Impacts of Oak-focused Silvicultural Treatments on the Regeneration Layer Nine Years Post-treatment in the Southern Appalachian Mountains of North Carolina

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Thesis submitted to the faculty of the Virginia Polytechnic Institute and State University in partial fulfillment of the requirements for the degree of

Master of Science
in
Forestry

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December 16th 2020
Blacksburg, VA

Keywords: Silvicultural Treatments, Ecosystem Restoration, Harvesting, Shelterwood

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ABSTRACT

Oaks *(Quercus spp.)* are an important part of the forested landscape in the eastern United States. Although oak is increasing in standing volume, an oak regeneration bottleneck has occurred throughout its range in recent decades. Subsequently, as oak overstory is being harvested, rarely is oak recruited into the overstory to maintain the historic dominance of overstory oak. In the absence of fire and subsequent canopy closure, mesic species have proliferated, frequently forming a dense understory, inhibiting oak regeneration success. This study was developed to determine species dynamics between oak and oak competitors in response to silvicultural treatments in the southern Appalachian Mountains of North Carolina. The treatments were: a shelterwood treatment (25-30% basal area reduction through mid-story removal with herbicides), a prescribed fire treatment (two late dormant season fires occurred over a 9-year period), a shelterwood and burn treatment (prescribed fire 3-5 years following 30-40% basal area removal), and an unmanaged control. To determine treatment impacts on the regeneration layer, importance value and stems ha^{-1} were calculated at the species group and individual species level 0- and 9- years post initial treatment. A principal component analysis and an analysis of basal area by treatment 0- and 9-years post-treatment were used to determine the influence of site-specific characteristics on regeneration layer response. The greatest relative increases in importance values were 1401% and 2995% for the red oak group and yellow-poplar (*Liriodendron tulipifera*), respectively, in the shelterwood and burn (SWB). Change in all species groups were predominantly influenced by the smallest size-class (<0.6 m tall), with the exception of northern red oak (*Q. rubra*) and yellow-poplar in the SWB. The SWB significantly reduced importance values of all shade tolerant species groups and was the only treatment to decrease red maple (*Acer rubrum*) importance value and density over the study years. The prescribed fire (RXF) treatment increased red oak group importance value, while simultaneously decreasing yellow-poplar importance value and increasing red maple importance value. Changes in the red oak group in the SWB and the RXF were driven by northern red oak and scarlet oak (*Q. coccinea*), respectively. Treatments do not appear to change the competitive status of the white oak group. Elevation was closely associated with the red oak group. Yellow-poplar importance value increases, white oak group importance value increases, and site index were closely associated. Decreases in basal area were greatest in the SWB, and the SWB was the only treatment to significantly decrease overstory basal area. The RXF and SWB treatments improved the competitive status of only some oak species, but modifications to these treatments may result in better control of yellow-poplar and red maple competition, further improving oak's competitive status. Site specific factors such as elevation and site index may have impacted the regeneration layer response to treatments.

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GENERAL AUDIENCE ABSTRACT

Oak-hickory (*Quercus* and *Carya* spp.) and oak-pine (*Quercus* and *Pinus* spp.) forest types occupy approximately 57 million and 11 million hectares of forestland in the eastern United States, respectively. Oaks are considered ecological and economic keystone species throughout the eastern U.S and maintenance of this genus in eastern U.S. forests has been a primary regional focus for decades.

Historic disturbance regimes are estimated to have been much different than they are today. Fire was a common disturbance mechanism prior to fire suppression in the early 20th century. Frequent fires maintained much of the oak component historically. In the absence of fire, the species found in the understories of mature oak stands are commonly mesophytic species, such as yellow-poplar (*Liriodendron tulipifera* L.) and red maple (*Acer rubrum* L.).

Over the last several decades, research has been conducted to investigate the impacts of treatments targeting the promotion of oak regeneration, but results have been varied and valuable long-term studies are rare. To determine the effects of treatments on the regeneration dynamics of oak and its competitors, four treatments were compared in the southern Appalachian Mountains. Treatments included a control, shelterwood harvest (SW), prescribed fire (RXF), and a shelterwood and burn (SWB). Stand structure and composition were monitored over a 9-year period post-treatment. Overall, results indicate the shelterwood and burn treatment has the greatest potential to improve the competitiveness of the red oak group in the regeneration layer, but yellow-poplar competition in the shelterwood and burn will need be addressed, considering its large increases in this treatment. Although increases in the red oak group were not as great as increases in the RXF treatment compared with the SWB, fire does show promise as a method to increase oak regeneration success. Changes in red oak group importance value varied with elevation, emphasizing results of treatments can be affected by site characteristics. Treatments were not successful at enhancing the competitive status of white oak (*Quercus alba* L.). Silvicultural treatments can be used to improve the competitive status of oak on sites in the southern Appalachian Mountains, but close monitoring of species dynamics throughout the rotation are needed to ensure long-term oak success.

ACKNOWLEDGMENTS

I would like express much gratitude to everyone who helped on this project and supported me along the way. First, I would like to thank my advisors, Dr. Dave Carter and Dr. Adam Coates. Without your continual guidance and involvement, this would not have been possible. I also would like to thank Dr. Tara Keyser with the U.S. Forest Service. She provided the opportunity to work with this project, and she has been an invaluable asset. Additionally, I would like to thank Alexander Byers, Adam McClure, and George Hahn for their assistance in the field. A final thanks to Michael Hollinshead for his assistance in the field and support over the last two years.

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Chapter 1. Introduction

Oaks (*Quercus* spp.) are foundational species in eastern US forests (Brose et al 2014, Dey et al. 2010, Hanberry & Nowacki 2016). They exist in many different forest types and many wildlife species depend on oaks for food and shelter (Dey et al. 2007, Gribko et al. 2002, McShea & Healy 2002, Smith 2006).

Throughout its range, oak is experiencing a regeneration bottleneck, with low oak recruitment into the mid- and overstory strata. These regeneration issues are considered to be caused by fire regime changes (Abrams 1992, Brose et al. 2010, Dey 2014). Historically, the eastern U.S. burned more frequently than it does today. Due to expansive fire suppression efforts conducted in the 20th century, the mean fire return interval has increased from 12.9 years pre-settlement to 45.2 years in eastern North America (Brose et al. 2014, Lafon et al. 2017).

With a lack of fire, mesophytic species have begun to outcompete oak in the understory and mid-story, although oak currently occupies a large portion of the overstory (Abrams 1995, McEwan et al. 2011, Nowacki & Abrams 2008). The resulting 'densification' of forests has led to insufficient light levels for long-term oak regeneration survival (Keyser et al. 2016). The current scope of the resulting oak regeneration problem has been well-documented (Aldrich 2005, Beck and Hooper 1986, Dey 2014, Fei et al. 2011, Moser et al. 2006, Peterson et al. 2019). Intervention will be needed to ensure oak remains a prominent component of our future forests.

Oak has several fire adaptations that give it a competitive advantage over fire-intolerant/mesophytic species (Brose et al. 2013, Burns & Honkala 1990, Dey et al. 2010, Johnson et al. 2019). Oak has hypogeal germination which places the root collar beneath the soil, protecting it from fire damage (Burns & Honkala 1990). It also selectively promotes root growth over stem growth, and is able to use carbohydrate reserves in the roots to resprout and grow rapidly after top-kill by fire (Brose & Van Lear 2004). Mature oak's thick bark protects the cambium from fire damage, and oak is able to compartmentalize wounds (Lorimer 1985, Smith & Sutherland 1999). Many mesophytic competitors of oak do not possess these traits, increasing their susceptibility to fire mortality and damage.

Exacerbating oak decline via fire suppression are recent management practices such as high-grading, diameter-limit cutting, and commercial clear-cuts, which, in the absence of fire, have promoted red maple and yellow-poplar on many historically oak-dominated sites. High-grading and diameter-limit cuts promote red maple and other shade tolerant species by selectively harvesting mature oaks while maintaining low light levels via the retention of poorly formed mature trees and mesophytic species in the mid- and overstories. Red maple can survive and rapidly occupy new growing space in understories with extremely low light levels (Burns & Honkala 1990). Commercial clear-cuts on historically oak-dominated sites can stimulate yellow-poplar in the seedbank and expose mineral soil suitable for newly fallen yellow-poplar seed to establish (Swaim et al. 2016). Yellow-poplar is a prolific seeder, and its seed remain viable for 4-7 years (Burns & Honkala 1990). Additionally, yellow-poplar grows fast when it is young, and it is able to easily outcompete slower growing oak in the regeneration layer (Beck & Hooper 1986, Swaim et al. 2016). Red maple is opportunistic in nature, and also responds positively to clear-cutting (Abrams 1998, Beck & Hooper 1986). Because of the response of yellow-poplar and red maple, intermediate treatments, such as burning, mechanical removal, or herbicides are needed to directly target these species, and often times, multiple treatments are needed.

Many studies have been conducted over the last few decades to determine the effects of silvicultural treatments on oak regeneration, and they have yielded varying results (Larsen & Johnson 1998, Loftis 1990, Schuler & Miller 1995). Adequate number and size of oak regeneration and understory light levels must be present to allow oaks to develop while inhibiting competing species, especially on higher quality sites (Dey 2014, Keyser 2016, Larsen & Johnson 1998). Sites in the southern Appalachian Mountains have diverse species assemblages and site characteristics. Understanding species dynamics and their interactions with site characteristics are essential to ensure oak regeneration success.

A research study was established in the Cold Mountain Game Lands in the southern Appalachian Mountains to determine the impacts of 4 treatments – control, shelterwood, prescribed fire, and a shelterwood and burn -- on oak regeneration and its competitors. The Cold Mountain Game Lands are located in western North Carolina, and are representative of oak-dominated sites in this region. To understand the response of regeneration pools to treatments, tree regeneration was sampled over a 9-year period, and changes in species importance values and stems ha^{-1} were quantified. Additionally, site characteristics were quantified to determine impacts of site-specific factors on the regeneration layer response.

This thesis includes a literature review of shortleaf pine and oak ecologies in Chapter 2. Chapter 3 presents experimental results, addressing species dynamics over a 9-year period under three silvicultural treatments in the southern Appalachian Mountains. Chapter 4 provides a summary of what was learned as a result of this study and highlights additional research questions that may be addressed in future studies.

Chapter 2. Literature Review

2.1 Changes in Eastern US Mixed Hardwood-Pine Ecosystems

Oak species (*Quercus* spp.) and shortleaf pine (*Pinus echinata*) were more prominent components of eastern US forests than they are today. These species can grow in pure and mixed stands across a vast range of site conditions (Burns & Honkala 1990, Lawson 1990). For both oak and shortleaf pine, frequent disturbances historically played a major role in their persistence (Bragg 2016, Nowacki & Abrams 2008). With changes in land use and disturbance regimes across much of the range of oaks and pines, these species are experiencing decline. Prior to anthropogenic suppression, fire decreased competitive pressures from mesophytic species and favored oak and shortleaf pine (Nowacki & Abrams 2008). Oak and shortleaf pine are considered to have greater significant ecological value compared to their current competitors, and the loss of these species as significant components of eastern US forests could be detrimental. Understanding the role of disturbance in regeneration success of oak and shortleaf pine will be vital to insure their future presence within these landscapes.

2.2 Shortleaf Pine

2.2.1 Shortleaf Pine Population Decline

Shortleaf pine (*Pinus echinata*) cover has declined 53% throughout its range since 1980 due to: land use changes (Guyette et al. 2007, Oswalt 2012), little leaf disease (Guldin 1986, Lawson 1990), pine beetle outbreaks (*Dendroctonus frontalis*) (Lawson 1990, Land & Rieske 2006, Elliot et al. 2012), loblolly pine replacement (*Pinus taeda*) (Bragg 2002, Hanberry 2013, Stewart et al. 2012*)*, and fire exclusion (Bragg 2016, Guldin 1986, Lawson 1990, Oswalt 2012, Stambaugh et al. 2007, Stewart et al. 2012). Research shows little natural regeneration is occurring to replace current shortleaf pine populations due to competition from hardwood species and limited seed sources (Blizzard et al. 2007, Guyette & Dey 1997, Guyette et al. 2007, Jensen & Gwayze 2007, Kabrick et al. 2015, Little & Moore 1949, Murphy & Nowacki 1997, Oswalt 2012), and this problem has been occurring for decades (Liming 1945, Little and Moore 1949). For example, in the western portion of its range, this compositional shift is further exacerbating the legacy effects of poor shortleaf pine management in the 1800s, when stands were typically burned following shortleaf pine harvesting, likely eliminating regeneration in the absence of a seed source to replenish losses (Guyette & Dey 1997, Guyette et al. 2007, Stambaugh et al. 2007). Although shortleaf pine can resprout following top-kill, frequent burning (i.e. 1- or 2-year intervals) may kill young shortleaf pine seedlings (Stambaugh et al. 2007). Additionally, in the Appalachian Mountains of Georgia and Tennessee, extensive logging and the absence of fire has resulted in compositional shifts from pine-oak woodlands and savannas to Virginia pine (*Pinus virginiana*), white pine (*Pinus strobus)*, and red maple (*Acer rubrum*) dominated forests (Brose et al. 2010). As a result, shortleaf pine forests have deviated from historic norms in composition and function across their range (Bragg 2002, Guyette & Dey 1997).

The loss of shortleaf pine and its associated structural diversity has ecological implications. Shortleaf pine's dominance in the shortleaf pine and shortleaf pine-oak forest types is largely defined by the predominant disturbance regime: mixed intensity and severity fires (Bragg 2002, Guyette et al. 2006, Guyette et al. 2007, Murphy & Nowacki 1997, Turner 1935). In the absence of fire or disturbance, these transitional shortleaf-dominated forests may quickly succeed to hardwoods (Brose et al. 2010, Matusick et al. 2020). Shortleaf pine and shortleaf pine-oak forests under a natural disturbance regime would commonly possess multi-aged stand structures with increased canopy gaps and decreased stand densities when accompanied by increased disturbance frequency (Bragg 2002, Masters et al. 2007, White & Lloyd 1998). Such structure often promotes greater regeneration, as well as grass and herbaceous species cover (Binkley et al. 2007, Stevenson 2017, Masters 2007, Meyers & Johnson 1978, Murphy & Nowacki 1997).

The structural diversity and increased understory sunlight associated with fire in shortleaf pine dominated forests benefits many wildlife species (Lay 1967, Masters 2007, Van Lear & Harlow 2002, Wilson et al. 1995). A decrease in fire dependent shortleaf pine communities has occurred since the era of fire suppression (Oswalt 2012, Stambaugh et al. 2007, Williams 1998). With this loss of valuable habitat, associated species have decreased, such as northern bobwhite quail (*Colinus virginianus*), Bachman's sparrow (*Peucaea aestivalis*), red-cockaded woodpecker (*Picoides borealis*), and many others (Guldin & Black 2018, Hedrick et al. 2007, Jackson 1988, Robbins & Easterla 1992, Van Lear & Harlow 2002). Efforts to restore shortleaf pine throughout its native range have been ongoing for decades. Research designed to inform these efforts have largely occurred in the western portion of this range, and much is still unknown about how to properly restore shortleaf pine in the southern Appalachians (Elliot et al. 2012, Pile & Waldrop 2016)

2.2.2 Shortleaf Pine and Fire

Across its range, shortleaf pine co-evolved with fire return intervals of 1- 18 years (Masters 2008). These fires were mixed intensity and severity (Brose et al. 2001, Flatley et al. 2013, Hart et al. 2008). Shortleaf pine relies on fire to promote a competitive advantage over hardwoods and less fire-adapted pines (Fan et al. 2012, Masters 2007, Murphy & Nowacki 1997, Williams 1998). Shortleaf pine has many fire adaptations that give it an advantage in systems with frequent fire. It develops thick, platy bark that insulates the cambium from heat damage during fires relatively early in its life, and it is an effective self-pruner, with reduced, retained ladder fuels (Garren 1943, Guldin 1986, Reifsnyder et al. 1967, Schwilk & Ackerly 2001). Additionally, shortleaf pine can resprout post-top-kill, similar to most competing hardwoods throughout its range. The seedlings resprout from a basal crook, which protects the dormant buds from extreme temperatures and damage (Little & Somes 1956, Mattoon 1915, Chapman 1942, Lilly et al. 2012). Although fire resistant, young shortleaf pine seedlings can be killed by fire. Trees with groundline diameters of less than 4 - 6 in. or heights less than 8 - 16 ft. are more likely to be killed by fires (Lawson 1990, Mattoon 1915). In a study of shortleaf pine burn frequencies, Stambaugh et al. (2007) found fire return intervals of 1 - 4 years are appropriate for shortleaf pine establishment, but longer intervals of 8 - 15 years allow pine to survive and ascend into the canopy.

2.2.3 Regeneration and Establishment

Limited seed sources, hardwood competition, and sporadic seed production make natural regeneration of shortleaf pine difficult (Barnette & Brissette 2007, Cain 2004, Lawson 1990, Liming 1945, Shelton & Wittwer 1996, Shelton & Wittwer 2004, Vose et al. 1997). Designing management plans to address these issues is vital for shortleaf pine regeneration success. Management options, such as herbicides, mechanical removal of competitors, prescribed fire, or a combination of these treatments may improve seedbed conditions (i.e. expose bare mineral soil), improve light conditions, and reduce hardwood competition (Baker 1992, Blizzard et al. 2007, Farrar 1998, Gwaze & Johanson 2013, Lawson & Kitchens 1983, Pile & Waldrop 2016, Vose et al. 1997). Timing these site preparation treatments in conjunction with good seed production years can improve establishment rates (Shelton & Wittwer 1996). Artificial regeneration options are available, but they are often expensive. Studies show containerized seedlings are most successful, followed by bareroot, and then direct seeding (Barnett & Brissette 2003, Barnett & Brissette 2004, Mann & Gwaze 2007). Overstory manipulations that increase understory light can be implemented to encourage establishment of this shade intolerant species (Baker et al. 1996, Blizzard et al. 2007, Jenson et al. 2007, Lawson & Kitchens 1983, Shelton & Wittwer 1996). The shelterwood system is most successful for natural regeneration when productive seed trees are present because the shade generated by the overwood can limit woody species competition (Baker 1992, Lawson 1990, Shelton & Wittwer 1996). Resource managers' understanding of silvics specific to shortleaf pine is key in increasing regeneration and establishment rates.

2.2.4 Non-structural Carbohydrates: Storage and Sprouting

Non-structural carbohydrate (NSC) storage, according to Chapin et al. (1990), is broadly defined as "resources that build up in the plant that can be mobilized in the future to support biosynthesis for growth or other plant functions." Non-structural carbohydrates are carbon compounds not incorporated into the structure of a plant, and they are primarily soluble sugars and starch (Hartman & Trumbore 2016). Soluble sugars generally support functions such as new growth, defense, and respiration, while starch is typically associated with storage for ensuing demands, such as regrowth in response to disturbance (Chapin 1990, Mooney 1973, Paula & Ojeda 2009). Storage fluctuations occur over multiple timescales. Plants can draw from stored NSCs in response to brief changes in growing conditions (e.g. intermittent cloud cover) as well as fluctuate NSC usage seasonally (Furze et al. 2019, Richardson et al. 2012, Zhu et al. 2012). Storage occurs at the expense of growth (Sala et al. 2012, Wiley & Helliker 2012). Reserves are lowest when plants are rapidly growing, and reserves are replenished when growth slows

(Chapin 1990, Furze et al. 2019). Some other studies suggest that carbon (C) storage is not strictly a source-sink relationship (Chapin et al. 1990, Hoch and Körner 2003, Kobe 1997, Sala et al. 2012). Sala et al. (2012) found that C storage can be an active, not passive, process, and storage priority can compete with demands for growth. Hoch and Körner (2003) found trees maintained a large amount of C in storage regardless of season, suggesting that storage did not always indicate surplus.

Sprouting ability is closely connected to carbohydrate storage allocation (Bell & Ojeda 1999, Clarke & Knox 2009, Knox & Clarke 2005, Kozlowski et al. 1991, Pate et al. 1990, Walters et al. 2005). Multiple studies discovered that sprouting species have higher root starch concentrations (Bell & Ojeda 1999, Knox & Clark 2005, Pate et al. 1990). Even under nutrient limiting conditions, sprouters allocated more resources to storage (Knox & Clarke 2005, Pate et al. 1990). Research shows prolific sprouters have larger root to shoot ratios (Nzunda et al. 2008) and higher whole plant non-structural carbohydrate concentrations than poor sprouters (Bowen & Pate 1993, Nzunda et al. 2008). Non-structural carbohydrate and biomass allocation to roots allows sprouters to survive under increased fire frequencies or other disturbances (Bond & Midley 2001, Furze et al. 2018, Knox & Clarke 2005). In a study in the southern Appalachian Mountains, Beck and Hooper (1986) found 86% of the dominant and codominant trees resulted from stump sprouts 20 years after a clearcut. The sprouters are able to rapidly remobilize the belowground resources to reoccupy the space (Bond& Midley 2001, Del Tredici 2001, Nezunda et al. 2008).

2.2.5 Shortleaf Pine and Sprouting

Shortleaf pine has the ability to resprout post top-kill. Its seedlings develop a basal crook in the shape of an “S” or “J” that places cotyledons just below the soil surface (Little & Somes

1956, Mattoon 1915, Stone & Stone 1954). Shade-grown seedlings may produce crooks at 6-7 years old, but open grown seedlings may see crook development occur within the first year of life (Little & Somes 1956). Basal sprouts can emerge from dormant buds that exist in the basal crook (Fowells 1965, Little & Somes 1956). If the stem is killed by browse or fire, new growth begins from these dormant buds (Fowells 1965, Little & Somes 1956). Sprouting declines when stems reach 15-20 cm in diameter at breast height (DBH) or 8-12 years of age (Chapman 1942, Lawson 1990, Mattoon 1915). Mattoon (1915) stated shortleaf pine maintains its sprouting ability through age 8 for vigorously growing seedlings, and 10-12 years of age for slow-growers. Understanding sprouting is necessary, because as previously stated, it gives shortleaf pine a competitive advantage over hardwoods and other pines and allows it to persist post-disturbance (Ashe 1910, Chapman 1942, Murphy & Nowacki 1997, Turner 1935, White & Lloyd 1998).

Shortleaf pine regeneration is often inhibited by hardwood competition (winter-deciduous woody plants) (Baker 1992, Little and Moore 1949). The ability of shortleaf pine to escape these competitive pressures may be reliant upon the timing of top-kill from disturbance and the composition of its competition. Non-structural carbohydrate fluctuations may vary among life forms. Martínez- Vilalta et al. (2016) compared conifers and winter-deciduous trees to determine NSC allocation patterns throughout the year. Conifers showed a peak in starch concentrations belowground in early spring and in the leaves in late-spring/early-summer. Soluble sugars showed their peak in the roots and leaves in the winter months. Conversely, winter-deciduous species showed maximum starch concentrations belowground in late summer, and soluble sugar in the leaves were highest in the spring and early summer, when concentrations were lowest belowground (Martínez- Vilalta et al. 2016). Hoch & Kormer’s (2003) findings largely agreed with those of Martínez-Vilalta et al. (2016) as they found winter-deciduous species showed a NSC peak in the leaves at the end of May and early June, while evergreen species showed their peak slightly earlier in April. In a study of loblolly (*Pinus taeda*), slash (*Pinus elliottii*), and longleaf pines (*Pinus palustris*), Mims et al. (2018) found that, among all pines, there were higher root total non-structural carbohydrate (TNC) values in March compared to October. Also, longleaf pine, a highly fire-adapted species, generally had greater TNC in the roots than slash and loblolly, which are less fire-adapted. Timing of top-kill in April when TNC is highest in the roots of conifers and lowest in the leaves of winter-deciduous species could potentially increase shortleaf pine regeneration, while decreasing hardwood regeneration or regeneration of other undesirable pine species.

2.2.6 Shortleaf Pine Sprouting Studies

Researchers have conducted multiple shortleaf pine sprouting studies throughout its range, and the results of these studies are summarized in Table 1. Notably absent in the literature are studies investigating the influence of timing and method of top-kill on the sprouting ability of shortleaf pine in the southern Appalachians. Nevertheless, among the studies in Table 1, several variables were consistently influential on the sprouting ability of shortleaf pine: (1) basal crook and surface temperature, (2) method of top-kill, and (3) season of top-kill. Higher basal crook or surface temperatures across studies resulted in lower percentages of shortleaf pines resprouting (Bradley et al. 2016, Lilly et al. 2012). Lilly et al. (2012) found higher average basal crook temperature or average surface temperature negatively affected sprouting potential and sprout survival (see Table 1 for specific basal crook and surface temperatures). Additionally, basal crook temperature is a better predictor of sprouting potential than surface temperature (Lilly et al. 2012). Bradley et al. (2016) and Clabo & Clatterbuck (2015) studied method of top-kill (i.e. clipping or burning) effects on sprouting in 1- and 2-year-old seedlings. Clipping resulted in higher percentages of stems that sprouted in Clabo & Clatterbuck (2015) and Bradley et al. (2016). Interestingly, in the 3-year-old seedlings, sprouting percentages were higher in the August burn treatment than the March clip treatment, but this could be due to larger seedlings escaping top-kill by fire (Clabo & Clatterbuck 2019). Across all studies, comparing season of top-kill, growing season treatments saw fewer trees resprout and the resulting sprouts tended to be less vigorous (i.e. less height growth) compared to the dormant season treatments (Bradley et al. 2016, Shelton & Cain 2000, Clabo & Clatterbuck 2019). The Clabo and Clatterbuck (2015) results showed a weak, negative correlation between pre-treatment seedling height and post-top-kill sprout production. Understanding impacts of method, season, and temperature of top-kill can improve seedling sprouting success and inform management decisions.

2.2.7 Potential Management Implications

Shortleaf pine decline is concerning for natural resource managers based upon its historical significance (Oswalt 2012), supported habitat (Hedrick et al. 2007), and ecosystem attributes (Binkley et al. 2007, Stevenson 2016). More research is needed to determine potential management solutions to remedy its decline and restore system functionality. Most shortleaf pine research is conducted in the Arkansas and Missouri Ozarks, where several large, remnant stands of shortleaf pine exist. Few shortleaf pine studies and no top-kill studies have been conducted in the southern Appalachian Mountains, despite its historic presence and importance in this region (Ayres & Ashe 1905). Simulating the disturbance regime responsible for shortleaf pine's presence with prescribed fire alone or in combination with other silvicultural treatments might provide a means for shortleaf pine restoration (Shelton & Wittwer 1996). Understanding the connection between shortleaf pine's sprouting ability and seasonal non-structural carbohydrate fluctuations may inform treatment implementation to improve regeneration and restoration efforts.

2.3 Oaks

Recent attention focused on shortleaf pine has not diminished continued interest in eastern oak species (Brose and Waldrop 2006). As co-occurring species in many locations throughout much of shortleaf pine's native range, oak species were once enhanced by similar disturbance histories on the native landscape (Lafon et al. 2017). For nearly 50-60 years, forest managers and landowners have been interested in best management practices for oak regeneration across the eastern US (Brose et al. 2013, 2014).

Most current overstories maintain oak as a dominant component across the forested, eastern U.S. However, oak regeneration is in decline in many of these stands (Waldrop et al. 2016). As a result, multiple management strategies have been suggested and researched to determine techniques that may enhance oak regeneration (Oakman et al. 2019). These enhancements must account for competition from more mesophytic tree competition, including, but not limited to, red maple (*Acer rubrum*), yellow-poplar (*Liriodendron tulipifera*), sassafras (*Sassafras albidum*), and blackgum (*Nyssa sylvatica*). Additionally, many undisturbed stands in the eastern US also have well-developed mid-stories, dominated by shrubs, such as mountain laurel (*Kalmia latifolia*) and great rhododendron (*Rhododendron maximum*). These shrub understories prohibit tree regeneration due to their broad canopies and intense shading of the forest floor (Brose 2016).

Oak has several fire-adapted traits (Brose et al. 2013, Burns & Honkala 1990, Dey et al. 2010, Johnson et al. 2019). Oak dormant buds are protected from damage through hypogeal germination, where the root collar is located below the soil surface (Burns & Honkala 1990). Oak selectively allocates growth to their roots systems, which allows them to sprout prolifically after top-kill (Brose & Van Lear 1998). Additionally, oak's thick bark protects the cambium from damage, and if damage occurs, it compartmentalizes wounds, preventing decay (Lorimer 1985, Smith & Sutherland 1999). These adaptations give oak an advantage over fire intolerant competitors when fire is present.

Oakman et al. (2019) investigated the long-term impacts of repeated treatments targeted to 1) reduce potentially hazardous wildland fuels, 2) reduce total tree basal area and shrub cover, and 3) increase oak regeneration. Results showed, in the mechanical only treatment, shrub species increased. Oaks significantly increased in the combination mechanical and burn and burn only treatments when compared to the mechanical only and control treatments, but red maple also responded positively to those treatments. This suggests mechanical removal may not be surrogate for fire. A combination of treatments was most successful in creating conditions to promote oak, but follow up treatments may be needed to address oak competitors. Soil properties may have influenced the results of the Oakman (2018) study. Dukes et al. (2019) conducted a study on the same site and found soil chemistry was not significantly altered long-term, although significant differences were detected among treatments, 1-2- and 2-4 years post-treatment. This suggests an increase in treatment intensity may be necessary to affect soil chemistry long-term, creating potential nutrient limitations that select against oak's common competitors.

Some attention has been given to managing mixed pine – hardwood forests to meet ecological goals. A study conducted in the southern Appalachian Mountains evaluated the success of the fell-and-burn technique at establishing shortleaf pine among hardwoods 34 years after initial harvest (Pile and Waldrop 2016). Moderately productive sites resulted in the best establishment of shortleaf pine, and on dry and intermediate sites, desirable oak species were maintained. On productive sites, red maple outnumbered oak, suggesting additional treatments may be needed to favor oak or pine on these sites.

These studies and many others show creating conditions for successful oak and pine regeneration is very complex. Responses to treatments differ based upon site characteristics, species dynamics before and after treatments, treatment intensity, soil characteristics, and other factors. Understanding potential interactions between these factors and silvicultural treatments will be important to insure oak and pine regeneration success in the southern Appalachian Mountains.

2.4 Research Justification

To continue the long-term investigation of these concerns, a research study was designed in western NC. In this study, 4 silvicultural treatments were evaluated: 1) untreated control (CON), 2) shelterwood (SW), 3) prescribed fire (RXF), and shelterwood and burn (SWB). In the CON, no management occurred over a 9-year period. The SW treatment removed 25-30% basal area without overstory removal (Loftis 1990a). Non-oak, mid-story trees were targeted with herbicide. For the RXF, two dormant season fires occurred over 9 years. For the SWB treatment, 30-40% of overstory basal area was removed, leaving a predominantly oak overstory (Brose et al. 1999). A prescribed fire was then conducted 3-5 years after the initial overstory removal. Additionally, the study included a control treatment, where no silvicultural modifications occurred. Regeneration, mid-story, and overstory characteristics by species were monitored. Additionally, density changes elevation, slope position, aspect, site index, terrain shape, landform index, and soil characteristics were recorded.

Hypotheses:

1) Importance value of the red oak group would increase the greatest in the SWB treatment.

2) Oak stem densities would increase the greatest in the RXF treatment.

3) Site-specific factors, such as greater basal area reductions and lower site index, would be ted to greater increases in oak importance value.

Chapter 3. Impacts of oak-focused silvicultural treatments on the regeneration layer nine years post-treatment in the southern Appalachian Mountains of North Carolina

3.1 Introduction

Oak (*Quercus* spp.) was a prominent genus in eastern US deciduous forests prior to European settlement (Fei et al. 2011, Hanberry & Nowacki 2016). Oaks are an ecological and economic keystone species (Abrams et al. 1995, Hanbery & Nowacki 2016, Smith 2006). The oak-hickory and oak-pine forest cover types currently occupy approximately 43% of the eastern US forests (Moser et al. 2006). Different oak species are found across a diverse range of ecosystems and their distribution is largely influenced by site quality (Brose et al.2014). Chestnut oak (*Q. prinus*), scarlet oak (*Q. coccinea*), and black oak (*Q. velutina*) are commonly found on upper slopes and dry ridges with dry, shallow soils. Northern red oak (*Q. rubra*) grows well on cool, moist sites (Keyser et al. 2016). White oak distribution is only limited by extremes in soil moisture or dryness (Burns & Honakala 1990). Black oak is commonly found on poor, shallow, and dry sites, but its growth is best on moist and well-drained soils (Burns and Honakala 1990).

Across its vast range, oak has significant ecological importance. Oak forests, woodlands, and savannas support diverse plant communities (Brudvig 2010, Holzmueller et al. 2009, Lettow et al. 2014). Oak forests are partially maintained by small-scale gap dynamics (Brose et al. 2014, King & Muzika 2014). The resulting structural heterogeneity leads to increased understory light levels and understory diversity, supporting a wide array of wildlife habitat (Dickenson 2004).

Many species of birds, mammals, and insects rely on oak for food, shelter, and stability. Oak leaves form the basis of many food chains, and certain bird species are closely associated with oak ecosystems (Brose et al. 2014, McShea & Healy 2002, Rodewald & Abrams 2002).

Additionally, acorns, with their high nutrient content, are a major food source for species such as birds, deer, black bear, and small rodents (Keyser et al. 2016, Smith 2006). The furrowed bark of oak trees provides better shelter for insects when compared to other smooth bark species, such as red maple (Brose et al. 2014) These are long-term system functions as oaks are typically a long-lived species, and this longevity provides ecosystem stability (Keyser et al. 2016). In the midst of the declining presence of oak, important ecosystem functions may be lost.

Furthermore, oak provides economic value. Oak has historically maintained one of the top stumpage prices of all hardwood species in the eastern US (Brose et al. 2014). It is used to make many wood products, such as furniture, cabinets, flooring, and whiskey barrels. These products support jobs within those industries, as well (Brose et al. 2014, Smith 2006).

Historic disturbance regimes of the eastern US were much different than they are today. Fire, via anthropogenic and natural sources, was more frequent prior to aggressive, active fire suppression that began in the 1920s (Abrams 1992, Van Lear et al. 2000). Fire, in combination with other disturbances, created a more open canopy structure (Crow 1988, Brose 2014, Nowacki & Abrams 2008). Oak has several fire adaptations that provide a competitive advantage when frequent fires occur: thick bark, selective resource allocation to roots, and resprouting ability (Signell et al. 2005).

Conditions in the early 1900s were especially favorable for oak (Smith 2006). Considering oak’s disturbance adaptations, during the period of intense grazing, logging, and fire, oak was able to persist (Arthur et al. 2012). The oak dominated regeneration layer was able to ascend into the canopy as disturbances began to decrease around the turn of the century. Oaks need a sufficient (10-30 year) fire-free interval to establish, which occurred during the fire suppression era (Dey 2014). Oaks invaded the cutover and burned lands and, from these conditions, emerged into the uniformly aged oak forests commonly found throughout the eastern US today (Arthur et al. 2012, Dey 2014). Historically, these forests would have been a mosaic of different ages and size classes as a result of a combination of more frequent, low to moderate severity disturbances (Arthur et al. 2012).

Although oak is increasing in volume under current stand conditions, the proportion of oak is decreasing in relation to its competitors (Fei et al. 2011). In the past, fire promoted oak and disfavored fire-intolerant species (Abrams et al. 1995, Nowacki & Abrams 2008). Current forest conditions in the eastern US are typified by an increasing presence of mesophytic, fire-intolerant species, often capable of out-competing oak in the regeneration layer, increasingly so as site quality increases (Rodewald 2003, Dey 2014). In result, very little oak regeneration has successfully transitioned into the overstory over the last several decades (Crow 1988, Fei et al. 2011, Lorimer 1984, McEwan 2011). Without silvicultural intervention, oak forests are likely to succeed to other species or be composed of substantially less oak than in historic overstories (Abrams 1996, Fei et al. 2011, Moser et al. 2006).

Successful oak recruitment into the overstory often requires oak regeneration of adequate size (≥ 0.64 cm - 1.27 cm diameter or ≥ 1.22 cm - 1.83 m tall) and density (≥ 247 - 494 stems ha^{-1}) prior to overstory removal, especially on productive sites (Dey 2014, Keyser et al. 2016). Oak needs intermediate light levels to develop. Oak can survive under low light levels for some time, but growth is limited and mortality is high (Larsen & Johnson 1998, Walters & Reich 1996). Oak growth is greatest at light levels between 20-50% full sunlight, but light requirements may vary by species (Brose 2008, 2011, Johnson et al. 2019). In the absence of light environment modifications following disturbance, shade tolerant species tend to dominate oak sites (Nowacki & Abrams 2008). Groninger & Long (2008) studied clearcutting impacts on oak competitive status in the Shawnee National Forest in Illinois 15-26 years after overstory removal. The least amount of oak was found on more productive sites due to competition from yellow-poplar. On drier sites, without significant competition from yellow-poplar, oak was able to persist. Their study suggests more intensive treatments may be needed on higher quality sites to address competition, specifically from yellow-poplar.

Much research has been conducted over the last several decades investigating impacts of silvicultural treatments on oak regeneration. Shelterwood harvesting has become a widely accepted technique to regenerate oak, but advance regeneration must be present prior to the final harvest (Keyser et al. 2016) and results may vary based upon numerous factors, including but not limited to, site quality and previous land-use history.

Intermediate treatments are often necessary to address post-harvest competitors and to develop the oak regeneration pool, but these treatments are often not carried out. Promoting the establishment of oak regeneration can take 10-25 years (Sander 1972, Keyser et al. 2016). A prescribed burn is an intermediate treatment practitioners may utilize to increase oak regeneration. A single, dormant season burn typically fails to improve the competitive status of oak (Keyser et al. 2019), but multiple dormant season fires or a single, growing season burn have been successful (Brose et al. 2013, Dey & Hartman 2005). Conversely, fire may negatively impact oak in some cases (Alexander et al. 2008, Blankenship & Arthur 2006). Fires occurring close to acorn drop can cause significant acorn mortality, and young oak seedlings are very susceptible to fire mortality (Brose 2014). Additionally, fire can stimulate growth of oak competitors, such as yellow-poplar and red maple (Dey et al. 2009, Schuler et al. 2013, Waldrop et al. 2008). A combination of treatments can result in increased oak regeneration, but these tend to enhance shade intolerant species prevalence, as well (Albrecht & McCarthy 2006, Oakman

2019, Pile & Waldrop 2016). Close monitoring is needed to assess the effectiveness of intermediate treatments, and altering prescriptions may be necessary to meet adequate oak regeneration levels prior to overstory removal.

Compounding difficulties with oak management, different species of oak respond differently to treatments (Brose 2011, Brose & Rebbeck 2017). When comparing different shelterwood harvest methods on seed-origin oak, Brose (2011) found northern red oak survived more frequently under low light conditions than white oak (*Q. alba*). Northern red oak growth responded more readily to increases in light, but so did oak's competitors. Smaller increases in light levels increased white oak survival. Understanding the interaction between treatments and the responses of different species of oak and their competitors is important to ensure oak regeneration success (Dey et al. 2014, Larson & Johnson 1998, McShea et al. 2007).

Some oak silvicultural studies have been conducted in the Appalachian region. The responses of oak and its competitors vary by disturbance type and intensity and site quality (Beck & Hooper 1986, Holzmueller et al. 2009, Keyser et al. 2019, Loftis 1993, Signell et al. 2005). Atwood et al. (2011) compared five different silvicultural systems implemented in the Appalachian Mountains using importance value, average height, and stem density to quantify changes by species groups among different treatments. They found increased basal area retention across treatments led to less oak and yellow-poplar, and increased red maple importance value. Their results suggested that continued management intervention in the stand to control competing species would be important to promote oak. Oakman (2019) studied the effects of mechanical cutting of shrubs, burning, and a combination of the two on the vegetation layer. They found a combination of mechanical removal and burning was most successful in promoting oak, although yellow-poplar also responded positively. Another study conducted in the southern

Appalachian Mountains evaluated the success of the fell-and-burn treatment at establishing oak and pine across site productivity gradients. Oak establishment was best on dry to intermediate sites, and red maple outnumbered oak on productive sites (Pile & Waldrop 2016).

For this study, four treatments were evaluated: 1) untreated control, 2) shelterwood, 3) prescribed fire, and 4) shelterwood and burn. The regeneration layer, mid-story, and overstory were inventoried for 9 years post-treatment. Site characteristics, including soil and physiographic data, were also collected for each treatment replication.

Our goal was to determine the response of the oak regernation layer and its common competitors to four treatments, relative to each other, in oak-dominated stands in the southern Appalachian Mountains. Specifically, we aimed to:

1. Quantify the change in importance value of the red oak group, the white oak group, and oak competitors in response to 4 different silvicultural treatments -- control, oak shelterwood, prescribed fire, and shelterwood and burn – 9 years post-treatment
2. Quantify changes in stem density of oak, at the species level, and changes among oak's major competitors across treatments and size classes.
3. Determine the contribution of site-specific factors to the change in importance value of the red oak group, the white oak group, yellow poplar, and red maple.

We hypothesized:

1. Red oak group importance value would increase most following the SWB treatment.
2. Oak stem densities would increase most in the RXF treatment.
3. Site-specific factors, such as greater basal area reductions and lower site index, would be related to greater oak importance values increases.

3.2 Methods

3.2.1 Site Description

The study site was located on the Cold Mountain Game Lands (CMGL) in western North Carolina. This site has steep, mountainous terrain (elevation: 980 m to 1259 m ASL). Site index range was 15.5 to 32.6 m at base age 50. Average regeneration (stems ha^{-1}) across the study site was 15,063. Mid-story and overstory density and basal area pre-treatment are included in Table 2. The CMGL are an upland mixed-oak forest. The mid-story generally consists of blackgum (*Nyssa sylvatica*), red maple (*Acer rubrum*), sourwood (*Oxydendrum arboretum*), and silverbell (*Halesia tetraptera*). Common overstory trees are sugar maple (*A. saccharum),* black cherry (*Prunus serotina*), yellow-poplar (*Liriodendron tulipifera*), northern red oak (*Quercus rubra*), black oak (*Q. velutina*), chestnut oak (*Q. prinus*), scarlet oak (*Q. coccinea*), white oak (*Q. alba*), hickory (*Carya* spp.), and red maple.

3.2.2 Experimental Design

On the CMGL, 16 5-ha units were selected where upland oak was the predominant forest cover type (Figure 1). A completely randomized design was used to randomly assign 4 treatments to the 16 units (4 replications per treatment). Units selected: 1) had no known recent history (< 20 years) of substantial disturbance, 2) had minimal ericaceous shrub cover, 3) were fully stocked, and 4) possessed trees that were greater than 70 years old.

3.2.3 Treatments

The study consisted of four treatments: 1) untreated control (CON), 2) shelterwood (SW), 3) prescribed fire (RXF), and 4) shelterwood and burn (SWB). The treatments SW, RXF, and

SWB were selected because they are commonly utilized to maintain and promote oak regeneration in this region.

For the CON, no silvicultural treatments occurred. The SW was based on guidelines presented in Loftis (1990b): 25-30% basal area removal without reducing the overstory. Garlon 3A was applied in September 2008, prior to leaf-fall, with the hack and squirt method. All non-oak and hickory trees between ≥ 0.5 cm and ≤ 25 cm DBH were marked and targeted for the herbicide treatment.

For the RXF treatment, each unit received two late dormant season burns. The first prescribed burns occurred in February 2009 for two of the replicate RXF units and April 2010 for the remaining two replicate RXF units. The second prescribed burns were conducted in April 2014, April 2014, or March 2015.

The SWB was based on guidelines presented in Brose et al. (1999). An establishment cut that reduced stand basal area by 40-50% was conducted. Oak and hickory species, when possible, were retained during the harvest. A dormant season prescribed burn was then implemented 3-5 years after the initial overstory removal. Units in the SWB were harvested before the growing season in 2010 or 2011 and burned in March of 2015 or 2016.

3.2.4 Data Collection

Six 0.05 ha overstory plots (12.6 m radius) were located within each 5-ha treatment unit (Figure 2). Plots were placed in a 3 m by 2 m array. Three of the 6 overstory plots were randomly selected for data collection. A mid-story plot (5.6 m radius) was concentrically nested within the 0.05 ha overstory plots. Aspect and elevation were measured at each plot center.

Additional topographic variables measured at each plot included landform index (LFI) (McNab 1992) and terrain shape index (TSI) (McNab 1989).

Prior to treatment, all live overstory trees (stems ≥ 25 cm diameter at breast height (DBH)) within each 0.05 ha plot and all mid-story trees (stems ≥ 5 cm DBH and < 25 cm DBH) within the concentrically nested 0.01 ha plot were stem-mapped and tagged, and species and DBH were recorded. Tree status (live/dead) was recorded 9 growing seasons after the initial treatment was completed (i.e., 9 growing seasons after the collection of pre-treatment data in CON; 9 growing seasons after the first of 2 burns in RXF; 9 growing seasons after the harvest in SWB; 9 growing seasons after the herbicide treatment in SW). Stem diameter of all tagged stems was recorded again in 2013, at which time new ingrowth into the mid-story and overstory size classes were recorded.

To quantify edaphic conditions, soil samples were obtained in 2018, post-treatment. Samples were collected at random points located within each 0.05 ha plot from three depths: 0-15 cm, 15-60 cm, and 60-100 cm. Each sample was between 350-400 cm^3. Each depth was collected and bagged separately per plot and allowed to air dry (at 60°C until constant mass was achieved) prior to chemical and physical sampling. Lab analyses focused on exchangeable K, Mg, Na, Ca, and cation exchange capacity (CEC). Texture class and coarse fragment volume were also determined at each depth level per plot.

To quantify treatment effects on woody regeneration, two 0.004 (3.6 m radius) ha subplots were established within each 0.05 ha overstory plot (Figure 2). These subplots were 8 m and 45° and 225° from the plot center and permanently monumented. Species and size-class were recorded for all regeneration prior to treatment and again 9 growing seasons after the initial treatment. Size-classes were: 1) < 0.3 m tall, 2) ≥ 0.3 < 0.6 m tall, 3) ≥ 0.6 < 0.9 m tall, 4) ≥ 0.9 <

1.2 m tall, 5) ≥ 1.2 m tall and < 3.8 cm DBH and 6) ≥ 3.8 < 5 cm DBH (these were tallied and DBH was recorded to the nearest 0.1 cm).

Species were assigned to 1 of 11 species groups: striped maple (*Acer pensylvanica)*, red maple, sugar maple, hickory, yellow-poplar, other mid-tolerant species, the red oak group, other shade intolerant species, other shade tolerant species, and the white oak group. Species and group designations are included in Table 3, and stems densities per species groups are included in Table 4**.**

Absolute biomass (g) was calculated using the one variable aboveground biomass equation found in Daryaei and Sohrabi (2015). Absolute density was the number of stems of a given species per 0.004 ha regeneration subplot. Relative biomass (relative dominance) was the total biomass (g) of given species group divided by total biomass (g) of all species groups on the 0.004 ha regeneration plot, then multiplied by 100. Relative density was the total stems per 0.004 ha of a given species group divided by the total stems on that 0.004 ha regeneration plot, the multiplied by 100. Importance value was calculated as the sum of relative dominance and relative density. Importance value was calculated by species groups (Table 3).

Stems ha^{-1} was calculated for yellow-poplar, red maple, and hickory, and at the species level for all oak: white, black, chestnut, northern red, and scarlet at years 0 and 9 post initial treatment. The 6 original size classes as defined above were combined into 3. New size classes designations to species groups. They were defined as: size class 1 (< 0.6 m tall), size class 2 (≥ 0.6 < 1.2 m tall), or size class 3 (≥ 1.2 m tall and < 5.0 cm DBH). Absolute changes by size class and totals stems from years 0 to 9 post-treatment were recorded.

3.2.5 Statistical Analyses

3.2.5.1 Regeneration Layer

Using JMP® 15.2.1 (SAS Institute Inc, Cary, NC, USA), we used mixed effects analyses of variance (ANOVAs). For regeneration layer importance value analyses, treatment, species group, and the interaction between species group and treatment were included as fixed effects, and regeneration plot was included as a random effect. For density, treatment, species, and the interaction between treatment and species were included as fixed effects, and regeneration plot was included as a random effect. ANOVAs were conducted in the following order: 1) pre-treatment importance value, 2) post-treatment absolute change in importance value, 3) post-treatment relative change in importance value, 4) post-treatment absolute change in total stems ha^{-1}, 5) post-treatment absolute change in stems ha^{-1} of stems < 0.6 m tall, 6) post-treatment absolute change in stems ha^{-1} of stems $\geq 0.6 < 1.2$ m tall, 7) post-treatment absolute change in stems ha^{-1} of stems ≥ 1.2 m tall and < 5 cm DBH. Tests of absolute change in importance value and absolute change in stems ha^{-1} included pre-treatment importance value and pre-treatment stems ha^{-1}, respectively, as covariates (ANCOVA). Post-hoc tests were conducted using Tukey's HSD to test differences among treatments within species groups.

3.2.5.2 Basal Area

Additionally, basal area (m^2 ha^{-1}) pre-treatment and 9 years post-treatment and relative change in basal area (%) over the 9-year period were analyzed using a mixed-effects analysis of variance (ANOVA) for the mid-story, overstory, and total basal area. Treatment was included as a fixed effect and plot as a random effect. ANOVA's were conducted as follows: 1) pre-treatment mid-story basal area (m^2 ha^{-1}), 2) mid-story basal area (m^2 ha^{-1}) 9 years post-treatment, 3) relative change in mid-story basal area (%) over the 9-year period, 4) pre-treatment overstory basal area (m^2 ha^{-1}), 5) overstory basal area (m^2 ha^{-1}) 9 years-post treatment, 6) relative change in overstory basal area (%) 9 years post-treatment, 7) total basal area pre-treatment (m^2 ha^{-1}), 8) total basal area 9 years post-treatment (m^2 ha^{-1}), and 9) relative change in basal area (%) over the 9-year period. For post-treatment values, pre-treatment was included as a covariate (ANCOVA). Post-hoc tests were conducted using Tukey's HSD to test differences among treatments.

3.2.5.3 Principal Component Analysis (PCA)

An abbreviated list of predictor variables from the full suite of 227 predictor variables was selected to investigate *apriori* hypotheses specific to site-quality and competition. Values were recorded by plot for site specific factors: elevation, TSI, LFI, site index, aspect transformation, Ca (ppm), K (ppm), Mg (ppm), NH_4-N (ppm), and NH_3-N (ppm). Site characteristics and the red and white oak groups, red maple, and yellow-poplar changes in importance value at the plot level were included in the PCA. Predictor variables were analyzed with absolute and relative changes in importance value in two separate PCA analyses.

3.3 Results

3.3.1 Regeneration Layer

All metrics resulted in significant interactions between treatment and species group or species: importance value pre-treatment (F = 4.93, $p < 0.05$), absolute change in importance value (F = 6.31, $p < 0.05$), relative change in importance value (F = 5.77, $p < 0.05$), absolute change in total stem density (F = 5.02, $p < 0.05$), absolute change in density of stems < 0.6 m tall (F = 3.62, $p < 0.05$), absolute change in density of stems ≥ 0.6 < 1.2 m tall (F = 2.58, $p < 0.05$), and absolute change in density of stems ≥ 1.2 m and < 5 cm DBH (F = 7.10, $p < 0.05$). The order of results will be as follows the: 1) red oak group, 2) white oak group, 3) hickory, 4) red maple and yellow-poplar group, and 5) other competing species groups.

3.3.1.1 Red Oak Group

3.3.1.1.1 Importance Value

Red oak group importance value was significantly greater in the CON (23.65 ± 4.01) and RXF (19.38 ± 3.95) than the SWB (4.96 ± 3.89) prior to treatment (Figure 3, Table 5). The red oak group absolute change in importance value increased significantly in the SWB (14.87 ± 4.40) and RXF (13.37 ± 4.4) compared with the SW (-2.35 ± 4.34) (Figure 4, Table 6). Relative change in importance value increased significantly in the SWB (1400.56 ± 290.97) compared to the CON (69.86 ± 299.22) and SW (28.04 ± 293.13) (Figure 5, Table 7). Absolute changes were statistically similar between the CON, RXF, and SWB. Relative changes were statistically similar between the CON, SW, and RXF.

3.3.1.1.2 Stem Densities

Prior to treatments, importance value of the red oak group was largely driven by density of stems in the smallest size class (Figure 6). Northern red oak was the only species within the red oak group to have some stems in larger size classes (Figure 6). Northern red oak in the SWB (2308.16 ± 509.52 stems ha^{-1}) had total stem density increases greater than the RXF (606.63 ± 530.44 stems ha^{-1}) and the SW (-150.36 ± 508.48 stems ha^{-1}) (Figure 7, Table 8). Total stem density increases were four times greater in the SWB than the RXF. Scarlet oak stem densities varied in response among treatments, although differences were not significant. Black oak experienced little changes across all treatments.

Changes in red oak group stem densities were influenced most by changes in stems < 0.6 m tall (Figures 6 and 9). Driving those changes was northern red oak. Northern red oak stem densities significantly differed among treatments in stems < 0.6 m tall and stems ≥ 1.2 m tall and < 5 cm DBH (Figure 8; Tables 9, 10, and 11). Increases in northern red oak stems < 0.6 m tall in the SWB (1841.14 ± 467.37 stems ha^{-1}) were significantly greater than the SW (-209.14 ± 467.99 stems ha), and the SW was the only treatment to experience decreases. Northern red oak stems ≥ 1.2 m tall and < 5 cm DBH in the SWB (221.24 ± 49.84 stems ha^{-1}) were significantly greater than all other treatments. Resulting stem densities 9 years post-treatment were greatest for northern red oak in the SWB. Most stems were in < 0.6 m tall, although some stems were in larger size classes (Figure 9).

3.3.1.2 White Oak Group

3.3.1.2.1 Importance Value

The white oak group were significantly greater in the CON (24.42 ± 4.42) than the SW (3.36 ± 4.23) prior to treatments (Figure 3, Table 5). Neither absolute or relative changes in importance value differed significantly among treatments (Figure 4; Tables 6 and 7).

3.3.1.2.2 Stem Densities

The RXF treatment (274.88 ± 191.14 stems ha^{-1}) saw chestnut oak total stem density increase significantly greater than the CON (-540.23 ± 201.14 stems ha^{-1}), although increases were only 275 stems ha^{-1}. White oak total stem density changes were minimal among treatments (Figure 7, Table 8).

Significant changes in total chestnut oak stems were largely driven by stems < 0.6 m tall (Figure 8; Tables 9, 10, and 11). Stems < 0.6 m tall saw significant differences among treatments for chestnut oak. For chestnut oak stems < 0.6 m tall, increases were greatest in the RXF (246.74 ± 172.22 stems ha^{-1}) and were significantly greater than the CON (-536.9 ± 181.84 stems ha^{-1}). Resulting stem densities 9 years post-treatment were low for white oak among treatments, and for chestnut oak, they were greatest in the control (Figure 9)

3.3.1.3 Hickory

3.3.1.3.1 Importance Value

Prior to treatments, importance value for hickory did not differ (Figure 3, Table 5). Additionally, absolute and relative change in importance value did not differ among treatments (Figures 3 and 4; Tables 6 and 7).

3.3.1.3.2 Stem Density

Overall change in stem density did not differ by treatment, but it did differ for stems < 0.6 m tall and ≥ 1.2 m tall and < 5 cm DBH (Figure 7, Table 8). For stems < 0.6 m tall, hickory increases were greater in the RXF (515.79 ± 197.90 stems ha^{-1}) than the SWB (-283.25 ± 192.79 stems ha^{-1}). Hickory density increases were greater in the SWB (187.5 ± 37.47 stems ha^{-1}) than all other treatments for stems ≥ 1.2 m tall and < 5 cm DBH (Figure 8; Tables 8, 9, 10, and 11). Hickory densities 9 years post-treatment were greatest in the RXF treatment (Figure 9).

3.3.1.4 Major Oak Competitors: Red Maple and Yellow-Poplar

3.3.1.4.1 Importance Value

Prior to treatments, red maple importance values differed significantly among treatments and yellow-poplar did not (Figure 3, Table 5). Red maple had significantly lower importance values in the SW (15.28 ± 5.56) than RXF treatment (38.23 ± 5.56). Yellow-poplar importance values were low across all units prior to treatment.

Post-treatment, red maple's absolute changes in importance value differed significantly between treatments, while relative values did not (Figures 4 and 5; Tables 6 and 7). Red maple absolute change in importance value decreased significantly in the SWB (-8.67 ± 3.54) compared to the CON (9.59 ± 3.62), and the SWB was the only treatment to reduce the importance value of red maple 9 years later. Both absolute and relative change in importance value of yellow-poplar differed by treatment (Figures 4 and 5; Tables 6 and 7). Absolute increases of yellow-poplar in the SWB (32.91 ± 4.94) were significantly greater than all other treatments, and were around 32 times greater than the RXF treatment (1.28 ± 4.92). The RXF treatment had the lowest increases in absolute and relative changes in importance value of yellow-poplar. Additionally, relative changes in yellow-poplar were greatest in the SWB (2954.51 ± 464.93) and significantly greater than the CON (256.01 ± 464.93), SW (593.65 ± 464.93), and RXF (102.01 ± 464.93).

3.3.1.4.2 Stem Densities

Red maple did not have significantly different changes in total stems ha^{-1} by treatment, but yellow-poplar did have significant differences (Figures 7, Table 8). Increases in yellow-poplar in the SWB (2756.33 ± 373.97 stems ha^{-1}) were significantly greater than all other treatments, and increases were statistically similar among SW (557.33 ± 376.40 stems ha^{-1}), the RXF (78.11± 373.15 stems ha^{-1}), and the CON (97.81 ± 378.40 stems ha^{-1}).

Red maple significantly differed by treatment in stems < 0.6 m tall only, and yellow-poplar significantly differed in stems < 0.6 m tall, ≥ 0.6 < 1.2 m tall, and ≥1.2 m tall and < 5 cm DBH (Figure 8; Tables 9, 10, and 11). Red maple stem density in the SWB (-498.13 ± 423.13 stems ha^{-1}) was significantly less than the RXF (1349.05 ± 423.13 stems ha^{-1}) for stems < 0.6 m tall. Yellow-poplar density increases for stems < 0.6 m tall, ≥ 0.6 < 1.2 m tall, and ≥ 1.2 m tall and < 5 cm DBH were significantly greater in the SWB (1347.69 ± 204.62 stems ha^{-1}, 402.67 ± 83.83 stems ha^{-1}, 995.82,± 157.36 stems ha^{-1}, respectively) than all other treatments. Red maple stem densities 9 years post-treatment remained high across all treatments. Densities of red maple were greatest in the RXF treatments (Figure 9). Post-treatment, of all species, yellow-poplar in the SWB had the greatest density of stems ≥ 1.2 m tall and < 5 cm DBH.

3.3.1.5 Other Competing Species Groups

3.3.1.5.1 Importance Value

Importance value pre-treatment significantly differed by treatment for sugar maple, white ash, striped maple, and other shade tolerant species (Figure 3, Table 5). Striped maple importance value was significantly less in the CON (5.02 ± 6.78) than the RXF (30.73 ± 6.69) treatment. Sugar maple importance value was greater in the SWB (40.18 ± 7.64) than the RXF (6.80 ± 7.88) and CON (6.40 ± 8.10). White ash importance value was greater in the SWB (54.60±6.72) than other treatments. Other shade tolerant species were significantly lower in the SWB (5.90 ± 5.69) than all other treatments.

Shade intolerant species generally responding more positively to the canopy manipulations in the SWB while shade tolerant species responded more positively to the CON and RXF, where canopies remained largely intact. Absolute change in importance value was significantly different among treatments for striped maple, sugar maple, white ash, and other shade intolerant species (Figure 4, Table 6). The SWB decreased striped maple (-18.87 ± 3.68) greater than all other treatments. Sugar maple decreased significantly in the SWB (-16.83 ± 3.53) compared to the RXF (-2.97 ± 3.46) and the SW (-1.91 ± 3.39). The importance value increases of white ash were significantly greater in the SW (4.25 ± 3.61) than the RXF (-11.89 ± 3.76) and SWB (-12.19 ± 3.89). Additionally, all other shade intolerant species importance values decreased in all other treatments besides the SWB, and the increases in the SWB were significantly greater (19.85 ± 4.53). The other shade intolerant species group was the only group to result in as significant change in relative importance value among treatments (Figure 5, Table 7). The relative change in importance values of all other shade intolerant species was greater in the SWB (380.81 ± 78.69) treatment than all other treatments.

3.3.2 Basal Area

3.3.2.1 Mid-story

Pre-treatment mid-story basal area did not differ by treatment (F = 1.11, p = 0.36) (Table 12). For post-treatment mid-story basal area treatment was significant (F = 10.35, p < 0.05). Tukey's post-hoc revealed the CON (5.9) and RXF (4.7) were similar, and the OSW (1.5) and the SWB (1.50) were similar. Treatment was significant for relative change in mid-story basal area (F = 17.86, p < 0.05). The CON (-16.4) and the RXF (-28.9) were similar, and the SW (-74.6) and the SWB (-86.9) were similar.

3.3.2.2 Overstory

Pre-treatment overstory basal area did not differ by treatment (F = 0.27, p = 0.85) (Table 11). Post-treatment basal area differed by treatment (F = 84.41, p < 0.05), and Tukey's post-hoc test revealed the SWB (5.7) had significantly lower basal areas than the CON (27.0), SW (28.8), and the RXF (29.3). Treatment was significant for relative change in basal area (119.26, p<0.05), and Tukey's post-hoc test revealed the relative change in basal area for the SWB (-76.2) was less than the CON (-2.7), the SW (-1.8), and the RXF (2.3).

3.3.2.3 Total

Total basal area pre-treatment did not differ by treatment (F = 0.38, p = 0.77) (Table 12). Post-treatment basal area significantly differed by treatment (F = 63.05, p < 0.05). Tukey's post-hoc revealed the SWB (7.9) had significantly less basal area than the CON (32.9), the SW (30.6), and the RXF (33.6). Relative change in basal area significantly differed by treatment (F = 77.67, p < 0.05). The SWB (-77.8) was significantly less than the CON (-3.8), SW (-14.2), and the RXF (-5.7).

3.3.3 Principal Component Analysis

PCA of absolute change in importance value resulted in some distinct groupings. The two components accounted for 35.8% of the variability in the data (Figure 10). Absolute change in the importance value of the red oak group was closely related to elevation, NH_4-N (ppm), and P (ppm) (Figure 10). These groups were related to the SWB (Figure 10). Changes in the absolute importance value of the white oak group were most closely associated with site index, Ca (ppm), and the absolute change in importance value of yellow-poplar. Additionally, K (ppm), NO_3-N (ppm), and Mg (ppm) were closely associated, and most related to the SW treatment.

The components of the relative change in importance value PCA accounted for 35.3% of the variability (Figure 11). Elevation, NH_4-N (ppm), P (ppm), and relative change in importance value of the red oak group were closely associated. These groups were related to the RXF and SWB treatments (Figure 11.). Site index, red maple relative change in importance value, and yellow-poplar relative change in importance value were related. Also, K (ppm) and Mg (ppm) were closely associated. Aspect transformation, LFI, and TSI were related. Relative change in white oak importance value appeared unrelated to other predictors.

3.4 Discussion

Overall, the treatments elicited different responses among species groups. These responses are largely based on shade tolerance and the degree of treatment intensity. The SWB caused the greatest reductions in overall basal area (87.9 m^2 ha^{-1}), while the CON caused the least (16.4 m^2 ha^{-1}). Reductions in basal area in the SWB were driven by overstory and mid-story reductions, while the RXF and SW saw minimal overstory reductions. Shade tolerant species groups decreased the most and shade intolerant species groups increased the most in the SWB. We can infer this treatment caused the most overall changes in the light environment due to greatest basal area reductions and considering shade intolerant species proliferation was greatest under this treatment while shade tolerant species presence was decreased. All mid-tolerant species groups, except the red oak group, responded negatively to the SWB, showing the red oak group responds differently to increased light levels than the other mid-tolerant species groups. This is consistent with findings in Brose et al. (2011) where northern red oak increased with increasing treatment intensity and light availability. The CON, SW, and RXF resulted in less changes in importance value across all shade tolerance levels, although the RXF did show some evidence of promoting the red oak group, while minimizing increases in red maple and yellow-poplar relative to the SW and CON.

The red and the white oak groups responded differently to the treatments. Although the red oak group responded positively in changes in importance value to two treatments (RXF and SWB), the white oak group did not respond positively in absolute change in importance value to any of the treatments. This is similar to results of Albrecht & McCarthy (2006), a study comparing the effects of fire, thinning, and their combination. In both our study and theirs, white oak decreased across all treatments, including the CON, but species in the red oak group responded positively to some treatments. However, in our study, decreases in absolute importance value of the white oak group were least in the SW, and the red oak group increased the most in the SWB, followed by the RXF. Unlike the results found in Albrecht and McCarthy (2006), however, increases in the red oak group in our study were primarily driven by northern red oak, not black oak.

The white oak group may be more sensitive to extremes in disturbance intensity, and have a narrower window for regeneration success. Brose et al. (2011) found small increases in light (from 4%-14%) greatly improved white and chestnut oak survival. Additionally, Dillaway et al. (2007) compared the response of white oak to different light intensities in a clear-cut, mid-story removal, and control. They determined white oak responded best to moderate increases in light. Considering overall basal area was reduced by 14.2% over the 9-year period in the SW, and the white oak saw the greatest relative increases in importance value in the SW, potentially increased basal area reductions would increase white oak success. In Brose (2008), northern red oak was more responsive to increases in light levels, while white and chestnut oak maximum growth occurred at mid-range light levels. The herbicide treatment in the SW may not have adequately increased understory light levels to allow for white oak group success, but the SWB, conversely, may have increased light levels too dramatically. Oak growth is best at light levels between 30-50%, and little growth occurs at levels less than 15% of full sunlight (Brose 2008, Dey et al. 2008, 2012). However, this study suggests the response of oak to changes in light is species-specific.

Absolute decreases in importance value were great for the white oak group in the RXF and SWB, while the red oak group experienced large increases in those treatments. This could be related to the slower growth of white oak or the more rapid response of red oak to changes in light conditions. Alexander et al. (2008) found survival was greater for the red oak group (black, northern red, and scarlet oaks) than the white oak group (white, chestnut, and chinkapin (*Quercus muehlenbergii*) oaks) in stands burned three times in the spring in Kentucky, although, the white oaks were much smaller than red oaks prior to treatments. The red oak group was taller in burned stands than unburned stands, particularly in areas where greater basal area reductions and fire intensities occurred. Rebbeck et al. (2011) studied the response of white, chestnut, and northern red oaks to light availability. Among all species, white oak had the slowest growth. Both our study and these studies indicate the red oak group responds more readily to disturbance than the white oak group, and white most likely was smaller and more susceptible to fire damage than the red oak group, prior to treatment installation.

The timing of the burn or the timing of the acorn maturation may have also negatively impacted white oak group survival. Acorns in the litter and small oak seedlings are susceptible to fire-induced mortality (Greenburg et al. 2012, Johnson et al. 2019). Korstian (1927) found that white oak acorns are more susceptible to fire-induced mortality than red oak acorns due to differing times in acorn production. Additionally, acorns in the white oak group are considered more palatable to wildlife species than acorns in the red oak group due to higher tannin content found in red oak group acorns, potentially leading to fewer acorns across sites (Kirkpatrick and Pekins 2002). These are important considerations when applying treatments.

The red oak group increased in absolute importance value in the RXF and SWB to similar amounts, but the relative change in importance value in the red oak group revealed it increased around three times more in the SWB than the RXF. Also, absolute increases in importance value of the red oak group were similar in RXF and CON. Red maple stems ha^{-1} increased the most following the RXF treatment, but this increase was largely driven by increases in stems < 0.6 m tall. Considering the significantly greater relative increases in the SWB, this treatment appeared more effective than the RXF treatment at increasing the red oak group importance value. On the other hand, there may be value in considering the response of red oaks to the RXF. The RXF treatment had better control over yellow-poplar competition. Unexpectedly, absolute and relative changes in importance value did not show the same results for red maple. The RXF treatment saw the lowest increases in red maple relative importance value when compared with the CON and SW. Fire may provide promise for improving the red oak group's competitive status on these sites while minimizing competition from oak's two major competitors, red maple and yellow-poplar.

Interestingly, the red oak group increased in importance value in the CON treatment, while the white oak group did not. This is similar to results in Brose et al. (2011), where survival of northern red oak was greater than white, chestnut, and black oaks in uncut stands. Additionally, Dillaway et al. (2007) found older white oak seedlings growing under closed canopies had lower root non-structural carbohydrates than younger seedlings. In our study, white oak growing in a suppressed position may not have possessed the ability to respond to increased light with treatments. In long-unburned stands, the red oak group may potentially be in a better competitive position than the white oak group prior to disturbance due to its ability to improve its status under limited light levels, regardless of treatment. Understanding the differing shade tolerance levels of oak species can help guide management decisions to favor certain oak species, and most likely one treatment will not benefit both the red oak group and the white oak group. More intermediate treatments and active management may be needed if specific management goals include the white oak group and, more specifically, white oak.

Adequate stocking and size of advance oak regeneration prior to overstory removal is important for oak success (Dey et al. 2010). Considering the large stem density and importance value increases of the red oak group in the SWB, this treatment has the potential to increase the red oak group to meet stocking goals. Additionally, this treatment was able to reduce the competition of shade tolerant species groups, including red maple.

Although increases in red oak group importance value were substantial in the SWB, yellow-poplar increased two times more than the red oak group in relative importance value. Prior to treatment, importance values were near-zero for yellow-poplar, but the combination of the burn and subsequent increased light levels created conditions suitable for yellow-poplar proliferation (Shearin 1972). Yellow-poplar is a prolific seeder, and its seeds remain viable in the seedbank for 4-7 years. Its seeds quickly germinate and grow in response to increased light conditions (Burns and Honkala 1990). Similar to our results, Dey et al. (2009) found yellow-poplar limited red oak success over time in response to treatments with overstory removal and basal area reductions. Oakman et al. (2019) also found greater oak increases and intense yellow-poplar competition in response to a combination of mechanical removal and fire. Follow-up treatments may be necessary to address yellow-poplar competition. Fire or herbicides could be potential solutions. Because yellow-poplar has fast initial growth when young (Burns & Honkala, 1990), yellow-poplar is subject to fire-induced mortality, but it quickly develops thick enough bark to withstand fire as a mature tree (Smith & Sutherland 1999). Considering the response of yellow-poplar, addressing it with follow-up treatments such as herbicide, mechanical removal, or fire following a SWB will likely be essential to promote oak in these systems (Brose et al. 2013). If using fire as a follow-up treatment, it will be important for it to occur early in yellow-poplar's development.

Changes in stems ha^{-1} were largely influenced by changes in stems < 0.6 m tall. Treatments had the greatest impact on smaller seedlings, and minimal impact on larger seedlings. Yellow-poplar was the only species to see significant changes in stems ≥ 0.6 < 1.2 m tall and stems ≥ 1.2 m tall and < 5 cm DBH, and these changes occurred only in the SWB. Considering the relatively small importance value of yellow-poplar prior to treatments, we can infer yellow-poplar is able to grow quickly and occupy space in response to light increases. If managing for oak when mature, seed-bearing yellow-poplar are or have been present recently, addressing yellow-poplar in a timely manner will be important.

Red oak group changes in the SWB were largely driven by increases in northern red oak density. Northern red and scarlet oak increased similarly in the CON and RXF treatments.

Northern red oak stem densities increased to greater quantities than yellow-poplar in stems < 0.6 m tall in the SWB, but the importance value of yellow-poplar increased more than the importance value of the red oak group. Yellow-poplar importance value increases were influenced by increases in larger size classes. The RXF treatment stimulated the growth of red maple stems < 0.6 m tall. Additionally, yellow-poplar stems < 0.6 m tall increased the least in the RXF treatment. Brose et al. (2010) found single, medium to high intensity burns were sufficient to suppress competition from yellow-poplar and red maple in the piedmont of Virginia, while oak and hickory compositions were maintained on sites receiving medium to high intensity burns in the spring and summer. The results of these studies and ours show additional prescribed fires could: 1) decrease the red maple component, and 2) continue to suppress potential yellow-poplar competition, while allowing oak numbers to increase.

Grouping of oaks into the red and white oak groups, as is commonly done, may have obfuscated results. Our results suggest, the response of black oak, although in the red oak group, responded more similarly to species in the white oak group (white and chestnut oaks). Brose & Rebbeck (2017), after studying the response of acorn-origin oak seedlings in Pennsylvania to different light environments, grouped oak species into two categories based on their response to light changes: 1) chestnut and northern red oak and 2) white and black oak. These differences among species are not necessarily reflected in the analysis of importance value by white and red oak groups and thus warranted species-specific analyses.

In general, for other competing species, the SWB benefitted the shade intolerant species greatest, but was the only treatment to decrease all shade tolerant species. Shade tolerant species responded positively to the RXF and CON treatments, suggesting that maintaining an intact canopy benefits these species. In the last several decades, mesophytic species have negatively affected oak regeneration success (Arthur 2012). Using treatments that negatively affect shade tolerant species, such as the SWB, could be valuable for land managers whose objectives including decreasing oak's shade tolerant competitors. On the other hand, although the SWB decreases competition from shade tolerant species, shade intolerant species responded positively. Follow-up treatments will be needed to address these species for oak's competitive status to be improved long-term.

Hickory, like oak, has ecological value. Hickory provides valuable food sources for wildlife species due to its mast production (Fralish 2004). Additionally, hickory is well-adapted to drought (Burns & Honkala 1990). In the face of future climate change, with potential changes in weather patterns expected, these species may provide valuable, forest resilience contributions. Hickory is a common oak associate, and, like oak, is fire-adapted (Eyre 1980, Fralish 2004). With decreases of fire, hickory is seeing similar regeneration problems (Pierce et al. 2006). Choosing treatments that benefit oak and hickory may be of interest to land managers. Similar to northern red oak, hickory stem density ≥ 1.2 m tall and < 5 cm DBH increased, but hickory density increases were greatest in the RXF for stems ≥ 0.6 < 1.2 m tall. The SWB treatment may be a viable option to increase larger stem density on sites with larger hickory seedlings present. Considering the increases in density of stems ≥ 0.6 < 1.2 m tall in the RXF treatment, sites with overstory hickory but little hickory regeneration, may benefit from the prescribed fire treatment.

Many different site factors interact to determine oak success (Dey et al. 2009, Kabrick et al. 2008, Loftis 1990). Sites in the southern Appalachian Mountains contain many microsite differences which lead to variable treatments intensities and inconsistent results within and among stands. The PCA showed the absolute change in importance value in the red oak group regeneration layer varied closely with elevation and NH_4-N (ppm). The multivariate analyses suggest sites higher in elevation (in this study, elevation range was 980-1259 m) are associated with the red oak group. The white oak group was less associated with physical site characteristics, such as elevation or terrain shape index, but white oak was closely associated with site index and absolute change in yellow-poplar. This suggests white oak was more commonly found on higher quality sites, and it could potentially explain the minimal response of the white oak group because oak on higher quality sites probably experienced more intense competition. Absolute change in importance value of red maple had no association with site characteristics, and this is consistent with the findings of Abrams (1998) that red maple is a "super-generalist" and can do moderately well on a wide variety of site conditions. This species will likely continue to be problematic across oak-dominated sites in the southern Appalachian Mountains.

Other site-specific factors impacting regeneration layer response are mid-story and overstory changes produced by treatments. Examination of relative change in basal area of the mid-story and overstory over 9 years revealed the SWB generated significant decreases in overstory basal area, while other treatment impacts on the overstory were minimal. Mid-story decreases were similar between the SW and SWB, and decreases were greater than decreases in the CON and RXF treatments. Considering the changes in the SWB and the changes in importance value that occurred for the red oak group in this treatment, overstory manipulation in combination with mid-story reductions can improve the competitive status of the red oak group on sites in the southern Appalachian Mountains, greater than mid-story manipulation alone.

For the SWB, targeted basal area reduction for the initial overstory harvest was 30-50%. Fire was then implemented 3-5 years after the initial overstory removal. The 78% reduction in overstory basal area in the SWB exceeded that threshold 9 years post-treatment. Additionally, the mid-story basal area reductions in the SWB were 87.9%. We can suspect that fire was the main contributor to these additional basal area reductions. This most likely drastically increased the light environment, encouraging the red oak group response, but also allowing yellow-poplar to proliferate. Loftis (1990) suggests reductions in basal area should decrease with increasing site quality because, similar to our study, greater reductions in basal area on high quality sites resulted in yellow-poplar establishment. Potentially greater overstory basal area retention in our study could deter yellow-poplar growth and establishment, while still benefitting oak.

In the SW, increased basal area reductions may have possibly improved the response of the white oak group to the SW treatment. Relative increase in importance value of the white group was greatest in the SW treatment. Total basal area reductions in the SW were 14.2% over the 9-year period. Objectives of this treatment suggest 25-30% initial reductions. Although reductions may have been greater when evaluated closer to the time of herbicide application, it appears those reductions are diminishing. Rebbeck et al. (2011) found the greatest white oak diameter increases occurred at 18% full sunlight compared with 6% and 25%. Moderate increases in mid-story basal area reductions in the SW could potentially increase light levels for a longer period of time, and encourage a greater white oak group response to this treatment.

One potential influence on the results could be the size of the oak regeneration prior to treatments. Oak seedlings could have been very small in size. The sites selected for this study were fully stocked, closed canopy, and had experienced minimal prior disturbance. Our analysis of density by size class revealed most stems of all species were in the smallest size class (< 0.6 m tall) pre-treatment. Small oak seedlings could have been more susceptible to fire-induced mortality due to inadequate root development (Johnson et al. 2019). Alexander et al. (2008) showed sprouting capability and fire resilience are positively correlated. To take advantage of their fire adaptations, burning must be delayed until oaks reach adequate size. Sander (1972) suggests that it can take 20-30 years to develop adequate oak regeneration in previously undisturbed stands. Potentially, a longer, active management period to increase the presence of advance oak regeneration would be better to insure oak success after overstory removal.

Additionally, treatments utilizing fire potentially did not have uniform effects. This may have led to variability in fire's ability to select against mesophytic species and favor oaks across treatments. In a study looking at the impacts of thinning and burning, Iverson et al. (2008) found oak response differed across sites due to a lack of uniformity in terrain and fire intensity. The southern Appalachian Mountains contain considerable microsite differences and fire effects are seldom uniform in intensity and severity. Brose (2010) found that increases in oak dominance increased with burn severity. Additionally, hot burns in late spring were closely associated with oak increases and red maple and yellow-poplar decreases (Brose et al. 1999, Brose & Van Lear 1998). Increased fire intensity has value for oak. Adjusting the timing of fire could have created more intense fires, yielding different results for oak and oak's competitors, even across differing site conditions (Brose et al. 2014).

Similar to the results of our study, Brose et al. (1999) found yellow-poplar competition inhibited oak growth following a shelterwood and burn, but their results suggest season of burn interacts with intensity to favor either oak or yellow-poplar. In low intensity, dormant season burns, yellow-poplar had greater density and stocking than oak. Conversely, in medium- to high-intensity burns during the growing season, yellow-poplar was scarce, and free to grow oaks were abundant. In our study, some oak species increased in number and size in response to a SWB that included a late dormant burn. This suggests, in our SWB treatment, additional treatments such as herbicide or fire will be needed to address yellow-poplar in order for oak to successfully ascend into the mid-story and, eventually, the overstory.

In conclusion, although we saw decreases from some competing species in treatments, additional measures need to be taken to ensure oaks successfully transition into the mid-story. Yellow-poplar and red maple competition consistently inhibit oak regeneration success and were commonly a factor in all treatments. Due to the current conditions of our oak forests, improving the status of regeneration layer oak amid competition is a long-term and intensive process. Fire alone or in combination with a shelterwood harvest appeared to benefit oak in the regeneration layer at the expense of many competitors. Furthermore, oak species respond differently to treatments, and improving the competitive status of white oak may be more difficult than other oak species. Modification of the SW, RXF, or SWB could have yielded different, and potentially better, results for both the red oak and white oak group.

3.5 Conclusion

We studied the impacts of prescribed fire and shelterwood cuttings on species compositional dynamics of oak and oak competitors in the southern Appalachian Mountains. Species responded differently to treatments. The SWB increased the competitiveness of the red oak group, but it also elicited greater yellow-poplar importance value increases. On the other hand, the SWB decreased competition from all shade tolerant species groups, and was the only treatment to decrease red maple importance value. For the red oak group to be successful long-term in the SWB, yellow-poplar will require control prior to and likely after overstory removal. On the other hand, red maple and yellow-poplar increased the least in the RXF treatment. Although the red oak group increases in the RXF were not as great as the SWB, it may be a viable treatment option for improving oak competitiveness, especially if an additional burn is added or higher intensity fires are utilized. Fires conducted frequently years prior to a SWB treatment may also generate more positive outcomes for oak post-overstory removal. To conclude, the RXF and SWB treatment in this study improved oak competitive status, but modifications to these treatments may be needed to ensure long term oak success.

All oak species do not respond similarly to treatments. With our study, although northern red oak stem density increased in the SWB, white oak stem density changes did not differ among treatments. Red oak has better survival under low light levels and responds more readily to catastrophic disturbance than white oak (Abrams 2003). More research will be needed to determine treatments that will benefit the white oak species.

Considering the results of our study and other similar studies, intermediate treatments involving mid-story removal via prescribed fire, mechanical, or herbicide treatments, in combination with moderate canopy disturbance via partial harvesting, are likely to improve the status of oak amid competition. Canopy reductions should decrease with increasing site quality, and, depending on oak regeneration status and competition, intermediate treatments may be needed pre- and post-overstory removal for oak to successfully ascend into the canopy. Slight alterations to the SW, such as additional canopy manipulations, in addition to mid-story control, may potentially improve white oak response.

The process of achieving adequate size and density of oak regeneration prior to overstory removal is an intensive and long-term process that should begin during the initiation or stem exclusion stage of stand development and continue through stand regeneration. With the complexity of species dynamics across oak’s range, especially in the southern Appalachian Mountains, close monitoring and subsequent treatment adjustments must be made to ensure oak success throughout stand rotation.

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3.7 Figures

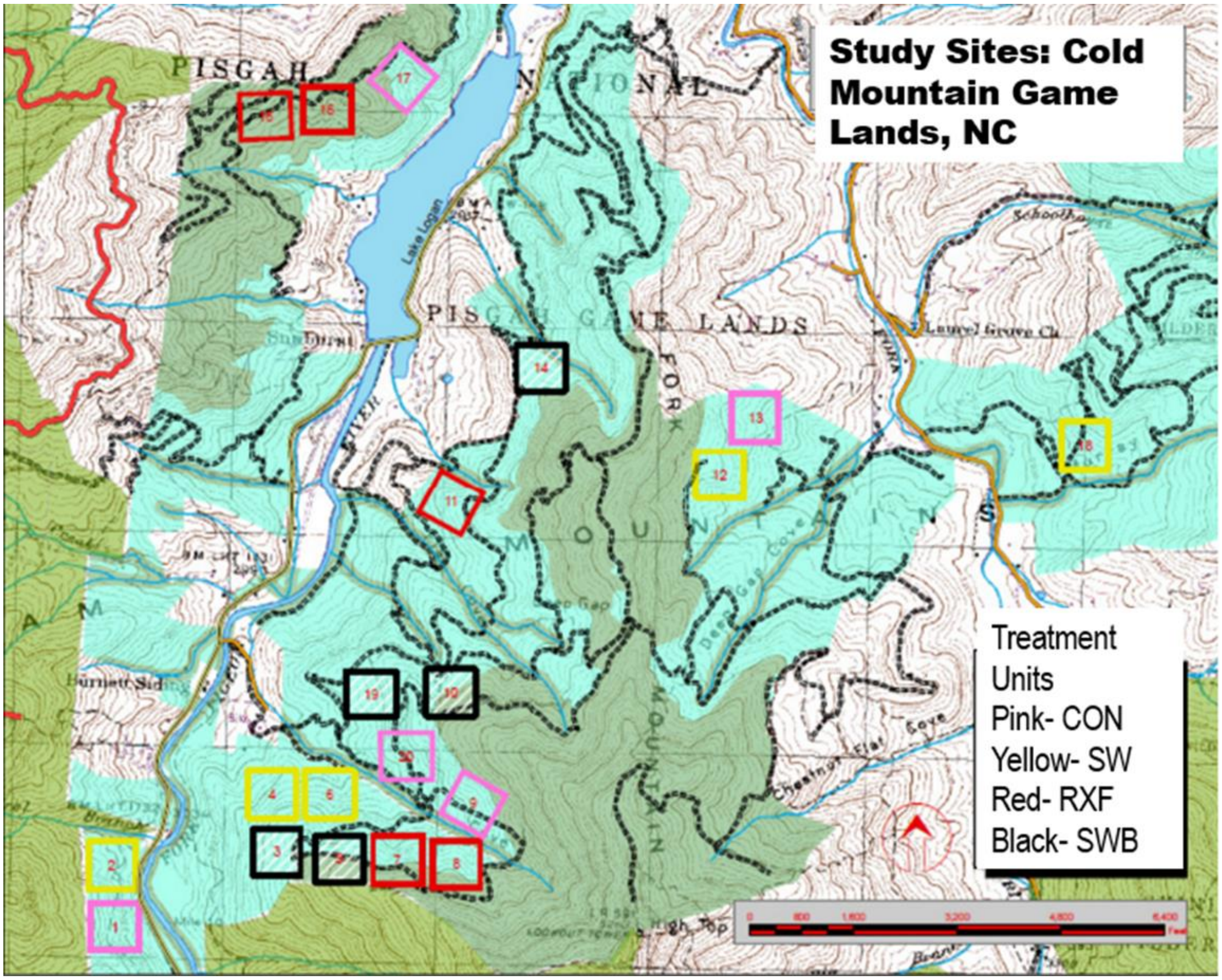

Figure 1. Treatment units (5 ha) located on sites in Cold Mountain Game Lands, Haywood County, NC, USA. Units are numbered 1-20. Units 1, 2, 8, and 19 were not included in the study. CON = control, SW = shelterwood, RXF = prescribed fire, and SWB = shelterwood and burn.

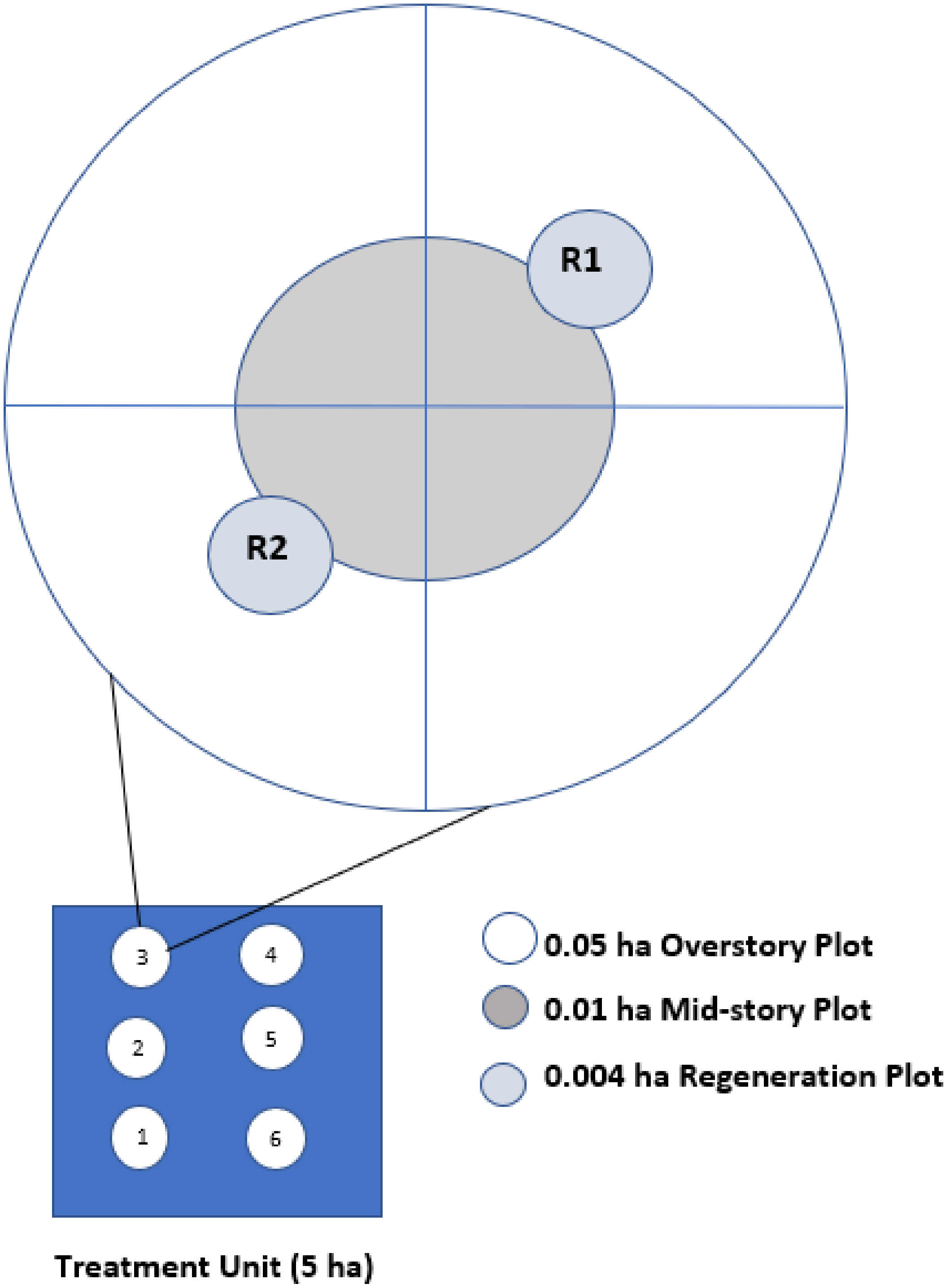

Figure 2. Diagram of treatment unit (0.05 ha), overstory plot (0.05 ha), nested mid-story plot (0.01 ha), and nested tree regeneration plot (0.004 ha) located on sites in Cold Mountain Game Lands, Haywood County, NC, USA.

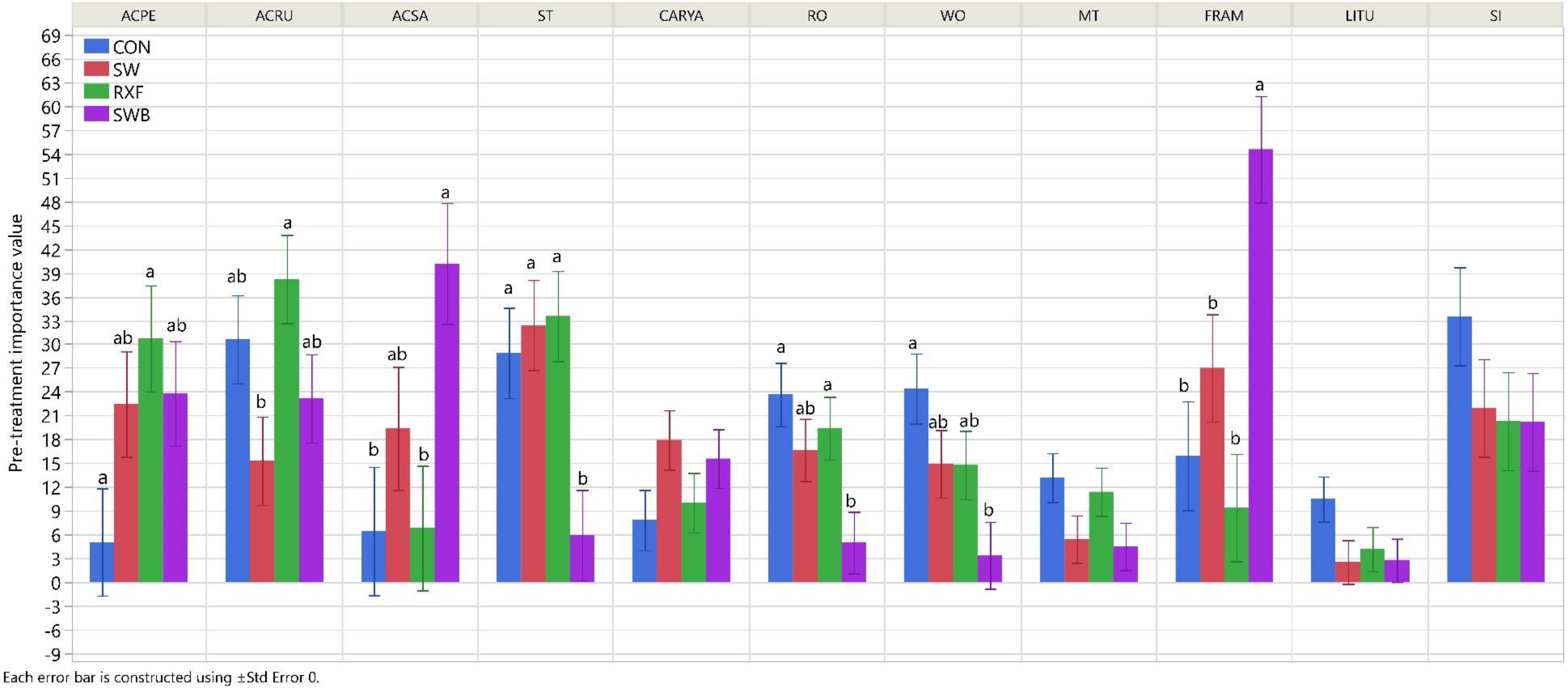

Figure 3. Pre-treatment importance value (± LS mean standard) by species group, striped maple(ACPE), red maple(ACRU), sugar maple (ACSA), other shade tolerant species (ST), hickory (CARYA), red oak group (RO), white oak group (WO), other mid tolerant groups (MT), white ash (FRAM), yellow-poplar (LITU)**,** and other shade intolerant species (SI), and treatment, control (CON), shelterwood (SW), prescribed fire (RXF), and shelterwood and burn (SWB) on sites in Cold Mountain Game Lands, Haywood County, NC, USA. Tukey's HSD differences are within species group and are noted by letter distinctions.

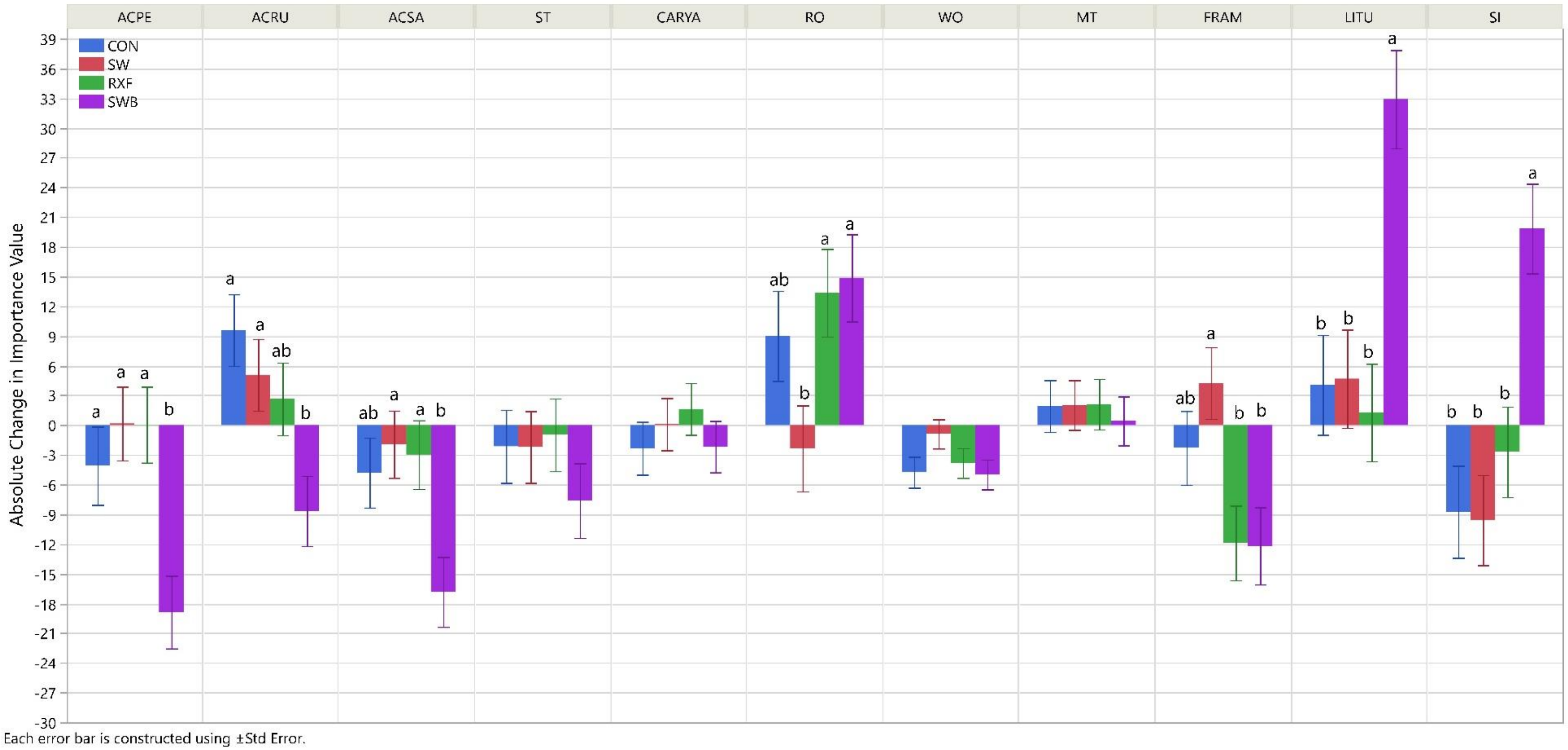

Figure 4. Absolute change in importance value (± LS mean standard) by species group, striped maple(ACPE), red maple(ACRU), sugar maple (ACSA), other shade tolerant species (ST), hickory (CARYA), red oak group (RO), white oak group (WO), other mid tolerant groups (MT), white ash (FRAM), yellow-poplar (LITU)**,** and other shade intolerant species (SI), and treatment, control (CON), shelterwood (SW), prescribed fire (RXF), and shelterwood and burn (SWB) on sites in Cold Mountain Game Lands, Haywood County, NC, USA. Tukey's HSD differences are within species group and are noted by letter distinctions.

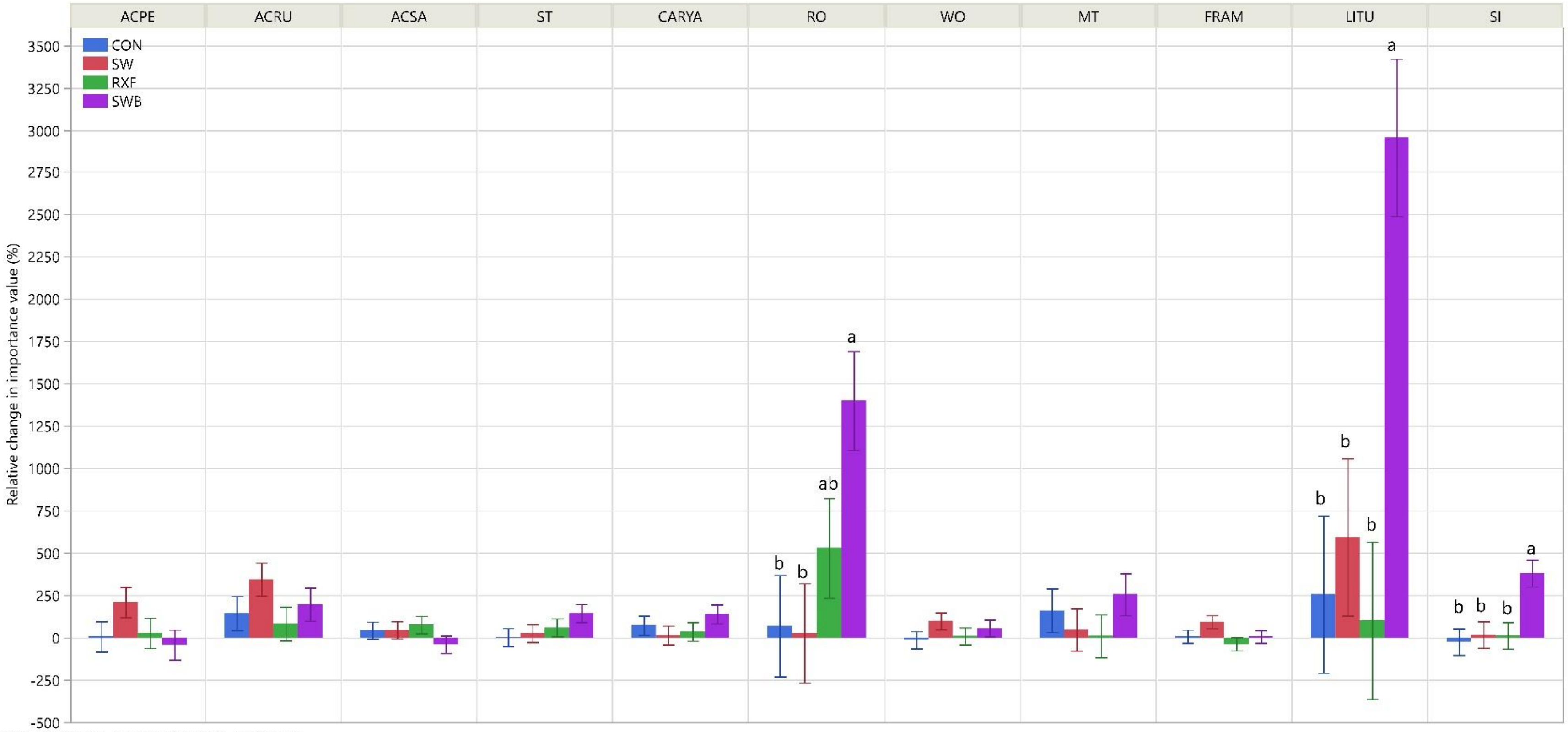

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Figure 5. Relative change in importance value (%) (± LS mean standard) by species group, striped maple(ACPE), red maple(ACRU), sugar maple (ACSA), other shade tolerant species (ST), hickory (CARYA), red oak group (RO), white oak group (WO), other mid tolerant groups (MT), white ash (FRAM), yellow-poplar (LITU), and other shade intolerant species (SI), and treatment, control (CON), shelterwood (SW), prescribed fire (RXF), and shelterwood and burn (SWB) on sites in Cold Mountain Game Lands, Haywood County, NC, USA. Tukey's HSD differences are within species group and are noted by letter distinctions.

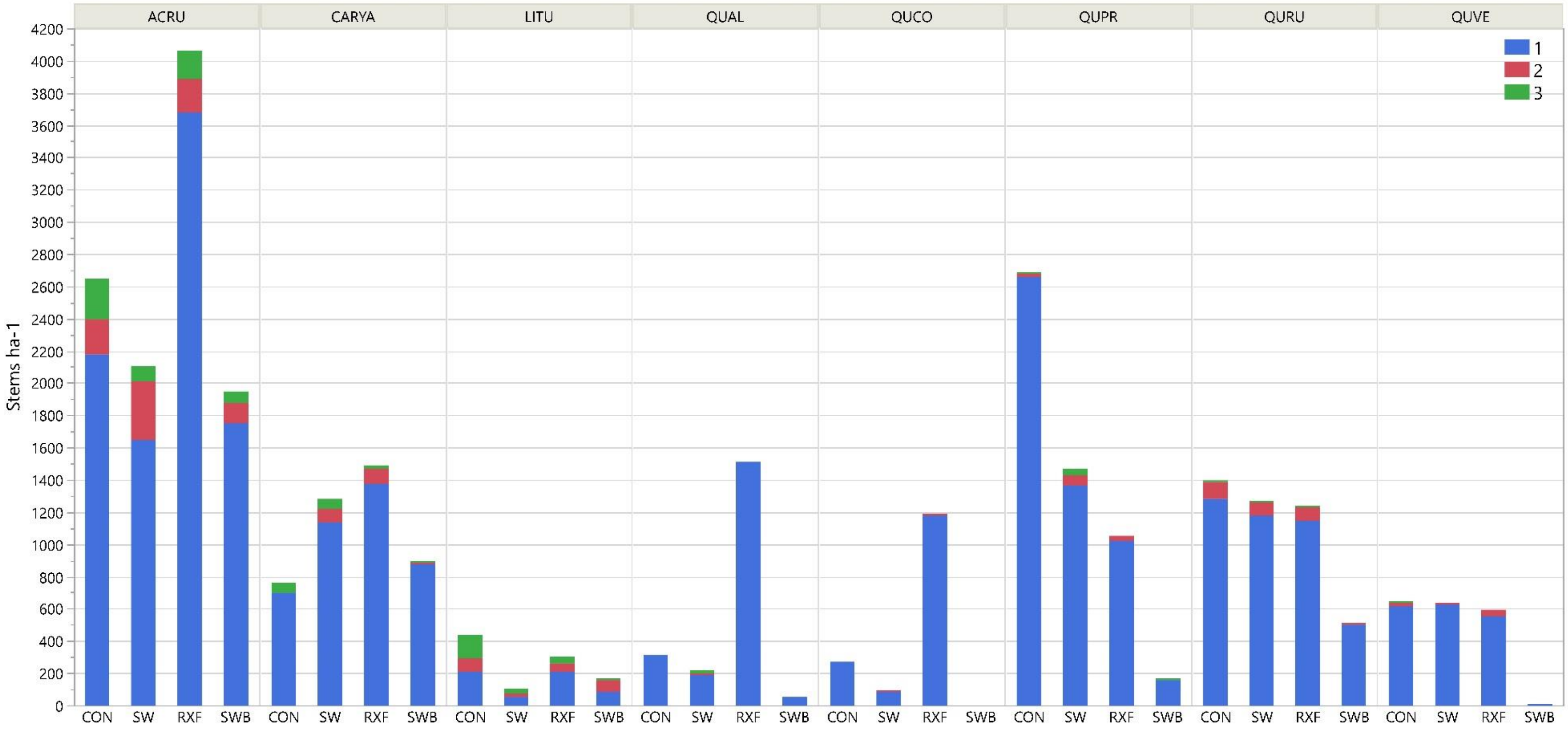

Figure 6. Pre-treatment stems ha^{-1} (± mean standard) by treatment, control (CON), shelterwood (SW), prescribed fire (RXF), and shelterwood and burn (SWB) and species, red maple (ACRU), hickory (CARYA), yellow-poplar (LITU), white oak (QUAL), scarlet oak (QUCO), chestnut oak (QUPR), northern red oak (QURU), and black oak (QUVE). Size class 1 contains stems < 0.6 m tall, size class 2 is stems ≥ 0.6 < 1.2 m tall, and size class 3 is stems ≥ 1.2 m tall and < 5 cm DBH. Densities obtained on sites in Cold Mountain Game Lands, Haywood County, NC, USA.

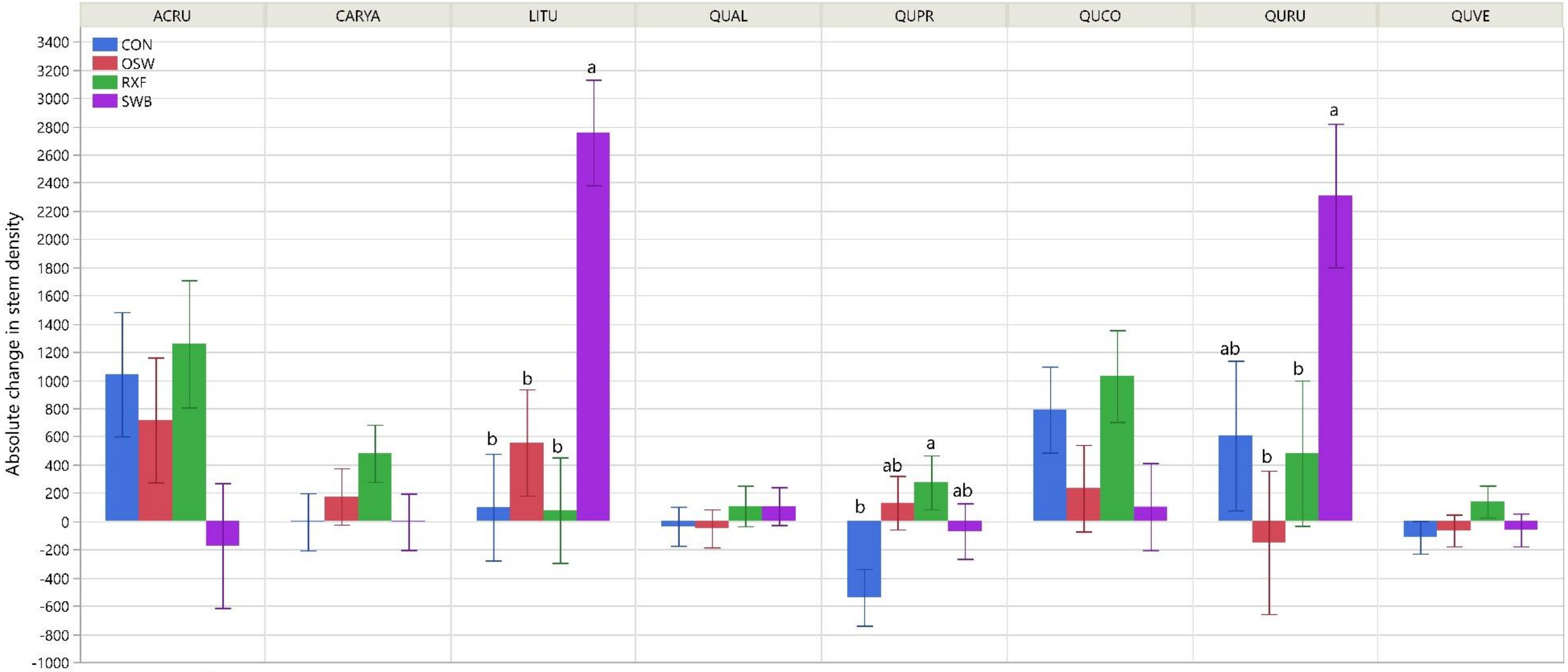

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Figure 7. Absolute change in total stems ha^{-1} (± LS mean standard) over a 9-year period by treatment, control (CON), shelterwood (SW), prescribed fire (RXF), and shelterwood and burn (SWB) and species, red maple (ACRU), hickory (CARYA), yellow-poplar (LITU), white oak (QUAL), scarlet oak (QUCO), chestnut oak (QUPR), northern red oak (QURU), and black oak (QUVE). Densities obtained on sites in Cold Mountain Game Lands, Haywood County, NC, USA. Tukey's HSD differences are within species and are noted by letter distinctions.

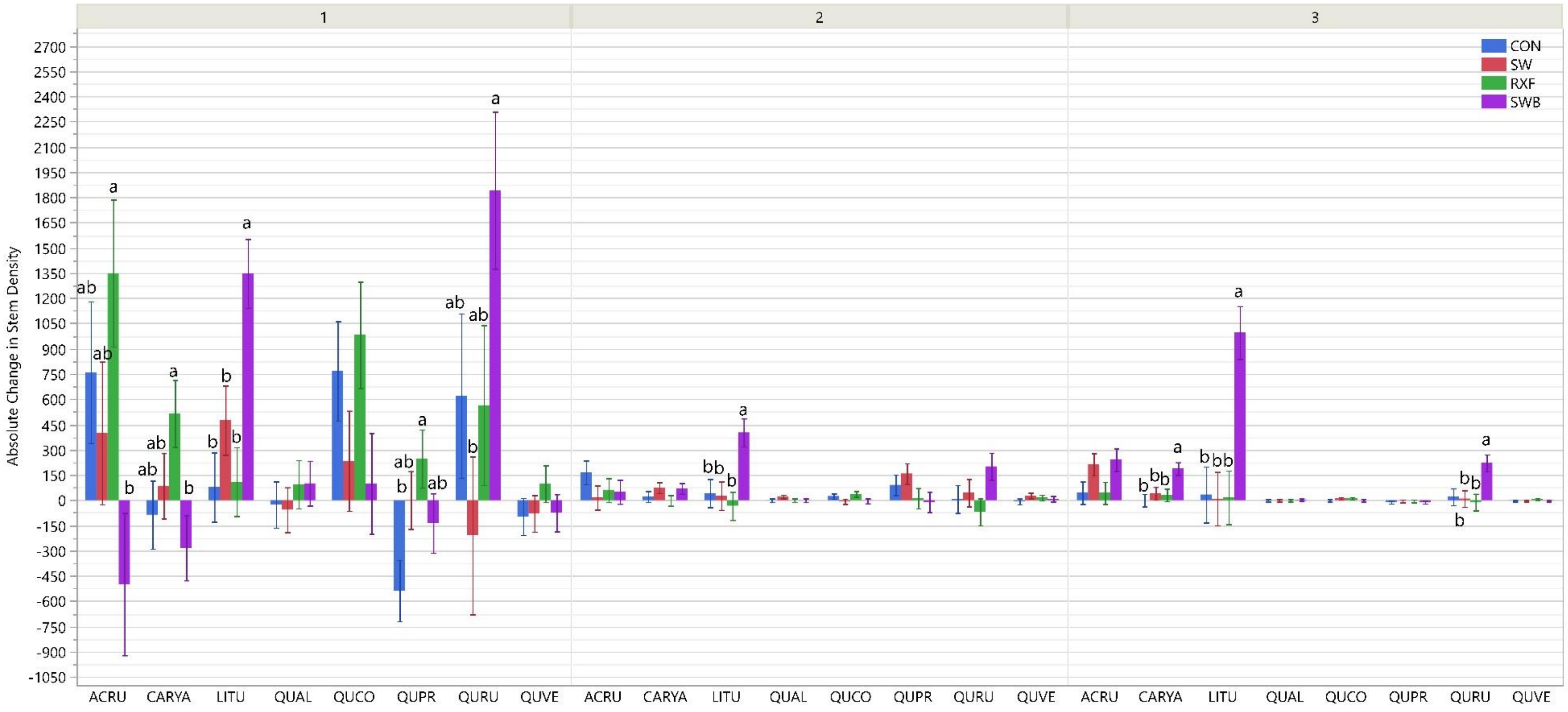

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Figure 8. Absolute change in stems ha^{-1} (± LS mean standard) over a 9-year period by treatment, control (CON), shelterwood (SW), prescribed fire (RXF), and shelterwood and burn (SWB) and species, red maple (ACRU), hickory (CARYA), yellow-poplar (LITU), white oak (QUAL), scarlet oak (QUCO), chestnut oak (QUPR), northern red oak (QURU), and black oak (QUVE). Size class 1 contains stem < 0.6 m tall, size class 2 is stems ≥ 0.6 < 1.2 m tall, and size class 3 is stems ≥ 1.2 m tall and < 5 cm DBH. Densities obtained on sites in Cold Mountain Game Lands, Haywood County, NC, USA. Tukey's HSD differences are calculated within species and are noted by letter distinctions.

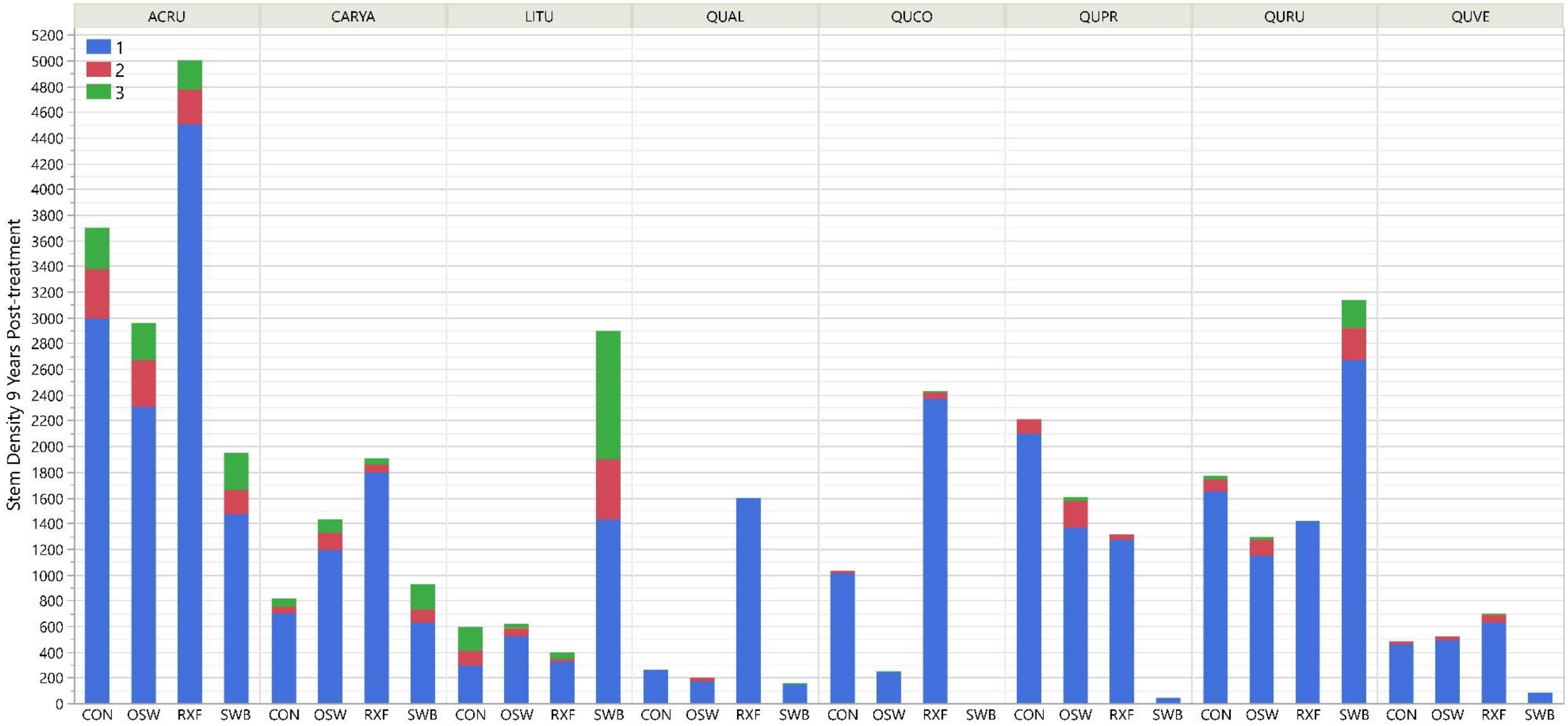

Figure 9. Stems ha^{-1} (mean standard ±) 9 years post-treatment by treatment, control (CON), shelterwood (SW), prescribed fire (RXF), and shelterwood and burn (SWB) and species, red maple (ACRU), hickory (CARYA), yellow-poplar (LITU), white oak (QUAL), scarlet oak (QUCO), chestnut oak (QUPR), northern red oak (QURU), and black oak (QUVE). Size class 1 contains stems < 0.6 tall, size class 2 is stems ≥ 0.6 <1.2 m tall, and size class 3 is stems ≥ 1.2 m tall and < 5 cm DBH. Densities obtained on sites in Cold Mountain Game Lands, Haywood County, NC, USA

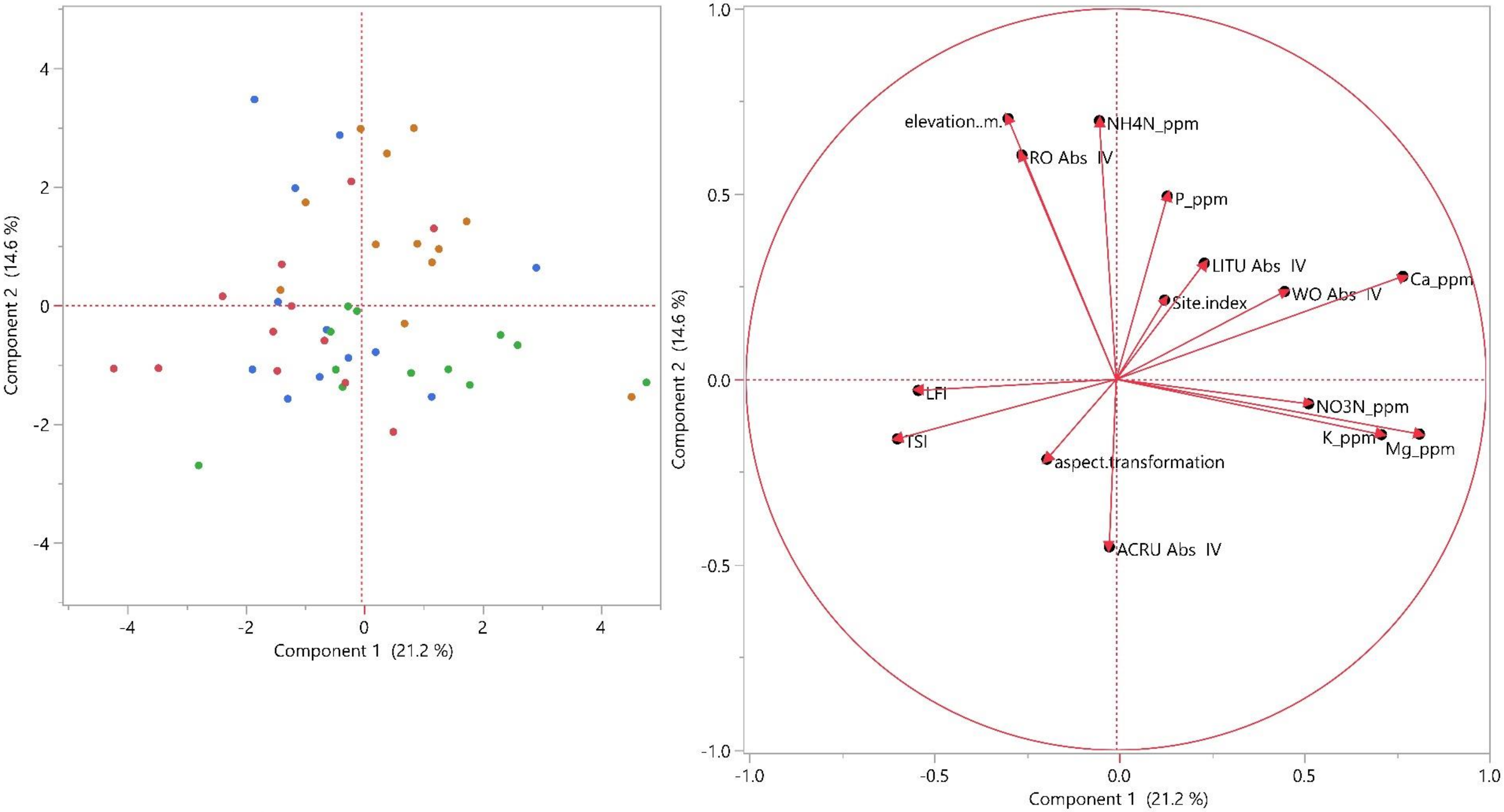

Figure 10. Principle component analysis for initial importance value of striped maple (ACPE), red maple (ACRU), sugar maple (ACSA), other shade tolerant species (ST), hickory (CARYA), red oak group (RO), white oak group (WO), other mid tolerant species (MT), white ash (FRAM), yellow-poplar (LITU), and other shade intolerant species (SI), absolute change in importance value of the red oak group, the white oak group, red maple, and yellow-poplar, and site characteristics elevation (m), site index, aspect transformation, terrain shape index (TSI), landform index (LFI), and soil characteristics post-treatment obtained on sites in Cold Mountain Game Lands, Haywood County, NC, USA. Control (CON) = red, shelterwood harvest (SW) = green, prescribed fire (RXF) = blue, and shelterwood and burn (SWB) = orange.

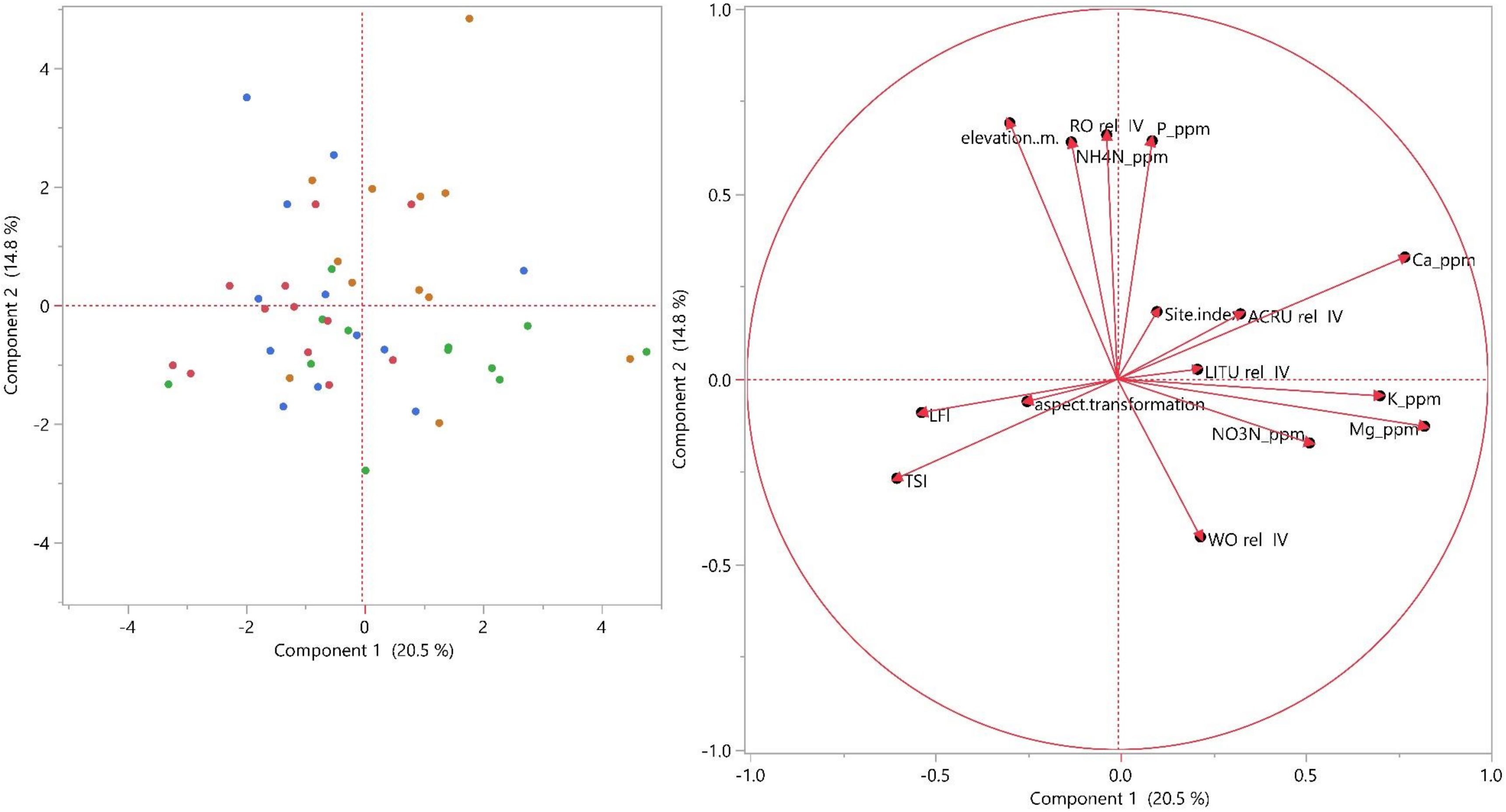

Figure 11. Principle component analysis for initial importance value of striped maple (ACPE), red maple (ACRU), sugar maple (ACSA), other shade tolerant species (ST), hickory (CARYA), red oak group (RO), white oak group (WO), other mid tolerant species (MT), white ash (FRAM), yellow-poplar (LITU), and other shade intolerant species (SI), relative change in importance value of the red oak group, the white oak group, red maple, and yellow-poplar, and site characteristics elevation (m), site index, aspect transformation, terrain shape index (TSI), landform index (LFI), and soil characteristics post-treatment obtained on sites in Cold Mountain Game Lands, Haywood County, NC, USA. Control (CON) = red, shelterwood harvest (SW) = green, prescribed fire (RXF) = blue, and shelterwood and burn (SWB) = orange.

3.8 Tables

Table 1. Summary of relevant shortleaf pine sprouting studies and their results.

Study	Age (Years)	Clip/ Burn	Location	Time of Year	Time of Remeasurement (Post Treatment)	Max Burn Temperature (℃)	% Top-killed	% Resprout	# Sprouts	Height of Tallest Sprout (cm)
Clabo & Clatterbuck (2019)	1 to 3	both	Cumberland Plateau	March clip (MC) April burn (AB) July burn (JB) Nov. Burn (NB)	1 growing season	(1 year) AB-335.9 JB-380 NB-453.2 (2 year) A-446.9 J-472.8 N-435 (3 year) M-408.2 J-258.3	(1 year) A – 63 J-57 N-73 (2 year) A-88 J-73 N-44 (3 year) A-44 J-30	(1-year-old) AB-42.7 JB- 38 NB-48 MC-75.8 CO-75.8 (2-year-old) AB- 58.7 JB-49.3 NB-52.7 MC-67.3 CO-82 (3-year-old) AB-69.3 JB- 46.7 MC- 52, CO- 76	(1 yr)- AB- 2.6 JB- 5 NB- 2.8 MC-2.1 CO-0.9 (2 yr) AB- 5 JB-10.9 NB- 15.2 MC-4.7 CO- 0.3 (3yr) AB 21.4, JB 9.1, MC-28.6 CO-0.5	(1 yr) AB- 103 JB-78 NB-99.3 MC-129.8 CO- 212.3 (2 yr) AB- 121.5 JB-54 NB-50.1 MC- 119.5 CO-203.6 (3-yr) AB- 55 JB - 24.1 MC- 55.8 CO- 185.6
Clabo & Clatterbuck (2015)	1	Burn (B) Clip (CL)	Cumberland Plateau	March	1 growing season	512-770°F		B- 42.6, CL- 75.3, Control (CO)- 75.3	B- 2.8 CL- 6.2 CO- 1.3	B- 19.2 CL-26.2 CO- 37.5
Lilly et al. (2012)	6	Burn	AR Ozarks	April	2 months (June),8 months (January)	Alive- 80, 256 Sprouted- 89,297 Dead-112, 326	93%	56 resprouted initially, then 38 of those died	2 months out: 1-51	1-24
Bradley et al. (2016)	1, 2	both	Oklahoma	August and March	35- 43 days later	August- 304 March- 550	100%	March Burn (2014) 50, August burn (2014) 56, March burn (2015) 63, clip 100	Clip- 7.75, Burn-6	
Shelton & Cain (2000)	1	burn	SE Arkansas	January August				August 0, control 91, January 95		control 90.6, winter burn 16.3

Table 2. Pre-treatment mid-story and overstory (± mean standard) stems ha^{-1}. CON = control, SW = shelterwood, RXF = prescribed fire treatment, SWB = shelterwood and burn treatment, obtained on sites in Cold Mountain Game Lands, Haywood County, NC, USA.

Treatment	**Mid-story**		**Overstory**	
	Density (stems ha^{-1})	**Basal Area (m^2 ha^{-1})**	**Density (stems ha^{-1})**	**Basal Area (m^2 ha^{-1})**
CON	550(62)	6.5(1.1)	202(19)	27.2(2.8)
SW	467(77)	6.7(1.1)	220(15)	28.8(2.6)
RXF	533(78)	7.7(1.1)	217(23)	29.9(2.7)
SWB	309(69)	4.7(1.2)	210(16)	30.4(2.6)

Table 3. Species designations to species groups.

Species Group	**Common Name**	**Scientific Name**
Striped maple (ACPE)	striped maple	*Acer pensylvanicum*
Red maple (ACRU)	red maple	*Acer rubrum*
Sugar maple (ACSA)	sugar maple	*Acer saccharum*
Hickory (CARYA)	hickory	*Carya* spp.
White ash (FRAM)	white ash	*Fraxinus americana*
Yellow poplar (LITU)	yellow poplar	*Liriodendron tulipifera*
Other mid tolerant species (MT)	american chestnut	*Castanea dentata*
	cucumber tree	*Magnolia acuminata*
	mountain magnolia	*Magnolia fraseri*
	northern catalpa	*catalpa speciosa*
	white pine	*Pinus strobus*
	yellow birch	*Betula alleghaniensis*
Red oak group (RO)	black oak	*Quercus velutina*
	northern red oak	*Quercus rubra*
	scarlet oak	*Quercus coccinea*
Other shade intolerant species (SI)	black cherry	*Prunus serotina*
	black locust	*Robinia pseudoacacia*
	black walnut	*Juglans nigra*
	butternut	*Juglans cinerea*
	fire cherry	*Prunus pensylvanica*
	sassafras	*Sassafras albidum*
	sweet birch	*Betula lenta*
	virginia pine	*Pinus virginiana*
Other shade tolerant species (ST)	alternate leaf dogwood	*Cornus alternifolia*
	american holly	*Ilex opaca*
	beech	*Fagus grandifolia*
	Buckeye	*Aesculus flava*
	eastern hemlock	*Tsuga canadensis*
	flowering dogwood	*Cornus florida*
	hophornbeam	*Ostrya virginiana*
	mountains holly	*Ilex montana*
	musclewood	*Carpinus caroliniana*
	blackgum	*Nyssa sylvatica*
	serviceberry	*Amelanchier arborea*
	silverbell	*Halesia tetraptera*
	sourwood	*Oxydendrum arboreum*
	white basswood	*Tilia heterophylia*
	witch hazel	*Hamamelis virginiana*
White oak group (WO)	chestnut oak	*Quercus prinus*
	white oak	*Quercus alba*

Table 4. Pre-treatment (± mean standard) stems ha^{-1} by species group, striped maple (ACPE), red maple (ACRU), sugar maple (ACSA), other shade tolerant species (ST), hickory (CARYA), red oak group (RO), white oak group (WO), other mid tolerant groups (MT), white ash (FRAM), yellow-poplar (LITU)**,** and other shade intolerant species (SI) on sites in Cold Mountain Game Lands, Haywood County, NC, USA.

Species Group	**Stems ha^{-1}**
ACPE	852(136)
ACRU	2690(312)
ACSA	1047(236)
ST	1122(135)
CARYA	1107(102)
RO	1964(230)
WO	1867(274)
MT	339(52)
FRAM	1888(271)
LITU	253(56)
SI	1935(197)
Total	**15063(755)**

Table 5. Pre-treatment importance value (± LS mean standard) by species group, striped maple (ACPE), red maple (ACRU), sugar maple (ACSA), other shade tolerant species (ST), hickory (CARYA), red oak group (RO), white oak group (WO), other mid tolerant groups (MT), white ash (FRAM), yellow-poplar (LITU)**,** and other shade intolerant species (SI), and treatment, control (CON), shelterwood (SW), prescribed fire (RXF), and shelterwood and burn (SWB) on sites in Cold Mountain Game Lands, Haywood County, NC, USA. Tukey's HSD differences are within species group and are noted by letter distinctions.

Species Group	Control	Shelterwood	Prescribed Fire	Shelterwood and Burn
ACPE	5.02 (6.78)b	22.45(6.65)ab	30.73(6.69)a	23.77(6.61)ab
ACRU	30.62(5.56)ab	15.28(5.56)b	38.2(5.56)3a	23.15(5.56)ab
ACSA	6.40(8.10)b	19.39(7.76)ab	6.80(7.88)b	40.18(7.64)a
ST	28.91(5.69)a	32.41(5.69)a	33.55(5.69)a	5.90(5.69)b
CARYA	7.80(3.81)	17.91(3.74)	10.01(3.76)	15.56(3.72)
RO	23.65(4.01)a	16.65(3.92)ab	19.38(3.95)a	4.96(3.89)b
WO	24.42(4.42)a	14.90(4.28)ab	14.76(4.33)ab	3.36(4.23)b
MT	13.17(3.10)	5.39(3.01)	11.37(3.03)	4.48(2.98)
FRAM	15.92(6.85)b	27.01(6.75)b	9.37(6.77)b	54.60(6.72)a
LITU	10.46(2.85)	2.51(2.76)	4.14(2.79)	2.71(2.73)
SI	33.52(6.17)	21.96(6.17)	20.29(6.17)	20.20(6.17)

Table 6. Absolute change in importance value (± LS mean standard) by species group, striped maple (ACPE), red maple (ACRU), sugar maple (ACSA), other shade tolerant species (ST), hickory (CARYA), red oak group (RO), white oak group (WO), other mid tolerant groups (MT), white ash (FRAM), yellow-poplar (LITU)**,** and other shade intolerant species (SI), and treatment, control (CON), shelterwood (SW), prescribed fire (RXF), and shelterwood and burn (SWB) on sites in Cold Mountain Game Lands, Haywood County, NC, USA. Tukey's HSD differences are within species group and are noted by letter distinctions

Species Group	Control	Shelterwood	Prescribed fire	Shelterwood and burn
ACPE	-4.08(3.94)a	0.17(3.73)a	0.04(3.83)a	-18.87(3.68)b
ACRU	9.59(3.62)a	5.09(3.62)a	2.64(3.65)ab	-8.67(3.54)b
ACSA	-4.80(3.52)ab	-1.92(3.39)a	-2.97(3.46)a	-16.83(3.53)b
ST	-2.14(3.69)	-2.21(3.62)	-0.97(3.66)	-7.62(3.75)
CARYA	-2.34(2.67)	0.09(2.63)	1.63(2.62)	-2.18(2.59)
RO	9.0(4.55)ab	-2.35(4.34)b	13.37(4.42)a	14.87(4.40)a
WO	-4.75(1.57)	-0.87(1.47)	-3.82(1.49)	-4.98(1.49)
MT	1.93(2.63)	2.04(2.50)	2.12(2.54)	0.44(2.47)
FRAM	-2.30(3.73)ab	4.25(3.61)a	-11.89(3.76)b	-12.19(3.89)b
LITU	4.06(5.05)b	4.69(4.95)b	1.28(4.92)b	32.91(4.94)a
SI	-8.74(4.66)b	-9.59(4.54)b	-2.69(4.57)b	19.85(4.53)a

Table 7. Relative change in importance value (± LS mean standard) by species group, striped maple (ACPE), red maple (ACRU), sugar maple (ACSA), other shade tolerant species (ST), hickory (CARYA), red oak group (RO), white oak group (WO), other mid tolerant groups (MT), white ash (FRAM), yellow-poplar (LITU)**,** and other shade intolerant species (SI), and treatment, control (CON), shelterwood (SW), prescribed fire (RXF), and shelterwood and burn (SWB) on sites in Cold Mountain Game Lands, Haywood County, NC, USA. Tukey's HSD differences are within species group and are noted by letter distinctions.

Species groups	**Control**	**Shelterwood**	**Prescribed fire**	**Shelterwood and burn**
ACPE	7.14(89.20)	210.51(89.20)	27.59(89.20)	-41.92(89.20)
ACRU	145.5(100.22)1	344.68(98.05)	82.05(98.82)	196.76(97.28)
ACSA	43.71(50.83)	46.59(50.83)	76.82(50.83)	-40.30(50.83)
ST	3.00(52.85)	25.93(52.85)	60.68(52.85)	145.16(52.85)
CARYA	72.83(55.62)	14.50(55.62)	36.88(55.62)	139.06(55.62)
RO	69.86(299.22)b	28.04(293.13)b	530.12(295.20)ab	1400.56(290.97)a
WO	-13.16(50.47)	99.48(49.62)	10.09(49.80)	55.64(49.38)
MT	160.80(128.44)	48.00(125.03)	10.16(126.27)	255.99(123.80)
FRAM	7.35(39.18)	93.90(38.73)	-37.77(38.82)	6.46(38.61)
LITU	256.01(464.93)b	593.65(464.93)b	102.09(464.93)b	2954.51(464.93)a
SI	-24.76(78.69)b	17.79(78.69)b	12.95(78.69)b	380.81(78.69)a

Table 8. Absolute change in total stems ha^{-1} (± LS mean standard) by species, red maple (ACRU), hickory (CARYA), yellow-poplar (LITU), white oak (QUAL), scarlet oak (QUCO), chestnut oak (QUPR), northern red oak (QURU), and black oak (QUVE), and treatment, control (CON), shelterwood (SW), prescribed fire (RXF), and shelterwood and burn (SWB) on sites in Cold Mountain Game Lands, Haywood County, NC, USA. Tukey's HSD differences are within species and are noted by letter distinctions

Species	**Control**	**Shelterwood**	**Prescribed fire**	**Shelterwood and burn**
ACRU	1041.77(439.83)	717.60(442.02)	1257.38(451.78)	-172.99(443.35)
CARYA	-5.72(202.14)	174.95(199.68)	480.56(202.87)	-3.95(200.07)
LITU	97.81(378.40)b	557.33(376.40)b	78.11(373.15)b	2756.33(373.97)a
QUAL	-36.53(138.41)	-51.85(134.65)	106.63(143.69)	105.53(134.09)
QUCO	791.20(303.76)	233.56(306.37)	1029.56(325.46)	101.93(308.64)
QUPR	-540.23(201.14)b	130.07(190.09)ab	274.88(191.14)a	-70.36(196.00)ab
QURU	606.63(530.44)ab	-150.36(508.48)b	480.93(515.36)b	2308.16(509.52)a
QUVE	-114.68(115.27)	-66.27(113.86)	138.90(113.88)	-62.95(116.58)

Table 9. Absolute change in stems ha^{-1} < 0.6 m tall (± LS mean standard) by species, red maple (ACRU), hickory (CARYA), yellow-poplar (LITU), white oak (QUAL), scarlet oak (QUCO), chestnut oak (QUPR), northern red oak (QURU), and black oak (QUVE), and treatment, control (CON), shelterwood (SW), prescribed fire (RXF), and shelterwood and burn (SWB) on sites in Cold Mountain Game Lands, Haywood County, NC, USA. Tukey's HSD differences are within species and are noted by letter distinctions.

Species	Control	Shelterwood	Prescribed fire	Shelterwood and burn
ACRU	760.(420)ab	399(424)ab	1349(437)a	-498(423)b
CARYA	-86.33(201.82)ab	85.71(194.43)ab	515.79(197.90)a	-283.25(192.79)b
LITU	78.27(205.18)b	474.94(205.88)b	109.52(205.18)b	1347.69(204.62)a
QUAL	-25.26(137.87)	-56.99(133.73)	95.04(142.92)	100.40(132.84)
QUCO	768.50(294.88)	233.59(297.57)	982.38(315.79)	98.86(299.54)
QUPR	-536.90(181.84)b	1.24(171.12)ab	246.74(172.22)a	-135.43(176.35)ab
QURU	621.24(488.84)ab	-209.14(467.99)b	564.38(474.77)ab	1841.14(467.37)a
QUVE	-97.01(110.06)	-78.55(108.40)	97.85(108.57)	-74.05(110.11)

Table 10. Absolute change in stems ha^{-1} ≥ 0.6 <1.2 m tall (± LS mean standard) by species, red maple (ACRU), hickory (CARYA), yellow-poplar (LITU), white oak (QUAL), scarlet oak (QUCO), chestnut oak (QUPR), northern red oak (QURU), and black oak (QUVE), and treatment, control (CON), shelterwood (SW), prescribed fire (RXF), and shelterwood and burn (SWB) on sites in Cold Mountain Game Lands, Haywood County, NC, USA. Tukey's HSD differences are within species and are noted by letter distinctions.

Species	Control	Shelterwood	Prescribed fire	Shelterwood and burn
ACRU	165.47(71.20)	15.51(71.65)	60.11(71.20)	50.57(71.46)
CARYA	22.17(32.27)	75.35(32.12)	-1.34(32.37)	70.49(32.12)
LITU	42.14(83.94)b	26.42(84.10)b	-33.43(83.78)b	402.37(83.83)a
QUAL	-0.32(10.660	21.51(10.70)	-0.22(10.60)	-0.22(10.56)
QUPR	90.90(60.40)	158.18(60.95)	11.37(60.38)	-10.45(60.78)
QUCO	24.19(16.37)	-7.59(15.74)	36.96(15.92)	-3.40(15.49)
QURU	7.71(82.31)	44.60(80.40)	-69.38(80.75)	200.97(80.59)
QUVE	-7.77(17.44)	27.15(16.85)	15.36(17.14)	7.78(16.73)

Table 11. Absolute change in stems ha^{-1} ≥ 1.2 m and < 5 cm DBH (± LS mean standard) by species, red maple (ACRU), hickory (CARYA), yellow-poplar (LITU), white oak (QUAL), scarlet oak (QUCO), chestnut oak (QUPR), northern red oak (QURU), and black oak (QUVE), and treatment, control (CON), shelterwood (SW), prescribed fire (RXF), and shelterwood and burn (SWB) on sites in Cold Mountain Game Lands, Haywood County, NC, USA. Tukey's HSD differences are within species and are noted by letter distinctions.

Species	Control	Shelterwood	Prescribed fire	Shelterwood and burn
ACRU	43.86(66.61)	213.56(656.92)	43.89(65.72)	240.36(66.18)
CARYA	0.00(37.39)b	41.67(37.39)b	31.25(37.33)b	187.50(37.47)a
LITU	33.60(166.35)b	9.10(158.41)b	16.22(159.30)b	995.82(157.36)a
QUAL	-1.85(6.98)	-1.22(6.67)	-0.98(6.76)	3.15(6.54)
QUPR	-11.65(8.33)	-4.16(8.26)	-3.95(8.24)	-11.83(8.11)
QUCO	0.00(7.37)	10.42(7.37)	10.42(7.37)	0.00(7.37)
QURU	20.00(49.66)b	9.59(49.66)b	-11.25(49.66)b	221.24(49.84)a
QUVE	-2.60(5.30)	-2.60(5.24)	7.81(5.24)	-2.60(5.24)

Table 12. Mid-story, overstory, and total basal area pre-treatment (m^2 ha^{-1}), post-treatment (m^2 ha^{-1}), and relative change in basal area (%) over the 9-year period (LS mean standard ±) by treatment on sites in Cold Mountains Game Lands, Haywood County, NC, USA. CON = control, SW = shelterwood, RXF = prescribed fire, and SWB = shelterwood and burn. Significant p-values are in bold.

Basal Area m^2 ha^{-1}

		Pre-treatment	**Treatment p-value**	**9 Years Post-treatment**	**Treatment p-value**	**Relative Change (%)**	**Treatment p-value**
Mid-story	CON	6.5(1.1)		5.9(0.7)a		-16.4(8.6)a	
	SW	6.7(1.1)		1.5(0.7)b		-74.6(8.2)b	
	RXF	7.7(1.1)		4.7(0.7)a		-29.9(8.4)a	
	SWB	4.7(1.2)	p = 0.36	1.5(0.8)b	**p < 0.001**	-87.9(8.6)b	**p < 0.001**
Overstory	CON	27.4(2.8)		27.0(1.4)a		-2.7(4.1)a	
	SW	28.8(2.6)		28.8(1.3)a		-1.8(3.8)a	
	RXF	29.9(2.7)		29.3(1.4)a		-2.3(3.9)a	
	SWB	30.4(2.6)	p = 0.84	5.7(1.3)b	**p < 0.001**	-76.2(3.8)b	**p < 0.001**
Total	CON	33.3(3.0)		32.9(1.5)a		-3.8(4.1)a	
	SW	35.6(2.8)		30.6(1.5)a		-14.2(3.9)a	
	RXF	37.4(2.9)		33.6(1.5)a		-5.7(4.0)a	
	SWB	36.0(2.9)	p = 0.77	7.9(1.6)b	**p < 0.001**	-77.8(4.1)b	**p < 0.001**

Chapter 4. Conclusion

Oak (*Quercus* spp.) has been a foundational species in our eastern US forests for thousands of years (Abrams 2002). Oak ecosystems persisted with periodic fire up until the early 20th century due to oak's many fire adaptations (Abrams 1998, Hanberry & Nowacki 2016). Around the turn of the century, fire exclusion polices resulted in less fire, greater forest canopy closure, and increased mid-story densities (Dey et al. 2010). These conditions led to the proliferation of mesic species, such as red maple (*Acer rubrum)* and yellow-poplar (*Liriodendron tulipifera)* (Nowacki & Abrams 2008). Under current forest conditions, oak volume is increasing, but very little oak is being recruited into the overstory (McEwan et al. 2011). Much research has been conducted over the last several decades to determine the impacts of silvicultural treatments on oak regeneration. This study was developed to compare the effects of four treatments: 1) an unmanaged control, 2) shelterwood (SW), 3) prescribed fire (RXF), and 4) a shelterwood and burn (SWB) on regeneration layer dynamics in the southern Appalachian Mountains of North Carolina. The regeneration, mid-story, and overstory layers were monitored over a 9-year period post-treatment, site characteristics were recorded at the plot-level, and regeneration layer stem densities and importance values were quantified.

Overall, the results indicate species respond differently to respective treatments. The SWB greatly increased the absolute importance value of the red oak group and yellow-poplar. Changes in red oak group density in the SWB were largely driven by northern red oak (*Q. rubra*), and yellow-poplar density increases in the SWB were the result of increases in stems < 0.6 m tall and stems ≥1.2 m tall and <5 cm DBH. On the other hand, the SWB decreased the importance value of shade tolerant species groups, and it was the only treatment to see decreases in red maple. White oak group importance value and density did not vary between treatments.

Increases in red oak group importance value and density in the RXF occurred, but, in some instances, were statistically similar to the CON. Changes in importance value of the white oak group were associated with: 1) site index and 2) initial importance value of shade tolerant species groups. Changes in importance value of the red oak group were associated with 1) elevation and 2) NH_4-N (ppm). Silvicultural treatments improved oak competitive status, but responses varied as a result of site-specific characteristics.

Similar to our results, several other studies found yellow-poplar and oak responded positively to treatments combining fire with mechanical removal or herbicides prior to final harvest (Brose 2010, Brose & Van Lear 1998, Dey et al. 2009, Loftis 1990, Oakman et al. 2019). On the other hand, Brose et al. (1999) found oak increased and yellow-poplar competition was minimized in a SWB, but these results occurred at the highest fire intensities. Iverson et al. (2008) concluded increases in canopy openness of 8.5-19%, followed by a burn, resulted in successful establishment of oak. This is likely less canopy openness than our SWB treatment. Across most studies, outcomes show oak can increase following silvicultural treatments that increase understory light levels, but there is a narrow window for oak success amid its competitors. As treatment intensity increases, shade intolerant species respond, and with less intense treatments, shade tolerant species remain intense competitors (Hodges and Gardiner 1993). The complexity of responses among species in the regeneration layer is further complicated by differing site conditions and within-genus differences among oaks.

The results of our study and others highlight the importance of monitoring oak and competing species throughout the entire rotation and especially during the regeneration process. Managers should be adaptive to changing post-harvest conditions, adjusting prescriptions if the desired oak response is not occurring. In our study, for example, adding an additional burn in the

RXF treatment, conducting canopy reductions in the SW, or targeting yellow-poplar in the SWB prior to or after the final harvest could improve oak competitive status. Additional research regarding fire frequency following harvest treatments and burning in different seasons to potentially alter fire intensity and severity may also be warranted (Dukes et al. 2020). To conclude, in this study, silvicultural treatments improved the competitive status of oak regeneration, but adjustments to treatments will be needed to ensure oak’s successful ascension into the canopy.

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