OVERSTORY DENSITY AND ITS EFFECT ON OAK REGENERATION ABUNDANCE AND OAK UNDERSTORY HEIGHT GROWTH IN THE MISSOURI OZARK HIGHLANDS

A Thesis presented to the Faculty of the Graduate School

University of Missouri-Columbia

In Partial Fulfillment

Of the Requirements for the Degree

Master of Science

by

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AUGUST 2008

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

OVERSTORY DENSITY AND ITS EFFECT ON OAK REGENERATION ABUNDANCE AND OAK UNDERSTORY HEIGHT GROWTH IN THE MISSOURI OZARK HIGHLANDS

Presented by Jason L. Green

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ACKNOWLEDGEMENTS

I can directly attribute my interest in the natural resources field to my dad, Johnny Green, and friend Ed Kuhlmann. From an early age, I was often running beagles, hunting, exploring, fishing, and hunting morel mushrooms. Much of this passion I owe to them.

I told my wife before we were married that I wanted to pursue my master's degree in forestry. She quietly told me to go for it, both of us not realizing the many sacrifices that would come as a result. She has supported me unconditionally through the entire process. Thanks Sheri, I love you.

Dr. Dave Larsen, I appreciate you taking me on as a graduate student. I could not have learned as much as I did if it were not for your knowledge and our many lunch conversations. Thank you for your patience and guidance. I would also like to thank the rest of my committee, Drs. Steve Shifley and Johann Bruhn.

I would like to thank Mom, Dad, and Amy for the many meals and company that we shared during the process. You have always been there and supported my educational pursuits. Special thanks go to Ed, Rhonda, and Jeff Kuhlmann for the many hunting and fishing outings that helped me keep my sanity. The spring and fall are both special times during the year, and I won't forget the times we shared over the past several years. I love you all.

Adam Saunders deserves great recognition for his assistance. Adam assisted me with much of my data analysis. He gave significant contributions to this project, and I am grateful to have him as a friend. Dr. Christie Spinka and Dr. John Fresen also helped keep us square with data analysis.

There are several others who I would also like to thank especially Dr. John Dwyer, Hector Gonzalez, Dr. Jian Yang, Dr. Hong He, Dr. Zhang Yangjian, Hojung Kim, Bo Zhou, Katie Menzel, Elizabeth Blizzard, Steve Schell, Erik and Sara Otto, and Stuart and Allison Blake. These people helped me throughout my career at the University of Missouri, but more importantly are great friends that always lent an ear just to listen.

Finally, I am especially grateful for the Missouri Department of Conservation funding this project. Also, the Missouri Department of Conservation field staff collected and assembled the data used in this project. They spent many laborious hours gathering data and I am very thankful to have such a useful dataset.

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CHAPTER 1

INTRODUCTION

Forests in Missouri are managed in using a variety of techniques. Managed forests are subjected to various silvicultural treatments to control the amount and composition of the overstory, understory, or advance reproduction; primary and secondary growth rates; and canopy closure of the overstory. Foresters use these treatments to alter the structure, composition, and dynamics of the forest to fit their management objectives.

The Missouri Forest Ecosystem Project (MOFEP) (Brookshire and Shifley, 1997; Shifley and Brookshire, 2000; Shifley and Kabrick, 2002) was designed by the Missouri Department of Conservation (MDC) as a long term study to determine how forests change through time as a result of even-aged, uneven-aged, and no harvest management. Each treatment affects the growth response of the residual woody vegetation both in the understory and overstory. The MOFEP project provides a unique opportunity to study how various silvicultural treatments affect woody vegetation through time.

Controlling stand density is often a primary objective of forest management as this influences growth rates of residual overstory trees, overstory crown expansion, height growth rate of the understory, forest health, and the abundance and species composition of the forest floor. The density, species composition, and dynamics of the understory are quite important as these trees may have the capacity to become the next dominant and codominant trees in the overstory. An understory tree's potential to become the next overstory tree is also dependant on its ability to grow in height at such a rate that it out pace competitors.

Fortunately, the MOFEP project is designed well to investigate these types of relationships. This study will serve as a supplement to the many other MOFEP research projects and may benefit those who are interested in Missouri upland oak stand dynamics in regards to regeneration abundance, regeneration height growth, and overstory crown expansion.

OBJECTIVES

The general objectives of this study are first, to understand the regeneration dynamics of understory reproduction and, second, to understand canopy expansion dynamics of trees in the Missouri Ozark Highlands.

Specifically, this study will: a) evaluate how overstory density affects regeneration abundance; and b) evaluate how overstory density affects understory height growth.

HYPOTHESIS

This study tests the following hypotheses for upland oak forests in the Missouri Ozark Highlands: a) the abundance of regeneration of all species will decrease with increasing overstory density; and b) the height growth of understory trees will decrease with increasing overstory density.

CHAPTER 2

LITERATURE REVIEW

The MOFEP project began in 1989. This project was established by the Missouri Department of Conservation as long-term study to evaluate the effects of even-aged, uneven-aged, and no harvest management regimes in the southeast Missouri Ozark Highlands. The sites are located in Carter, Reynolds, and Shannon Counties (Figure 1) (Brookshire and Shifley, 1997).

The MOFEP project includes more than 25 related studies which include neotropical birds, reptiles and amphibians, litter and canopy invertebrates, small mammals, the physical environment, and overstory and understory vegetation (Brookshire and Shifley, 1997). Forest vegetation is the common link among all MOFEP ecosystem studies (Brookshire and Dey, 2000).

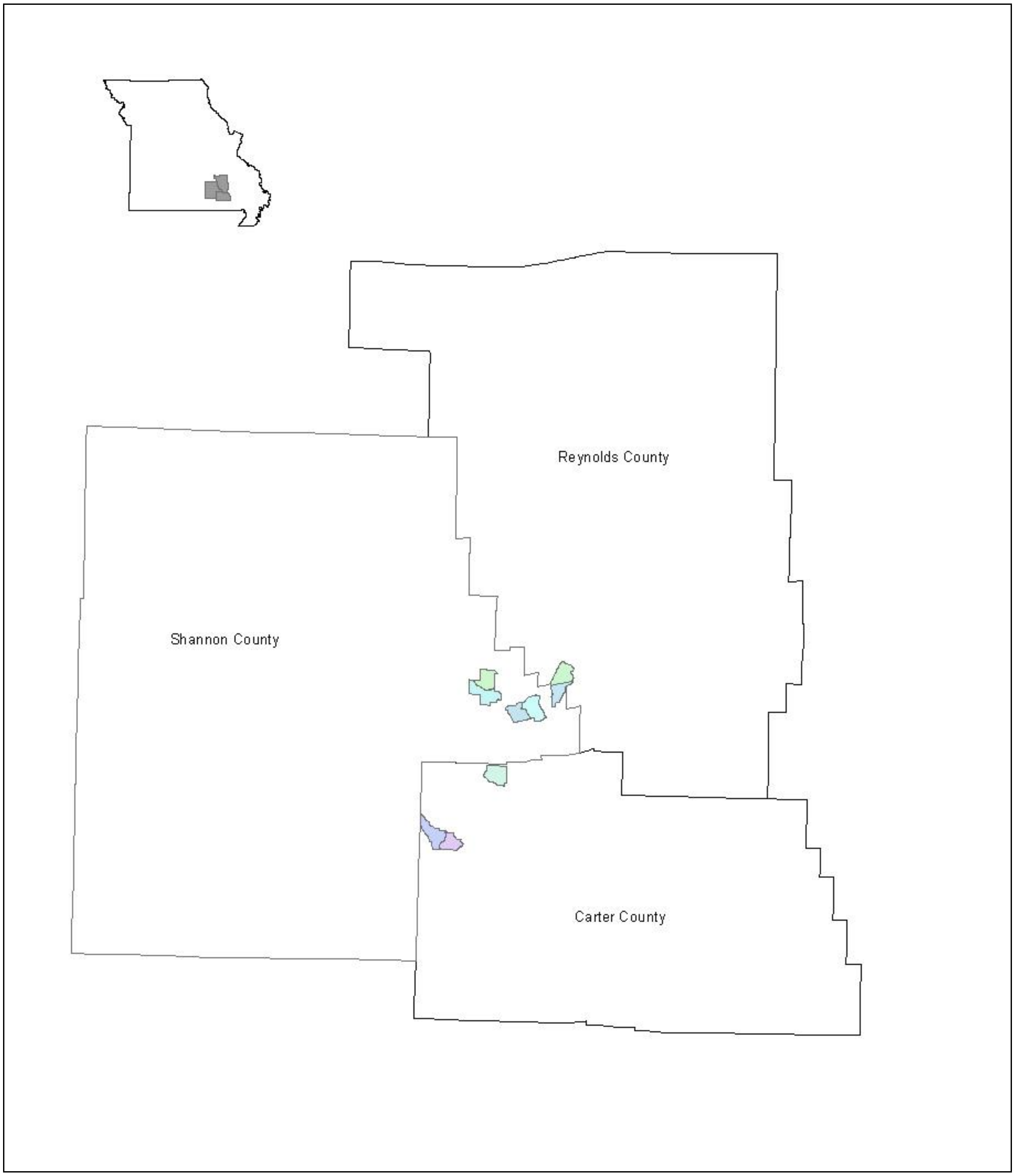

Figure 1: Location map of MOFEP counties and sites in Missouri, USA

Forest succession and stand development are closely related and play a fundamental role in understanding the dynamics of regeneration, understory height growth, and overstory crown expansion in oak forests. Oak in the Ozark Highlands is dependent on disturbance to perpetuate the stand (Abrams, 1992; Larsen et al., 1997; Larsen and Johnson, 1998). The type and degree of disturbance may vary and be influenced by both anthropogenic activities (timber harvests, grazing, etc.) and natural phenomena (tornados, fire, drought, etc) (Guyette and McGinnes, 1982; Guyette and Cutter, 1991; Abrams, 1992; Cutter and Guyette, 1994; Larsen et al., 1997; Larsen and Johnson, 1998). Prior to European settlement, fire on the landscape occurred approximately 3-4 years (Guyette and McGinnes, 1982; Guyette and Cutter, 1991; Abrams, 1992; Cutter and Guyette, 1994) Oaks in this region are drought tolerant and depend on their ability to dieback, resprout, and accumulate in the understory for successful regeneration and succession into the next cohort and commonly grow in areas that are prone to fire (Larsen and Johnson, 1998). Forest succession is the process in which predictable plant, animal, and microbial communities are successively replaced by new species through time in a particular ecosystem (Kimmins, 1987).

The four stand development stages described by Oliver and Larson (1996) are useful in understanding stand dynamics. They are: the stand initiation stage, the stem exclusion stage, the understory reinitiation stage, and the old-growth complex forest stage (Oliver and Larson, 1996). These stages are somewhat predictable and can be seen across various treatments. Stand initiation (Oliver and Larson, 1996) is usually caused by a large scale disturbance that kills the majority of ovestory trees but may leave the forest floor largely intact depending on the type of disturbance. Examples in Missouri may include tornados, extremely hot fires, and clearcutting. A stand initiating disturbance may drastically change the forest floor environment by altering the light regime, litter layer, or chemical composition of the soil. Many pioneer tree species begin to regenerate in freed growing space, growing from seed, advance reproduction, and sprouts. These small trees rapidly exploit the newly created growing space created by the death of the overstory. Trees that grow the fasted are also the quickest to fill growing space. This advantage allows them to potentially dominate the stand, often until the next major disturbance. Species composition is often a reflection of the type of disturbance and previous stand history that may determine which tree species have an initial advantage over other competing species. Soil and climate also play an important role in determining which species will be present after a disturbance (Oliver and Larson, 1996).

Oaks in the Ozark Highlands are highly dependent on exploiting soil and climate conditions (Larsen and Johnson, 1998). Oak is relatively drought tolerant and seem to out compete other species that cannot tolerate droughty conditions often encountered in the Ozark Highlands (Larsen and Johnson, 1998; Johnson et al., 2002). This advantage, along with rapid height growth after release, allows oaks to make up a large proportion of the species composition in the Ozark Highlands.

The stand initiation stage is usually caused by a stand replacing event that destroys most or all of the overstory trees (Johnson, 2004). This stage usually lasts approximately 20 years for eastern oak species (Johnson et al., 2002). It is a period of intense competition for resources and growing space among trees (Johnson, 2004). Clearcuts are a prime example of a stand replacing disturbance. In the Ozark Highlands, oaks appear to respond very well to this type of silvicultural treatment (Roach and Gingrich, 1968) and usually become the dominant tree species.

The stem exclusion stage of development (Oliver and Larson, 1996) occurs when new stems occupy available space and prevent new trees from regenerating and joining the rising level of the main canopy. This stage usually occurs approximately 20 years after a stand initiating disturbance (Johnson et al., 2002). Trees that are able to compete well in this phase of development begin to differentiate and occupy more growing space. Trees that cannot keep up succumb to subordinate crown positions or mortality. Trees may rapidly form four distinguishable crown classes: dominant, codominant, intermediate, and suppressed. In single-species stands, trees are constantly in competition and some trees are able to dominate the stand while others are killed. This phenomenon is known as self thinning (Peet and Christensen, 1987). Mixed species stand function similarly, in which two or more pioneer species may grow rapidly early and dominate the stand. (Oliver and Larson, 1996). However, species dominance may change after a disturbance (Oliver and Larson, 1996)

The understory reinitiation stage (Oliver and Larson 1996) begins when woody plants begin to develop and grow on the forest floor under the canopy of overstory trees. Most of the new understory species are shade tolerant species, because the overstory canopy blocks most available light. These plants also grow relatively slowly because only a small amount of light is available for photosynthesis (Oliver and Larson, 1996). This stage for oaks in the Eastern United States typically lasts 10 to 20 years before the end of a rotation, which is approximately 80 to 120 years after the stand initiating disturbance. This stage is very important because post-disturbance succession could lead to a stand that is made of primarily shade tolerant species depending on the type and magnitude of disturbance.

The old growth or complex forest is characterized by areas that are not prone to catastrophic disturbances and trees are allowed to grow until they killed by other means. The means of death can be caused by wind, disease, drought, age, or other factors and tend be more significant as trees become older. Forests in the Ozarks experience this as natural mortality kills large overstory trees and create canopy gaps (Johnson et al., 2002). As these overstory trees die, trees in the understory reinitiation stage gradually grow into the overstory. This process is able to occur in some instances without disturbances and is known as the "old growth condition" (Oliver and Larson, 1996).

FACTORS THAT EFFECT REGENERATION ABUNDANCE AND ADEQUACY

Most oak forests in the United States rely on natural regeneration, and, therefore depend on an accumulation of advance reproduction below parent trees (Larsen and Johnson, 1998). The establishment and survival of seedlings in the understory can influence the post harvest forest structure. Consequently, effective silvicultural treatments should focus on stand composition and structure (Johnson, 1993; Dey et al., 1996; Larsen and Johnson, 1998; Larsen et al., 1997; Loewenstein and Guldin, 2004). By doing so, foresters have the ability to control the amount of regeneration that may become the next overstory trees after harvest.

Upland oak regeneration in Missouri is highly dynamic. Oaks are capable of long term survival in the understory (Johnson, 1993; Dey et al. 1996; Larsen et al., 1997; Larsen and Johnson, 1998; Johnson et al., 2002). Successful oak regeneration is dependent on survival and accumulation of oak in the understory followed by release (Johnson, 1993). The periodic release of oak regeneration is typically a disturbance based event that lowers the overstory density adequately enough to allow enough light to penetrate to the forest floor for adequate height growth (Larsen et al., 1999). Lowering stocking to 50 ft^2 or less increases the likelihood of sustaining oak reproduction (Larsen et al., 1999) and reduces stocking below the B-line (Gingrich, 1967). The abundance of oak regeneration is also highly correlated with the percent sunlight that reaches the forest floor (Carvel and Tryon, 1961). Carvell and Tryon (1961) also found that stands that have had minor disturbances such as light burning, grazing, or thinning generally had more oak regeneration abundance than undisturbed stands. They attribute this to a greater light availability to the forest floor (reduced overstory density) because of repeated disturbances. However, oak regeneration in the Ozark Highlands can accumulate in the absence of disturbance (Liming and Johnston, 1944) and tends to accumulate on drier sites where overstory density is low (Carvell and Tryon, 1961; Johnson et al., 2002). Oaks are well adapted to disturbances on xeric sites characteristic of the Ozark Highlands (Johnson et al., 2002).

Typically oak reproduction in the understory during the understory reinitiation stage of stand development experiences periodic dieback and resprouting, which promotes the development of large root systems. The accumulation of seedling sprouts with large root systems offer the potential for rapid height growth following release (Dey et al., 1996). The accumulation and density of regeneration beneath the understory are important factors in stand development. When a disturbance reduces the overstory density, oaks that have accumulated may have a competitive advantage in root development and rapidly occupy freed growing space. In the Ozarks Highlands hickories (*Carya* spp. Nutt.), sassafras (*Sassafras albidum* Nutt.), blackgum (*Nyssa sylvatica* Marsh.), and flowering dogwood (*Cornus florida* L.) rarely become canopy dominants (Dey et al., 1996).

In order for oak regeneration to be successful, a proportion of regeneration must grow into the overstory and eventually become canopy dominant and codominant trees. Recruitment of oak advance reproduction into the overstory can only be obtained through a reduction of overstory density that redistributes light and growing space. However, oaks usually remain in the understory and are not recruited into the overstory until overstory removal (Dey et al., 1996). Overstory removal is typically accomplished through disturbances of various types and magnitudes and can range from a single tree death resulting in a canopy gap, to large scale disturbances such as insect outbreaks, tornados, or clearcutting (Johnson et al., 2002). Oak saplings in the Missouri Ozarks appear to have the ability to compete with older and larger trees after a partial cutting and in small gaps (Lorimer, 1983) but also appear to be pioneer species in clearcuts.

Oak dominated stands of the oak-hickory type are generally categorized as either sucessionally stable or sub-climax (Barrett, 1995). Stands that are sucessionally stable tend to occur on poor to medium sites that are droughty typical of the Ozark Highlands. Oaks generally outcompete non-oaks and persist as canopy dominants (Barrett, 1995). It is these sites that oak regeneration is able to accumulate over time and generally outcompete shade tolerant species. However, higher quality sites (75+ ft on the 50 year site index curve) are considered sub-climax and succession favors the development of shade tolerant species (Johnson, 1993; Barrett, 1995; Johnson et al., 2002). Site quality and site are useful in determining silvicultural methods used to manage oak in the Central Hardwood region (Johnson, 1993; Larsen and Johnson, 1998; Johnson et al., 2002).

It has been suggested that even-aged management can effectively grow oak sawtimber in the Central Hardwood region (Roach and Gingrich, 1968; Johnson, 1993). Roach and Gringrich (1968) also stated that two distinct cuts, reproduction and intermediate cuts, may be performed during the rotation. They explain that upland hardwoods in the Central Hardwood region are generally not suitable for single tree selection or group selection to if oak reproduction is desired. Although this method is highly effective for timber production and facilitating oak reproduction, it is not the only successful method in the Missouri Ozarks (Johnson and Krinard, 1976; Larsen et al., 1997; Larsen et al., 1999; Loewenstein and Guldin, 2004; Iffrig et al., 2004). Pioneer Forest, a privately owned timber company in the Missouri Ozarks, has been successfully maintaining an oak dominated forest while practicing single-tree selection since the early 1950's (Iffrig et al., 2004). Continuous forest inventory plots have been collected on Pioneer Forest since 1952 and these data indicate that single tree selection has been successful for regenerating oaks in the Missouri Ozark Highlands. This style of management may be more suitable for other private forest owners who own smaller tracts of land and still want to produce regular periodic income (Iffrig et al., 2004). Both even-aged and uneven-aged systems appear to work well for recruiting oak reproduction in the Missouri Ozark Highlands. Typically, management goals, management objectives, and site characteristics will determine the silvicultural treatment applied to the stand.

Sander et al. (1976, 1984) developed a method to evaluate adequacy of oak advance reproduction prior to harvest and ensure adequate oak reproduction following a clearcut. To be adequately stocked with oaks, the stand must be 30% stocked with oaks that have a mean diameter of 3 inches, which is based on

Gingrich's (1967) stocking tables for upland hardwoods. Sander et al. (1976) classified advance oak reproduction in the understory to their probability of becoming future dominant and codominant trees following overstory removal. Understory oak trees that are at 4.5 inches in diameter at the time of treatment are tallied and graded for probability of future success. According to the guide, 433 oak trees per acre of advance reproduction trees at least 4.5 feet tall are needed to adequately regenerate a stand with site indices between 50 ft and 75 ft on a 50 year site index curve (Sander et al., 1976; 1984).

Overstory density directly influences regeneration abundance. Larsen et al. (1997) examined how overstory density affected regeneration abundance of both oaks and non-oak species in uneven-aged stands. This study focused on developing success criteria for oak regeneration and determining if the abundance of regeneration prior to harvest would meet those criteria at differing overstory densities. After defining success criteria and developing probabilistic models, they found that probabilities of success of all species and of oaks alone increased with decreasing overstory density (Larsen et al., 1997). The group of all species combined showed higher probabilities of regeneration success than oaks alone. However, a large proportion of the all species group included many species that rarely become canopy dominants in the Ozark Highlands (e.g., *Sassafras albidum* Nutt., *Cercis canadensis* L., *Amelanchier arborea* Michx., *Cornus* *florida* L., and *Crataegus* spp. L.). Larsen et al. (1997) also found that for overstory density greater than 87 ft^2 / acre, none of the regeneration met the size or density criteria. Although this study did describe general trends in success probabilities, there was a high amount of variance success of reproduction density and size across all overstory densities. They attribute the variation as an indication that on any given site in the Ozark highlands, almost any combination of reproduction size and density can be found. Even though the models indicated a high degree of variance of oak regeneration success probabilities, they describe the importance of regulating overstory density to sustain advance reproduction in uneven-aged stands in the Missouri Ozark Highlands.

Previously, Tryon and Carvell (1958) found that decreasing understory density was associated with increasing overstory density; which they attribute to low light intensity in the understory and increased competition with overstory vegetation.

FACTORS THAT EFFECT UNDERSTORY HEIGHT GROWTH

Site characteristics play an important role in determining species composition, site quality, and succession (Johnson et al., 2002). Site characteristics and site index vary widely across the landscape (Kabrick et al., 2000).

Acording to Kabrick et al. (2000) the Missouri Ozark Highlands are characterized by an assortment of dissected, high plateaus that have been eroded for many millennia creating variable topography and relief across the landscape. Clear, spring fed rivers have cut into the plateaus creating relief of 200-450 ft (50-150 m) and on occasion up to 1000 ft (300 m). Elements of karst geology are common and include caves, springs, and sinkholes. The bedrock is primarily composed of Ordovician and Cambrian dolomites and sandstones. Silurian, Devonian, Mississippian, and Pennsylvanian bedrock (limestone, chert, sandstone, and shale) comprise a minor part of the landscape and are more frequent around the border of the section. Igneous formations are located in the eastern part of the Ozark Highlands and form the highest point of the section. This part of Missouri has not been glaciated and most of the soils have been exposed for at least 250 million years (Brookshire and Dey, 2000). Soils in the Ozark highlands have been highly weathered and are Ultisols and Alfisols. Most of the soils in these ecological landtypes have the one or more of the following soil series: Clarksville, Coulstone, Poynor, Doniphan, and Ocie (Kabrick et al., 2000). These varying physical site attributes play an important role in determining soil characteristics and species composition across the landscape (Kabrick et al., 2000).

Regulating overstory density is often the primary method that managers use to regulate both the understory and overstory size structure and species composition. Unfortunately, very little research has been conducted on how overstory density affects the height growth of understory trees in the Missouri Ozarks. Height growth of understory trees is an important factor in stand development, because it directly affects the number of understory trees that will eventually be recruited into the overstory. In fact, Sander (1972) stated that reducing overstory density will increase the height growth rate of the understory trees.

One of the few studies of understory height growth was done by Sander (1971). Sander investigated the early height growth of new oak sprouts after clearcutting in southeastern Ohio. He found that the height growth was fastest on sprouts that originated from the largest stems of advance reproduction. In fact, stems that were originally over 1 inch in diameter at the ground produced the fastest growing sprouts, and stems that were less than 0.5 inches did not have a height growth rate that would allow them to grow to a position as a dominant or codominant tree. Similarly, McGee and Bivens (1984) examined the understory response of white oaks to a shelterwood release. They found that released trees increased in both diameter and volume. However, released trees had a high degree of variability in height growth. Schlesinger (1978) found similar height growth results with released white oak poles. He found that the larger trees that initially exhibit the most rapid growth before treatment will continue to exhibit the greatest growth 20 years after release. He recommended that larger understory trees that demonstrate the most recent rapid growth should be retained and released. Schlesinger stated that suppressed trees offer little potential for future management and growth (Schlesinger, 1978).

Thinning is a silvicultural treatment used to improve understory height growth. Minckler (1957, 1967) studied the height growth and diameter growth of pole sized white oaks at 2 and 10 years after crop tree release. He examined crown health and vigor as indicators of future performance of tree growth after release. Suppressed and overtopped trees were defined as trees that had low vigor, low crown ratios, and malformed crowns, all of which are indicators of poor vigor and health (Minkler, 1957). At year 10 following release, the height growth of former intermediate trees and overtopped trees was greater than that of similar trees in stands that were untreated (Minkler, 1967). Height growth of codominant trees, however, did not increase, most likely because they were already in a favorable crown class that supported good height growth rates. Height growth of suppressed trees was less than that of codominant trees in the same stand and suppressed trees would probably not compete successfully in the future to become dominant or codominant trees without further release. Minkler proposed that white oak crop trees be selected based on quality and form (Minkler, 1967).

Sander (1972) examined regeneration height growth in clearcuts and partial cut stands. Regeneration height growth within clearcuts and partially cut stands were similar. Sander also found that only a few of the best performing trees on partial cut stands (>4.5 ft tall and <2 inches in diameter at ground level) grew fast enough to fill the opening created by partial cutting. Sander verified that these best performing trees would grow well enough to become a principle oak component in the overstory following future cuts. In contrast, all of the reproduction in the uncut plot grew slowly. Sander hypothesized that in uncut plots, height growth rates of all reproduction would continue to be low and mortality to be high, especially on the smaller reproduction types. Sander stated that this trend would continue unless a harvest regime was implemented (Sander, 1972).

The origin of the oak reproduction, whether true seedlings, advance reproduction, or stump sprouts, directly influences the height growth rates following a stand initiating disturbance. For instance, true oak seedlings that germinate immediately after overstory removal have a relatively low probability of survival to maturity (McGee and Hooper, 1970). Most upland oak stands rely heavily on advance reproduction and stump sprouts as significant contributors to restocking after disturbance (Ross et al., 1986; Johnson et al., 2002). A study by Liming and Johnston (1944) found that annual height growth of was significantly greater in sapling sprouts than in true seedlings on sites that experienced frequent burning. Sander (1972) found that regeneration, true seedlings, and advance reproduction that were less than 4.5 feet tall and had roots and stems that were the same age, had poor height growth after cutting. He doubted that any of the classes would ever grow into the dominant or codominant crown class. This trend is further supported by Johnson et al. (2002) and Tryon and Carvell (1958) in which survival of advance reproduction decreases with increasing size and only a fraction of advance reproduction survive to the next size class. By age 12 over 90 percent of trees in the true seedling class were in the suppressed crown class. Trees that were able to compete successfully and grow fast enough to achieve dominant or codominant status, were advance reproduction that before treatment was greater than 4.5 feet in height.

Sander primarily examined advance reproduction height growth and disregarded stump sprouts. However, stump sprouts are important in oak regeneration in the Missouri Ozarks and may contribute greatly to the new stand after overstory removal (Johnson, 1975; Johnson, 1977; Dwyer et al., 1993). Stump sprouts often have faster height growth than other forms of regeneration because they have an established and root systems. Johnson (1975, 1977) examined the growth and development of stump sprouts of oaks and found that the probability of sprouting generally decreases with increasing stump diameter. Generally, the probability of a coppiced stem becoming a codominant or larger tree greatly decreases when stems are larger than 8 inches at stump diameter (Johnson, 1977). This trend was found for scarlet, blackjack, post, and black oaks.

There have been few studies that focus specifically on the affect of overstory density on understory height growth, and fewer yet that specifically examine oaks. A study by Wampler (1993) examined the affect of overstory density on the height growth of understory Douglas-fir (*Pseudotsuga menziesii*) under partial overstory retention. Wampler's study found that as few as 5 overstory trees per acre could significantly reduce the height growth of understory trees. She found similar results when examining basal area and percent canopy closure. The principal conclusion for this study was that height growth of understory Douglas-fir trees increases with decreasing overstory density (Wampler, 1993).

Understory height growth is an important factor in recruiting oaks into the overstory. However, only a few studies have examined the response of specifically oak species and the response of understory oak height growth to varying overstory density (Sander, 1971; Sander and Clark, 1971; Sander, 1972; McGee and Bivens, 1984;). McGee and Bivens (1984) found that relatively large understory trees with large, well developed crowns and straight stems, responded with greater diameter and volume growth than medium or low quality trees after complete overhead release. However, height growth specifically, was highly variable and not statistically significant between the three different quality classes. Stump sprout height growth on released stumps, conversely, was approximately 2 feet taller than unreleased stumps.

A study by Sander (1972) indirectly examined the effect of overstory density on height growthby measuring the effect of three residual overstory densities (complete cut, partial cut, and uncut) on understory height growth. The results were similar to other studies by Tryon and Carvell (1958) and Sander and Clark (1971) and showed that even a relatively low density of overstory trees reduces the average annual height growth of reproduction. Sander and Clark (1971) stated that complete overstory removal was necessary to provide the most favorable conditions for reproduction height growth.

CHAPTER 3

METHODS

This study was a component of the Missouri Ozark Forest Ecosystem project (MOFEP) (Brookshire and Shifley, 1997; Shifley and Brookshire, 2000; Shifley and Kabrick, 2002). MOFEP includes 9 study sites which range in size from 772 to 1271 acres and were selected based on the following criteria: 1) study sites had to be at least 600 acres in size; 2) were at contiguous tracts with minimal edge; 3) free from manipulation for the past 40 years or longer; 4) owned by the Missouri Department of Conservation; 5) located in the southeast Ozarks; 6) were in close proximity of each other (Brookshire and Dey, 2000). Most of the overstory trees ranged from 50-70 years in age. Some trees over years in age were found on all study sites, and a few were over 140 years old (Brookshire and Dey, 2000).

This study used 90 1/20 acre repeat measurement canopy mapped vegetation subplots for data analysis (Jensen, 2002). Measurements were taken in 1994 to obtain baseline information about each stand before treatment. Treatments of the following types: clearcut, even-aged intermediate, uneven-aged group selection, uneven-aged single tree selection, and uncut control plots, were applied in 1996. Canopy mapped subplots were remeasured in 1999 and

2004 to evaluate the effects of treatments on the vegetation. There were 72 selected subplots that were selected in 1994. Half of the subplots were selected from ELT 17 (south and west slopes), while the remaining ½ were selected from ELT 18 (north and east slopes). In 1999 eighteen more clearcut subplots were added in order to include a more balanced proportion treatment types bringing the total number of subplots to 90. Subplots were nested within 0.5 acre plots across 9 different treatment sites (Jensen, 2000).

The data collected at MOFEP were originally designed specifically to be evaluated with analysis of variance techniques and were collected across all study sites as part of a designed, replicated experiment to study the effects of even-aged, uneven-aged, and no-harvest management on vegetation and wildlife. A total of 648 0.5 acre vegetation plots were spatially distributed with the constraint that at least one plot fell within each stand on the MOFEP study. Additional plots were determined randomly. Each plot was permanently marked to periodically monitor change continually at the same locations (Brookshire and Dey, 2000). Half acre plot data was not directly used for this study. However, these plots are important because canopy mapped plots are nested within the overstory 0.5 acre plots.

Study site, plot, and subplot attributes are further described in detail later. Trees in 0.5 acre plots (Figure 2) were permanently marked near ground level with aluminum nails on all trees ≥4.5 inches DBH (Jensen, 2000). Multiple stemmed trees were considered separately if the fork was below 4.5 inches DBH. Data collected on individual trees included species, DBH, crown class, and tree condition, and site index. These data were not directly used in the analysis. However, these plots are very important because the canopy mapped subplots are nested within the overstory plots.

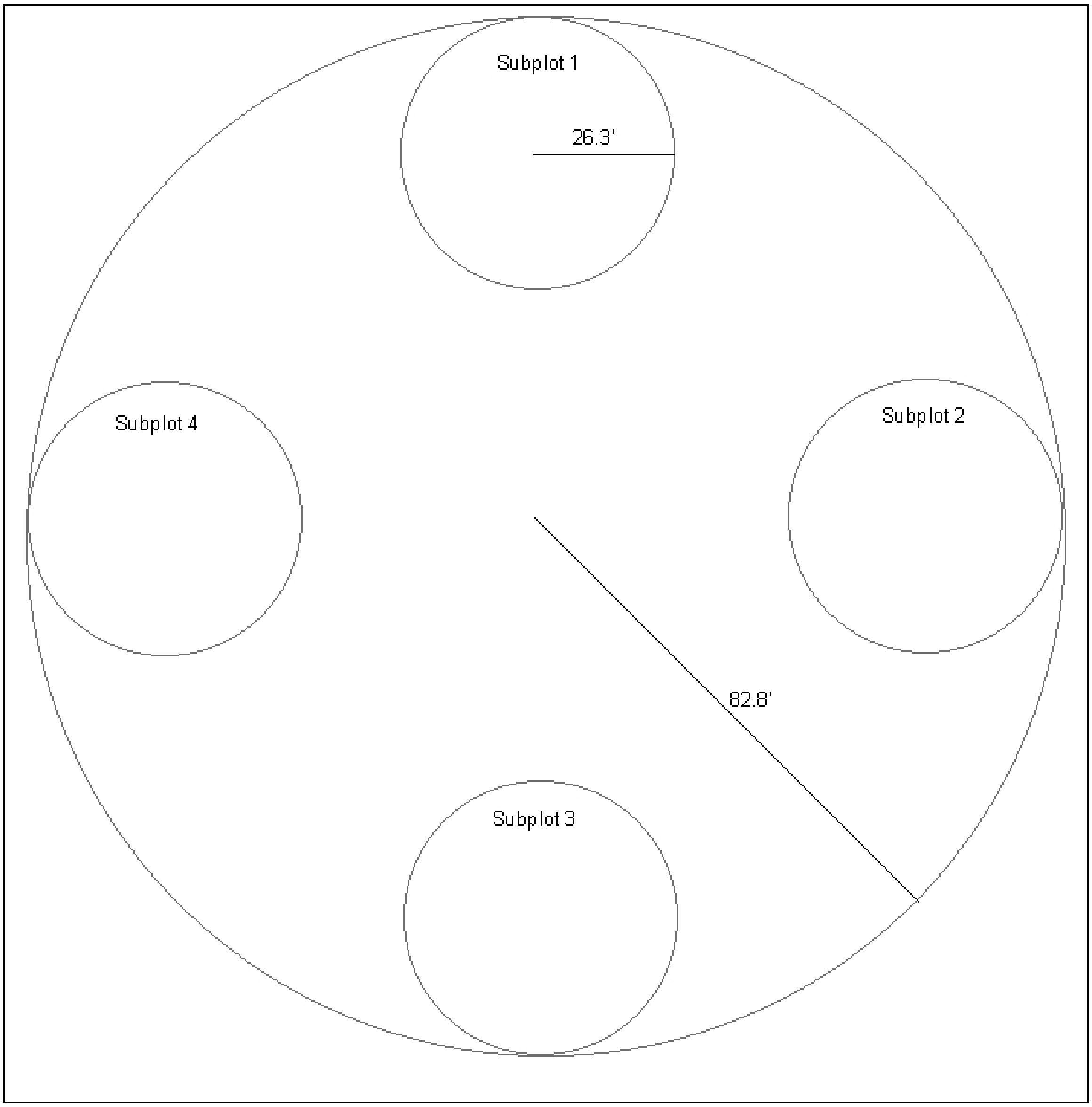

Figure 2: MOFEP plot design illustrating 1/2 acre plot with four nested 1/20 acre subplots (Jensen, 2000).

There are four 0.05 subplots nested within the 0.5 acre plots and located 56.5 feet from the center of the 0.5 acre plot. Data collected for each 0.05 acre plots included all live trees, shrubs, and vines that were 1.5≤ x ≥4.5 inches DBH and ≥3.3 feet in height. Tree canopies were mapped on one subplot, usually the northernmost subplot of 90 of the 0.5 acre main plots. These will be called canopy mapped subplots from this point forward. Canopy mapped inventory collection started on the northern subplot, labeled subplot 1. Canopy mapping was done only within subplot 1 where the ELT's were a 17, 18 or 23. However, occasionally subplot 1 fell within a unique ELT or was not accessible. Therefore, several canopy mapped inventories were collected in one or more other subplots. Data collected in the canopy mapped subplots included the following for each tree: sequential number (which was permanently marked), azimuth and distance from subplot center (for mapping purposes), species, DBH, height (≥1 meter), crown ratio, and two crown diameters per tree measured in cardinal directions. The ecological landtype (ELT) and harvest treatment type were recorded for each plot.

Tree data for plots and subplots were originally collected in 1994 (pre-treatment baseline data), measured again in 1999 (post-treatment), and remeasured in 2004. These data provide a unique opportunity to study how trees change through time.

For this project, trees were classified as either overstory trees or understory trees. Overstory trees were trees that were >4.5 inches DBH. Trees smaller than 4.5 inches DBH were considered understory trees. Regeneration was then classified as a subset of the understory as trees that were at least 3.3 ft tall and <1.6 inches in diameter (Dey et al., 1996). Basal area (BA) per acre was calculated from canopy mapped overstory tree data on the 0.05 acre canopy mapped subplot. Basal area was used as the standard for stand density measured in ft^2/acre throughout this study.

Three different harvest treatments (even-aged managment, uneven-aged management, and no harvest manamgent) were applied to the MOFEP site.

Data were examined for missing, errant, or inconsistent values. In most cases these problems could be resolved by comparing the three measurements over time for each subplot and selecting the majority value (e.g. missing species codes) or identifying erroneous codes (e.g. switched height and DBH measurements).

DATA ANALYSIS

Methods for Evaluating the Effect of Overstory Density on Regeneration Abundance

A primary goal of this study was to evaluate general trends in the success probabilities of regeneration abundance at differing overstory densities. The method used to evaluate success was similar to the method used by Larsen et al. (1997). A total of 90 plots were used in this analysis. Logistic regression was used to estimate success of obtaining *x* stems per acre at a given *y* size class as a function of overstory density. Logistic regression was used due to the stochastic nature of predicting regeneration abundance. Historically, logistic regression models have been successfully used for several other regeneration models which are also based on probabilistic methods (Sander et al., 1984; Dey et al., 1996; Larsen et al., 1997; Johnson et al., 2002). Regeneration success for number of oak stems (*x)* and height class (*y)* criteria were defined for three different height criteria, each criterion producing differing success probabilities. Models were then fit by logistic regression based on the defined success criteria. This method has been used to predict success probabilities for regeneration and future stocking on clearcuts (Sander et al., 1984; Johnson and Sander, 1988) and for uneven-aged stands (Larsen et al., 1997). The equation is of the following form:

1. $P_s = \exp(b_o + b_1\text{BA})/(1+\exp(b_o + b_1\text{BA}))$

where P_s is the probability of occurrence of the minimum height class of reproduction, BA (ft^2/acre) is overstory density, and the coefficients b_0 and b_1 are estimated from the data. Data for logistic regression are required to be in a binomial format of 1 or 0. Therefore, the dependent variable data, P_s, is constrained to either 0 or 1. Data was confined to the following minimum threshold heights: ≥3.33 ft, ≥6.56 ft, and ≥9.84 ft. Four density classes were defined for two species classes, oaks and all species. For both red oak and white oak species, success criteria were densities measured in trees per acre of ≥125, ≥250, ≥500, and ≥1000. For non-oaks, success criteria were densities of ≥600, ≥1200, ≥2500, and ≥5000 trees per acre. Each species group was then regressed for each height threshold and density combination. Density was measured in basal area and calculated from live basal area after treatment (basal area in 1999) using 0.05 acre canopy mapped data. The diameter threshold for regeneration was set at trees ≤1.6 inches (4 cm) DBH as the maximum size class of regeneration at the time of treatment.

Methods for Evaluating Understory Height Growth Response to Differing Overstory Density

This dataset provided a unique opportunity to evaluate how understory average annual height growth changes with changing overstory density.

However, there were several assumptions and data management issues that needed to be addressed before an accurate analysis could be conducted.

This analysis used trees that resprouted or were established immediately following treatment in 1996. Since the data were taken only every 5 years, it was assumed that understory trees begin height growth at treatment year.

Data for this analysis include only new trees or new sprouts. Trees were removed from the analysis if they met any of the following criteria:

1) Trees >4.5 inches DBH tree at any time period
2) Average annual height growth that exceeded 3 feet per year (most likely a tree that was not previously measured or tagged in 1994)
3) Released trees that were not measured in 1994 and initially appear to have excellent height growth rates between 1994-1999, but grow at a rate between 1999-2004 that indicates that the tree was suppressed rather than a new stem or sprout stem
4) All non-oaks that are considered shrubs or rarely develop into overstory trees (i.e. flowering dogwood, serviceberry, Carolina buckthorn, plum spp., hop-hornbeam, hawthorn, mulberry, and elm spp.)
5) Trees exhibiting negative height growth.

Mean annual height growth of understory trees was examined over an 8 year period (1996-2004). Height observations were available for 314 understory red oaks, 324 white oaks and 1962 understory non-oaks trees. This analysis used individual trees for the analysis rather than plot averages. Logistic regression was used to estimate from overstory density (BA/ acre) in 1999 the probability obtaining height growth $\geq x$. This type of model was used due to the stochastic nature of predicting height growth. The equation is of the following form:

$$2. \quad P_s = \exp(b_0 + b_1 \mathrm{BA})/(1 + \exp(b_0 + b_1 \mathrm{BA}))$$

where P_s is the probability of occurrence of the minimum height growth of understory trees (i.e. trees ≤ 4 inches DBH), BA is overstory density (ft^2/acre), and the coefficients b_0 and b_1 are estimated from the data. Data for logistic regression are required to be in a binomial format of 1 or 0. Therefore, the dependent variable data, P_s, is constrained to either 0 or 1. Data were analyzed using mean annual height growth thresholds of ≥0.5 ≥1.0 ft, ≥1.5 ft, ≥2.0 ft, ≥2.5 ft and ≥3.0 ft. Each species group (red oak, white oak, and non-oaks) was then regressed for each mean annual height growth threshold. Overstory density was measured in basal area per acre and calculated from live basal area after treatment (BA 1999) using 0.05 acre canopy mapped data. This type of analysis was used to explain general trends of the effect of overstory density on the average annual height growth of understory trees.

The overstory densities of the raw data were divided into eight different density groups (0-20, 21-40, 41-60, 61-80, 81-100, 101-120, 121-140, 141-160 ft^2/

acre). For each density group, the actual probability for a height growth threshold level was calculated from the data for understory trees (i.e. proportions of success vs total trees in that density groups). For example, there were 250 trees that grew in height 2 ft or less out of 750 total trees. The success probability for 2 ft of height growth was 66% in this group. These observed probabilities were compared to predicted probabilities that were estimated from parameters derived from the logistic regression. The median density (BA) of each group was used as the independent (predictor variable) in equation 2. This method was used for each density class and each height growth threshold.

Table 1: Number of understory trees by treatment type.

	Treatment		
	Even-aged Management	Uneven-aged Management	No Harvest Management
Non-oak	1673	219	70
Red oak	279	29	6
White oak	268	53	3

An analysis of variance was also used to evaluate height growth differences due to the following criteria:

1) Differences between red oaks, white oaks, and non-oaks in the following overstory density classes: 0, 1-20, 21-40, 41-60, 61-80, 81-100, and 100+ ft^2/ acre.
2) Differences between oaks and non-oaks in the following overstory density classes: 0, 1-20, 21-40, 41-60, 61-80, 81-100, and 100+ ft^2/ acre with differing ELT's (17 and 18).

A mixed effects ANOVA with a split plot design was used, which accounts for variance due to plot differences. The analysis tested for differences at α = 0.05 (except where noted) using least squared difference for mean separations. Mean annual height growth by plot was examined. In addition to examining the effect of basal area on height growth, this analysis allowed for easy comparison for the following understory height growth differences: between the oak groups and non-oaks, differences between ecological landtypes 17 (south and west facing slopes) and 18 north and east facing slopes) while maintaining defined basal area classes.

CHAPTER 4

RESULTS

THE EFFECT OF OVERSTORY DENSITY ON REGENERATION ABUNDANCE

The frequency of plots that met both height and abundance thresholds decreased with increasing overstory density for red oak, white oak, and non-oak reproduction (Table 2 and 3, Figures 3 through 11). The logistic regression models (Table 4 and 5) also illustrate that the probability of success decreases with increasing regeneration height thresholds. Although the models describe general trends in average success probability, logistic regression models for red oak, white oak, and the non-oak group had high variance (Table 4 and 5).

The models also illustrate that for red oak species, none of the plots met any of the size and density success criteria when basal area exceeded 90 ft^2 / acre. For white oaks only 1 plot met the 3.3 ft success criteria when basal area exceeded 150 ft^2 / acre. For the non-oak group, only 2 plots met the success criteria when basal area exceeded 150 ft^2/acre at the 3.3 ft height threshold and at the 6.6 ft threshold. Consistently, the non-oak group had higher densities for all height thresholds had higher reproduction abundance across all levels of basal area.

Reproduction of all three species groups increased in density and size with decreasing overstory density. The trend was consistent through all size, density, and species classes. However, regeneration size and abundance under any given basal area varied greatly. This may indicate that on any plot chosen at random, almost any combination of reproduction size and density is possible (Larsen et al., 1997).

Table 2: Observed numbers of subplots above and below the specified height and density thresholds for red oak and white oak seedlings (n=90)

Reproduction height class threshold (ft)	Reproduction density class threshold (trees/acre)	Observed no. of plots: Below threshold	Observed no. of plots: Above or equal to threshold
	Red Oak seedlings		
≥3.3	≥125	69	21
	≥250	80	10
	≥500	84	6
	≥1000	90	0
≥6.6	≥125	78	12
	≥250	85	5
	≥500	88	2
	≥1000	90	0
≥9.8	≥125	84	6
	≥250	87	3
	≥500	90	0
	≥1000	90	0
	White Oak seedlings		
≥3.3	≥125	58	32
	≥250	70	20
	≥500	83	7
	≥1000	87	3
≥6.6	≥125	69	21
	≥250	81	9
	≥500	87	3
	≥1000	88	2
≥9.8	≥125	81	9
	≥250	87	3
	≥500	89	1
	≥1000	89	1

Table 3: Observed numbers of subplots above and below the specified height and density thresholds (n=90)

Reproduction height class threshold (ft)	Reproduction density class threshold (trees/acre)	Observed no. of plots: Below threshold	Observed no. of plots: Above or equal to threshold
	Non-oak seedlings		
≥3.3	≥600	17	43
	≥1200	39	19
	≥2500	67	2
	≥5000	84	1
≥6.6	≥600	63	27
	≥1200	84	6
	≥2500	89	1
	≥5000	90	0
≥9.8	≥600	77	13
	≥1200	87	3
	≥2500	90	0
	≥5000	90	0

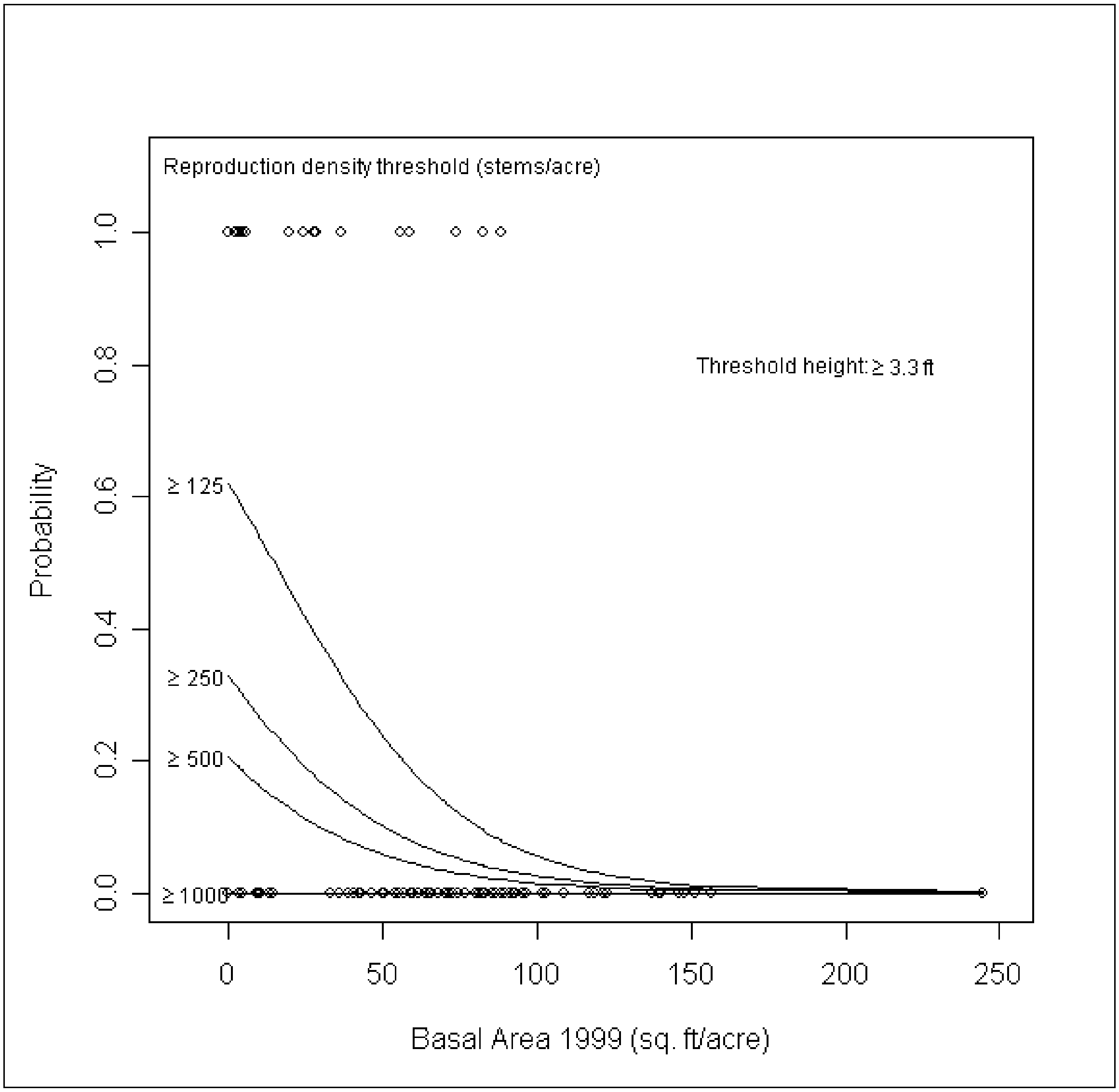

Figure 3: The estimated probability of obtaining at least 125, 250, 500, or 1000 red oaks per acre at least 3.3 ft tall for a given residual overstory basal area, 8 years after overstory treatment. Diamonds represent plots that met (1.0) or did not meet (0.0) height and abundance thresholds.

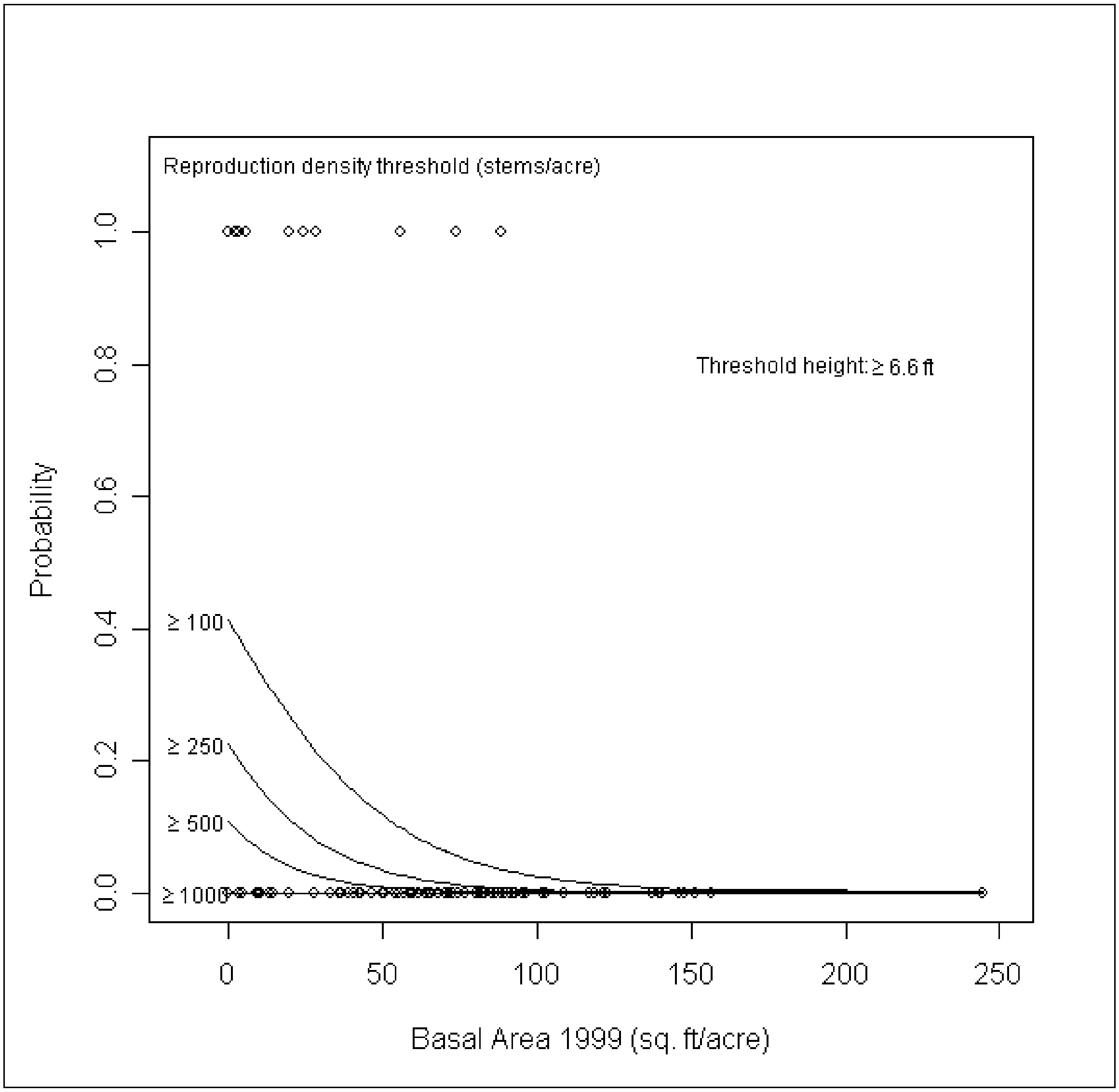

Figure 4: The estimated probability of obtaining at least 125, 250, 500, or 1000 red oaks per acre at least 6.6 ft tall for a given overstory basal area, 8 years after treatment. Diamonds represent plots that met (1.0) or did not meet (0.0) height and abundance thresholds.

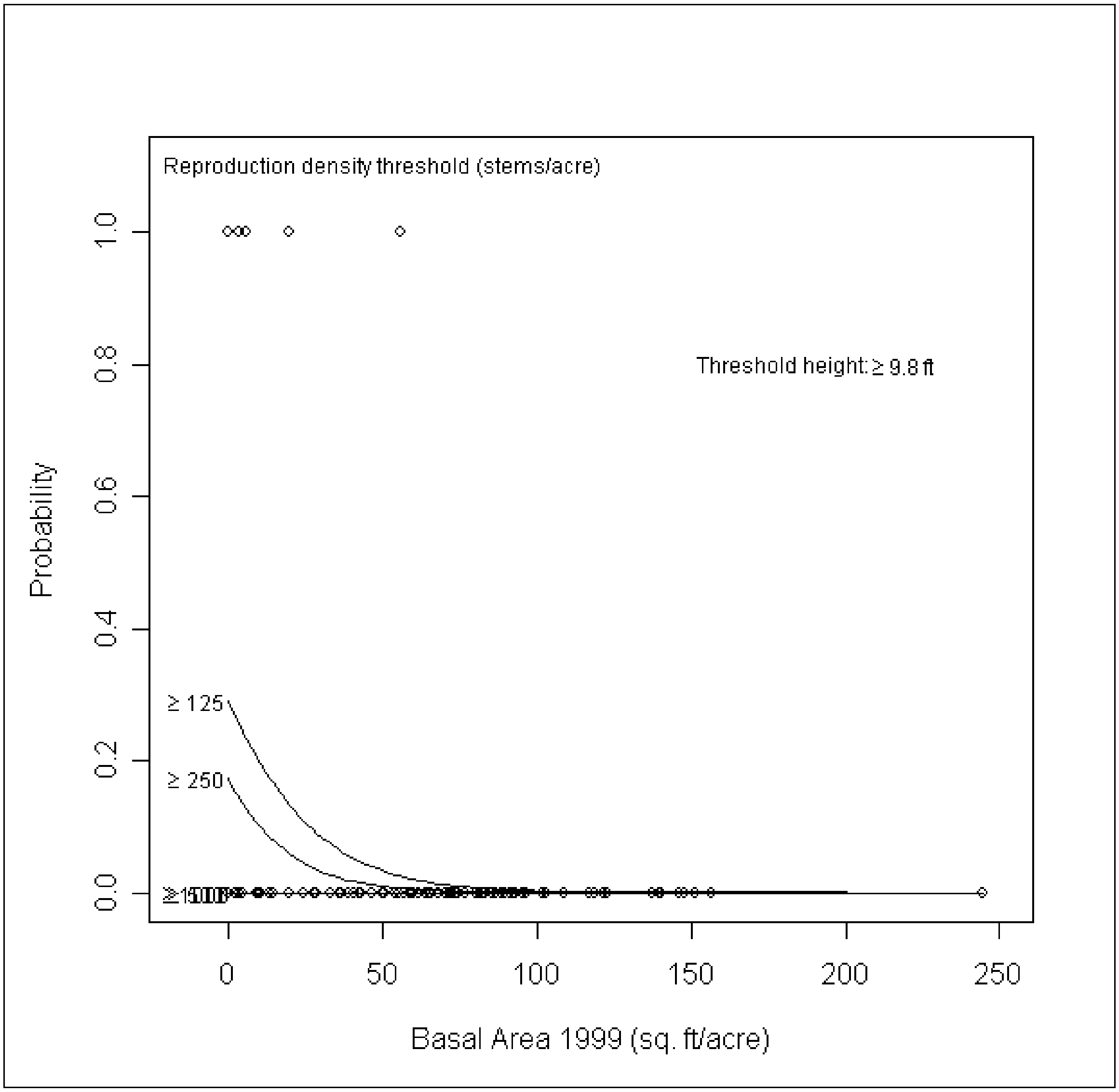

Figure 5: The estimated probability of obtaining at least 125, 250, 500, or 1000 red oaks per acre at least 9.8 ft tall for a given overstory basal area, 8 years after treatment. Diamonds represent plots that met (1.0) or did not meet (0.0) height and abundance thresholds.

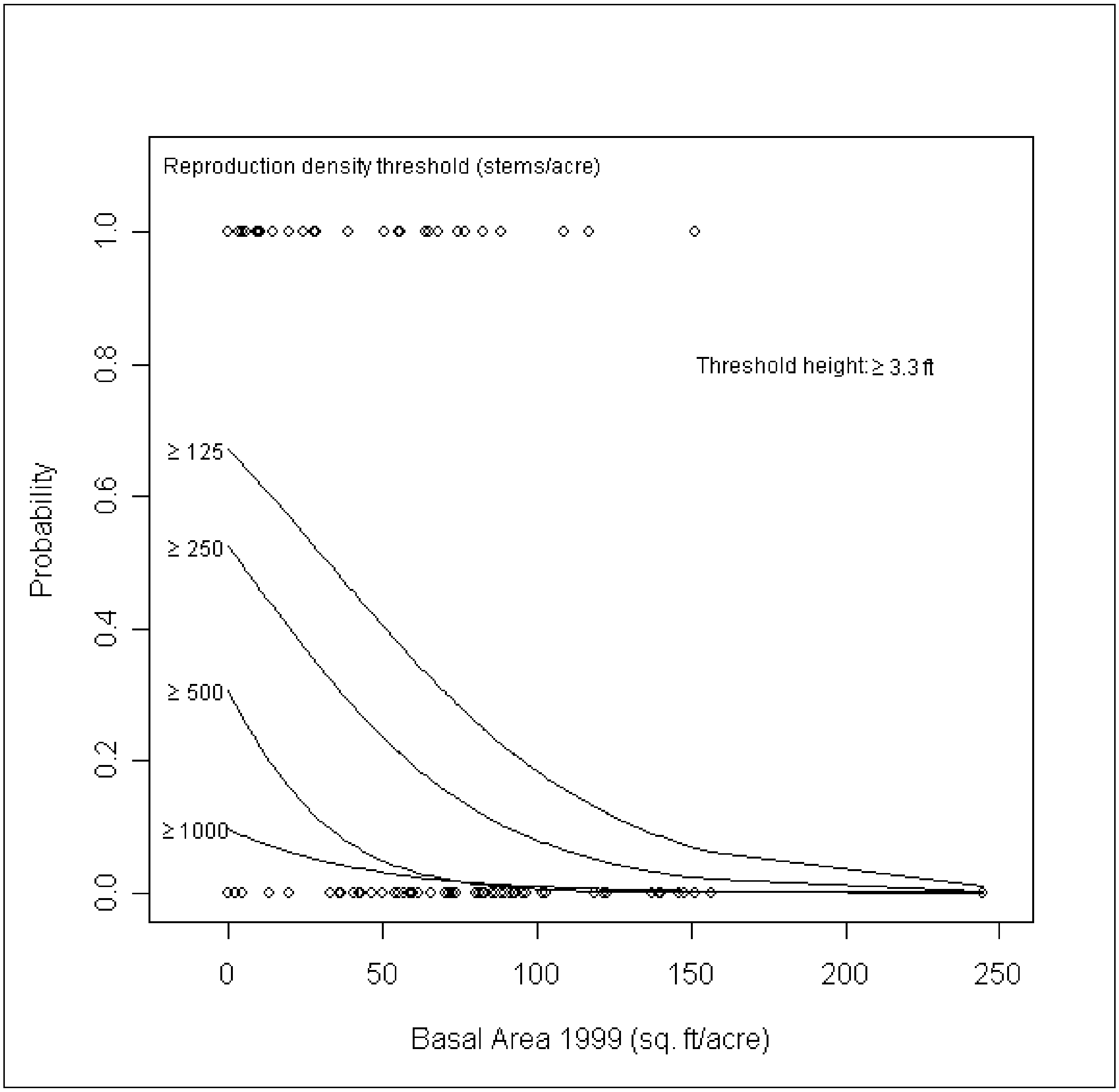

Figure 6: The estimated probability of obtaining at least 125, 250, 500, or 1000 white oaks per acre at least 3.3 ft tall for a given residual overstory basal area, 8 years after overstory treatment. Diamonds represent plots that met (1.0) or did not meet (0.0) height and abundance thresholds.

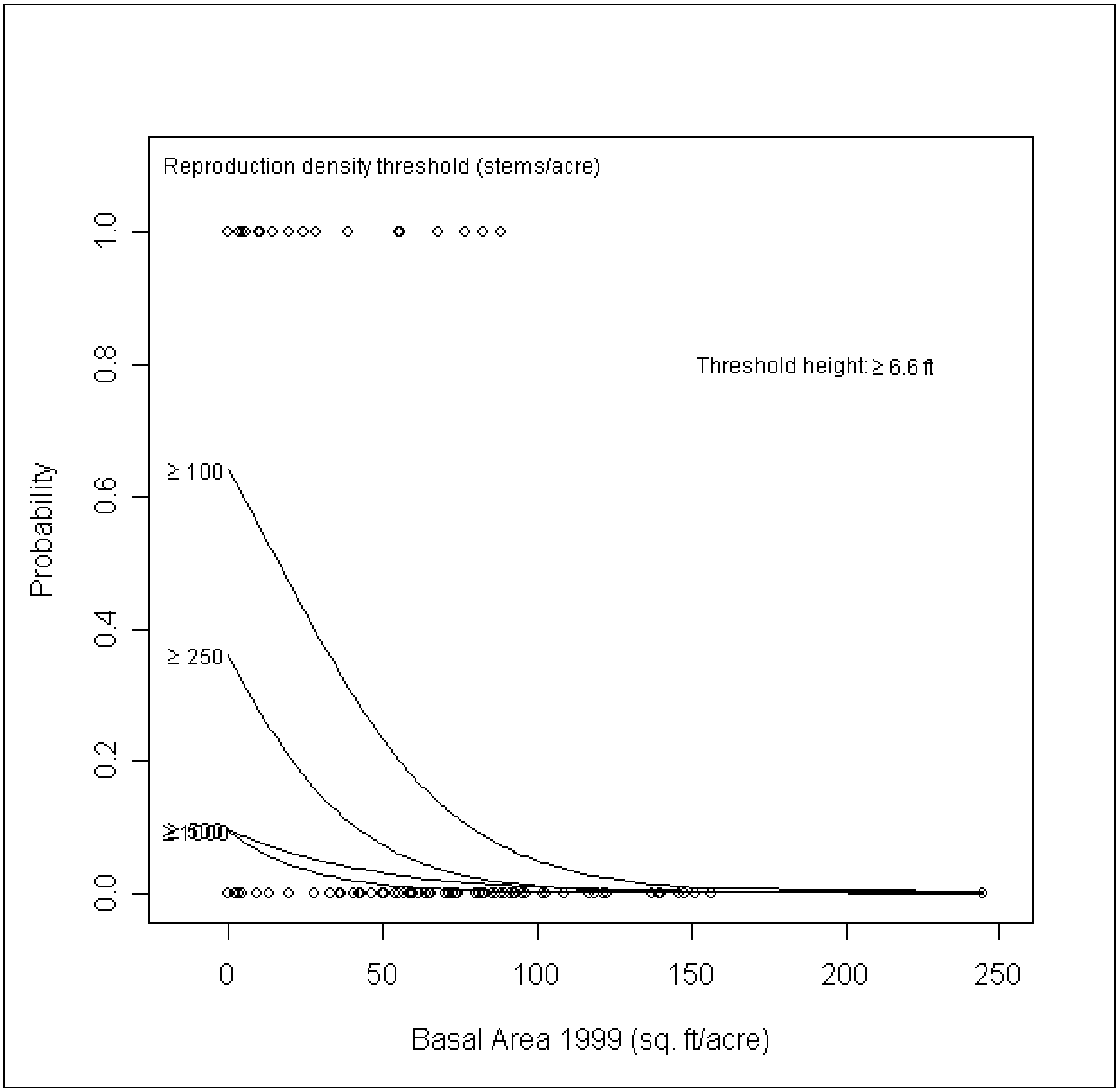

Figure 7: The estimated probability of obtaining at least 125, 250, 500, or 1000 white oaks per acre at least 6.6 ft tall for a given overstory basal area, 8 years after treatment. Diamonds represent plots that met (1.0) or did not meet (0.0) height and abundance thresholds.

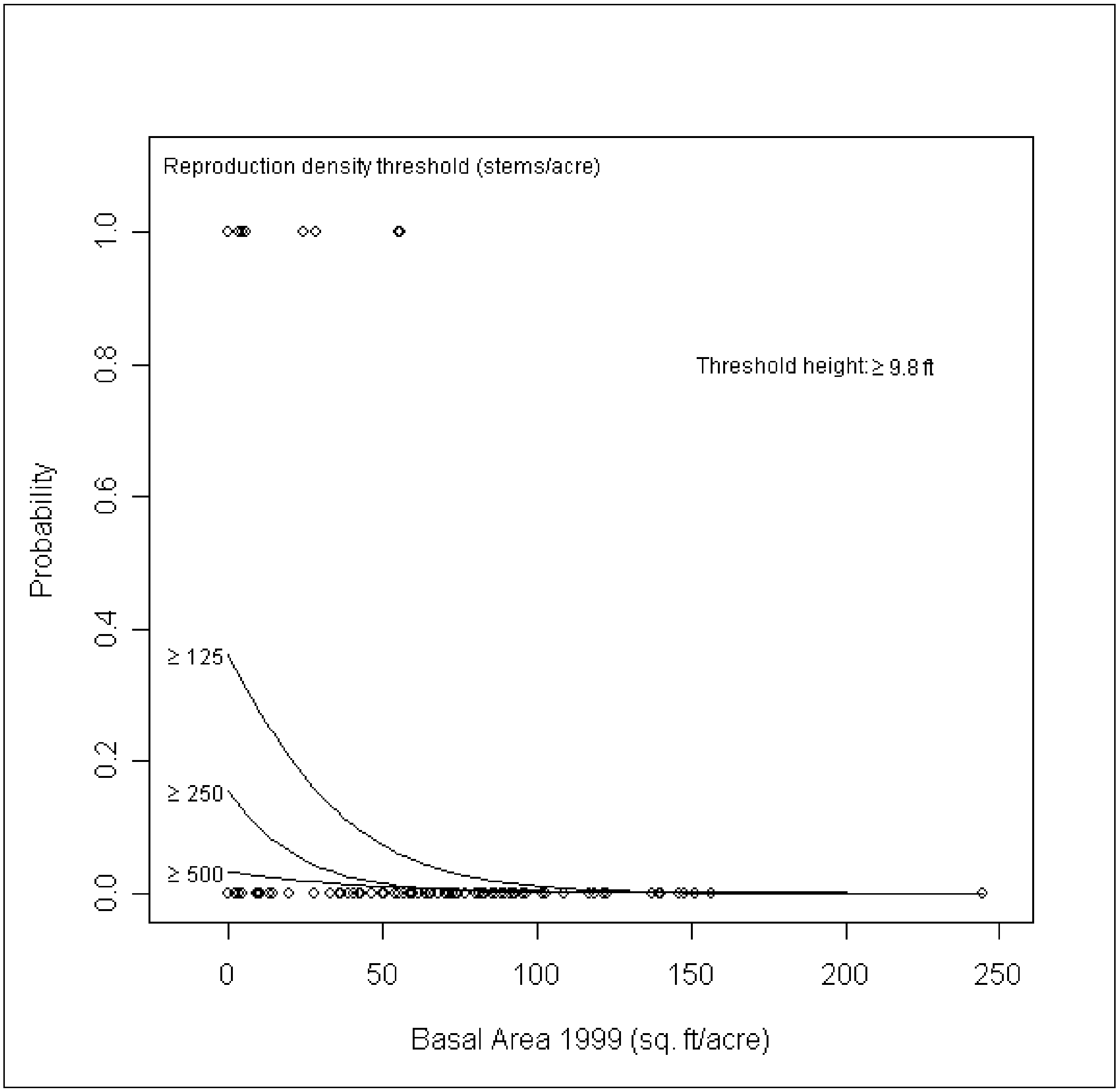

Figure 8: The estimated probability of obtaining at least 125, 250, 500, or 1000 white oaks per acre at least 9.8 ft tall for a given overstory basal area, 8 years after treatment. Diamonds represent plots that met (1.0) or did not meet (0.0) height and abundance thresholds.

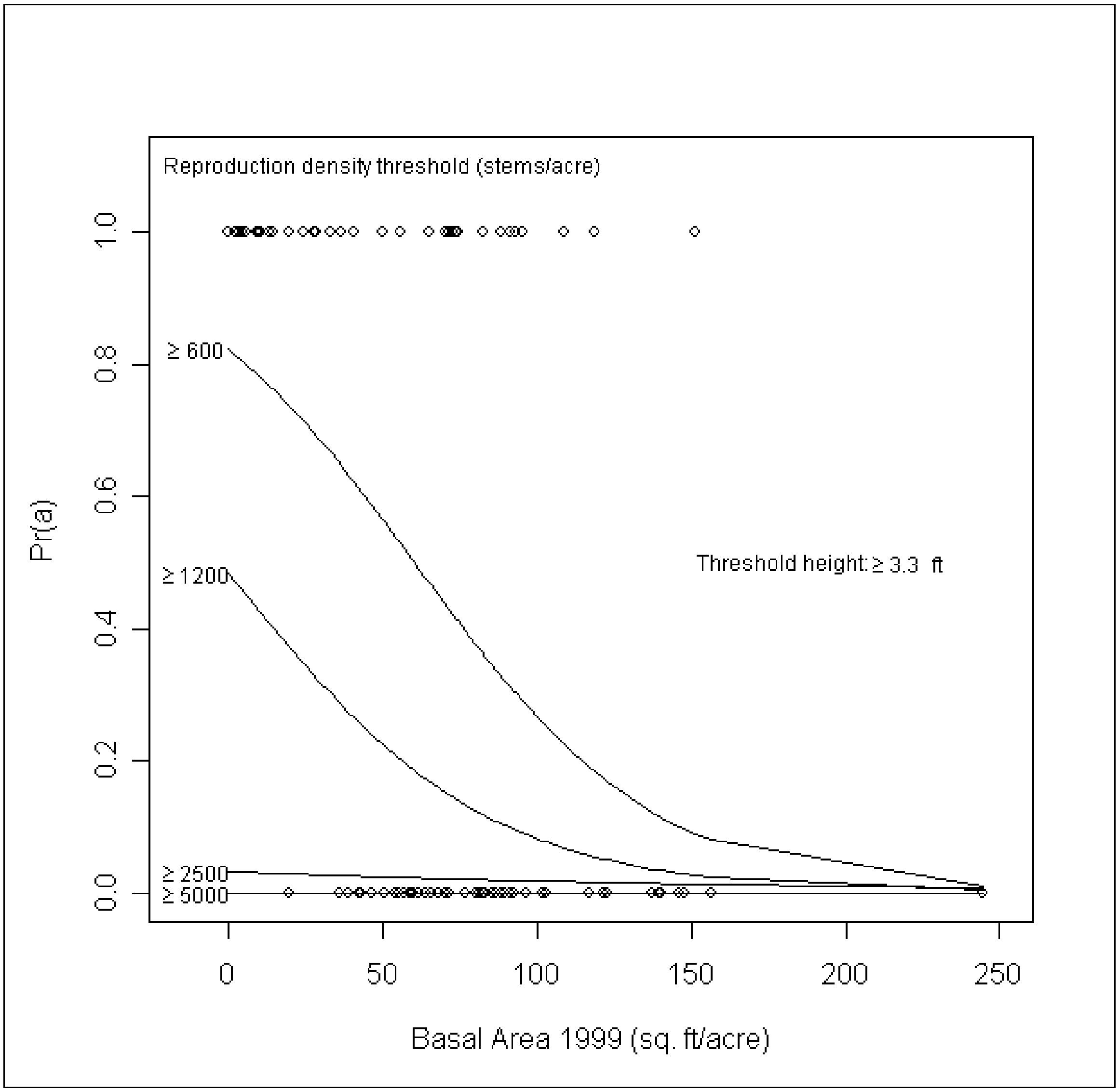

Figure 9: The estimated probability of obtaining at least 600, 1200, 2500, or 5000 per acre of non-oaks at least 3.3 ft tall for a given residual overstory basal area, 8 years after overstory treatment. Diamonds represent plots that met (1.0) or did not meet (0.0) height and abundance thresholds.

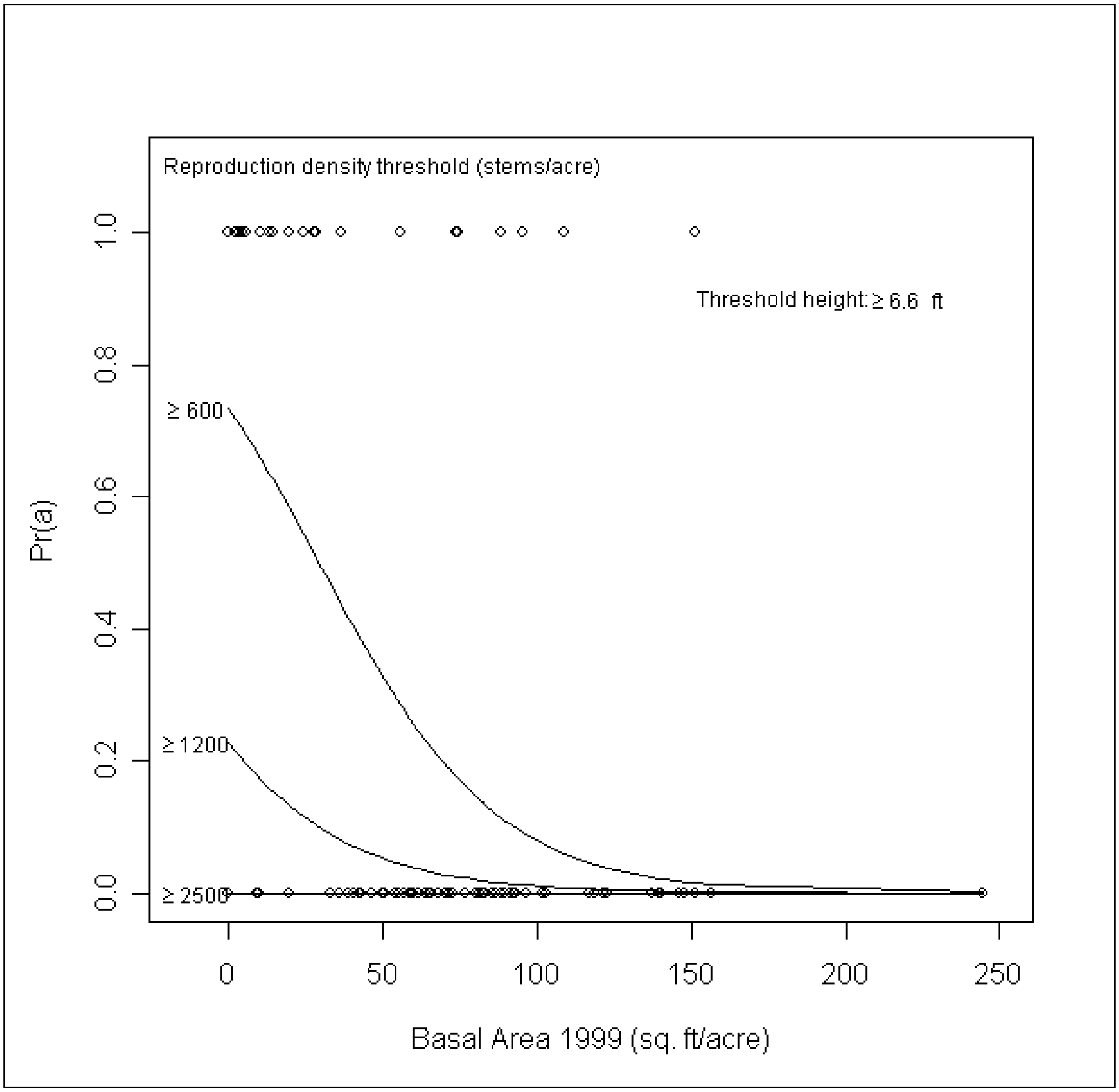

Figure 10: The estimated probability of obtaining at least 600, 1200, 2500, or 5000 stems per acre of non-oaks at least 6.6 ft tall for a given residual overstory basal area, 8 years after overstory treatment. Diamonds represent plots that met (1.0) or did not meet (0.0) height and abundance thresholds.

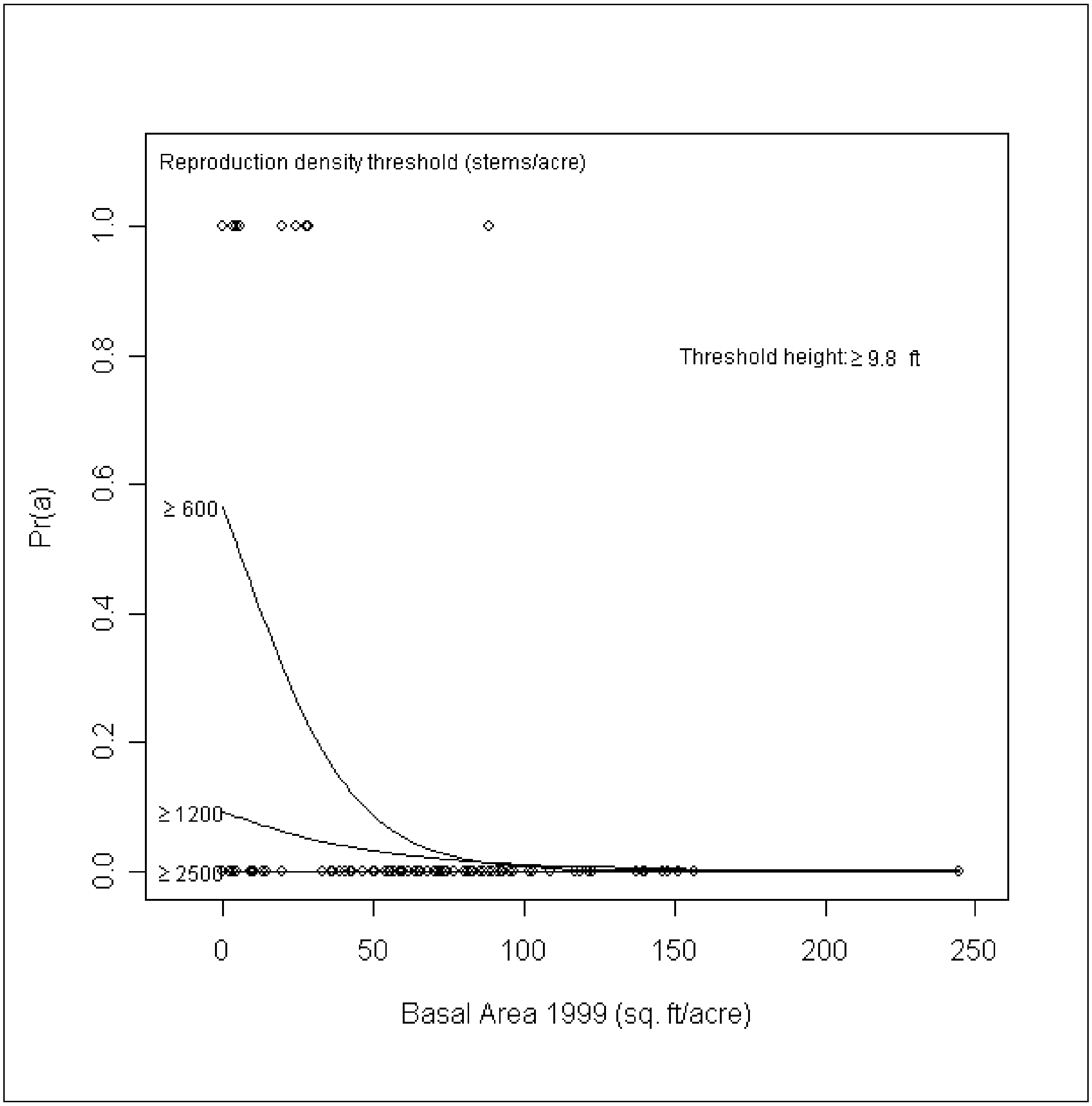

Figure 11: The estimated probability of obtaining at least 600, 1200, 2500, or 5000 stems per acre of non-oaks at least 9.8 ft tall for a given residual overstory basal area, 8 years after treatment. Diamonds represent plots that met (1.0) or did not meet (0.0) height and abundance thresholds.

Table 4: Logistic regression parameters for estimating the probability of obtaining a specified reproduction density and height on a 0.05 acre plot for red oaks and white oaks (n=90).

Reproduction height class (ft)	Reproduction density class (trees/acre)	Model coefficients**					
		b_0			b_1		
	Red Oak Seedlings						
≥3.3	≥125	0.4921	(-0.4451)		-0.0333	(0.0087)	*
	≥250	-0.7162	(0.4989)		-0.0295	(0.0112)	*
	≥500	-1.3523	(0.5945)	*	-0.0288	(0.0141)	*
	≥1000	-2.66E+01	(6.50E+04)		3.27E-17	(8.03E+02)	
≥6.6	≥125	-0.3522	(0.4747)		-0.0335	(0.011)	*
	≥250	-1.2446	(0.6128)	*	-0.0425	(0.0199)	*
	≥500	-2.112	(0.8782)	*	-0.0536	(0.04)	*
	≥1000	-2.66E+01	(6.50E+04)		3.27E-17	(8.03E+02)	
≥9.8	≥125	-0.897	(0.5700)		-0.0498	(0.0210)	*
	≥250	-1.573	(0.7324)	*	-0.0615	(0.0381)	
	≥500	-2.66E+01	(6.50E+04)		3.27E-17	(8.03E+02)	
	≥1000	-2.66E+01	(6.50E+04)		3.27E-17	(8.03E+02)	
	White oak Seedlings						
≥3.3	≥600	0.71	(0.4186)	*	-0.022	(0.0064)	*
	≥1200	0.0966	(0.4313)		-0.0255	(0.0078)	*
	≥2500	-0.8206	(0.5452)		-0.0432	(0.0170)	*
	≥5000	-2.2394	(0.8117)	*	-0.0245	(0.0183)	
≥6.6	≥600	0.5766	(0.4506)		-0.0355	(0.009)	*
	≥1200	-0.5763	(0.5083)		-0.0395	(0.1400)	*
	≥2500	-2.2394	(0.8117)	*	-0.0245	(0.0183)	
	≥5000	-2.2716	(0.8995)	*	-0.0422	(0.0316)	
≥9.8	≥600	-0.5763	(0.5083)		-0.0395	(0.014)	*
	≥1200	-1.6974	(0.7397)	*	-0.0510	(0.0308)	
	≥2500	-3.3856	(1.3593)	*	-0.0244	(0.0314)	
	≥5000	-3.3856	(1.3593)	*	-0.0244	(0.0314)	

Note: The values inparentheses are the SE of the parameter estimates

*Parameter estimate is significantly different from 0 (*p*≥0.05).

**For the model $P_s = \exp(b_o + b_1\mathrm{BA})/(1+\exp(b_o + b_1\mathrm{BA}))$

Table 5: Logistic regression parameters for estimating the probability of obtaining a specified reproduction density and height on a 0.05 acre plot for non-oaks (n=90).

Reproduction height class (ft)	Reproduction density class (trees/acre)	Model coefficients**					
		b_0			b_1		
	Non-oak Seedlings						
≥3.3	≥600	1.5344	(0.4664)	*	-0.0255	(0.0065)	*
	≥1200	-0.0634	(0.4319)		-0.0236	(0.0077)	*
	≥2500	-3.4159	(1.1567)	*	-0.0061	(0.0167)	
	≥5000	-2.66E+01	(6.50E+04)		3.27E-17	(8.03E+02)	
≥6.6	≥600	1.0159	(0.4607)	*	-0.0348	(0.0082)	*
	≥1200	-1.2235	(0.5850)	*	-0.0336	(0.0153)	*
	≥2500	-2.66E+01	(6.50E+04)		3.27E-17	(8.03E+02)	
	≥5000	-2.66E+01	(6.50E+04)		3.27E-17	(8.03E+02)	
≥9.8	≥600	0.2668	(0.4838)		-0.0528	(0.0147)	*
	≥1200	-2.285	(0.8193)	*	-0.0231	(0.0278)	
	≥2500	-2.66E+01	(6.50E+04)		3.27E-17	(8.03E+02)	
	≥5000	-2.66E+01	(6.50E+04)		3.27E-17	(8.03E+02)	

Note: The values inparentheses are the SE of the parameter estimates

Parameter estimate is significantly different from 0 ($p \geq 0.05$*).

**For the model $P_s = \exp(b_o + b_1 \mathrm{BA})/(1+\exp(b_o + b_1 \mathrm{BA}))$

THE EFFECT OF OVERSTORY DENSITY ON UNDERSTORY HEIGHT GROWTH

The logistic regression explains general trends for the effect of overstory basal area on mean annual height growth of the understory. The logistic regression models illustrate that the probability of all species groups that meet the specified height growth threshold decreases with increasing overstory density (Table 6). Furthermore, the proportion of trees that achieved a given mean annual height growth decreased with increasing overstory density for all species groups (Table 6). The oak species groups had higher average annual height growth probabilities than the non-oak group across nearly all height growth classes (Figures 12, 13, 14). This trend is consistent throughout the data except for the lowest mean annual height growth threshold of at least 0.5 ft per year for which red oaks, white oaks, and non-oaks exhibited similar probabilities at the average annual height growth threshold of ≥0.5 ft per year. However, no oaks met the mean annual height growth change criteria when basal area exceeded 135 ft^2/ acre. The non-oak species group had no understory trees that met the height growth criteria when basal area exceeded 140 ft^2/ acre.

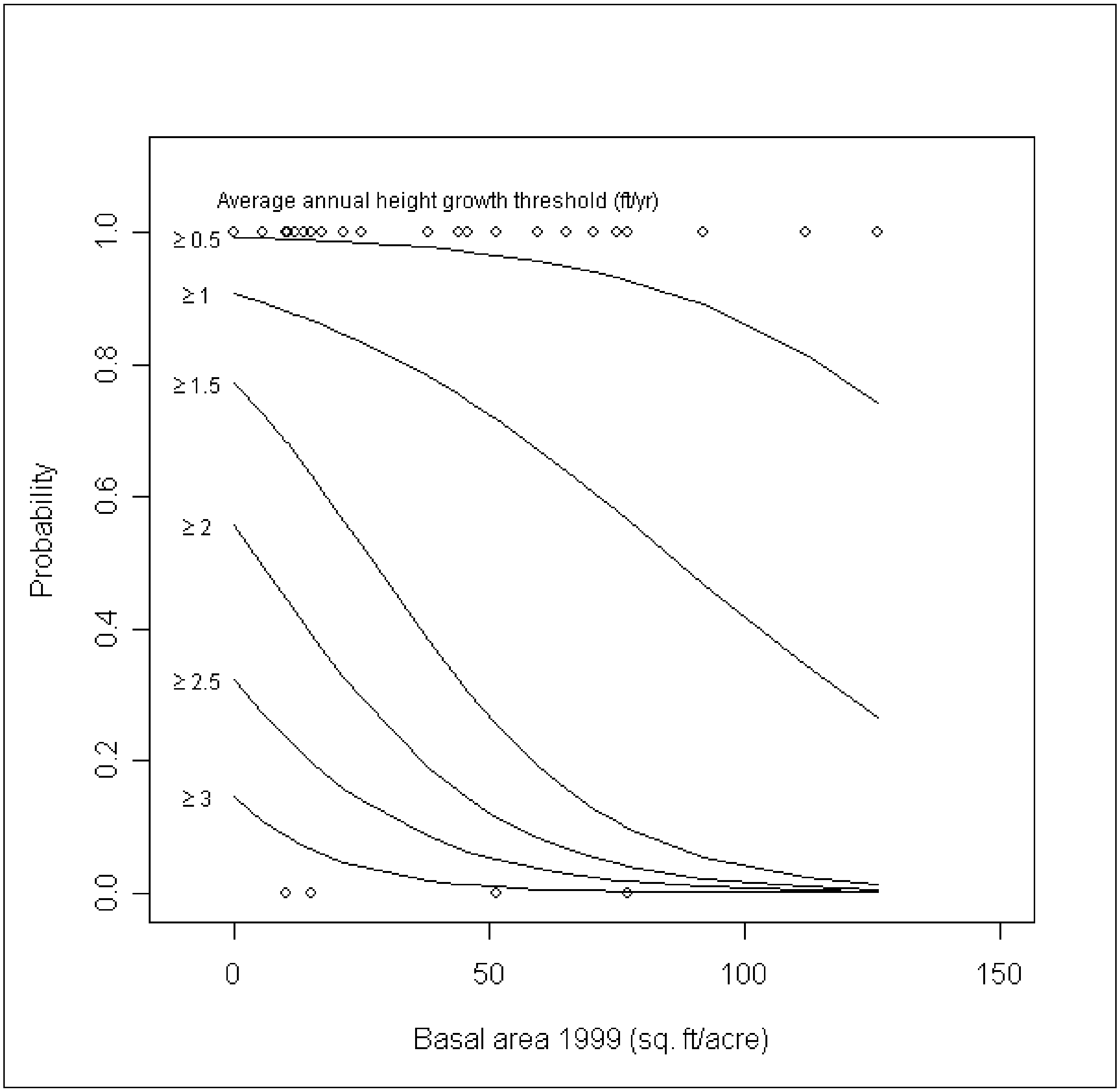

Figure 12:The estimated probability that understory red oak trees will have at least 0.5, 1.0, 1.5, 2.0, 2.5, or 3.0 ft of mean annual height growth for a given overstory basal area. Diamonds represent plots that met (1.0) or did not meet (0.0) height and abundance thresholds.

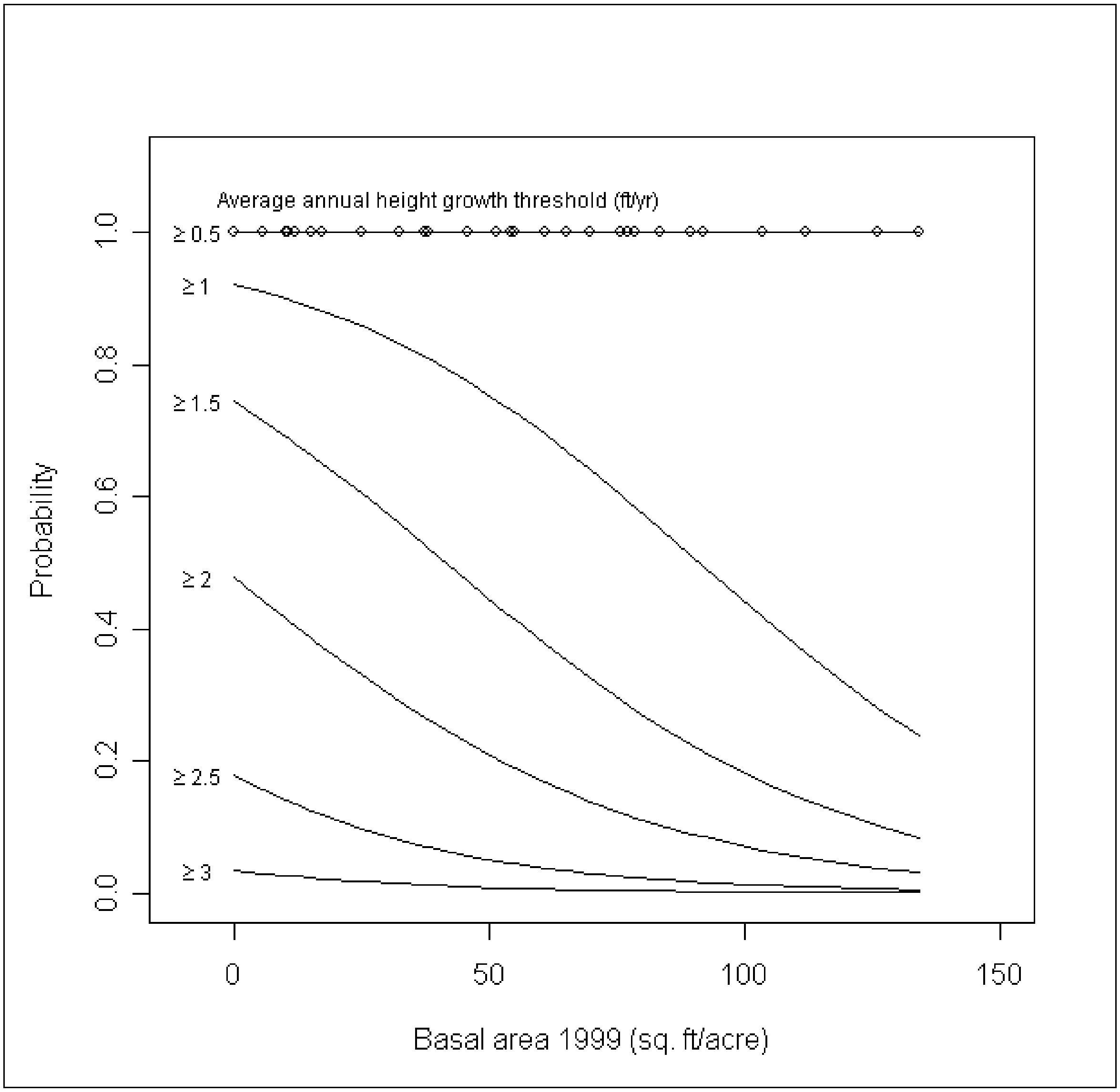

Figure 13:: The estimated probability that understory white oak trees will have at least 0.5, 1.0, 1.5, 2.0, 2.5, or 3.0 ft of mean annual height growth for a given overstory basal area. Diamonds represent plots that met (1.0) or did not meet (0.0) height and abundance thresholds.

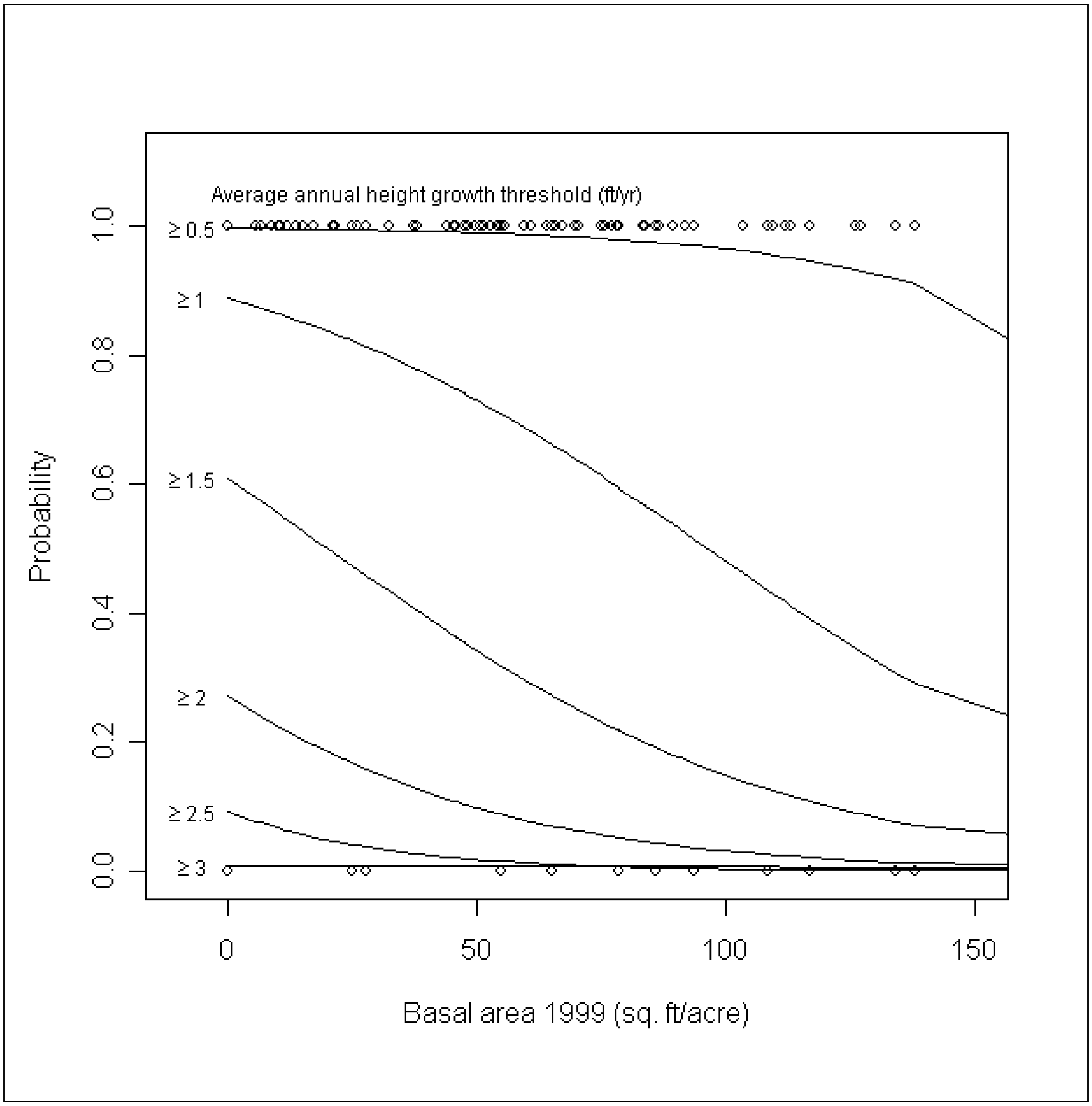

Figure 14: The estimated probability that understory non-oak trees will have at least 0.5, 1.0, 1.5, 2.0, or 2.5 of mean annual height growth for a given overstory basal area. Diamonds represent plots that met (1.0) or did not meet (0.0) height and abundance thresholds.

Table 6: Observed numbers of trees above and below the specified average annual height growth threshold

Understory mean annual height growth threshold (ft/yr)	Observed no. of trees: Below threshold	Observed no. of trees: Above or equal to threhold
Red oak seedlings (n=314)		
≥0.5ft	5	309
≥1.0ft	45	269
≥1.5ft	110	204
≥2.0ft	175	139
≥2.5ft	237	77
≥3.0	282	32
White oak seedlings (n=324)		
≥0.5ft	0	324
≥1.0ft	49	275
≥1.5ft	120	204
≥2.0ft	202	122
≥2.5ft	282	42
≥3.0	316	8
Non-oak seedlings (n=1962)		
≥0.5ft	16	1946
≥1.0ft	358	1604
≥1.5ft	964	998
≥2.0ft	1554	408
≥2.5ft	1835	127
≥3.0	1948	14

Table 7: Logistic regression parameters for estimating the probability of obtaining an average annual height growth on a 0.05 acre plot.

Reproduction mean annual height growth (ft)	Model coefficients**					
	b₀			*b₁*		
	Red oak understory (n=314)					
≥0.5ft	4.937	(0.6801)	*	-0.0308	(-0.0115)	*
≥1.0ft	2.2743	(0.2124)	*	-0.0262	(-0.0057)	*
≥1.5ft	1.2223	(0.1556)	*	-0.0447	(-0.0075)	*
≥2.0ft	0.2336	(0.1392)		-0.0443	(-0.0094)	*
≥2.5ft	-0.7446	(0.1528)	*	-0.043	(-0.0127)	*
≥3.0	-1.7719	(0.2108)	*	-0.0581	(-0.0248)	*
	White oak understory (n=324)					
≥0.5ft	2.66E+01	(-2.41E+04)		3.40E-18	(684.9)	
≥1.0ft	2.4727	(0.2316)	*	-0.0271	(0.0048)	*
≥1.5ft	1.065	(0.1532)	*	-0.0258	(0.0047)	*
≥2.0ft	-0.0905	(0.1409)		-0.0249	(0.0058)	*
≥2.5ft	-1.5233	(0.1920)	*	-0.0284	(0.0110)	*
≥3.0	-3.316	(0.4061)	*	-0.0291	(0.0249)	*
	Non-oak understory (n=1962)					
≥0.5ft	5.8895	(0.4085)	*	-0.026	(0.0045)	*
≥1.0ft	1.966	(0.0781)	*	-0.0181	(0.0016)	*
≥1.5ft	0.3849	(0.0548)	*	-0.0185	(0.0017)	*
≥2.0ft	-0.9833	(0.0634)	*	-0.0263	(0.0032)	*
≥2.5ft	-2.3	(0.1007)	*	-0.0327	(0.0070)	*

Note: The values inparentheses are the SE of the parameter estimates

*Parameter estimate is significantly different from 0 ($p \geq 0.05$).

**For the model $P_s = \exp(b_o + b_1 BA)/(1+\exp(b_o + b_1 BA))$

Similar to the logistic regression, the ANOVA illustrated that clearcuts provide the maximum average height growth of understory trees for red oaks, white oaks, and non-oaks (Table 8). Mean annual height growth of understory red oaks were 2.11 feet taller than white oaks and 2.48 feet taller than non-oaks in clearcuts (Table 8). However, relatively small increase in overstory density significantly reduced the mean annual height growth rate of understory trees regardless of species and showed no significant height growth difference between species classes (Table 8). Understory oaks had 8 year growth that was approximately 30% less for the overstory basal area of 1-20 ft^2 / acre when compared to clearcuts. Furthermore, understory trees in basal area classes over 21 ft^2/acre had 8 year height growth that was approximately 50% less than understory trees on clearcuts.It should also be noted that regardless of density class, the lowest average height growth change was nearly 5 feet over the 8 year period. Although height growth of 4.7 feet in a ten year span is far from superior, it is at least some degree of height growth.

On ELT 17 (south and west facing slopes), oaks grew on average 3.5 feet taller than non-oaks on clearcuts (α=0.0001) over the 8 year period. Oak understory trees also grew 1.5 feet taller than non-oaks in the 1-20 ft2/acre class (α=0.07). However, after overstory basal area was increased by any amount, there were no significant differences in height growth between oaks and non-oaks. On ELT 18 (north and east facing slopes), only density classes of 21-40 ft^2/acre showed significant differences in height growth(α=0.08) favoring non-oaks.

All of the results from the ANOVA are similar to the results in the logistic regression. Both show that understory height growth increases with decreasing overstory density. This trend is maintained throughout all density classes and regardless of species class. The results also conform to understanding of species specific tolerance of shade, red oaks being the least tolerant, white oaks being somewhat tolerant, and non-oaks being tolerant.

Table 8: Least squared difference comparison of red oak, white oak, and non-oak height growth over an 8 year period across varying overstory density classes. The height difference estimate was calculated for by subtracting mean height growth in species column A and subtracting the mean height growth values from species column B. (DF=99)

	Species Comparison (A-B)					
Density Class	A	B	Difference Estimate	Error	t-Value	Pr > |t|
CC	Non-oak	Red Oak**	-2.4769	0.6392	-3.87	0.0002
CC	Non-oak	White Oak	-0.3574	0.6392	-0.56	0.5773
CC	Red Oak**	White Oak	2.1195	0.6392	3.32	0.0013
1-20	Non-oak	Red Oak	-0.9347	0.6704	-1.39	0.1663
1-20	Non-oak	White Oak	-0.4361	0.6942	-0.63	0.5313
1-20	Red Oak	White Oak	0.4986	0.6942	0.72	0.4743
21-40	Non-oak	Red Oak	1.4175	0.8773	1.62	0.1093
21-40	Non-oak	White Oak	0.9130	0.8195	1.11	0.2679
21-40	Red Oak	White Oak	-0.5044	0.9472	-0.53	0.5955
41-60	Non-oak	Red Oak	0.3659	0.6201	0.59	0.5565
41-60	Non-oak	White Oak	0.4909	0.5629	0.87	0.3853
41-60	Red Oak	White Oak	0.1250	0.6518	0.19	0.8484
61-80	Non-oak	Red Oak	1.1728	0.6955	1.69	0.0949
61-80	Non-oak	White Oak	-0.08295	0.6406	-0.13	0.8972
61-80	Red Oak	White Oak	-1.2558	0.7357	-1.71	0.0910
81-100	Non-oak	Red Oak	0.8934	0.9653	0.93	0.3570
81-100	Non-oak	White Oak	-0.3334	0.9653	-0.35	0.7305
81-100	Red Oak	White Oak	-1.2268	1.0600	-1.16	0.2499
100+	Non-oak	Red Oak	1.2840	0.7778	1.65	0.1020
100+	Non-oak	White Oak	0.06881	0.7778	0.09	0.9297
100+	Red Oak	White Oak	-1.2152	0.9125	-1.33	0.1860

* Designates the species with greater height growth over the 8 year study period

** Designates the species with significantly greater height growth over the 8 year study period

CHAPTER 5

DISCUSSION

THE EFFECT OF OVERSTORY DENSITY ON REGENERATION ABUNDANCE

The results of this study indicate that the probability of regeneration reaching a given height 8 years after treatment oak species group and all species combined group decreases with increasing overstory density. Furthermore, oaks were less abundant as a group than competing tree species. However, many of the non-oaks will not become overstory canopy dominants. Oak has the ability to persist in the understory while experiencing dieback and resprouting, which promotes root development. These characteristics may give oak regeneration a competitive advantage when the overstory is removed. Oak regeneration with well developed root systems may be more effective at capturing and occupying freed growing space. Other species use varying competitive strategies which include differences in seed production, height growth, survival rates, and sprouting potential (Larsen et al., 1997). Even though the all species combined group had higher tree abundance, many of these tree species have a life history much different than oak which may allow them to develop differently than oak. Therefore, species survival on any given site may depend on both species-specific life histories and post disturbance species competition. These two factors may play an important role in determining future overstory composition.

The success probabilities of oak regeneration abundance that met the designated height thresholds also decreased with increasing height. These results are supported by previously published theories of regeneration dynamics (Tryon and Carvell, 1958; Sander, 1972; Johnson et al., 2002). The observed growth rates for understory trees were highly variable by species and overstory basal area. However, the regression models illustrate the probable rates of deceasing reproduction density and size with increasing overstory density.

These models and equations can be used by forest managers to predict how various reductions in overstory density affect regeneration abundance in the Ozark Highlands. Managers can examine current forest overstory density, refer to the estimated probability of regeneration abundance, and determine whether a reduction in overstory density is needed to encourage a high probability of success for obtaining oak reproduction. Oaks in the Ozark Highlands are dependent on the accumulation of oak reproduction in the understory over time (Sander, 1971; Johnson, 1993) and regeneration abundance appears to be significantly influenced by overstory density (Larsen et al., 1997). Therefore, overstory density reductions may aid in increasing regeneration abundance.

For red oak and white oak species, none of the plots met the height or density threshold criteria when basal area exceeded 90 ft^2 / acre and 150 ft^2 / acre respectively. Depending on management goals, it may be necessary to reduce overstory stocking below the B-level according to the Gingrich (1967) stocking diagram. When overstory density is at B-level, the average tree diameter has minimum stocking for full utilization of growing space (Gingrich, 1967). A reduction of overstory density below the B-level will reduce overstory density to allow enough sunlight to penetrate to the forest floor to stimulate growth of advance reproduction. The all species group had several plots with successful regeneration with overstory densities higher than 90 ft^2 / acre. This is most likely a function of the all species combined group having many species that are more shade tolerant than oaks and can persist with higher overstory densities.

Results are also similar to Larsen et al. (1997) in which success probabilities increased with decreasing overstory density. This study was conducted in Pioneer Forest on the Current River drainage in the Missouri Ozark Highlands. The MOFEP site is also located in the Missouri Ozark Highlands and is similar to Pioneer forest in terms of location, species composition, site productivity, and topography. However, the MOFEP site and Pioneer Forest have been managed using different management techniques. Pioneer Forest uses the uneven-age single tree selection method. Trees are selected for harvest based on vigor, quality, species, and spacing. Rarely are group openings used, except in special circumstances such as areas of oak decline. Nevertheless, the effects of overstory density on regeneration abundance are similar regardless of management styles.

THE EFFECT OF OVERSTORY DENSITY ON UNDERSTORY HEIGHT GROWTH

Height growth of the understory is an important factor in stand development because trees that grow the fastest are most likely to become overstory dominant and codominant trees. Oaks are well adapted to disturbances of varying frequency and intensity which may give them a competitive advantage over non-oaks. Oak saplings often experience significant root development while they dieback and accumulate in the understory. This allows them to rapidly grow and occupy growing space when it becomes available. Although non-oaks have greater abundance across all plots (Table 1), results of the logistic regression indicate that oak species have the capacity to outgrow non-oak species across nearly all height growth classes. Probabilities for success for oaks and non-oaks were similar only at the ≥0.5 ft average annual height growth threshold. The percentage of oaks and non-oaks that grew ≥0.5 ft/year was 99.2% and 99.2% respectively. This may indicate that for any species at any level of density, it is relatively easy to obtain average annual height growth of 0.5 ft/ year. However, it is doubtful that trees growing <1 ft / year would compete well enough to be successfully recruited into the overstory. In all other height growth thresholds, oaks had higher probabilities of height growth success than non-oaks. This supports the idea that most non-oak species less frequently become canopy dominants in the Ozark Highlands. One might assume when examining species abundance that the all species group, which had consistently higher densities than oak (Figures 3 through 8), may dominate species composition after overstory removal. However, the average annual height growth of oak at the height growth thresholds appear to surpass the non-oak group, at least over the 8 year study period.

Typically, oaks are not recruited into the overstory until overstory removal (Dey et al., 1996). After overstory removal, annual height growth becomes an important factor in determining tree status as an overstory dominant or codominant tree. Therefore, density should be reduced to below B-level stocking to allow for understory recruitment into the overstory. Oaks and non-oaks experienced no height growth when overstory basal area exceeded 135 ft^2/ acre and 140 ft^2/ acre respectively. When practicing even–aged management, group selection, and/or thinning, stand density must be reduced below B-level to stimulate understory oak height growth before harvest if the management goal is recruitment of the understory into the overstory.

Forest managers can use the results of the logistic regression to estimate the probability of obtaining height growths of trees at a specified stand density. The estimates can be useful for estimating understory height growth for a wide variety of treatments. These results illustrate general trends in the understory height growth in stands of a given density.

When comparing red oaks, white oaks, and non-oaks (Table 8) it is apparent that clearcuts provide the best height growth for both oaks and non-oaks. When overstory basal area exceeds 20 ft^2/ acre, it appears that understory non-oaks have similar height growth when compared to understory red and white oaks. These results are not statistically significantly different from each other but may offer practical implications for forest managers. A consequence of retaining overstory basal area is a decrease in understory height growth. However, it is rare for non-oaks to dominate the landscape in the Ozark Highlands. Therefore, other dynamics play a stronger role in determining future overstory dominance. For instance, height growth of understory trees may be dependent on their proximity and orientation to overstory trees. Gap openings may provide a gradient of height growth depending on the distance from the edge of the gap opening. It is expected that trees near the center of the gap opening would have the greatest annual height growth because these trees experience greater light availability and less competition from the overstory. In contrast, understory trees near the edge of the gap may have less height growth due to decreased light availability and increased competition from overstory trees. Uneven-aged stands most likely function in a similar manner and have exponentially more "edge". Sander (1972) described a similar phenomenon when he found that for a few understory trees in partial cut stands, height growth response was sufficient enough to eventually produce dominant or codominant trees. Unfortunately the ANOVA does not describe this scenario because it uses plot averages. Examining understory at a local level rather than a plot level may reveal this scenario. Overstory density, spatial location, and proximity to overstory trees may all be important factors in determining the average annual height growth of understory trees.

High overstory density may encourage non-oaks to better compete with oaks. Height growth for oaks and non-oaks were similar once basal area exceeded 20 ft^2 / acre (Figure 11). This is most likely attributed to non-oaks being more shade tolerant and having much different life histories than oaks. Similarly, red oaks were significantly taller than white oaks and non-oaks in clearcuts. However, any increase in overstory density created conditions that allowed white oaks, red oaks, and non-oaks to grow similarly in height (Table 8). Also, although not statistically significant, overstory basal area classes over 60 ft^2/ acre appear to favor white oaks over red oaks. This attribute may be indicative of red oaks primarily being early successional species with relatively low shade tolerance while white oaks are able to compete with shade tolerant non-oaks under varying degrees of shading. Non-oaks and white oaks appear to have similar height growth when basal area is over 60 ft^2/ acre. Therefore, when basal area is increased above 60 ft^2/ acre, white oaks and non-oaks are the favored species for height growth performance.

As stated earlier, it is rare for non-oaks to dominate the landscape in the Ozark Highlands. Oak dominance in the Ozark Highlands may be contributed to adaptations such as being drought tolerant, the ability to dieback and resprout promoting root development, relatively low mortality, stump sprouting capabilities, and fire tolerance. These adaptations give oaks a competitive advantage to persist and rapidly occupy growing space once it becomes available. It is also important to note that this dataset examines only a 10 year period. Oaks are well adapted to a variety of disturbances and a 10 year period may not be a sufficient time period for oak to express these adaptations. The results are a short glimpse of the understory dynamics within a 10 year period and only 8 years after treatments were applied. Nevertheless, the results are important in understanding initial response of understory trees to silvicultural treatments that regulate overstory density.

Understory height growth is dependent on adequate sunlight. Therefore, thinning the stand below the B-level according to the Gingrich (1967) stocking diagram may be necessary to stimulate height growth. When overstory density is at B-level, the average tree diameter has minimum stocking for full utilization of growing space (Gingrich, 1967). A reduction of overstory density below the B-level will reduce overstory density to allow enough sunlight to penetrate to the forest floor to stimulate height growth of the oak understory.

CHAPTER 6

CONCLUSIONS

SUSTAINING OAK REGENERATION IN THE OZARK HIGHLANDS IS DEPENDANT ON REGULATING OVERSTORY DENSITY

Oak regeneration abundance is highly dependent on overstory density. The logistic regression models for oak regeneration indicate that regeneration abundance for a given height threshold and density threshold increases with decreasing overstory density. This trend is consistent for all size, density, and species classes. These regression models provide general guidelines that illustrate average expected outcomes of regeneration at a given overstory density. They show that in the Ozark Highlands, relatively high regeneration densities of large reproduction can be obtained with low overstory densities. For oak species none of the plots met the regeneration abundance and height criteria when basal area exceeded 90 ft^2 / acre. This trend may suggest that oaks are required to experience some type of disturbance that lowers stand density below 90 ft^2 / acre to have any oak reproduction. The all species combined group had several plots with that met the defined abundance and height thresholds when overstory densities were higher than 90 ft^2 / acre.

Controlling regeneration abundance is usually limited to treatments made to the overstory. Therefore, foresters must concentrate on controlling overstory stand densities to encourage regeneration at an abundance level that meets management objectives. These models provide guidelines that illustrate the average expected regeneration abundance at a specified overstory density.

OAK UNDERSTORY HEIGHT GROWTH IS DEPENDENT ON THE REGULATION OF OVERSORY DENSITY

Height growth of understory oak is highly dependent on overstory density. The logistic regression models illustrate that understory height growth increases with decreasing overstory density. No height growth was observed when overstory basal area exceeded 135 ft^2/ acre. However, height growth of understory trees may also depend on their proximity and orientation to overstory trees. It is expected that trees near the center of a gap opening would potentially have the greatest annual height growth when compared to other trees in the gap because these trees experience greater light availability and less competition from the overstory. Understory trees that are near overstory trees are expected to have annual average height growth that is less than trees near the center of the gap opening. Uneven-aged single tree selection stands most likely function in a similar manner to group openings.

FUTURE RESEARCH

There are several opportunities for future research with this dataset and the ongoing data collection at the MOFEP site. This data only examines a time period of 10 years for regeneration abundance and 8 years for post treatment height growth of new trees. This is a relatively small time period and can this study can be reevaluated if this type of data is continuously collected for the next several inventory periods. The data is extremely stochastic and evaluating future species composition, height growth, and canopy closure are all important considerations when making forest management decisions. Therefore, it is invaluable that this research be reexamined in 10 years to evaluate if similar stand dynamics processes are continuing at this site.

Crowns of a tree are the driving force of height and diameter growth. Thinning or crop tree release essentially frees growing space for both the tree roots and canopy. However, there are consequences to using various thinning regimes. If a stand is thinned too hard, the residual trees may develop epicormic sprouts. However, if a stand is thinned too lightly, there may be no effect on the diameter growth of the tree. These are expected trade-offs for given thinning intensities. Realistically, moderate thinning or thinning early and often may provide a tolerable level of diameter growth while minimizing the probability for epicormic sprouts.

Unfortunately, the data collected was not suitable for this study. Simple improvements could be made to the MOFEP project to make this part of the study feasible. First, crown class is a simple measure that takes a relatively short amount of time. This measurement is essential in determining the lateral crown expansion of dominant and codominant trees. Defining a crown class is a simple way of assigning status to a tree. Once a crown class is assigned, it would be quite easy to evaluate crown growth for the four typically used crown classes. Stem analysis may also serve a very accurate measurement of lateral crown expansion. One could examine terminal bud growth of branches of crop trees to determine the rate of expansion in relation to height growth, treatment type, and/or residual basal area. However, stand history must be known in order to analyze crown growth. The current MOFEP dataset provides all of the necessary elements except for crown class and stem analysis. Stem analysis is not realistic for this type of long-term study due to the nature of destructive sampling. However, crown class data is relatively easy to collect and would drastically improve this part of the study. This question merits a closer examination since crown dimensions directly influence both height and diameter growth rates.

CHAPTER 7

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