences in CSI within species were tested using ANOVA ($\alpha = 0.05$). Error bars are standard errors.

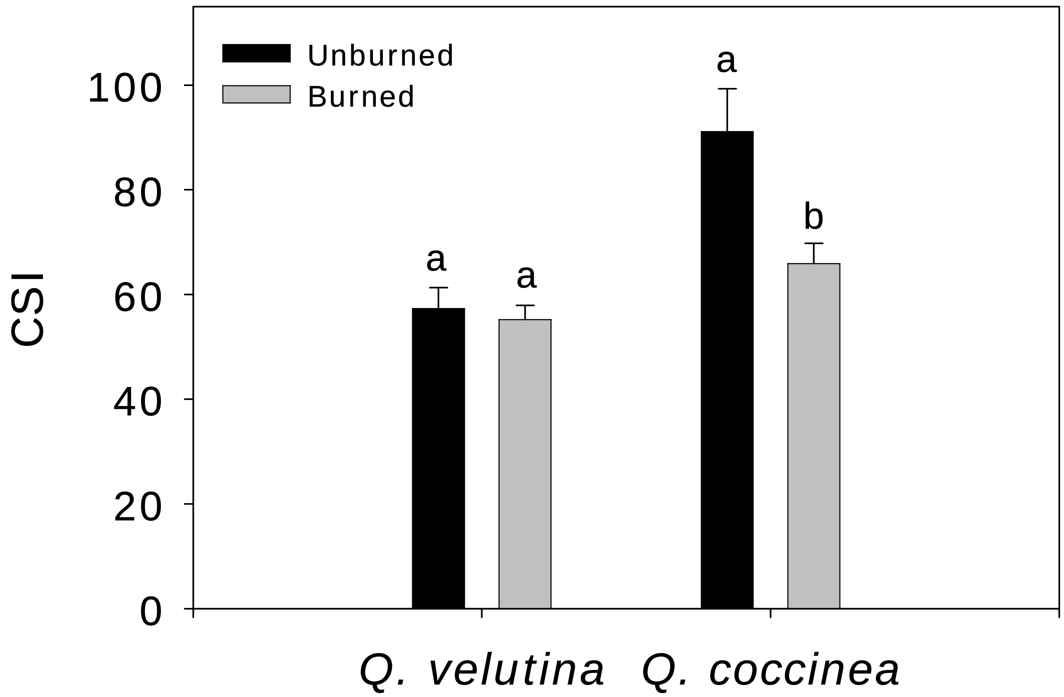
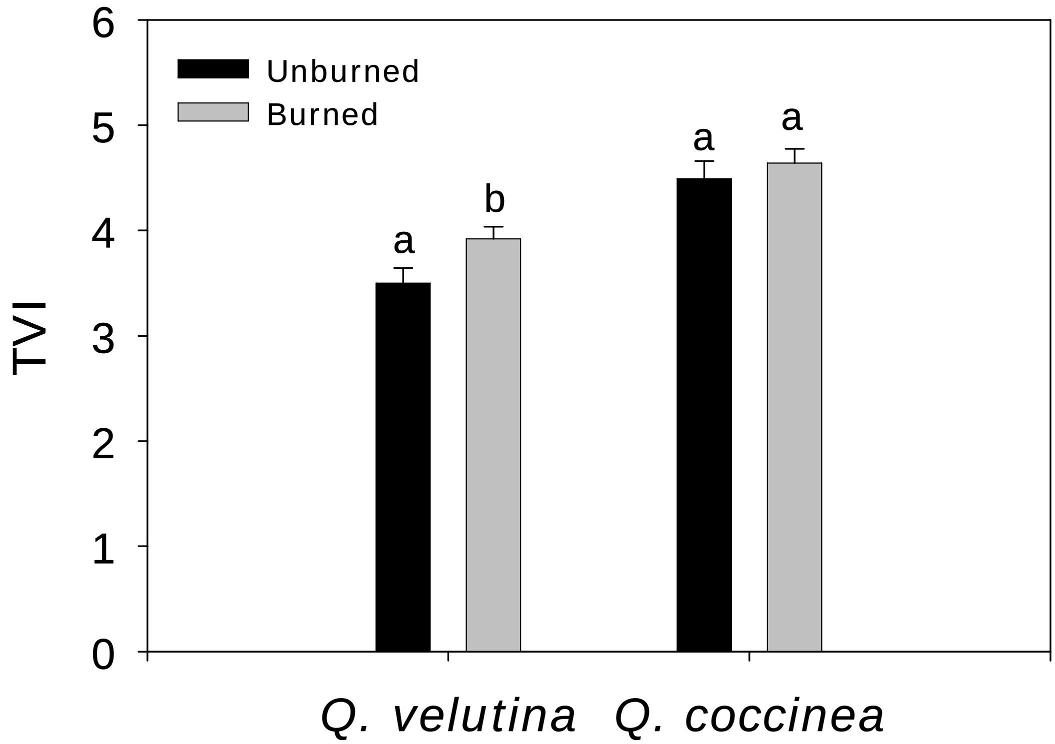


Figure 3.5. Comparison of tree vigor indexes (TVI) in burned and unburned plots for *Quercus velutina* and *Quercus coccinea*. Differences in CSI within species were tested using ANOVA (α = 0.05). Error bars are standard errors.



Discussion

Prescribed fire has the potential to severely damage trees which may lead to reduced vigor in surviving trees (Wendel and Smith 1986). Results from this study indicate that *Quercus coccinea*, a fire sensitive upland Ozark species (Paulsell 1957, Johnson 1990), has decreasing tree vigor with increasing extent of fire injury. Fire injury in *Quercus velutina* was not correlated with tree vigor, which may be due to uneven sampling of trees across fire injury classes. Based on examination of fire-caused injuries for this study and others, *Quercus velutina* is considered more fire tolerant than *Quercus coccinea* (Paulsell 1957, Scowcraft 1966, Harmon 1984), and therefore it may be better adapted to maintaining vigor following fire injury.

Few studies have linked fire injury and tree vigor in overstory trees. In the West, Rundel (1973) found a relationship between basal fire scar size and crown damage in *Sequoiadendron giganteum* Lindl. A study in oak-dominated shelterwood stands in the Piedmont of Virginia showed that fire damage to the boles of *Fagus grandifolia* Ehrh. and *Acer rubrum* L. manifested itself as declining crown conditions (Brose and Van Lear 1999). Others have measured vigor of hardwood trees pre- and postburn but presented no results on their findings (Loucks 2004, Signell et al. 2005).

The lower CSI of *Quercus coccinea* supports other research showing that fire decreased the proportion of oaks with healthy crowns (Brose and Van Lear 1999). Other studies examining *Quercus* showed relatively low tree vigor conditions immediately following prescribed fire and a severe wildfire (Anderson and Brown 1983, Wendel and Smith 1986, Dagit 2002). Loucks and Arthur (2004) observed that crown dieback was highest in areas of high fire intensity where bark char also tended to be highest, although no results were provided in Loucks's (2004) final report. Results from this study link bark char with fire damage and eventual reduced crown vigor in *Quercus coccinea*.

There was no difference in the TVI of *Quercus coccinea* in burned and unburned areas. The lack of difference could be explained by the metric used to measure tree vigor. Calculations of TVI relied on weighting the CSI by the SSA, and *Quercus coccinea* in unburned areas had a relatively high mean SSA due to larger mean diameters and tree heights.

Quercus velutina is considered a relatively fire tolerant species due to its comparatively thick bark (Harmon 1984). Thicker bark can insulate the cambium from fire-caused injury and prevent injury-related crown dieback. This may account for more than one-third of sampled *Quercus velutina* showing no signs of fire injury. The CSI for *Quercus velutina* was not different between burned and unburned areas, but the higher TVI in burned areas reflects the capacity for trees in burned areas to support a crown with less surface area than trees in unburned areas. It is possible that *Quercus velutina* is able to better compete with other species for crown space in burned areas.

Pyrodendrochronology studies have indicated the existence of pre-EuroAmerican settlement fire regimes across the Missouri Ozarks (Guyette and Cutter 1991, Guyette and Cutter 1997, Batek et al. 1999, Guyette et al. 2002). Many have concluded that the historic vegetation of the Missouri Ozarks consisted of fire-tolerant species that adapted with fire over many decades (Nigh 1992, Hartman 2005, Nelson 2005). Reconstruction of pre-EuroAmerican vegetation in the Missouri Ozarks has shown that *Quercus velutina* was a major overstory component of woodlands and forest, while *Quercus coccinea* was of relatively minor importance (Nelson 1997, Batek et al. 1999, Harlan 2007). Results from this study lend further support that *Quercus velutina* is well adapted to a fire-dependent community while *Quercus coccinea* is relatively intolerant of repeated burning.

It is unclear why *Quercus coccinea* and *Quercus velutina* had higher mean diameters and heights in unburned areas. Although the basal area in burned (21.5 ± 6.1 m^2 per ha) and unburned areas (21.4 ± 5.3 m^2 per ha) is nearly identical, it is possible that the unburned areas selected for study sites were of higher site quality and productivity than areas targeted for woodland restoration and prescribed fire management. Interpretation of the CSI and TVI results should be made with caution until more is known about possible differences in environmental conditions in burned and unburned areas.

One more caveat of this study involves interpreting the results based on statistical differences. I expected that burning would negatively impact overstory tree vigor for *Quercus coccinea* and *Quercus velutina*, and the previous chapter confirms that both species are relatively sensitive to fire-related scarring. Although TVI was negatively correlated with fire injury in *Quercus coccinea*, the relationship was very weak and may not be biologically significant. Differences in CSI for *Quercus coccinea* and TVI for *Quercus velutina* were statistically significant at $\alpha = 0.05$, but may not reflect biologically significant findings. To ensure confidence in these findings, repeated design studies should be implemented to confirm or refute relationships between tree vigor and prescribed burning.

Management Implications

Managers utilizing prescribed fire need to understand the relationship between fire injury and reduced tree vigor in fire intolerant species. Fire injury may not lead to reduced vigor in fire tolerant species such as *Quercus velutina*, but this study directly links fire damage with reduced tree vigor in *Quercus coccinea*, the most fire intolerant upland Ozark species. The generalized approach used to compare tree vigor in burned and unburned areas provides more evidence that *Quercus coccinea* is less vigorous in burned areas, while the relatively fire tolerant *Quercus velutina* may actually be more vigorous. Removal of *Quercus coccinea* from areas targeted for prescribed fire management may be necessary if reduction in overstory tree vigor is a concern. Although this study does reveal statistical differences in tree vigor due to prescribed burning, other independent studies are needed to lend further support to these findings.

CHAPTER 4: EFFECTS OF PRESCRIBED BURNING ON GROUND FLORA VEGETATION

Introduction

Prescribed fire is used in forests across the eastern United States for various silvicultural goals. Many goals include stimulating oak and pine regeneration, reducing hazardous fuel loads, increasing cover and diversity of herbaceous vegetation, and maintaining fire-dependent natural communities (Brockway and Lewis 1997, Brose and Van Lear 1998, Vose 2000, Elliott and Vose 2005, Phillips et al. 2007). In Missouri, prescribed fire goals include restoring and maintaining glade and woodland communities, reducing density of the woody understory, and increasing the vigor and abundance of native ground flora (Hartman 2005, Nelson 2005).

Responses of Ground Flora to Prescribed Fire

Herbaceous plants in the ground flora represent the most diverse component of plant communities in eastern oak-dominated forests (Hutchinson et al. 1999) and in upland forests of the Missouri Ozarks (Grabner et al. 1997, Sasseen 2003). Herbaceous communities are affected by numerous factors such as climate (Rideout et al. 2003), moisture and fertility (Hutchinson et al. 1999, Hutchinson 2004), microtopography (Beatty 1984), leaf litter (Beatty and Sholes 1988), and disturbance (Marsh 2005, Glasgow 2006). A disturbance such as prescribed fire influences herbaceous communities due to stimulation of seedbanking species, release of nutrients following leaf litter consumption, and top-killing and subsequent resprouting of understory and midstory trees (Gilliam and Christensen 1986, Hutchinson et al. 2005, Boener 2006).

Research has shown mixed responses of herbaceous communities to prescribed fire in oak-dominated forests. Some studies report increased species richness of herbaceous vegetation following fires (Masters 1991, Wilhelm and Masters 1994, McGee et al. 1995, Nuzzo et al. 1996, Arthur et al. 1998, Sparks et al. 1998, Elliott et al. 1999, Taft 2003, Phillips et al. 2007), while others report little postfire changes in herbaceous vegetation following prescribed burning (Dolan 1994, Kuddes-Fischer and Arthur 2002, Rideout et al. 2003, Dolan and Parker 2004, Elliott and Vose 2005, Marsh 2005).

Relative and absolute cover of herbaceous plant groups often increase following fire, including grasses (DeSelm and Clebsch 1991, Masters 1991, Elliott et al. 1999, McMurry et al. 2007, Phillips et al. 2007), forbs (Masters 1991, Nuzzo 1996, Sasseen and Muzika 2004, Hutchinson et al. 2005, McMurry et al. 2007, Phillips et al. 2007), legumes (Kuddes-Fischer and Arthur 2002, Sasseen and Muzika 2004), and sedges and herbaceous vines (Taft 2003). Top-killing of saplings in the ground flora layer often causes an immediate decrease in woody cover following prescribed fires (Bacone and Post 1986, Glitzenstein et al. 2003), but resprouting from species such as *Acer rubrum* L. and *Sassafras albidum* Nutt. often leads to increased density and cover following prescribed fire (Ducey et al. 1996, Hartman and Heumann 2003, Phillips et al. 2007).

Time Since Fire and Ground Flora Vegetation

Plants may either have an immediate response to fire, such as annual forbs (Hutchinson 2000), or a delayed response up to two years following fire (Phillips et al. 2007). In an oak sandstone barren in Illinois, forbs increased in cover one year after a prescribed fire but declined in cover by two years postburn, while grasses showed the opposite trend (Taft 2003). Following a prescribed burn in an Appalachian pine-oak forest, Marsh (2005) reported time since burning was positively related with woody cover and a negatively related with herbaceous cover. In a pine-hardwood forest in North Carolina, the relative cover of forbs and legumes increased one and two years following an April prescribed fire, while relative grass cover did not increase until two years postfire (Elliott et al. 1999). In an oak-dominated forest in Ohio, forb and graminoid cover did not respond to fire until two years after a spring burn (Phillips et al. 2007).

Response of Ground Flora Vegetation to Prescribed Fire in Missouri

In Missouri there has been many studies examining the effects of fire on ground flora vegetation. Paulsell (1957) examined herbaceous vegetation following prescribed fires at University Forest in southeast Missouri and reported increased abundance and species of grasses and forbs in annually burned plots. On glade and woodlands sites at Caney Mountain Conservation Area in Ozark County, March and April burns had relatively high grass production, while August burns had the highest forb production (Lewis et al. 1964). In the same study, all burns increased legume production, and by year three all burned areas had higher forb production than unburned areas.

Studies at The Nature Conservancy's Chilton Creek Management Area have shown increased cover of grasses, sedges, legumes, forbs, woody vines, and trees and shrubs following annual and periodic fires (Hartman and Heumann 2003). The same study showed a decrease in the frequency of trees and shrubs due to fire-related topkilling, and an increased frequency of grasses, sedges, forbs, and legumes. Sasseen (2003) and Sasseen and Muzika (2004) also examined fire effects at Chilton Creek and reported similar increases in cover for plant groups, except for a consistent decrease in relative cover of woody vines and an overall decrease in relative cover of grasses and sedges. A study in Reynolds County examined ground flora responses two months following a prescribed fire and found relative cover of forbs and graminoids increased on ridges, northeast-facing slopes, and southwest-facing slopes (McMurry et al. 2007).

Response of Exotic Plant Species to Fire

Exotic species often invade highly disturbed areas, such as old fields, pastures, and roadsides. In the Missouri Ozarks, open woodlands and forest edges may be colonized by exotic species (Smith 1997), although exotic plant species are relatively absent in the Ozarks (Grabner et al. 1997, Sasseen 2003). Two exotic species, *Elaeagnus umbellata* Thunb. (autumn olive) and *Rosa multiflora* Thunb. (multiflowered rose), are found in upland forests of the Missouri Ozarks (Grabner et al. 1997) and therefore may be present before prescribed burning.

Prescribed fire is unsuccessful at controlling *Elaeagnus umbellata* because it will vigorously resprout following topkill (Sather and Eckardt 1987, Smith 1997). Other sources speculate that the response of *Elaeagnus umbellata* populations to fire may be positive or negative (Huebner 2006).

Repeated burning has been suggested as an effective tool for controlling *Rosa mutiflora* invasion (Eckardt 1987, Smith 1997). A recent study in Ohio suggests that fire in conjunction with tree fall gaps will actually stimulate germination of *Rosa multiflora* and lead to increased height growth (Glasgow 2006). A recent synthesis of exotic plant species literature by Huebner (2006) lists *Elaeagnus umbellata* and *Rosa multiflora* as evaders of fire due to long lived propagules in the soil and the potential for long distance seed dispersal from sources outside of burned areas. Huebner (2006) furthermore suggests *Rosa multiflora* populations will increase in abundance following fire.

Fire Effects and Pseudoreplication

Replication of fire across the landscape is problematic in fire effects research due to the size and scope of landscape units (Hargrove and Pickering 1992). Many researchers improperly replicate samples that are not independent, a practice Hurlbert (1984) called pseudoreplication. In fire ecology studies, researchers typically use subsamples nested within treated areas (i.e. burn units) as independent samples, causing spurious results because of the lack of independence among subsamples. Plots sampled within units are not independent because of similar levels of fire intensity and environmental conditions within the treated unit (van Mantgem et al. 2001).

Many studies on the effects of fire on vegetation present results without acknowledging pseudoreplicated designs (Gilliam and Christensen 1986, Ducey et al. 1996, Schwartz and Heim 1996, Elliott et al. 1999, Glitzenstein et al. 2003, Elliot et al. 2004) while other researchers do concede some level of pseudoreplication (Nuzzo 1996, Taft 2003, Hutchinson et al. 2005, Marsh 2005). Methods to avoid pseudoreplication in fire effect research include before-after/control-impact (BACI) designs (Franklin et al. 2003), proper replication of treatments among landscape units (Brockway and Lewis 1997, Sparks et al. 1998), and avoiding hypothesis testing and reporting only observational results (Paulsell 1957, Lewis et al. 1964, Bacone and Post 1986, DeSelm and Clebsch 1991).

In Missouri, large landscape-level projects at the Joint Fire Science Program blocks in Reynolds County and the Chilton Creek Management Area in Shannon and Carter Counties allow for large-scale replication of treatments across landscape units to assess fire effects on vegetation (Sasseen 2003, Sasseen and Muzika 2004, McMurry et al. 2007). By treating separate fire events across the Ozarks as independent replicates, a generalized composite of fire effects can be inferred by examining vegetation trends across numerous sites.

Project Goals

This study examines ground flora vegetation cover in burned and unburned areas across the Missouri Ozarks with a landscape-level approach to studying fire effects. This study does not address species-specific responses to fire, but instead focuses on physiognomic plant group responses following multiple prescribed fires. Specifically, the cover of plant groups was compared across two aspects (northeast and southwest-facing slopes) and three treatments (unburned, burned within one year of sampling, and burned at least two years prior to sampling). Plant groups included for study include grasses, sedges, legumes, forbs, woody vines, shrubs, tree seedlings < 2 m in height, and exotic species. Specific hypotheses for each plant group are:

H_0: Absolute cover is not different among aspects and/or burn treatments

H_A: Absolute cover differs among aspects and/or burn treatments

Results from this study provide a generalized look at prescribed fire effects on ground flora cover across landscape-level burns in upland forests of the Missouri Ozarks.

Methods

Study Area

The study areas are located in upland forests across the Missouri Ozark Highlands (Figure 3.1). Data were collected from public and private lands located in the Current River Hills Ecological Subsection and the White River Hills Ecological Subsection (Nigh and Schroeder 2002). Study sites include Peck Ranch Conservation Area, Mule Mountain at Rocky Creek Conservation Area, Mill Mountain at Ozark National Scenic Riverways, and The Nature Conservancy's Chilton Creek Management Area in the Current River Hills; and Caney Mountain Conservation Area in the White River Hills. Dominant bedrock in the study area includes Ordovician Jefferson City-Cotter Dolomite at Caney Mountain; Precambrian St. Francois Mts. Volcanic Supergroup at Peck Ranch CA, Mule Mountain, and Mill Mountain; Ordovician Gasconade Dolomite and Cambrian Eminence-Potosi Dolomite at Peck Ranch CA and Chilton Creek Management Area; and Ordovician Roubidoux Sandstone and Dolomite at the south portion of Peck Ranch CA.

The Ozark Highlands are characterized as hilly to rugged lands with relatively thin, rocky soils. The pre-EuroAmerican settlement vegetation in the uplands was dominated by a mosaic of mixed-oak and pine-oak woodlands with a diverse ground flora composed of grasses and forbs (Nigh 1992). Fire suppression starting in the 1930s led to more closed forest conditions and reduced herbaceous cover. Current management objectives in the area include using prescribed fire to restore woodland conditions, including reducing woody understory and increasing forb and grass cover (Ozark National Scenic Riverways 2001, Nelson 2005).

Data Collection

Eighteen burn units were sampled from two Ecological Subsections: three units in the White River Hills and fifteen units in the Current River Hills. Each burn unit can be characterized as an upland oak- or pine-oak dominated forest matrix with glade inclusions and woodland intergrades. Burn units ranged in size from 10 ha to 660 ha. As of March 2006, each burn unit had at least one dormant season prescribed fire in the last five years, and the number of growing seasons since the last burn ranged from zero to five. A summary of information for each burn unit can be found in Table 2.1 and Table 2.2. In each burn unit, transects were established along the slope of the hill in forested areas with an oak-dominated overstory. The number of transects per burn unit varied according to the size of the burn unit.

Unburned areas (control) were also sampled throughout the study area. Areas were selected based on two criteria: 1) similar physiognomy (i.e. overstory species composition, stand structure) as burned areas and 2) close proximity to burned areas. Unburned areas selected for sampling include east of Denning Hollow near Mill Mountain; MOFEP Site 8 in Peck Ranch CA; an area north of Road 13, east of Road 14, and south and west of Boundary Road in Peck Ranch CA (hereinafter called Unburned Peck Ranch) (Figure 3.2); north of Road 3 near Sasser's Rock in Caney Mountain CA; and west of Road 3 near Holdman Hollow in Caney Mountain CA (Figure 3.3). Transects were established in control areas in the same manner as in burned areas.

Sampling occurred in 16 nested 1 m^2 quadrats within 20 m radius plots located along each transect. Transects were stratified by slope position (upper slope, middle slope, lower slope). Plots were systematically located within each slope position and were > 40 m from forest edge and > 75 m from other plots. If a plot location did not contain at least fifteen oaks ≥ 10 cm dbh, then the plot was relocated to the closest point that met this requirement. Plots per transect ranged from two (no middle slope position sampled) to three (all three slope positions sampled) based on the length of the hill. A total of seventy-eight burn plots and thirty-four unburned plots were sampled across the study area (Table 4.1). More plots were sampled in burned areas to capture variability that may be present due to burning. Open woodlands (canopy cover 10-50%), glades, and forested areas with relatively high overstory mortality were not sampled.

Once plots were established, distance tapes were used to determine lines through plot center from azimuths of 0° to 180° and 90° to 270°. For sampling, quadrats were placed with exact center at 4 and 16 m for each cardinal direction, and at 10 m from a line extending -22.5° and +22.5° from each cardinal direction (Figure 4.1). The percent cover of physiognomic plant groups within the quadrat were determined by ocular estimates and classified according to the Braun-Blanquet scale (Table 4.2) (Kent and Coker 1992). All plants with live foliage in the quadrat were included in cover assessments, even if rooting occurred outside of the quadrat. The eight physiognomic plant groups included grasses, sedges, forbs (including herbaceous vines and ferns), legumes, woody vines, shrubs, tree seedlings < 2 m in height, and exotics. Species were classified into plant groups following guidelines set in the Missouri Ozark Forest Ecosystem Project (Grabner et al. 1997). A walk-through identified any exotic species not sampled in a quadrat but within the plot. All sampling occurred from mid-May through August 2006.

Except for Compartment 17-East, all burn units had at least two prescribed fires in the last ten years. Because Compartment 17-East had only one burn, all percent cover data from this unit were excluded from subsequent analysis.

Table 4.1. Distribution of units and plots sampled by aspect and treatment.

Treatment		Aspect	
		SW-facing	NE-facing
Unburned (control)	Units	3	5
	Plots	16	18
Burned	Units	14	15
	Plots	33	45

Figure 4.1. Sampling scheme for placement of 1 m^2 quadrats in 20 m radius plots.

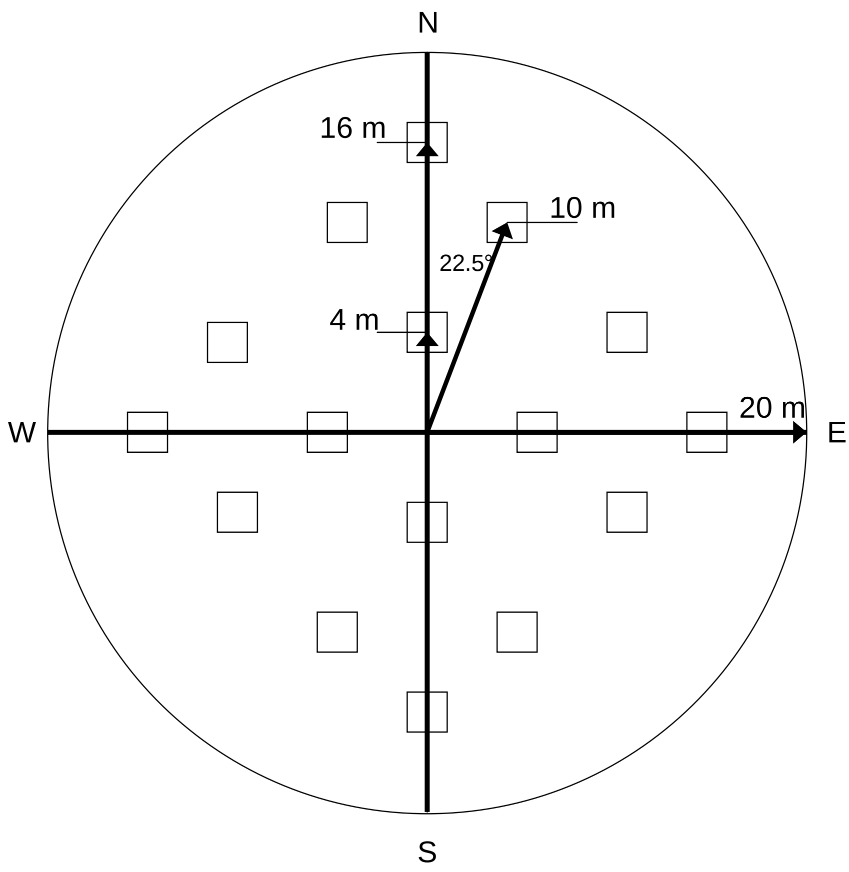


Table 4.2. Ground flora cover scale based on Braun-Blanquet scale (Kent and Coker 1992).

Value	Cover scale
0[1]	< 1%
1	1 – 5%
2	6 – 25%
3	26 – 50%
4	51 – 75%
5	76 – 100%

[1]Braun-Blanquet scale uses "+" instead of "0" for lowest cover value.

Analysis

The percent cover for each plant group was converted to a midpoint value. For each plant group, the quadrat midpoint values were used to determine plot-level mean cover. Burn units were stratified by aspect, and mean cover for each burn unit was determined for northeast and southwest-facing slopes. Burn unit cover values were transformed using a square root transformation that best normalized the data (Freeman and Tukey 1950).

Originally classification of units for analysis included separate treatment groups based on soil type and geologic bedrock. Due to low sampling numbers among soil types and geologic substrates, these factors were omitted for analysis. Burn units were classified as unburned (UB), burned within one year before sampling (B1), or burned greater than one year before sampling (B2). This represents a "natural snapshot experiment", where disturbance (fire) is assumed to be homogenous across all burn units and time since fire is the most important factor affecting vegetation cover (Diamond and Case 1986). Although this approach fails to address the complete temporal sequence of events that led to the current observed plant cover on all units, it does provide an opportunity to examine generalized prescribed fire effects on a landscape-level across the Missouri Ozarks.

A 3×2 mixed-model ANOVA was used to compare percent cover of plant groups by treatment on northeast and southwest-facing slopes. The fixed effect was the treatment (UB, B1, or B2) and aspect (northeast or southwest-facing) and the random effect was the sampling unit. Least square means were used to test for cover values equal to 0 and to test differences between treatments, aspect, and treatments by aspect. SAS Version 9.1 was used for all analyses:

```
PROC MIXED;
        CLASS TRT UNIT ASP;
        MODEL COVER = TRT | ASP;
        RANDOM UNIT (TRT ASP);
        LSMEANS TRT | ASP / PDIFF;
RUN;
```

where COVER = square root transformed percent cover for each physiognomic plant group, TRT = treatment (UB, B1, or B2), and ASP = aspect (northeast or southwest-facing slope). Exotics were excluded from all analysis because of low occurrence in quadrats.

Results

Cover of Plant Groups in Burned and Unburned Areas

For all aspects, burned areas had higher percent cover for all plant groups except legumes and shrubs (Figure 4.2, Table 4.3). In unburned units (UB), grasses had the lowest cover (2%), followed by sedges (3%), shrubs (5%), woody vines (6%), forbs (7%), and legumes and tree seedlings (14%). In units burned within one year from sampling (B1), sedges had the lowest cover (3%), followed by shrubs (5%), grasses (6%), woody vines (7%), forbs (9%), legumes (11%), and tree seedlings (18%). In units burned two years or more before sampling (B2), plant cover followed the same trend as B1 units, except plant cover of legumes was 12% and tree seedling cover was 16%.

In general, the maximum cover for all plant groups was higher in B1 or B2 than in UB (Table 4.3). For grasses on southwest-facing slopes the maximum cover in B1 and B2 was 10% and 14% compared to 4% in UB. On northeast-facing slopes grass cover followed the same trend by treatment (UB = 2%, B1 = 8%, B2 = 10%). On southwest-facing slopes, the maximum cover of legumes in B2 was twice the cover found on UB. For trees on northeast-facing slopes, the maximum cover in B1 and B2 was 22% and 23% compared to 4% in UB. Maximum cover of trees on southwest-facing slopes was also higher in B1 (22%) and B2 (18%) compared to UB (15%). The minimum cover for all plant groups was similar among treatments and aspects with one exception. On northeast-facing slopes for UB, the minimum cover of legumes was 14% while the minimum cover in B1 and B2 was 9% and 10%.

Among aspects and treatments, there was no difference in percent cover for sedges, legumes, forbs, woody vines, or shrubs (Figure 4.2, Table 4.5). For grasses and tree seedlings, there was a significant difference in cover between burned and unburned units. For northeast and southwest-facing slopes combined, least square means revealed that cover of grasses in UB was significantly lower from cover in B1 (t value = -2.81, $Pr > | t | = 0.009$) and B2 (t value = -2.28, $Pr > | t | = 0.03$) (Figure 4.3). For all aspects combined and for northeast-facing slopes, cover of tree seedlings was lower for UB compared to B1 (all aspects: t value = -2.62, Pr > | t | = 0.01; NE slopes: t value = -2.33, Pr > | t | = 0.03) (Figure 4.4).

Exotic Species Occurrence

The exotic shrub *Elaeagnus umbellata* was found in two unburned plots within the unit sampled near Unburned Peck Ranch (Table 4.4). In both plots, there was only one individual plant. One plant was found growing in a canopy gap created from decline-related crown dieback of an overstory *Quercus velutina* Lam. Three individual *Elaeagnus umbellata* shrubs were found in two burned plots in the Thorny Mountain burn unit, and one individual plant was found in one burned plot in the Little Thorny Mountain burn unit. In one burned plot *Elaeagnus umbellata* had a percent cover of 6-25% in one quadrat and had resprouted following fire. In the other two burned plots, *Elaeagnus umbellata* was found growing under single dead overstory oaks trees.

The exotic shrub *Rosa multiflora* was found in three burned plots in the units Compartment 5, Thorny Mountain, and Morrison Knobs (Table 4.4). One plot located near a field edge had three individual *Rosa multiflora* shrubs, and one individual had a cover of 1-5% in one quadrat. The other plots had one and two individual *Rosa multiflora* plants. There was no occurrence of *Rosa mutliflora* in unburned plots.

Table 4.3. Summary of percent cover data for all plant groups.

Plant group	Aspect	Treatment[1]	Units	Plots	Percent cover mean	stdev	min	max
Grass	SW-facing	UB	3	16	2.4	1.7	0.7	4.1
		B1	5	11	7.4	2.0	0.9	10.2
		B2	7	22	6.4	4.4	1.6	14.2
	NE-facing	UB	5	18	1.2	0.5	0.2	1.7
		B1	6	17	4.2	2.7	1.1	7.6
		B2	6	26	5.5	3.7	1.5	9.6
Sedge	SW-facing	UB	3	16	3.4	1.1	2.3	4.6
		B1	5	11	3.0	1.6	1.6	5.1
		B2	7	22	3.6	2.0	1.4	6.9
	NE-facing	UB	5	18	2.6	1.6	0.9	4.4
		B1	6	17	3.0	1.9	0.9	5.8
		B2	6	26	3.1	1.4	1.7	5.8
Legume	SW-facing	UB	3	16	9.6	5.4	3.7	14.4
		B1	5	11	14.1	5.4	7.1	19.7
		B2	7	22	14.9	8.4	4.2	29.9
	NE-facing	UB	5	18	15.9	1.3	14.2	17.7
		B1	6	17	9.4	3.4	6.9	14.6
		B2	6	26	9.9	4.8	5.2	18.0
Forb	SW-facing	UB	3	16	7.2	4.6	2.0	10.1
		B1	5	11	10.8	1.8	8.4	12.3
		B2	7	22	8.9	4.8	4.4	19.1
	NE-facing	UB	5	18	7.1	3.7	3.2	10.5
		B1	6	17	7.5	3.6	3.0	13.9
		B2	6	26	7.8	2.3	4.6	10.0
Woody vine	SW-facing	UB	3	16	6.0	4.2	2.0	10.3
		B1	5	11	6.8	4.7	2.1	14.1
		B2	7	22	6.2	2.9	1.1	10.1
	NE-facing	UB	5	18	6.1	1.8	4.4	8.4
		B1	6	17	6.9	5.3	2.2	16.6
		B2	6	26	6.3	3.4	1.9	10.1
Shrub	SW-facing	UB	3	16	6.4	2.4	4.4	9.0
		B1	5	11	5.5	2.2	3.1	8.1
		B2	7	22	4.5	2.8	0.5	9.2
	NE-facing	UB	5	18	4.1	1.4	2.0	5.8
		B1	6	17	5.3	2.8	2.1	9.6
		B2	6	26	5.0	1.5	2.4	6.4
Tree seedlings	SW-facing	UB	3	16	13.5	1.9	11.4	15.2
		B1	5	11	17.3	3.8	13.9	22.5
		B2	7	22	14.5	3.1	10.2	18.3
	NE-facing	UB	5	18	13.4	0.7	12.6	14.5
		B1	6	17	18.5	3.2	12.9	21.7
		B2	6	26	16.4	4.5	11.3	22.7

[1] "UB" = unburned; "B1" = burned in 2005 or 2006; "B2" = burned before 2005

Table 4.4. Occurrence of exotic plant species found in burned and unburned areas.

	Elaeagnus umbellata		*Rosa multiflora*	
	Unburned	Burned	Unburned	Burned
No. of individuals found	2	6	0	3
Plot occurrences	5.9%	3.8%	0%	3.8%
Quadrat occurrences	0	1	0	1
Highest plot cover	<0.5%	1.4%	0%	0.6%

Figure 4.2. Mean and standard error for percent cover of physiognomic plant groups for northeast and southwest-facing slopes combined. Different letters represent significant differences in within plant group least square means (α = 0.05).

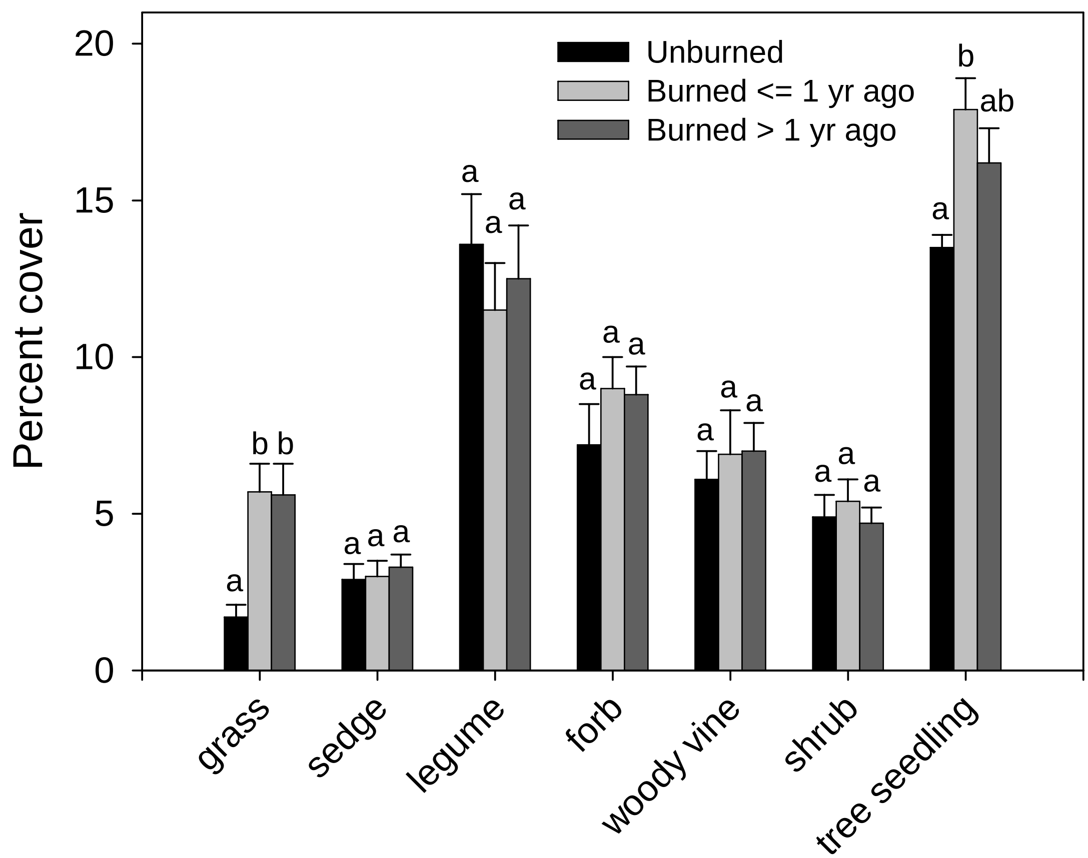


Table 4.5. F-values and p-values for mixed-model ANOVA results determining differences in percent cover by treatment and aspect. Bold values are significant at α = 0.05.

	Grass	Sedge	Legume	Forb	Woody vine	Shrub	Tree seedling
Treatment	**4.14**	0.15	0.07	0.75	0.03	0.78	**3.47**
	(0.03)	(0.86)	(0.93)	(0.48)	(0.97)	(0.47)	**(0.04)**
Aspect	2.51	0.67	0.01	1.01	0.05	0.48	0.70
	(0.12)	(0.42)	(0.93)	(0.32)	(0.83)	(0.49)	(0.41)
Treatment *	0.52	0.18	2.76	0.49	0.01	1.21	0.24
aspect	(0.60)	(0.83)	(0.08)	(0.61)	(0.99)	(0.31)	(0.79)

Figure 4.3. Mean and standard error for percent cover of grasses by treatment (UB = unburned) and aspect. Different letters represent significant differences in least square means (α = 0.05).

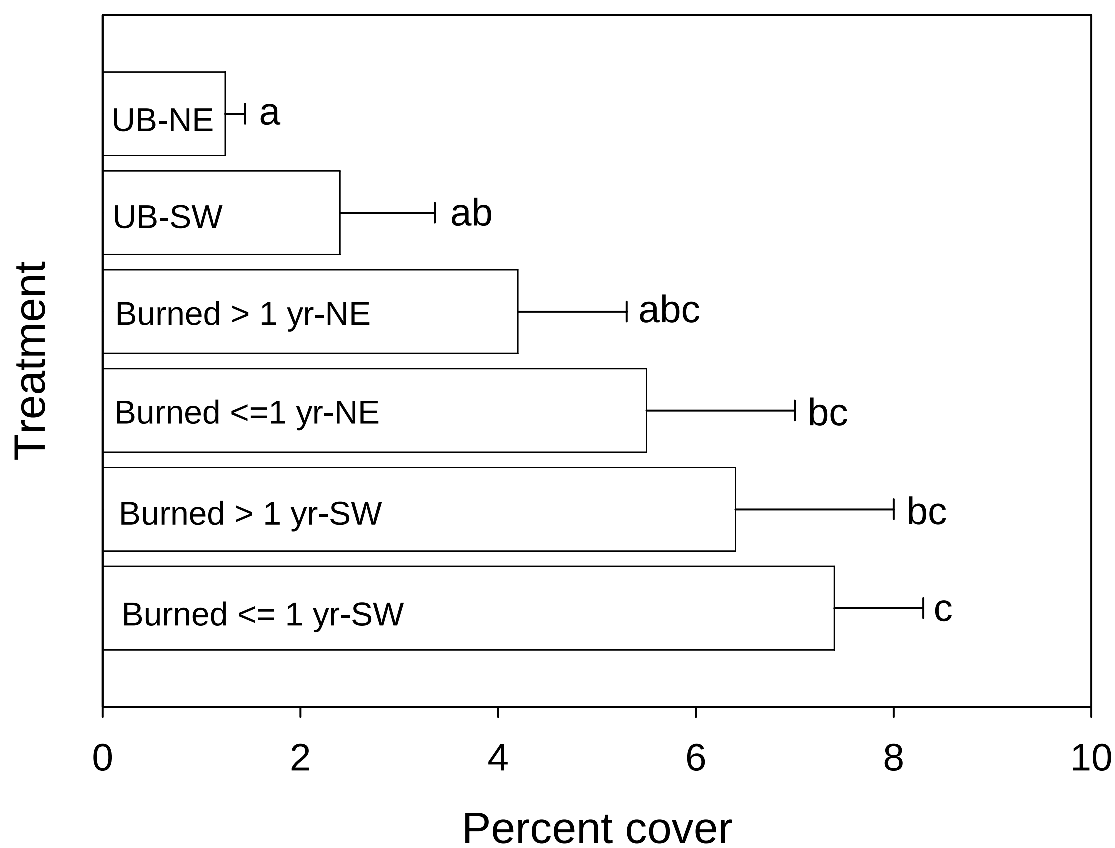
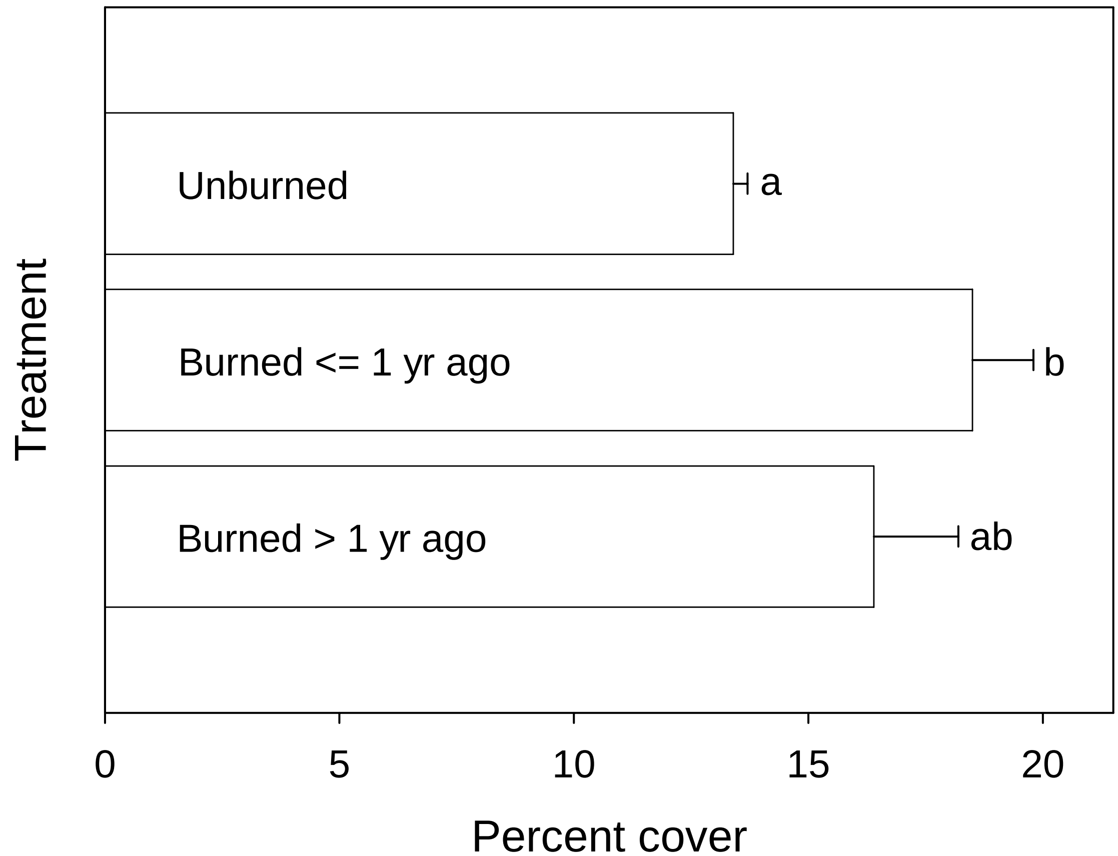


Figure 4.4. Mean and standard error for percent cover of tree seedlings (< 2 m in height) on northeast-facing slopes. Different letters represent significant differences in least square means (α = 0.05).



Discussion

Cover of Plant Groups in Burned and Unburned Areas

With the exception of grasses and tree seedlings, the cover of ground flora in upland forests of the Missouri Ozarks has not been greatly affected by repeated prescribed fires. Dolan and Parker (2004) found no consistent changes in the herbaceous community following burned and thinned treatments in an Indiana oak-hickory forest. In longleaf pine-wiregrass stands, Brockway and Lewis (1997) found no differences in shrub, vine, or forb cover between stands burned for thirty-eight years and unburned reference stands. In shortleaf pine-hardwood stands, there was no difference in percent cover of ground flora between a once burned and unburned stand (Elliot and Vose 2005). Other studies in the eastern United States have reported little differences in ground flora cover following prescribed fire in oak-dominated stands (Kuddes-Fischer and Arthur 2002, Rideout et al. 2003, Hutchinson et al. 2005, Phillips et al. 2007).

Research in oak-dominated forests of the eastern United States has shown similar results for grass cover following multiple prescribed fires. Following prescribed fires in upland oak forests of Tennessee, cover of graminoids increased in annually and periodically burned plots while cover decreased in unburned plots (DeSelm and Clebsch 1991). In oak-dominated forests of Ohio, the herbaceous layer in annually burned stands was three times greater than cover in unburned stands, largely due to increases in the frequency of grasses and summer forbs (Hutchinson 2004, Hutchinson et al. 2005). The higher grass cover in burned areas for this study was most likely due to the reduction in leaf litter following repeated burns which provided more favorable conditions for seed germination. Correlation analysis confirmed a moderate negative relationship between grass cover and litter depth ($\rho = -0.38$, $p < 0.001$).

In eastern oak forests, tree seedlings often respond with increased cover or frequency immediately following low intensity fires due to prolific sprouting of topkilled saplings (Hutchinson 2006). Arthur et al. (1993) found the herbaceous layer was dominated by tree seedlings following fires in a Kentucky oak-pine forest. A study in Connecticut found that woody species increased in density following an April prescribed fire in a white pine-oak stand (Ducey et al. 1996). A single prescribed fire in oak-dominated stands in Ohio led to increased woody cover in the herbaceous layer (Phillips et al. 2007). Field observations from this study and others reveal that in the Missouri Ozarks higher tree cover in burned areas is principally due to the prolific resprouting of *Sassafras albidum* and *Acer rubrum* immediately following fire (Hartman and Heumann 2003).

In Missouri upland oak forests, several studies found similar trends in ground flora vegetation following prescribed fire. At Chilton Creek Management Area, research has shown that annual and periodic burning increased the cover of all plant groups in the herbaceous layer, including grasses and tree seedlings (Hartman and Heumann 2003). Others found similar increases in ground flora cover following fires at Chilton Creek, with the exception of decreased relative cover of graminoids in some burned areas (Sasseen 2003, Sasseen and Muzika 2004). Immediately following a spring prescribed fire in Reynolds County, McMurry et al. (2007) found increased relative cover of graminoids on northeast and southwest-facing slopes, largely due to increases in *Panicum* and *Carex* spp. At University Forest in southeast Missouri, Paulsell (1957) found increased number of tree seedling stems less than 2 feet in height and increased number of grass species following annual and periodic fires.

Exotic Species

The relatively low abundance of exotics found in this study is similar to other studies examining herbaceous communities in the Missouri Ozarks. Sasseen (2004) reported that before burning treatments less than 1% of ground flora composition was composed of one exotic species (*Rosa multiflora*), and by four years postburn *Rosa multiflora* had been entirely eradicated. Examination of ground flora in 648 plots for the Missouri Ozark Forest Ecosystem Project (MOFEP) revealed that two upland exotics, *Elaeagnus umbellata* and *Rosa multiflora*, occurred in less than 0.5% of all plots (Grabner et al. 1997). Following management treatments there was little or no increase in exotic occurrence across the MOFEP study area.

Prescribed burning is not effective at controlling *Elaeagnus umbellata* because it vigorously resprouts following topkill (Sather and Eckardt 1987, Smith 1997). Although there was little evidence of fire-caused invasion of *Elaeagnus umbellata*, a vigorous shrub that resprouted following fire was found in the study area.

Repeated prescribed burning has been suggested as an effective control of *Rosa multiflora* invasion (Eckardt 1987, Smith 1997), although a study in Ohio reported that recruitment and subsequent height growth of *Rosa multiflora* was linked with high intensity fires and tree-fall gaps (Glasgow 2006). Exotics found in this study were most often found in areas in close proximity to roads and in areas of overstory dieback. Exotics are often found in close proximity to roads because roads may act as corridors for seed dispersal and provide suitable habitat for propagules that serve as reservoirs for future invasion (Parensdes and Jones 2000, Gelbard and Belnap 2003), but invasion into interior hardwood forests is limited without major disturbances (Watkins et al. 2003). Prescribed fire alone may not stimulate exotic plant invasion in the Ozarks, but oak decline in conjunction with burning may increase the susceptibility of interior upland forests to exotic invasion because of increased light levels in the understory due to overstory crown dieback.

Other Studies and Pseudoreplication

Some studies have shown increases in the cover of sedges, legumes, forbs, shrubs, or vines following prescribed fire (Gilliam and Christensen 1986, Nuzzo 1996, Elliott et al. 1999, Kuddes-Fischer and Arthur 2002, Taft 2003, Marsh 2005). These studies treated subsamples within burn units as independent experimental units, whereas I treated burn units as the experimental units. Using subsamples as experimental units has been deemed pseudoreplication by Hurlbert (1984) and casts serious doubt on the validity of inferring results beyond the immediate study areas (van Mantgem et al. 2001). Pseudoreplication leads to an overestimation of treatments effects and causes an increased likelihood of committing a type I error (Hurlbert 1984).

A “natural experiment” such as this study provides an opportunity to study general vegetation responses to fire on a landscape-level scale. Although the results represent only a snapshot of vegetation cover during the sampling year and cannot fully compensate for differences in environmental variables and fire regimes among experimental units, the generality and scope of the study is beyond that of typical field experiments (Diamond and Case 1986). While some researchers feel that pseudoreplication may be necessary for landscape-level ecological studies (Hargrove and Pickering 1992, Oksanen 2001), results from this study indicate that "natural experiments" can be successful with appropriate site matching and proper replication of experimental units (Hurlbert 1984, Diamond and Case 1986, van Mantgem et al. 2001).

Management Implications

Use of fire to stimulate herbaceous vegetation, especially grasses and forbs, is a primary goal of many managers of upland forests in the Ozarks. Results from this study indicate that grass cover on northeast and southwest-facing slopes is stimulated under a variety of fire regimes and many different soil types and geologic substrates. Forb cover was also higher in burned areas, although the results were not statistically significant. The generalized approach of examining plant responses across all soil types combined may not be appropriate when studying forb responses following fire. Examination of forb cover should likely be more site specific, focusing on the effects of burning on forb responses in specific soil types.

Prescribed fire is also used to kill small saplings and reduce the woody understory in Ozark uplands. Under a variety of fire regimes examined in this study, prescribed burning did not lower cover of woody vines, shrubs, or tree seedlings less than 2 m in height. Prescribed burning actually stimulated tree seedling cover immediately following fire, although the cover was similar to cover in unburned areas within two years postburn. When reduction of woody understory is a management goal, higher intensity fires may be needed to effectively reduce cover of woody species in Ozark upland forests.

CHAPTER 5: IMPLICATIONS FOR USE OF PRESCRIBED FIRE IN UPLAND FORESTS OF THE MISSOURI OZARKS

Fire-Caused Scarring and Mortality

Results from this study indicate that bark char height, a proxy for fire intensity, is the most important postfire predictor of the percentage of trees scarred and size of scars for major Ozark timber species. Species sensitivity to scarring followed trends similar to other fire research in the Ozarks, with *Quercus coccinea* and *Quercus shumardii* as the most fire sensitive upland tree species, followed by *Quercus velutina*, *Quercus alba*, *Carya* spp., *Quercus stellata*, and *Pinus echinata*. Bark char and species sensitivity are the two most important factors when assessing postfire injury to upland tree species.

Landscape features were also important predictors of percent of trees scarred and scar size. Trees on southwest-facing slopes are more likely to scar than trees on northeast-facing slopes, likely due to differences in environmental variables that affect fire intensity. Models developed from this study indicate that small diameter sawtimber trees at upper slope positions are likely to form large scars due to increasing fire intensity as fire moves upslope. For example, sawtimber *Quercus alba* ≤ 30 cm dbh located at a high fetch and on southwest-facing slopes are predicted to have scars of 3 to 4-m following moderate to severe fires. Other landscape factors known to influence fire intensity, such as slope steepness and slope position, need to be considered when using prescribed fire.

Small diameter trees are often killed following moderate to severe fires. Fire intensity, as measured by bark char height on hardwoods, is positively related to the dbh of the largest fire-killed tree in upland forests. Land managers should expect mortality from relatively larger trees in areas with high stem bark char (approximately 2-m in height) in comparison to areas with low bark char (< 0.5-m in height).

Tree Vigor of Quercus coccinea *and* Quercus velutina

Tree vigor decreases as fire-caused scarring increases in overstory *Quercus coccinea*. Although the relationship was weak, it does indicate that fire related injury may manifest itself in reduced vigor of overstory trees. Other indicators of tree vigor indicate that *Quercus coccinea* is less vigorous in burned areas, while *Quercus velutina* may be more vigorous in burned areas. When overstory tree vigor is a concern, removal of *Quercus coccinea* in areas targeted for prescribed fire management might be necessary.

Ground Flora Cover

This study showed that upland Ozark forests burned over the last 9-20 years have higher grass cover than unburned forests in the same area, most likely due to reductions in leaf litter. Tree cover is also stimulated immediately following fire due to resprouting of *Acer rubrum* and *Sassafras albidum*, but by two or more years following fire tree cover is similar to cover in unburned areas. The generalized approach used for this study did not allow for detection of other plant group responses to fire, likely due to grouping of data across geologic substrates and soil types. Assessment of fire responses for plant groups such as forbs needs to occur at a more detailed level.

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