Effects of Commercial Thinning on White-tailed Deer Forage Availability and Ecological Restoration Objectives in Loblolly Pine Stands

by

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A thesis submitted to the Graduate Faculty of
Auburn University
in partial fulfillment of the
requirements for the Degree of
Master of Science

Auburn, Alabama
May 5, 2019

Keywords: Forage, Georgia, Loblolly pine, Prescribed fire, Thinning, White-tailed deer

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Abstract

Planted pine (*Pinus* spp.) stands represent 19% of the forested land in the southeastern U.S. Though often managed for timber production, many landowners have alternative objectives, such as improving habitat quality for game species like white-tailed deer (*Odocoileus virginianus*). Commercial thinning and prescribed fire at mid-rotation can enhance and maintain habitat quality for deer by increasing coverage of preferred forage plants. However, the relationship between thinning intensity and deer forage availability has not been well documented. Therefore, we conducted an operational-scale, manipulative experiment in which we thinned five loblolly pine (*P. taeda*) stands to residual basal areas of 9, 14, and 18 m^2/ha within the Piedmont physiographic region of Georgia. We evaluated the effects of these treatments, with and without prescribed fire, on deer forage, and also measured the accuracy and precision of commercial logging crews at achieving target thinning prescriptions for ecological restoration efforts.

Acknowledgments

This project was funded by the Division of Wildlife and Freshwater Fisheries within the Alabama Department of Conservation and Natural Resources (ADCNR), along with the Federal Aid in Wildlife Restoration Act. This project was part of a larger collaborative effort between the School of Forestry and Wildlife Sciences at Auburn University, ADCNR's Division of Wildlife and Freshwater Fisheries, the Warnell School of Forestry and Natural Resources at the University of Georgia, and the Wildlife Resources Division within the Georgia Department of Natural Resources (GADNR). Weyerhaeuser Company provided additional support. I would like to thank committee member Dr. James Martin, as well as Dr. Karl Miller of Warnell, Ms. Kristina Johannsen of GADNR, and Drs. Darren Miller (currently of National Council for Air and Stream Improvement) and Daniel Greene of Weyerhaeuser Company for their support throughout this research.

I also thank my advisor, Dr. William Gulsby, for his guidance and patience as I developed into a researcher. I feel truly honored to be one of his first advisees and have enjoyed developing my research and management skillset as part of his team. Along those same lines, I would like to thank my other committee members, Drs. Stephen Ditchkoff and Rebecca Barlow. Both have provided me with valuable insight, both professionally and personally. Dr. Barlow's support and Dr. Ditchkoff's prodding have helped motivate me to achieve things that I wouldn't have otherwise.

I thank Allison Colter for her support throughout this research. Together, we have endured countless challenges, and I am proud to have completed this leg of the project with her.

Finally, I would like to extend a special thanks to my family. Mom and Dad (Brenda and Vernon Keene), thank you for raising me and for your help in shaping my passion for the outdoors, as well as for the push to always give my best effort. Without your guidance, I would have never made it to this point and for that I will always be grateful. Rachel, thank you for being such an amazing supporter. I can't express enough how much your patience and kindness have meant to me throughout this process. From being a listening ear to serving as a fill-in volunteer when I needed an extra set of hands, you have gone above and beyond what I could have ever imagined and I hope that I can return the favor as we move forward with our lives.

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CHAPTER 1

INTRODUCTION & LITERATURE REVIEW, OBJECTIVES, STUDY AREAS, AND THESIS FORMAT

INTRODUCTION & LITERATURE REVIEW

Timber production generates a combined $37.1 billion in annual revenue in Alabama and Georgia (Alabama Forestry Commission 2017, Georgia Forestry Commission 2017). Across the Southeast, planted loblolly pine (*Pinus taeda*) stands, which account for nearly 10% of all forested land in the region, are a major contributor to the region's forest products industry (Wear and Greis 2002, Oswalt et al. 2014). Because of the economic importance of timber production, most loblolly pine stands are managed to maximize sawtimber volume at final harvest (Miller et al. 2009). Although pine sawtimber and pulpwood prices have remained relatively stable throughout the recent past (Timber Mart-South 2019), landowners receive revenue from pine stands at only a few discrete points in time throughout a 25–30 year rotation; typically during mid-rotation, when one or more thinning operations are implemented, and at final harvest. Though these harvests are usually profitable, some landowners prefer additional sources of intermediate revenue.

For example, in recognition of the demand for hunting access, many industrial private forest (IPF) owners in the southeastern U.S. implement hunt-lease programs to provide an annual revenue source to offset management costs (Barlow et al. 2007, Davis et al. 2017). In 1998, an estimated $40M was generated from hunt-lease programs on private lands throughout the region

(Marsinko et al. 1998), but research has shown that properties receiving some level of wildlife habitat management often bring greater income (Hussain et al. 2007). On other properties, such as those managed by state wildlife management agencies, maximizing hunter opportunity and satisfaction may be a primary objective (Carley and Grado 2000). For example, the Wildlife Section of the Alabama Department of Conservation and Natural Resources' (ADCNR) Division of Wildlife and Freshwater Fisheries is charged with managing nearly 300,000 ha of public land within the state, including over 46,000 ha that are actively managed for wildlife habitat (ADCNR 2016–2017 Annual Report). Because white-tailed deer (*Odocoileus virginianus*: hereafter, deer) are the most sought after game species in the United States (USFWS 2018), both IPF owners and state wildlife agencies often consider providing quality habitat for this species a priority objective.

Finally, many non-industrial private forest owners (NIPFOs) enjoy deer hunting on their own properties. In fact, Southern (i.e., southeastern United States and Texas) NIPFOs spend an average of $3,081 annually on property designated for hunting (Macaulay 2016). Additional data gathered from various government agencies showed that Southern landowners spent an average of $367/person/ha on property purchased specifically for hunting, and hunters owned or leased a total of 24M ha of hunting property in the South (Macaulay 2016). Given the popularity of deer as a game species, particularly in the Southeast, it is reasonable to assume the majority of this land was purchased or leased with the objective of hunting and managing for deer. Because of the interest in deer hunting and management among NIPFOs, IPF owners, and public land managers, along with the extensive coverage of loblolly pine throughout the region (Wear and Greis 2002), there is significant interest in the joint management of loblolly pine plantations for both timber production and deer habitat objectives.

A relatively extensive body of research has been devoted to the effects of loblolly pine management practices on deer forage quality and abundance. Habitat quality for deer generally increases with increasing coverage of highly palatable and nutritious plants, usually forbs and a select number of woody species (Blair and Enghardt 1976, Warren and Hurst 1981). White-tailed deer are considered concentrate selectors, meaning that they feed on the most nutritious parts of the most nutritious plants (Hewitt 2011). Thus, deer have the ability to persist in a variety of ecosystems and subsist on a wide variety of plants including grasses, forbs, shrubs, and saplings. However, silvicultural treatments throughout the life of a stand strongly influence deer habitat quality, both positively and negatively.

Immediately prior to stand establishment, managers have a variety of tools at their disposal. At this stage, the main factor driving management decisions from a silvicultural perspective is the control of competing vegetation, particularly hardwoods that might impede the successful establishment of loblolly seedlings (Nilsson and Allen 2003, Jones et al. 2009). The most common site preparation treatments include mechanical disturbance, broad-spectrum and selective herbicides, and prescribed fire (Jones et al. 2009, Lane et al. 2011). Fortunately, some site preparation treatments are also consistent with deer management objectives. For example, Lane et al. (2011) found that chemical site preparation treatments reduced the presence of non-pine woody vegetation and, following initial decreases, forage availability rebounded by year four. Additionally, Jones et al. (2009) found that a combination of chemical and mechanical site preparation, followed by a banded herbaceous release treatment post-planting, produced the greatest deer forage biomass on sites in the Gulf Coastal Plain of Mississippi. However, broadcast (vs. banded) application of herbicides that target herbaceous competition can result in significant declines in deer forage availability and are not generally recommended within stands managed for deer (Jones et al. 2009, Lane et al. 2011).

Following establishment, loblolly pine stands provide abundant deer forage for several years due to high sunlight availability at the forest floor (Scanlon and Sharik 1986). However, intensive stand establishment and release treatments can result in increased pine growth rates, thereby decreasing the time between planting and pine canopy closure (Lane et al. 2011, Campbell et al. 2015). At canopy closure, pine growth rates decline as trees begin to compete with each other for light and below-ground resources (Assmann 1970, Oliver 1981). Left unmanaged, a stand will eventually enter what is referred to as the "stem exclusion" phase of forest stand dynamics (Oliver 1981, Oliver and Larson 1996). In this phase, direct competition and density-mediated issues such as insect infestation and disease, will lead to pine mortality and a subsequent reduction in stand value compared to stands maintained at optimal stocking (Oliver 1981, Smith et al. 1997). For deer, closed canopy loblolly pine stands provide relatively little forage and the effects of crown closure on deer forage availability will remain until sunlight returns to the forest floor (Blair 1969). Fortunately, commercial thinning is a silviculturally and often profitable option to mitigate the effects of stem exclusion on stand development (Stokes and Watson 1996, Smith et al. 1997), and the canopy gaps created by thinning return sunlight to the forest floor and stimulate the development of deer forage plants (Blair and Enghardt 1976, Harrington and Edwards 1999, Peitz et al. 1999, Peitz et al. 2001).

The effects of thinning on the remaining crop trees have been well documented. For example, Ginn et al. (1991) removed 50% of the basal area in an 8-year-old loblolly pine stand in Virginia and observed a 51% increase in stem diameter and a 29% increase in basal area. They cited increased growth of lower limbs and a corresponding increase in photosynthetic potential of retained trees as the primary factor responsible for increased diameter growth. Similarly, Baldwin et al. (2000) reported that increased thinning intensity resulted in more cylindrical lower boles, upper stem taper, and increased crown length and foliage. They also found that light to moderate thinning resulted in greater timber volume and less growth allocated to the crown. Standard first commercial thinning operations are typically implemented between years 12–15 of a 30-year rotation (Cunningham et al. 2008), and remove approximately 20–25% of the basal area within a stand, generally leaving a residual basal area of approximately 18 m^2/ha (Huang and Konrad 2002). However, the exact timing of thinning depends on a variety of factors that influence tree growth rates (e.g., site index and precipitation; Stokes and Watson 1996). Nonetheless, the removal of pulpwood during thinning is sufficient to generate profit while retaining adequate growing stock within the stand (Siry 2002), provided that a pulpwood market is relatively close to the site (Dickens et al. 2004, Huang et al. 2005). In response to thinning, both diameter growth and crown expansion will continue until a second period of canopy closure when trees begin to compete with each other again (Peterson et al. 1997). To increase the amount of time between initial thinning treatments and subsequent canopy closure, increased thinning intensities that create more space between trees may be implemented.

Thinning operations can also significantly improve deer habitat quality. For example, Blair and Enghardt (1976) thinned 20-year-old loblolly pine stands in Louisiana at five-year intervals to basal areas of 23, 20, and 16 m^2/ha, and found that the lowest residual basal area treatment resulted in the greatest deer forage production. However, subsequent thins produced inconsistent results because of the development of a hardwood midstory. Favorable deer forage responses were also noted following thinning in loblolly pine stands in Virginia (Conroy et al. 1982), loblolly pine-hardwoods in Arkansas (Peitz et al. 1999, Peitz et al. 2001), longleaf pine-

(*P. palustris*) hardwoods in South Carolina (Harrington and Edwards 1999), ponderosa pines (*P. ponderosa*) in Washington (McConnell and Smith 1965), hardwoods in Tennessee (Lashley et al. 2011), and shortleaf pine- (*P. echinata*) hardwoods in western Arkansas (Masters et al. 1996). More specifically, thinning 6–11-year-old longleaf pine stands from 1440 trees/ha to approximately 635 trees/ha (~44% reduction) resulted in a significantly greater percent coverage of grasses, forbs, vines, and shrubs (Harrington and Edwards 1999). In western Arkansas, biomass of deer browse was greatest in loblolly stands receiving the most intensive thinning treatments (residual basal area of 15 m^2/ha and complete removal of midstory hardwoods; Peitz et al 1999). However, the most intensive thinning treatment implemented in these studies (15 m^2/ha) is still fairly conservative if maximizing deer forage is the primary objective. Thus, some have recommended even more intensive thinning regimes (e.g., Blair and Enghardt 1976). However, doing so would undoubtedly sacrifice timber volume (and future revenue), and there is evidence to suggest that thinning beyond 16 m^2/ha may have no benefit for forb coverage and may actually cause vine biomass to decrease (Traugott and Kushla, unpublished data). This suggests there may be a point of diminishing returns, beyond which the increased sacrifice of timber volume does not result in meaningful gains in deer forage.

Though generally beneficial, thinning operations can also result in unintentional release of midstory hardwoods (e.g., sweetgum [*Liquidambar styraciflua*], yellow poplar [*Liriodendron tulipifera*], and various oaks [*Quercus* spp.]) that compete with crop trees and shade the understory. However, hardwood removal can mitigate these negative effects. For example, Clason (1978, 1984) noted an increase in pine growth and development following hardwood removal in a 7-year-old loblolly pine stand. In those studies, hardwood removal also increased the efficacy of fire in top-killing hardwood stems later in the rotation.

Selective herbicides (e.g., imazapyr; Quicke et al. 1996) and prescribed fire (Brender and Cooper 1968) can also be used to control hardwood competition in loblolly pine stands. Prescribed fire is of particular interest due to its relatively low cost as a vegetation management tool within pine stands. Although young loblolly pines are vulnerable to fire-related mortality, susceptibility decreases as pines age and bark thickness increases (Stanturf et al. 2002). For example, following a low-intensity fire in an overcrowded loblolly pine stand, trees ≤6.4 cm DBH suffered high mortality, whereas all trees >6.4 cm DBH with bark thickness ≥1.78 cm survived (McNab 1977). Conversely, many hardwood species (e.g., sweetgum) are less heat tolerant, and therefore more vulnerable to top-kill from low-intensity fire at small diameters (Hare 1965), but timing of application is also important and summer fires are often considered more effective than winter fires for controlling hardwood saplings (Brender and Cooper 1968). Nonetheless, low-intensity prescribed fire during the dormant (i.e., January–March) and early growing (i.e., April–June) seasons still benefit pines by top-killing hardwoods and improving soil conditions (Schoch and Binkley 1986). Prescribed fires also consume pine litter, reducing fuel loading and wildfire risk (Stanturf et al. 2002).

Regardless of the approach, hardwood control is also of major importance when deer forage availability is a priority objective because midstory hardwoods shade and suppress herbaceous vegetation. For example, removal of all hardwoods ≥3 cm DBH in mature longleaf pine stands resulted in a 130–250% increase in deer forage biomass, depending on pine basal area (Blair and Feduccia 1977). Similarly, an Arkansas study demonstrated that overstory thinning alone was insufficient to increase biomass of some forage species within loblolly pine stands, midstory removal was also required (Peitz et al. 1999). Regardless of the objective (i.e., maximizing pine growth or deer forage availability), prescribed fire, selective herbicides, and mechanical hardwood removal during thinning remain the most effective options for limiting hardwood coverage in loblolly pine stands. For example, combinations of selective herbicides and prescribed fire can provide effective control of small hardwood trees and promote forb and grass development in the understory (Mixon et al. 2009), thereby benefiting deer. In fact, one study showed that thinned loblolly pines treated with a combination of herbicide, prescribed fire, and fertilizer provided nearly as much deer forage per hectare as soybean (*Glycine max*) food plots (Edwards et al. 2004).

Prescribed fire has the added benefit of cost-effectiveness. Edwards et al. (2004) reported costs of $25/ha for prescribed burns, compared to $173/ha for herbicide application. Because of the differences in cost and labor intensity (e.g. backpack spraying versus fire-line installation and burn procedures), prescribed fire is often preferred among private landowners. Fortunately, fire alone can increase deer forage availability (Dills 1970). In addition to hardwood control, fire removes the litter layer and maintains a target seral stage (Edwards et al. 2004), which can be manipulated by adjusting the return interval. A fire return interval ranging from 3–5 years is often considered optimal for promoting coverage of preferred deer forage species (Masters et al. 1993, Harper et al. 2016). Shorter fire return intervals preclude woody and semiwoody plants important for cover, browse, and soft mast production (Miller and Miller 1999), whereas longer return intervals may allow shrubs and hardwoods to become too large to control with future fire, requiring additional financial input (e.g., herbicide application) to control (Iglay et al. 2010). However, even proper application of prescribed fire will not benefit deer forage when light is limiting (Harper et al. 2016), highlighting the importance of combining fire with thinning in loblolly pine stands, as needed.

Relatively few studies have considered the tradeoffs associated with managing loblolly pine stands jointly for timber production and wildlife habitat. However, Carley and Grado (2000) modeled the economic tradeoffs of two different row thinning intensities established for maximized timber production (i.e., 25% removal of pines) and increased habitat quality for deer (i.e., 50% removal of pines). They concluded that land expectation values (LEV) were always greatest when managing for maximized timber production, especially as site index increased (Carley and Grado 2000). However, their study only compared two drastically different management regimes. Similar results were obtained from models produced by Barlow et al. (2007), who found that stands managed for maximized timber value produced greater LEVs than those that incorporated wildlife habitat objectives. However, they also concluded that wildlife habitat management could produce benefits (e.g. hunt-lease revenue, forest certification, federal conservation incentives) that could offset foregone timber revenue. Davis et al. (2017) took a similar approach, but included an intermediate management strategy that included joint timber and habitat management for deer or northern bobwhite (*Colinus virginianus*). They found that, although timber-only management resulted in the greatest LEV, differences between timber-only and joint timber and deer management could be offset by lease revenue. As a result, they concluded that joint management of loblolly pine for timber and deer habitat could be nearly as valuable as timber management alone.

Although these studies provide a useful starting point, there is still a need to evaluate the effects of joint management strategies across a range of management intensities at an operational scale. Therefore, we designed and implemented a study to investigate the effects of thinning intensity and prescribed fire on timber and wildlife objectives within loblolly pine stands. Specifically, we quantified changes in deer forage availability and habitat use in response to commercially thinning stands to residual basal areas of 18 m^2/ha, 14 m^2/ha, and 9 m^2/ha, with and without prescribed fire. We also evaluated the ability of commercial logging crews to accurately and precisely thin pine stands to target residual basal areas. The data and conclusions presented herein are the result of the first two growing seasons following the implementation of thinning treatments and the first growing season following prescribed fire.

OBJECTIVES

The research presented here is part of a multi-state project evaluating the effects of mid-rotation loblolly pine silvicultural treatments on both wildlife habitat and stand economics in Georgia and Alabama. The planned silvicultural treatments include the use of different thinning intensities, prescribed fire, selective herbicides, and fertilizers. As part of the initial efforts of this project, my specific objectives were to: (1) determine the response of deer forage to different levels of thinning intensity during the first two growing seasons following thinning operations, (2) determine the additive or interactive effect of prescribed fire on deer forage availability during the first growing season post-fire, (3) evaluate changes in deer use as a response to each treatment combinations, and (4) determine the accuracy and precision with which commercial logging crews were able to meet thinning prescriptions geared towards ecological restoration objectives.

STUDY AREAS

I conducted my study in five pre-commercial thin loblolly pine stands within the Piedmont physiographic region of Georgia (Figure 1.1). Stands were 15-20 years old at project initiation, previously forested in loblolly pine prior to stand establishment, and ranged in size from 36–53 ha. Three of the stands were located in Hancock County, GA and were owned and managed by Weyerhaeuser Company. The remaining two were located on Oconee Wildlife

Management Area (WMA) in Greene County, GA, and managed by the Georgia Department of Natural Resources' Wildlife Resources Division. The climate in the region was subtropical, with a mean annual high of 23.6 ℃, mean annual low of 9.9 ℃, and an average annual precipitation of 117.0 cm (Arguez et al. 2012). The topography across the region primarily consisted of rolling hills and elevation ranged from 134–195 m (NRCS 2002).

Two of the Weyerhaeuser stands contained moderately eroded, well drained soils comprised primarily of Lloyd gravelly loam and Cataula-cecil complex (NRCS 2017). The third Weyerhaeuser stand was comprised of well to excessively well drained soils predominantly consisting of Lakeland sand, Valcluse-Norfolk complex, Fuquay loamy sand, and Ailey-Vaucluse-Lucy complex (NRCS 2017). Soils in the stand on the northern portion of Oconee WMA were moderately eroded, well drained, and predominantly consisted of Lloyd gravelly loam and cecil gravelly loam (NRCS 2017). Soils in the stand on the southern portion of Oconee WMA were moderately to severely eroded, well drained, and predominantly consisted of Lloyd gravelly loam, Pacolet sandy loam, and cecil-Cataula complex.

THESIS FORMAT

The following chapters of my thesis are presented in manuscript format. Chapter 1 is comprised of an introduction and review of relevant literature. Chapters 2 and 3 are manuscript chapters that will each be submitted to peer-reviewed journals. Chapter 2 describes the effects of treatment combinations on white-tailed deer forage availability, as well as the observed response of white-tailed deer to these treatments. Chapter 3 describes the accuracy and precision of commercial logging crews, with implications for ecological restoration efforts that involve timber harvest.

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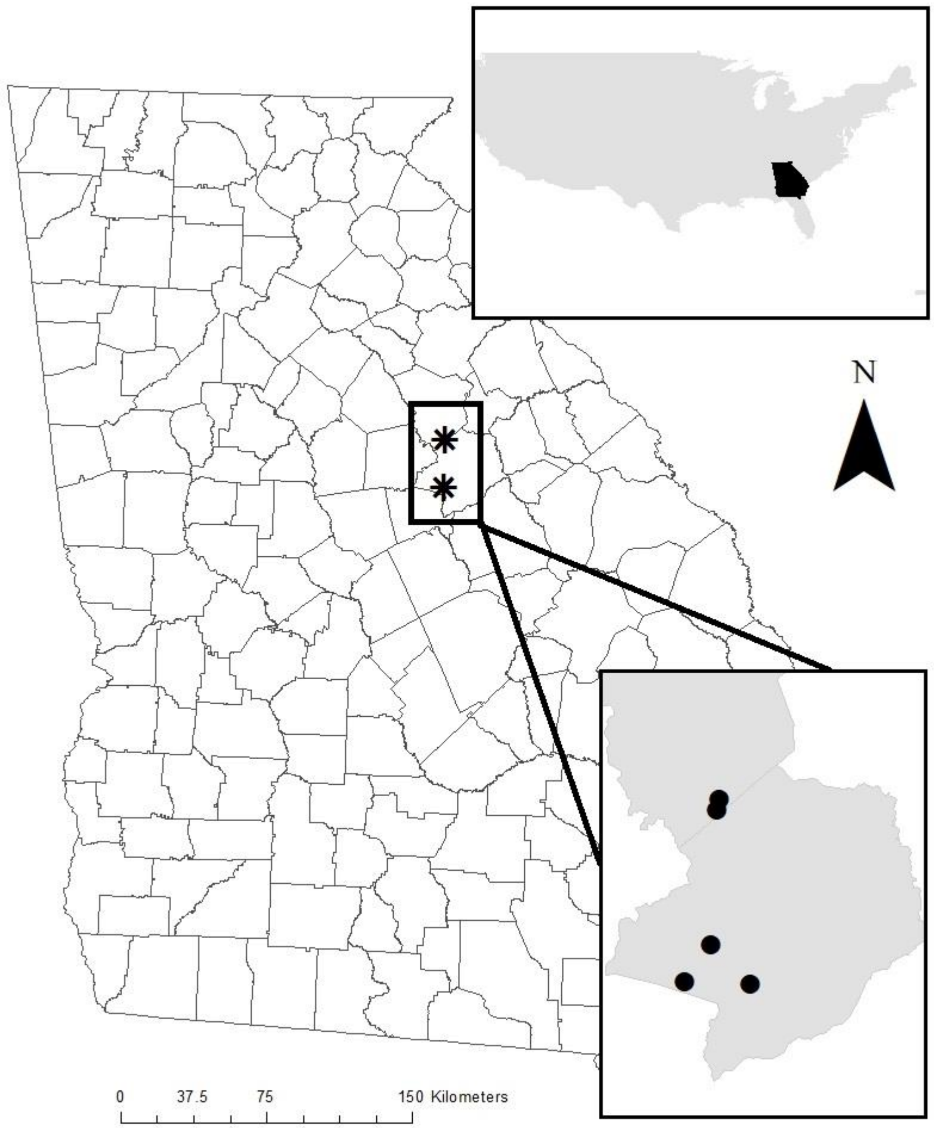

Figure 1.1. Location of study areas in Greene and Hancock counties, Georgia, USA where we evaluated the response of preferred white-tailed deer (*Odocoileus virginianus*) forage plants to three thinning treatments and prescribed fire in loblolly pine (*Pinus taeda*) stands, as well as the accuracy and precision of commercial logging crews during 2017–2018.

CHAPTER 2

EFFECTS OF THINNING INTENSITY AND PRESCRIBED FIRE ON WHITE-TAILED DEER FORAGE AVAILABILITY AND HABITAT USE IN LOBLOLLY PINE STANDS

ABSTRACT

Loblolly pine (*Pinus taeda*) plantations represent approximately 10% of the forested land in the southeastern United States. Though often managed to maximize sawtimber volumes at final harvest, many landowners also incorporate alternative objectives, such as improving habitat quality for game species like white-tailed deer (*Odocoileus virginianus*). Mid-rotation treatments such as commercial thinning and prescribed fire can improve habitat quality for deer by increasing coverage of forage plants within the understory. However, the relationship among thinning intensity, prescribed fire, and forage availability has not been quantified. Therefore, we estimated the percent cover of moderate to highly preferred deer forage plants in 5, 15-20-year-old loblolly pine stands thinned to three residual basal areas (i.e., 9 [low], 14 [medium], and 18 [high] m^2/ha), with and without prescribed fire, within the Piedmont physiographic region of Georgia. We did not detect a difference in coverage of deer forage plants among basal areas during the first growing season post-thin (2017). We applied prescribed fire during the late dormant season of 2018, and compared between-year increases in percent cover of deer forage among treatment combinations. The increase in percent cover of deer forage was nearly two-times greater for the medium basal area treatment compared to the high basal area treatment, but confidence limits were overlapping for the medium and low basal area treatments. Similarly, the increase in forb coverage was greater for the medium and low basal area treatments than the high basal area treatment. Increases in vine and bramble coverage were greater in unburned medium basal area units. Woody browse was not affected by any treatment combination. Our results suggest that thinning loblolly pine stands to 14 m^2/ha can increase coverage of deer forage plants during the first two growing seasons post-thin. Additionally, no measured parameters were informative for deer habitat use within our treatment units. Although we found no evidence to suggest increasing thinning intensity beyond this point results in further increases in deer forage availability, these differences may take >2 growing seasons to manifest.

INTRODUCTION

Planted loblolly pine (*Pinus taeda*) stands comprise approximately 10% of all forested land in the southeastern United States (Wear and Greis 2002, Oswalt et al. 2018). Most of these stands are managed primarily for production of quality sawtimber trees (Miller et al. 2009), an objective that is typically realized 25-30 years after stand initiation depending on factors, such as site index and stocking, that influence tree growth (Stokes and Watson 1996). During that period, stands generally generate revenue at few discrete periods (e.g., thinning and final harvest). To generate additional, consistent revenue, some have suggested non-industrial private forest owners (NIPFOs) consider leasing their property to hunters on an annual basis (Barlow et al. 2007, Macauley 2016, Davis et al. 2017). In contrast, public land managers are less dependent on timber revenue, instead focusing their management efforts on creating and maintaining quality habitat for wildlife, including game species like white-tailed deer (*Odocoileus virginianus*, hereafter deer). In general, deer are the most sought after big game species in the southeastern U.S. (Macauley 2016), so understanding the effects of forest management on both pine timber production and deer habitat quality are of importance to both public and private lands managers, albeit for different reasons.

Many loblolly pine stands are the product of an intensive management process designed to optimize establishment and growth rates by minimizing competition from non-pine woody species (Jones et al. 2009). Some of these treatments also increase coverage of herbaceous vegetation in the understory, which provides forage for deer and habitat for other wildlife species dependent on early successional plant communities (Blair and Enghardt 1976, Jones et al. 2009, Lane et al. 2011). However, competition control can also facilitate rapid canopy closure in loblolly pine stands, which limits sunlight and reduces coverage of herbaceous vegetation (Campbell et al. 2015). Regardless of management intensity, closed-canopy loblolly pine stands will remain essentially devoid of deer forage until mid-rotation treatments, usually thinning, allow sunlight to return to the understory.

From a silvicultural perspective, commercial thinning reduces intraspecific competition and improves pine growth (Stokes and Watson 1996, Smith et al. 1997). However, several have also documented the beneficial effects of thinning on deer forage abundance (Blair and Enghardt 1976, Harrington and Edwards 1999, Peitz et al. 1999, Peitz et al. 2001). For example, herbaceous, vine, and shrub cover were significantly greater in thinned longleaf pine stands compared to untreated controls (Harrington and Edwards 1999). Others have similarly reported an inverse relationship between overstory density and deer forage availability in loblolly pine stands (Blair and Enghardt 1976, Peitz et al. 1999). For example, Blair and Enghardt (1976) thinned loblolly pine stands to various residual basal areas, and found that deer forage availability was greatest in those thinned to the lowest residual basal area (16 m^2/ha). Peitz et al. (1999) performed a similar study and also found that biomass of deer forage plants was greatest in stands thinned to the lowest residual basal area (15 m^2/ha). However, these thinning intensities are relatively conservative for loblolly pine stands when creating and maintaining early successional vegetation in the understory is a primary or competing objective.

Although thinning generally promotes coverage of deer forage plants, it may also release non-pine woody vegetation in the understory, which competes with pines and forage plants for sunlight and below-ground resources (Brender and Cooper 1968, Iglay et al. 2010). However, periodic application of low intensity prescribed fire is a cost-effective option to limit coverage of woody plants and promote coverage of herbaceous vegetation that benefits wildlife such as deer (Harper 2007). For example, prescribed fire applied to thinned loblolly pine stands at 3- and 4-year intervals resulted in increased coverage of both herbaceous and woody browse species in western Arkansas (Masters et al. 1993). Similarly, Lashley et al. (2011) found that combining overstory reduction (i.e., retention and shelterwood cuts) with prescribed fire resulted in the greatest amount of deer forage in upland hardwood stands in Tennessee. However, they also reported the effects of prescribed fire were negligible in closed-canopy forests, emphasizing the importance of combining overstory reduction with fire. Finally, though many studies have evaluated the combined effects of various silvicultural treatments (e.g., Edwards et al. 2004, Mixon et al. 2009, Iglay et al. 2010), little is known about the interaction between fire and overstory density on deer forage availability across a range of thinning intensities in loblolly pine plantations.

Therefore, we initiated a manipulative, operational-scale study to increase knowledge surrounding the effects of thinning intensity and prescribed fire on deer forage availability in loblolly pine stands. We hypothesized percent cover and biomass of deer forage plants would increase with decreasing basal area, and that prescribed fire would decrease coverage of browse species and increase coverage of herbaceous forage species.

STUDY AREAS

We conducted our study in five pre-commercial thin loblolly pine stands within the Piedmont physiographic region of Georgia (Figure 2.1). Stands were 15-20 years old at project initiation, and ranged in size from 36-53 ha. All areas were forested in loblolly pine prior to the current rotation. Three of the stands were located in Hancock County and were owned and managed by Weyerhaeuser Company. The remaining two were located on Oconee Wildlife Management Area (WMA) in Greene County and managed by the Georgia Department of Natural Resources' Wildlife Resources Division. The topography across the region primarily consisted of rolling hills and elevation ranged from a minimum of 134 m to a maximum of 195 m (NRCS 2002).

The regional climate was subtropical, with temperatures ranging from a mean annual high of 23.6 °C to a mean annual low of 9.9 °C. Average annual precipitation was 117 cm (Arguez et al. 2012). Two of the Weyerhaeuser stands contained moderately eroded, well drained soils comprised primarily of Lloyd gravelly loam and Cataula-cecil complex. The third Weyerhaeuser stand was comprised of well- to excessively well-drained soils predominantly consisting of Lakeland sand, Valcluse-Norfolk complex, Fuquay loamy sand, and Ailey-Vaucluse-Lucy complex. Soils in the stand on the northern portion of Oconee WMA were moderately eroded, well-drained, and predominantly consisted of Lloyd gravelly loam and cecil gravelly loam. Soils in the stand on the southern portion of Oconee WMA were moderately to severely eroded, well-drained, and predominantly consisted of Lloyd gravelly loam, Pacolet sandy loam, and cecil-Cataula complex (NRCS 2017).

METHODS

Experimental design

We divided each block (i.e., stand) approximately into thirds, resulting in 3, 11-21 ha plots per block, and randomly prescribed a thinning treatment to each section for a total of 5 replicates per treatment. Thinning treatments included residual (post-thin) basal areas of 9 m^2/ha (low), 14 m^2/ha (medium), and 18 m^2/ha (high). The high residual basal area treatment represented a maximization of residual volume while maintaining tree vigor and mitigating density-related mortality following a first commercial thinning in loblolly pine stands managed primarily for timber (Dean and Baldwin 1992). In contrast, low and medium basal area treatments represented management alternatives landowners might employ in stands where wildlife habitat is a primary or competing objective to timber production, respectively. Commercial logging crews applied the thinning treatments to each stand during February-June 2017.

We subdivided each treatment plot into two subplots (i.e., split-plot design) and randomly assigned a prescribed fire treatment (fire or no fire) to one subplot, for a total of six treatment combinations. Subplots ranged in size from 5-11 ha. We applied low-intensity prescribed fire to assigned units using a strip-head ignition pattern during March-April 2018. In areas receiving incomplete coverage via strip-head ignitions, additional fire was applied to maximize coverage. Because an escaped fire resulted in the consumption of two “no fire” subplots, the final dataset contained a total of 13 unburned and 17 burned treatment subunits, which we analyzed accordingly.

Data collection

We sampled vegetation response to treatments during July-September 2017 and July-August 2018. Specifically, we randomly distributed 20, 20-m permanent transects throughout each plot (10 per subplot). Transects were ≥50 m from the nearest transect and subplot boundary, with each transect oriented perpendicular to harvest rows to avoid potential sampling bias associated with stand edges or harvest rows. We identified all plants <2 m in height that intersected transects. We estimated horizontal cover of each plant by measuring the portion of the plant that intersected the transect (i.e., line-intercept method).

From these data, we identified moderate to highly preferred deer forage plants based on available literature (Warren and Hurst 1981, Miller and Miller 1999). We grouped deer forage plants by growth habit, including forbs (both legume and non-legume), vines and brambles, and woody browse (i.e., woody plants, shrubs, and semi-woody browse such as poison ivy [*Toxicodendron radicans*]). For each transect, we calculated the overall percent cover of forage and percent cover of forage by growth habit during each year. In addition, we calculated the change in percent cover of forage by growth habit for each transect from 2017–2018.

We also used exclusion cages to estimate the effect of each treatment combination on biomass of moderate-to-highly preferred deer forage plants. Specifically, we randomly placed 3, 1-m^2 exclusion cages made from 1-m tall snow fencing within each subplot during March-April 2018. We positioned all cages ≥50 m from any edge and ≥25 m from other cages. During July 2018, we identified deer forage plants within each cage, and collected all parts of those plants consumed by deer (i.e., succulent stems, leaves, and growing tips) using hand shears. We placed collected samples in paper bags for transportation and storage. To facilitate efficient drying and prevent molding, we separated large samples into multiple bags. In the field, we placed all bagged samples in a shaded area until we transported them to a cooler or drying oven. In the lab, we first recorded a pre-drying (wet) mass for each sample. We then placed samples into a forced-air oven set to 60 °C for 48 h. After drying, we removed all samples from the oven and recorded their dry mass. Additionally, we placed a subset of empty bags into the oven for 48 h to determine the average dry mass of an empty bag. We then subtracted our average empty bag mass from each sample mass to calculate the dry mass of plant materials.

Finally, we deployed camera traps from 1 August–4 September of each year to evaluate deer responses to treatment combinations. Specifically, we placed cameras at two randomly generated locations ≥100 m apart within each subplot. We also ensured cameras were ≥50 m from subplot boundaries and oriented north to avoid glare from the sun. We programmed cameras to capture three images per motion-trigger event. All images were analyzed by one observer. For each image, we counted, sexed, and aged (i.e., fawn vs adult) each identifiable deer. Images that were obviously deer, but could not be aged or sexed, were included in total deer counts. To avoid double counting individual deer, we censored images taken ≤10 minutes apart.

Statistical analyses

We utilized mixed-effect analyses of variance (ANOVA) using package "nlme" (Pinheiro et al. 2018) in program R (R Core Team 2018) to test for the effects of thinning treatment on percent cover of deer forage during 2017, as well as the effects of thinning treatment and prescribed fire on coverage and biomass of deer forage in 2018. However, because prescribed fire was applied between 2017 and 2018, we analyzed the change in percent cover for each forage class from 2017–2018, similar to a before-after-control-impact (BACI) design (Conner et al. 2016). Due to uncertainty whether the thinning and fire treatments we evaluated had an additive or interactive effect on parameters of interest, we analyzed the data using both an additive and interactive model and used Akaike's Information Criterion, adjusted for small sample size (AICc), to evaluate the relative level of support for each model in package

“AICcmodavg” (Mazerole 2017). We also included a null model in each candidate set. We considered models within ≤2 ΔAICc points of the top model competitive, and used model-averaging to account for model selection uncertainty among informative parameters (those with confidence limits not overlapping zero) within competitive models using R package “MuMIn” (Barton 2018). In cases where the null model was the only competitive model, we considered our models uninformative and concluded that our variables of interest were poor predictors of the response. Research block and treatment subunit were included as random effects to account for variability within and among stands and subunits. We set α=0.05 for all tests.

We used generalized mixed-effect models with a Poisson distribution to test for the effects of treatment on the number of white-tailed deer images captured in each subplot using R package “lme4” (Bates et al. 2015). This approach used the number of deer photographed as a surrogate for habitat use by deer. As with the forage data, we included both additive and interactive models with thinning and fire treatments as fixed effects, and evaluated the relative support for each model, and a null model, using AICc. We used the same criteria as with the forage data for constructing the candidate model set, identifying informative predictors, and estimating effect sizes.

RESULTS

During 2017 (first growing season post-thin), there was similar percent cover of deer forage among treatments, regardless of growth habit (Table 2.1). However, we photographed 2 times as many deer in low residual basal area units as in high residual basal area units during 2017 (Table 2.2).

Both the additive and the interactive models were included in the confidence set of models for the change in percent cover of total deer forage from 2017–2018 (Table 2.3). Based on the model-averaged estimates, the increase in percent cover of total deer forage from 2017–2018 was greater in the medium basal area, compared to the high basal area, units. Specifically, percent cover of total deer forage increased by 6.8 percentage points in the high basal area treatment, compared to 12.4 percentage points in the medium basal area treatment (Table 2.4). The effect of the low basal area treatment approached statistical significance, and was estimated to result in a 10.2 percentage point increase in total deer forage from 2017–2018 (Table 2.4). Confidence limits associated with the parameter estimates for the medium and low basal area treatments overlapped considerably, indicating the increase in total deer forage from 2017–2018 likely did not statistically differ between these treatments.

The effects of thinning intensity and prescribed fire on change in percent cover of deer forage by growth habit varied. For forbs, the additive model received the greatest weight of support (Table 2.3). As expected, the increase in forb coverage was greater for the medium and low basal area treatments compared to the high basal area treatment. Specifically, forb cover increased 6.8 percentage points from 2017–2018 in the high basal area treatment, versus 12.7 and 11.8 percentage points in the medium and low basal area treatments, respectively (Table 2.4). However, confidence limits associated with the parameter estimates for the medium and low basal area treatments overlapped, indicating that the increase in forb cover from 2017–2018 likely did not differ between these treatments. Finally, there was no evidence that prescribed fire influenced the increase in forb cover from 2017–2018 (Table 2.4).

Both the additive and interactive models were in the confidence set of models predicting the change in cover of vines and brambles from 2017–2018 (Table 2.3), but the medium basal area treatment and fire were the only informative parameters from those models. Based on the model-averaged estimates, vine and bramble coverage increased 10.1 percentage points from

2017–2018 in the high basal area treatment, compared to 17 percentage points in the medium basal area treatment. Further, vine and bramble coverage increased 10.1 percentage points from 2017–2018 in unburned areas, versus only 4.8 percentage points in burned areas (Table 2.4). None of our models were good predictors of percent cover of woody browse (Table 2.3), forage biomass (Table 2.5), or use by deer during 2018 (Table 2.6).

DISCUSSION

Although the response of understory vegetation to thinning was almost immediately apparent across treatments (Figure 2.2), differences among thinning treatments did not manifest until 2018, the second growing season post-harvest. Similarly, Peitz et al. (1999) reported that biomass of deer browse increased in response to both thinning and midstory hardwood removal 2 years post-treatment in Arkansas, but effect sizes increased in subsequent years. Most similar studies do not report on vegetation responses until several years after silvicultural treatments are implemented. For example, the first report that deer forage increased with thinning intensity in loblolly pine stands was based on data collected approximately 14 years post-thinning (Blair and Enghardt 1976). Similarly, Lashley et al. (2011) reported on data collected in hardwood stands 6-7 years post-harvest. Therefore, our data help fill the information gap related to the timing of vegetation responses managers might expect after implementing silvicultural treatments to increase deer forage availability.

However, our hypothesis that deer forage would increase with decreasing basal area was not entirely supported by the data. Specifically, neither percent cover of total forage nor percent cover of any growth habit category consistently increased with decreasing basal area during 2017, or from 2017–2018. This finding was not completely unexpected for vines and brambles or woody browse given that we only monitored stands for 2 years post-treatment, and many browse species are perennial, woody plants that take longer to respond following disturbance (Peitz et al. 1999). We did, however, observe a relatively rapid response by sweetgum (*Liquidambar styraciflua*), which is not a preferred deer forage, within all treatment blocks. Because sweetgum can outcompete preferred deer forage plants, it is important for managers to recognize the need for additional treatments post-thinning (Jones et al. 2009).

However, our findings related to percent cover of total forage and forbs were consistent with data from a demonstration forest in Mississippi. In that study, forb biomass was greater for residual basal areas <20 m^2/ha, but did not continue to change in response to thinning below 16 m^2/ha (Traugott and Kushla, unpublished data). Similarly, Masters et al. (1993) reported that the relationship between overstory density and understory forage is curvilinear, suggesting that there may be an asymptote beyond which further decreases in overstory density will not result in additional increases in deer forage. In contrast, Blair and Enghardt (1976) thinned 20-year-old loblolly pine stands in Louisiana every five years to maintain residual basal areas of 23, 20, and 16 m^2/ha, and found that forage availability was indeed greatest in stands thinned to the lowest basal area. Peitz et al. (1999) reported similar results for loblolly pine stands in Arkansas. However, the lowest residual basal area treatments in those studies were relatively conservative compared to those in the current study. While we cannot be certain, it is possible that any differences in cover of deer forage between our medium and low residual basal area treatments will take >2 years to manifest.

As was the case for thinning intensity, our results related to the effects of prescribed fire on deer forage were not entirely consistent with our *a priori* hypothesis. Specifically, although the between-year change in coverage of vines and brambles was negatively affected by fire, which we expected, percent cover of woody browse did not decrease and percent cover of forbs did not increase in response to fire. The lack of a response of woody browse to fire likely resulted from the timing of our fire treatments. Specifically, we applied fire once, during the dormant season, which likely resulted in only top-kill and subsequent resprouting of woody plants from their root stock (Brender and Cooper 1968, Lashley et al. 2011, Harper et al. 2016). As a result, many of these species likely attained similar sizes during both 2017 and 2018 sampling seasons. In contrast, many of the vegetation communities that are most beneficial to deer are a product of repeated fires implemented at a semi-regular interval. For example, Masters et al. (1993) recommended a fire return interval of 3-5 years to maximize coverage of herbaceous and woody deer forage.

Nonetheless, fire did negatively impact the increase in vine and bramble coverage from 2017–2018. Because these plants are an important contributor to nutritional carrying capacity for deer (Miller and Miller 1999, Peitz et al. 1999, Peitz et al. 2001), applying prescribed fire immediately post-thinning could temporarily decrease habitat quality for deer. In addition, Lashley et al. (2015) reported that lactating does tend to avoid recently burned areas, likely due to a perceived lack of adequate cover. Accordingly, they recommended varying application of prescribed fire spatiotemporally across a property to avoid elimination or reduction of deer forage and cover across an entire property at the same time.

In contrast to the changes in percent cover of some forage categories we observed in response to thinning and fire, we did not detect a similar relationship for forage biomass, which is likely attributable to our sampling intensity. Specifically, we sampled biomass with only 3, 1-m^2 cages per 5-11 ha treatment unit. In contrast, Iglay et al. (2010) initially sampled biomass using 10, 1-m^2 cages per 10 ha treatment unit, but found that this sampling intensity resulted in high coefficients of variance. In response, they increased their sampling effort to 20 cages per treatment unit. Peitz et al. (1999, 2001) used an even more intensive sampling scheme, with 25, 1 m^2 subplots per 0.08 ha treatment unit.

Nonetheless, our findings relative to total deer forage coverage were consistent with an increase in nutritional carrying capacity from the high basal area treatment to the medium and low basal area treatments. However, because we did not quantify forage nutrient content for our biomass samples, we cannot be certain how the treatments we evaluated affected the magnitude or direction of their effects on nutritional carrying capacity. Regardless, nutritional carrying capacity is a relative index of the availability of a certain nutrient of interest, often energy or protein, which does not account for the availability of all required nutrients, requirement differences among age and sex classes, or changes in plant composition over time (Wood 1988). Accordingly, we believe that our percent cover estimates serve as a reasonable index of relative differences in nutritional carrying capacity among treatments.

Finally, although we captured images of nearly twice as many deer within low basal area units during 2017, none of our vegetation metrics provide a reasonable explanation for this observation. However, it is possible that the increased levels of disturbance associated with the low basal area treatment could have resulted in greater prevalence of young, high-nutrient growth that would be attractive during the late-summer, or perceived differences in cover or ease of movement (Lashley et al. 2015). Nonetheless, it is more likely that our treatment units, which were significantly smaller than the average home range size of white-tailed deer, were not independent of each other and the number of deer captured within each treatment unit was actually driven by other, unmeasured, factors.

MANAGEMENT IMPLICATIONS

Overall, our results suggest that managers should consider thinning to 14 m^2/ha or less when maximizing deer forage availability is a priority objective. However, we found no evidence to suggest thinning below this target will increase deer forage during the first two growing seasons post-thinning, though we are unsure if or how this will change in subsequent years. Similarly, while prescribed fire may result in an immediate decrease in vine and bramble availability for deer, repeated treatments may result in benefits over the longer term. However, the negative effects of fire on woody plants might be mitigated by using prescribed fire on only a subset of a property in any given year. Such practice will ensure that a diversity of successional stages are maintained across the property, while minimizing the disturbance in any one year. Finally, additional mid-rotation treatments like selective herbicides may be necessary to control undesirable hardwoods that compete with preferred deer forage plants, but are not effectively controlled with prescribed fire.

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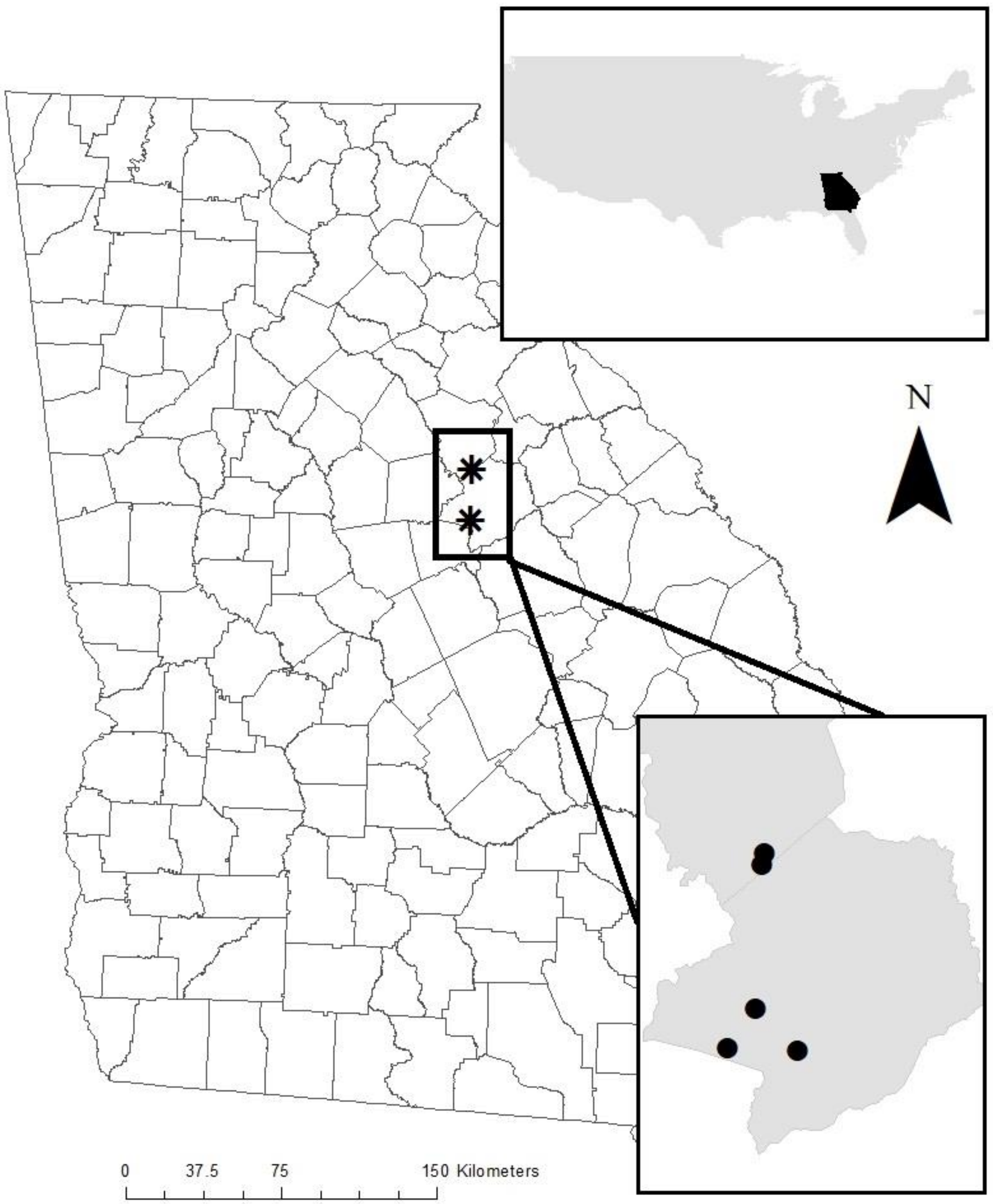

Figure 2.2. Location of study areas in Greene and Hancock counties, Georgia, USA where we evaluated the response of preferred white-tailed deer (*Odocoileus virginianus*) forage plants to three thinning treatments and prescribed fire in loblolly pine (*Pinus taeda*) stands during 2017–2018.

Figure 2.2. Images show understory response approximately eight weeks after the completion of thinning operations on study areas in Greene and Hancock counties, Georgia, USA where we evaluated the response of preferred white-tailed deer (*Odocoileus virginianus*) forage plants to three thinning treatments and prescribed fire in loblolly pine (*Pinus taeda*) stands during 2017–2018. (Photo credit: Allison G. Colter)

Table 2.1. Parameter estimates (β), standard errors (SE), 95% confidence limits (LCL and UCL), and *P*-values predicting the effects of residual basal area on the percent cover (%) of preferred white-tailed deer (*Odocoileus virginianus*) forage plants, overall and by growth habit, in loblolly pine (*Pinus taeda*) stands within the Piedmont physiographic region of Georgia during 2017.

Model	**β**	**SE**	**LCL**	**UCL**	***P*-value**
Total					
Intercept[a]	5.81	1.12	3.62	7.99	<0.001
Medium[b]	-0.85	0.73	-2.36	0.66	0.26
Low[c]	-0.93	0.73	-2.44	0.58	0.22
Forbs					
Intercept[a]	3.87	1.06	1.79	5.95	<0.001
Medium[b]	0.51	1.05	-1.65	2.66	0.63
Low[c]	1.13	1.05	-1.02	3.29	0.29
Vines and brambles					
Intercept[a]	6.18	1.48	3.27	9.08	<0.001
Medium[b]	-1.42	1.17	-3.84	0.99	0.24
Low[c]	-1.59	1.17	-4.01	0.82	0.19
Woody browse					
Intercept[a]	7.44	1.75	4.00	10.87	<0.001
Medium[b]	-1.61	1.54	-4.78	1.56	0.31
Low[c]	-2.33	1.55	-5.50	0.86	0.15

[a] High residual basal area (18 m^2/ha) treatment
[b] Medium residual basal area (14 m^2/ha) treatment
[c] Low residual basal area (9 m^2/ha) treatment

Table 2.2. Parameter estimates (β), standard errors (SE), 95% confidence limits (LCL and UCL), and *P*-values predicting the effects of residual basal area on the log of the number of white-tailed deer (*Odocoileus virginianus*) photographed in loblolly pine (*Pinus taeda*) stands within the Piedmont physiographic region of Georgia during August 2017.

Model	**β**	**SE**	**LCL**	**UCL**	***P*-value**
Intercept[a]	2.03	0.40	4.19	13.83	<0.001
Medium[b]	0.55	0.33	6.84	25.39	0.10
Low[c]	0.70	0.33	7.92	29.43	0.03

[a] High residual basal area (18 m^2/ha) treatment
[b] Medium residual basal area (14 m^2/ha) treatment
[c] Low residual basal area (9 m^2/ha) treatment

Table 2.3. Number of parameters (K), Akaike's Information Criterion (AICc), difference from lowest AICc (ΔAICc), and model weights (*w*) for models used to predict the effects of residual basal area and prescribed fire on the change in percent cover (%) of preferred white-tailed deer (*Odocoileus virginianus*) forage plants from 2017–2018, overall and by growth habit, in loblolly pine (*Pinus taeda*) stands within the Piedmont physiographic region of Georgia.

Model	***K***	**AICc**	**ΔAICc**	***w***
Total				
Basal area * fire	10	6616.50	0.0	0.51
Basal area + fire	8	6617.04	0.54	0.39
Null	5	6619.66	3.15	0.10
Forbs				
Basal area + fire	8	2246.51	0.0	0.70
Basal area * fire	10	2249.61	3.10	0.17
Null	5	2252.05	5.55	0.05
Woody browse				
Null	5	2043.21	0.00	0.89
Basal area + fire	8	2047.95	4.74	0.08
Basal area * fire	10	2049.95	6.73	0.03
Vines and brambles				
Basal area + fire	8	2173.03	0.00	0.53
Basal area * fire	10	2173.49	0.46	0.42
Null	5	2177.77	4.75	0.05

Table 2.4. Parameter estimates (β), standard errors (SE), 95% confidence limits (LCL and UCL), and *P*-values predicting the effects of residual basal area and prescribed fire on the change in percent cover (%) of preferred white-tailed deer (*Odocoileus virginianus*) forage plants from 2017–2018, overall and by growth habit, in loblolly pine stands (*Pinus taeda*) within the Piedmont physiographic region of Georgia.

Model	**β**	**SE**	**LCL**	**UCL**	***P*-value**
Total					
Intercept[a]	6.84	1.25	4.39	6.84	<0.001
Medium[be]	5.56	2.19	1.13	10.00	0.01
Low[ce]	3.42	1.69	-0.08	6.92	0.06
Fire[d]	1.16	1.70	-2.37	4.69	0.50
Forbs					
Intercept[a]	6.85	1.96	3.02	10.68	<0.001
Medium[b]	5.86	2.00	1.73	9.99	0.01
Low[c]	5.09	2.00	0.96	9.21	0.02
Fire[d]	2.88	1.69	-0.61	6.37	0.10
Vines and brambles					
Intercept[a]	10.13	2.01	6.21	14.06	<0.001
Medium[be]	6.90	3.33	0.37	13.43	0.05
Low[c]	3.07	2.11	-1.28	7.41	0.16
Fire[d]	-5.28	1.78	-8.94	-1.62	0.01

[a] High residual basal area (18 m^2/ha) treatment and no fire
[b] Medium residual basal area (14 m^2/ha) treatment
[c] Low residual basal area (9 m^2/ha) treatment
[d] Effect of prescribed fire treatments
[e] Weighted average of competing models

Table 2.5. Number of parameters (K), Akaike's Information Criterion (AICc), difference from lowest AICc (ΔAICc), and model weights (*w*) for models used to predict the effects of residual basal area and prescribed fire on biomass production of preferred white-tailed deer (*Odocoileus virginianus*) forage plants, overall and by growth habit, in loblolly pine (*Pinus taeda*) stands within the Piedmont physiographic region of Georgia during 2018.

Model	***K***	**AICc**	**ΔAICc**	***w***
Total				
Null	5	2374.08	0.00	0.83
Basal area + fire	7	2379.73	5.65	0.06
Basal area * fire	8	2381.93	7.84	0.02
Forbs				
Null	5	780.26	0.00	0.84
Basal area + fire	7	784.13	3.87	0.12
Basal area * fire	8	786.54	6.28	0.04
Woody browse				
Null	5	823.84	0.00	0.95
Basal area + fire	7	830.17	6.33	0.04
Basal area * fire	8	832.68	8.84	0.01
Vines and brambles				
Null	5	763.69	0.00	0.95
Basal area + fire	7	769.70	6.00	0.05
Basal area * fire	8	774.56	10.87	0.00

Table 2.6. Number of parameters (K), Akaike's Information Criterion (AICc), difference from lowest AICc (ΔAICc), and model weights (*w*) for models used to predict the effects of residual basal area and prescribed fire on the log of the number of white-tailed deer (*Odocoileus virginianus*) images in loblolly pine (*Pinus taeda*) stands within the Piedmont physiographic region of Georgia during August 2018.

Model	***K***	**AIC_C**	**ΔAIC_C**	***w***
Null	3	437.50	0.00	0.92
Basal area + fire	6	442.81	5.31	0.06
Basal area * fire	8	445.72	8.22	0.02

CHAPTER 3

ACCURACY AND PRECISION OF COMMERCIAL THINNING TO MEET ECOLOGICAL RESTORATION OBJECTIVES IN SOUTHERN PINE STANDS

ABSTRACT

The southeastern U.S. is one of the most biologically diverse regions of the world and much of this diversity is associated with southern pine (*Pinus* spp.) ecosystems and their fire-maintained plant communities. However, coverage of these systems has declined, in part, due to fire exclusion and management of relatively dense stands for fiber production. Although reintroduction of prescribed fire can be beneficial, thinning is also necessary to return sunlight to the forest floor and stimulate herbaceous vegetation in dense pine stands. However, thinning prescriptions associated with ecological restoration objectives are much lower than those typically employed in commercial thinning operations, and the effectiveness of such operations at achieving restoration objectives has not been evaluated. Therefore, we quantified the accuracy and precision with which commercial logging crews thinned pre-marked and unmarked mid-rotation loblolly pine stands to residual basal areas of 9, 14, and 18 m^2/ha. At all basal areas, logging crews were able to thin stands within ≤10% of the target, but precision was slightly greater in pre-marked stands. We believe the thinning accuracy and precision we observed are sufficient to achieve ecological restoration objectives, and that the added expense associated with pre-marking stands was not justified by the relatively minor increase in precision. Overall, it

appears as though commercial thinning operations are a viable means of reducing overstory pine densities to levels that better correspond with restoration objectives for declining species.

INTRODUCTION

The southeastern United States is a hotspot for biological diversity (Brockway and Lewis 2003, Noss et al. 2014). However, many endemic wildlife species within the region are in decline due to the loss of longleaf pine (*Pinus palustris*) woodlands and savannas (Jones and Dorr 2004, commonly referred to as open-pine systems). Some examples include the northern bobwhite (*Colinus virginianus*), gopher tortoise (*Gopherus polyphemus*), and red-cockaded woodpecker (*Leuconotopicus borealis*). For northern bobwhite, much interest in habitat restoration has to do with their economic and cultural importance as a game species, whereas gopher tortoises and red-cockaded woodpeckers are nongame species that serve important roles as ecosystem engineers. Historically, much of the Gulf Coastal Plain was comprised of mature longleaf pine savannas maintained with frequent, low-intensity fires that perpetuated a park-like understory comprised of early successional plant communities (Frost 1993, Landers et al. 1995, Hedrick et al. 2007). Today, most of these former longleaf stands have been converted to row-crop agriculture or short-rotation slash (*P. elliottii*) or loblolly (*P. taeda*) pine stands (Frost 1993, Alavalapati et al. 2002).

The silvics of loblolly pine are much different from the longleaf pine they have replaced. For instance, the crowns of loblolly pines are considerably denser than those of longleaf, resulting in greater canopy closure at an earlier age (Burns and Honkala 1990). At canopy closure, understory vegetation is essentially shaded out, save for some shade-tolerate plant species (Blair 1969). Loblolly pines are also less fire-tolerant than longleaf, making management for species reliant on frequent fire more difficult. Additionally, most loblolly pine stands are managed to maximize timber volume, an objective at odds with wildlife that require herbaceous understory plant communities (Brennan 1991, Miller et al. 2009). Fortunately, there is increasing interest in incorporating ecological objectives into loblolly pine management. Because reforestation is a slow process, taking advantage of the extensive coverage of loblolly pine is sometimes more optimal than clearcutting and converting loblolly stands to longleaf. Specifically, the presence of loblolly pines does not inherently preclude species reliant on early successional plant communities, and various mid-rotation loblolly pine treatments enhance coverage of these plants (Blair and Enghardt 1976, Conroy et al. 1982, Peitz et al. 1999). Further, thinning is required even in longleaf stands where increasing herbaceous plant coverage is an objective (Harrington and Edwards 1999).

As a result, thinning recommendations have been developed for a variety of species including gopher tortoises, northern bobwhites, red-cockaded woodpeckers, and others (Aresco and Guyer 1999, Walters et al. 2002, Little et al. 2006). For example, pine stands managed for northern bobwhite are generally thinned to basal areas between 9-14 m^2/ha, with some recommending basal areas as low as 7 m^2/ha (Masters et al. 2007). Similarly, Walters et al. (2002) recommend maintaining mature pine stands at low to moderate residual basal areas to maximize habitat quality for red-cockaded woodpeckers. Though there are relatively few mature longleaf pine stands remaining, artificial nest boxes allow for occupancy of red-cockaded woodpeckers in younger loblolly pine stands, provided that pines are of adequate size (Copeyon 1990, Allen 1991).

However, many of these wildlife-focused recommendations involve thinning stands to much lower tree densities than is typical for commercial logging operations (Huang and Konrad 2002). If logging crews are unable to consistently achieve these low target basal areas, ecological restoration efforts like creating or enhancing habitat for species of conservation concern could be impeded. In addition, although pre-thin marking operations can improve thinning accuracy and precision, such practices add considerable costs (Maggard and Barlow 2018). Therefore, we evaluated the accuracy and precision with which commercial logging crews were able to thin to three different target basal areas via two methods within mid-rotation loblolly pine stands. We predicted that accuracy and precision of thinning operations would decrease as the target basal area decreased, and that accuracy and precision would be greater for pre-marked stands versus those harvested via operator-select thinning.

STUDY AREAS

Study sites were located in the Piedmont physiographic region of Georgia within 5, 15-20-year-old, unthinned loblolly pine stands (Figure 3.1). All stands had ≥1 loblolly pine rotation prior to the establishment of the current stand, and ranged from 36-53 ha in size. Three of the stands were located in Hancock County, GA and were owned and managed by Weyerhaeuser Company. The remaining two were located on Oconee Wildlife Management Area (WMA) in Greene County, GA, and managed by the Georgia Department of Natural Resources' Wildlife Resources Division. The climate in the region was subtropical, with a mean annual temperature of 16.7 ℃, and mean annual precipitation of 117 cm (Arguez et al. 2012). The topography across the region primarily consisted of rolling hills and elevation ranged from a minimum of 134 m to a maximum of 195 m (NRCS 2002).

Two of the Weyerhaeuser stands contained moderately eroded, well drained soils comprised primarily of Lloyd gravelly loam and Cataula-cecil complex (NRCS 2017). The third Weyerhaeuser stand was comprised of well to excessively well drained soils predominantly consisting of Lakeland sand, Valcluse-Norfolk complex, Fuquay loamy sand, and Ailey-

Vaucluse-Lucy complex (NRCS 2017). Soils in the stand on the northern portion of Oconee WMA were moderately eroded, well drained, and predominantly consisted of Lloyd gravelly loam and cecil gravelly loam (NRCS 2017). Soils in the stand on the southern portion of Oconee WMA were moderately to severely eroded, well drained, and predominantly consisted of Lloyd gravelly lam, Pacolet sandy loam, and cecil-Cataula complex.

METHODS

Experimental design

We divided each block (i.e., stand) approximately into thirds, resulting in 3, 11-21 ha plots per block, and randomly prescribed a thinning treatment to each section for a total of 5 replicates per treatment. Thinning treatments included post-thin (residual) basal areas of 9 m^2/ha (low), 14 m^2/ha (medium), and 18 m^2/ha (high). The high residual basal area treatment represented the maximum retained volume while minimizing density-related mortality following a first thinning in loblolly pine stands managed primarily for timber production. In contrast, low and medium basal area treatments represented management alternatives landowners might employ in stands where habitat restoration is a primary or competing objective to timber production. Prior to thinning, all trees that were to be retained within Weyerhaeuser-owned stands were marked by commercial logging crews. In contrast, Oconee WMA stands were harvested via operator-select thinning after loggers thinned pre-marked “model” patches to obtain a visual reference for each target basal area. Thinning operations were implemented by commercial logging crews during February–June 2017.

Data collection

We conducted a 5% timber inventory within each treatment unit following the completion of thinning operations. Specifically, we systematically distributed 0.04-ha fixed-radius plots at a density of 1/0.8 ha throughout each unit. Within each plot, we measured the diameter at breast height (DBH) of all loblolly pine trees with a DBH ≥11.94 cm (i.e., merchantable diameter class), and used these data to calculate loblolly pine basal area at each plot. We also used a 10-factor wedge prism to estimate basal area at 20 systematically distributed sampling points throughout each unit. We counted all fully refracted trees, regardless of size, as well as every other borderline tree (i.e., a tree with which the refracted portion of bole aligns with, but does not overlap the main bole). For both sampling methods, we calculated an error rate for each sampling point by subtracting the target basal area from the observed basal area, dividing by the target, and multiplying the result by 100. We also calculated the standard deviation of basal areas within each treatment unit to determine whether consistency in observed basal area varied by treatment.

Statistical analyses

For both fixed and variable radius plots, we utilized mixed-effect analyses of variance (ANOVAs) using package "nlme" (Pinheiro et al. 2018) in program R (R Core Team 2018) to test for the effects of both the target basal area and the method of thinning (pre-marked vs. operator-select) on percent error [(observed-target)/target*100] of observed basal areas relative to the target, as well as the standard deviation (variation around the mean) of observed basal areas within each treatment unit. We included research block and treatment unit as random effects to account for the data structure associated with our study design. We set $\alpha=0.05$ for all tests.

RESULTS

Data from both fixed- and variable-radius plots suggested that observed basal area was greater than target basal area for plots receiving the low (9 m^2/ha) residual basal area treatment. Specifically, basal area was 6% (0.5 m^2/ha) greater than the target based on fixed-radius plots, and 16% (1 m^2/ha) greater than the target based on variable-radius plots. In addition, within variable-radius plots, observed basal area was 7.4% (1 m^2/ha) greater than the target for plots receiving the medium (14 m^2/ha) residual basal area treatment. Pre-marking stands for thinning cost $105/ha, but there was no evidence to suggest that pre-marking stands affected accuracy of thinning operations, regardless of sampling method (Table 3.1).

Precision of thinning operations was similar across basal areas based on fixed-radius plot data. However, the fixed-radius plot data indicated thinning precision was less (i.e., standard deviation increased) for stands thinned via operator-select. In contrast, variable-radius plot data indicated thinning precision was greater (i.e., standard deviation decreased) in low (9 m^2/ha) residual basal area plots than in high (18 m^2/ha) residual basal area plots. There was no evidence to suggest thinning precision differed between harvest methods based on variable-radius plot data (Table 3.2).

DISCUSSION

Although accuracy rates differed among basal areas, only the lowest residual basal area treatment resulted in an error rate >10%, according to variable-radius plot data. We believe this finding was more related to sampling method than an actual difference in operational effectiveness. Specifically, we only measured "merchantable" timber (i.e., ≥12 cm DBH) in our fixed-radius plots, excluding small diameter trees that could contribute relatively little to basal area calculations. In contrast, variable-radius plots include even small diameter trees in the calculation of basal area, provided they are close enough to the observer (Avery and Burkhart 2002, Packard and Radtke 2007). This is often the case in dense, young loblolly pine stands, which inflates basal area estimates. Though quick and easy to utilize, variable radius plots are most effective within stands comprised of large trees and a relatively open understory (Avery and Burkhart

2002). However, variable-radius plots are still commonly used in relatively young stands, and ecologists and managers need to understand the biases and benefits of various timber inventory techniques when working towards ecological restoration objectives.

Nonetheless, our accuracy estimates suggest that commercial logging crews were able to consistently thin stands to within 10% of prescribed basal areas. We consider this error rate acceptable given the variability in basal area recommendations for open pine focal species. For example, common basal area recommendations for northern bobwhite range from 7-14 m^2/ha (Masters et al. 2007). Similarly, red-cockaded woodpecker management guidelines typically recommend basal areas ranging from 9-18 m^2/ha, depending on whether the areas are designated for clusters or foraging (USFWS 1985, Porter and Labisky 1986). Finally, basal area recommendations for gopher tortoise habitat restoration are generally ≤7 m^2/ha (Aresco and Guyer 1999), suggesting that such recommendations are robust to minor variation in thinning accuracy.

We did, however, observe a statistically significant decrease in precision with regard to achieving target basal areas within plots harvested via operator-select thinning, and believe the implications of this finding depend on management objectives. Pre-marking cost \$105/ha in the current study, and averages \$83/ha across Alabama (Maggard and Barlow 2018). Therefore, marking timber prior to thinning adds considerable costs. However, precise spacing between trees maximizes sunlight availability and ensures even coverage of herbaceous understory plants. Conversely, decreased precision increases heterogeneity in canopy cover, thereby increasing variation in light availability along the forest floor. Such variation in light availability may benefit ectothermic reptiles and amphibians by providing access to solar radiation during cool seasons, as well as shade during warm seasons (Sutton et al. 2013). For example, Hyslop et al.

(2009) observed differences in seasonal microhabitat use among eastern indigo snakes (*Drymarchon couperi*), and found that snakes were more often located in areas with greater basal areas during warmer seasons. Conversely, during cooler weather, ectothermic species like indigo snakes could bask in more open areas within heterogeneous stands.

Recreating the effects of large-scale fires is unrealistic within the pine forests of the southeastern United States (Schwilk et al. 2009). Instead, efforts to restore desired understory community compositions should evaluate the use of alternative management techniques to reduce overstory densities and restore desired understory plant communities (McGuire et al. 2001, Outcalt 2005, Van Lear et al. 2005). Our results suggest that thinning operations conducted by commercial logging crews are a viable means of achieving this objective. With acceptable levels of accuracy and precision, commercial logging crews represent a readily available, and in some cases profitable, means of decreasing canopy cover to levels that maximize understory community development and habitat quality for many southern pine focal species of conservation concern.

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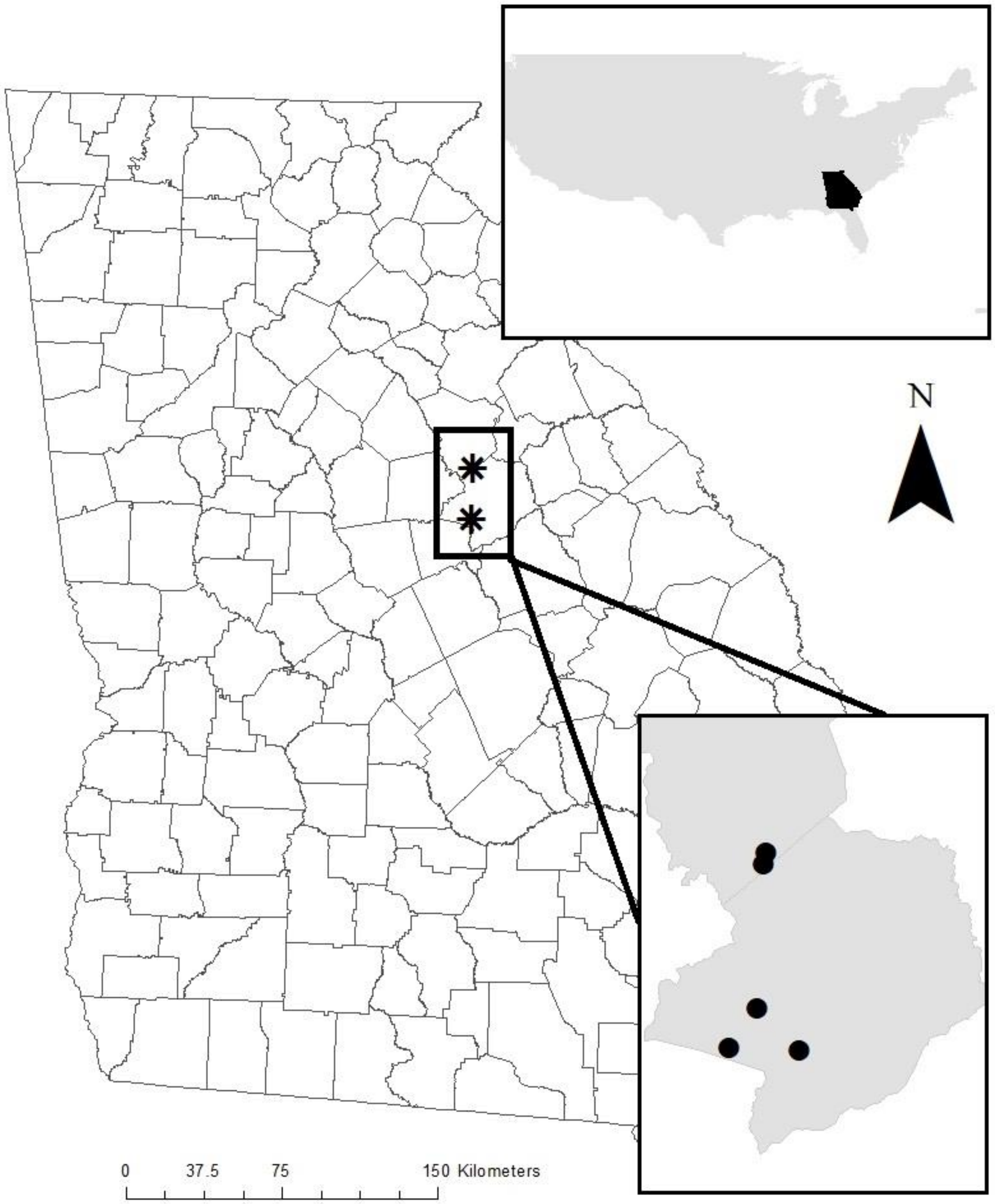

Figure 3.1. Location of study areas in Greene and Hancock counties, Georgia, USA where we evaluated the response of thinning accuracy and precision to three residual basal area treatments and harvest method in loblolly pine (*Pinus taeda*) stands during 2017.

Table 3.1. Model parameter estimates (β), standard errors (SE), 95% confidence limits (LCL and UCL), and *P*-values predicting the effects of basal area and harvest method on the accuracy [(observed-target)/target*100] of the harvest. Basal area was estimated using both fixed and variable-radius plots within loblolly pine (*Pinus taeda*) stands in the Piedmont physiographic region of Georgia during 2017.

Model	**β**	**SE**	**LCL**	**UCL**	***P*-value**
Fixed-radius Plots					
Intercept[a]	-9.49	9.08	-27.25	8.26	0.30
Medium[b]	7.95	4.12	-0.52	16.41	0.07
Low[c]	15.47	4.16	6.93	24.01	<0.001
Operator-select[d]	-9.82	13.93	-53.82	34.18	0.53
Variable-radius Plots					
Intercept[a]	-2.07	4.55	-10.97	6.84	0.65
Medium[b]	9.52	3.86	1.58	17.46	0.02
Low[c]	18.07	3.86	10.15	25.99	<0.001
Operator-select[d]	-5.01	6.37	-25.16	15.13	0.49

[a] High residual basal area (18 m^2/ha) treatment in pre-marked stands
[b] Medium residual basal area (14 m^2/ha) treatment
[c] Low residual basal area (9 m^2/ha) treatment
[d] Effect of operator-select thinning

Table 3.2. Model parameter estimates (β), standard errors (SE), 95% confidence limits (LCL and UCL), and *P*-values predicting the effects of basal area and harvest method on the standard deviation of basal area estimates following harvest. Data were collected using both fixed and variable-radius plots in loblolly pine (*Pinus taeda*) stands within the Piedmont physiographic region of Georgia during 2017.

Model	**β**	**SE**	**LCL**	**UCL**	***P*-value**
<u>Fixed-radius Plots</u>					
Intercept[a]	11.33	1.37	8.69	13.96	<0.001
Medium[b]	-1.61	1.75	-4.98	1.76	0.37
Low[c]	-1.38	1.75	-4.75	2.00	0.44
Operator-select[d]	4.60	1.46	0.28	8.92	0.05
<u>Variable-adius Plots</u>					
Intercept[a]	16.61	1.50	13.72	19.50	<0.001
Medium[b]	-3.34	1.92	-7.04	0.36	0.10
Low[c]	-6.07	1.92	-9.77	-2.37	0.004
Operator-select[d]	-0.11	1.60	-4.85	4.64	0.95

[a] High residual basal area (18 m^2/ha) treatment in pre-marked stands
[b] Medium residual basal area (14 m^2/ha) treatment
[c] Low residual basal area (9 m^2/ha) treatment
[d] Effect of operator-select thinning

Appendix

Table A1. Stand summaries, organized by research block. Stand summary includes location, age, controlling management agency, size, target basal area, fire treatment, and observed basal areas for all treatment units utilized within this study.

"North" (Oconee WMA)	Greene County, GA	Overall Size: 53.7 ha	Age: 15	Pre-thin BA: 27.5 m^2/ha	Date of Fire: 3-5-2018
Treatment Unit	**Size (hectares)**	**Target BA (m^2/ha)**	**FRP BA (m2/ha)**	**VRP BA (m2/ha)**	**Rx Fire**
80F	9.3	18	13.7	17.4	Y
80NF	9.2	18	9.3	13.1	N
60F	9.0	14	9.6	13.8	Y
60NF	8.4	14	8.7	12.9	N
40F	9.1	9	8.6	9.4	Y
40NF	7.8	9	6.9	9.4	N
"South" (Oconee WMA)	Greene County, GA	Overall Size: 37.7 ha	Age: 20	Pre-thin BA: 36.7 m^2/ha	Date of Fire: 3-5-2018
Treatment Unit	**Size (hectares)**	**Target BA (m^2/ha)**	**FRP BA (m2/ha)**	**VRP BA (m2/ha)**	**Rx Fire**
80F	5.2	18	16.7	17.9	Y
80NF	5.7	18	18.3	17.9	N
60F	6.4	14	15.5	15.6	Y
60NF	9.0	14	16.6	15.8	N
40F	5.9	9	10.9	10.1	Y
40NF	5.5	9	10.7	11.7	N
"Wall" (Weyerhaeuser Co.)	Hancock County, GA	Overall Size: 47.9 ha	Age: 15	Pre-thin BA: 32.1 m^2/ha	Date of Fire: 3-29-2018
Treatment Unit	**Size (hectares)**	**Target BA (m^2/ha)**	**FRP BA (m2/ha)**	**VRP BA (m2/ha)**	**Rx Fire**
80F	8.2	18	13.0	17.7	Y
80NF	8.6	18	16.0	16.3	N
60F	8.4	14	11.3	13.3	Y
60NF	7.3	14	12.0	13.5	Y*
40F	8.3	9	10.5	10.6	Y
40NF	7.1	9	9.9	9.9	Y*
"WCR" (Weyerhaeuser Co.)	Hancock County, GA	Overall Size: 46.1 ha	Age: 16	Pre-thin BA: 34.4 m^2/ha	Date of Fire: 4-3-2018
Treatment Unit	**Size (hectares)**	**Target BA (m^2/ha)**	**FRP BA (m2/ha)**	**VRP BA (m2/ha)**	**Rx Fire**
80F	10.8	18	18.0	20.9	Y
80NF	10.4	18	20.2	19.5	N
60F	6.2	14	15.9	14.7	Y
60NF	5.9	14	14.6	15.2	N
40F	6.2	9	11.1	12.9	Y
40NF	6.7	9	10.1	10.6	N
"PCR" (Weyerhaeuser Co.)	Hancock County, GA	Overall Size: 46.5 ha	Age: 16	Pre-thin BA: 32.1 m^2/ha	Date of Fire: 3-23-2018
Treatment Unit	**Size (hectares)**	**Target BA (m^2/ha)**	**FRP BA (m2/ha)**	**VRP BA (m2/ha)**	**Rx Fire**
80F	8.0	18	17.4	16.5	Y
80NF	7.9	18	15.4	18.6	N
60F	7.2	14	11.2	12.9	Y
60NF	7.3	14	14.9	17.9	N
40F	7.6	9	8.9	9.9	Y
40NF	8.5	9	8.5	10.3	N