THE EFFECTS OF SILVICULTURAL TREATMENTS ON OAK HEIGHT AND BASAL DIAMETER GROWTH AND OAK REGENERATION ABUNDANCE FOLLOWING A WOODY BIOMASS REMOVAL DURING HARVEST IN THE MISSOURI OZARKS

A Thesis presented to

The Faculty of the Graduate School

University of Missouri

In Partial Fulfillment

of the Requirement for the Degree

Master of Science

---

by

CHARLES L. HANSEN

Dr. John P. Dwyer, Thesis Supervisor

December, 2011

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

THE EFFECTS OF SILVICULTURAL TREATMENT ON OAK HEIGHT AND BASAL DIAMETER GROWTH AND OAK REGENERATION ABUNDANCE FOLLOWING A WOODY BIOMASS REMOVAL DURING HARVEST IN THE MISSOURI OZARKS

presented by Charles L. Hansen

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

____

Dr. John P. Dwyer

____

Dr. David R. Larsen

____

Dr. Robert Pierce

ACKNOWLEDGMENTS

First and foremost I want to identify my biggest hero, my father Dennis Hansen. I can say with full confidence that without my dad's guidance and support that I might not have made it this far. Dad you were my inspiration when it came to the appreciation of the natural world. From an early age you taught me about everything that I enjoy today as an adult whether it was hunting, fishing, camping, flint knapping or just being an observer of nature. You spent countless hours helping me conduct my research for this project and I want to let you know your help has not gone unnoticed or unappreciated. Thanks Dad, for everything.

Mom, you have always told me that if I put my mind to it I can do anything. You were absolutely right. You had faith in me when I didn't believe in myself and always encouraged me to be the best. You have been a great teacher and supporter throughout my life and never gave up one me. Thank you Mom, I won't disappoint.

Dr. John Dwyer, I appreciate you taking me on as a graduate student. I could not have learned as much as I have without you as an advisor. Thank you for your patience and guidance throughout the last three years. Allowing me to design and conduct my own research has taught me many valuable lessons. I would also like to thank the rest of my committee, Drs. Dave Larsen and Bob Pierce.

Dr. Mark Elerseick deserves great recognition and appreciation for his assistance with the analysis of my data. Without his patience and knowledge of the SAS program I might still be working on my thesis. Adam Saunders, you were great company down at University Forest. I thoroughly enjoyed helping you with your research and enjoyed your assistance with mine. Luke Lowenstein, thank you for your assistance with my research.

You were always up for the 5 hour drive and we always had a great time, minus my trip to the hospital.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ABSTRACT

Following a biomass harvest in the Missouri Ozarks, oak stump sprouts and seedling sprouts can significantly contribute to the presence of oaks in the future stand. It is important to understand how oak stump sprouts and seedling sprouts respond to a biomass harvest. A study to evaluate oak regeneration dynamics directly following a biomass harvest was initiated on the University Forest Conservation Area in Butler County, Missouri in the spring of 2009. Three hundred permanent subplots were established directly following the harvest to monitor 530 newly regenerated oak and hickory trees. The trees originated from either stump sprouts, seedling sprouts or in a rare event a seed. The height and basal diameter of the trees were monitored for 2 consecutive growing seasons. These measurements were used to produce a logistic regression model to determine the probability these trees would have of obtaining specific average annual height growth thresholds.

Results from a logistic regression analysis of the silvicultural study indicate that as over story density increases the probability of understory trees achieving a higher annual height growth threshold significantly decreases. When the over story basal area was reduced below 50 square feet per acre or less significant increases in height and basal diameter were observed. However, as over story basal area exceeded 50 square feet per acre especially once basal area surpassed 100 square feet per acre a significant decrease in height growth of understory trees was observed.

Results from the analysis of variance or ANOVA testing the differences between white oak, red oak and non-oak stump and seedling sprouts by treatment indicated that stump sprouts will readily out-compete advance regeneration as well as newly germinated seeds. However, both stump sprouts and advance regeneration responded well once the over story basal area was reduced to 50 square feet per acre or less. Oak and non-oak regeneration abundance was also affected by the removal of the over story. When basal area was reduced to or below 50 square feet per acre higher numbers of stems per acre of oak and non-oak regeneration was observed as well as decreased mortality of these species.

CHAPTER 1
INTRODUCTION

JUSTIFICATION

Missouri's forests have been managed using a variety of silvicultural techniques. These techniques are used to regulate the quantity and composition of overstory trees, regeneration and understory trees. Foresters and landowners can use various silvicultural treatments to adjust structure, composition, and dynamics of the forest in order to fit their managerial objectives. Today Missouri foresters and landowners may have another potential use timber other than just lumber products. In the case of the greenhouse gas emissions from the burning of fossil fuels and an increase in global warming, humans are looking for alternatives fuel sources for electricity, heat and vehicles.

One of these potential fuel sources is biomass in the form of whole trees, tree tops or small diameter trees harvested from Missouri forests. Wood has been utilized for heating and cooking for thousands of years with evidence suggesting human utilization of fire began 50,000 to 100,000 years ago(Bowman et al., 2009). Currently Missouri's forests have become over stocked due to lack of proper forest management practices. Now, many trees exhibit poor form and are not valuable in terms of lumber products, however there can be a use for these types of trees in the form of biomass for bio-fuels. Regeneration by seed, stump sprouts and seedling sprouts will then have the opportunity to be recruited into the canopy with the removal of these undesired trees.

Biomass harvesting, however, has been indicted for its potential lack of sustainability in terms of regeneration and soil nutrient loss due to frequent harvesting and poor management practices (Vanguelova et al., 2009; Stupak et al., 2010). However with proper managerial practices such as rotational harvesting, and allowing an adequate amount of years to pass before harvesting new biomass regeneration there is no reason to ascertain the idea that forests utilized for biomass production cannot be managed in a sustainable, productive manner (Stupak et al., 2010). In the case of this research experiment a mechanized biomass harvest ensued to remove small diameter trees and merchantable saw logs from 30 acres in the Missouri, Ozarks during the summer of 2009.

Timber from prior harvests at this site were probably sold to the T.J. Moss Tie Company during the 1920's which produced ties from trees that were larger than 12 inches in diameter (Dwyer, 1988). Local residents were contracted to harvest the timber which took place over several years leaving large trees with poor form, seedling sprouts and clumps of stump sprouts (Dwyer, 1988). The forests were also open range in Butler County during the 1920's with fire used as a mechanism to keep land clear for livestock. The use of fire and the presence of cattle at this time resulted in an even-aged stand of sprouts and advance regeneration. As fire and grazing regulations became more enforced the resulting forests consisted predominantly of red oak species and were approximately the same age (Dwyer, 1988). Forests at the research site today are quite overstocked with little natural regeneration present due to high competition for light on the forest floor. Trees are now approximately 90-100 years old and many of the red oak species are now exhibiting decline and mortality due to their close proximity to the end of their natural life span.

Today large scale, stand reinitiating disturbances are no longer present at the experimental site. Small scale disturbances such as blowdowns and single tree mortality do not recruit enough natural regeneration into dominant and codominant crown classes to perpetuate the site with quality timber. It has now become the responsibility of foresters, landowners and loggers to ensure proper oak regeneration is achieved by mimicking large scale disturbances in the form of timber harvests.

In order to evaluate the response of oak regeneration to human induced disturbance, two different silvicultural treatments, single tree selection and shelterwood in strips, were applied in order to reduce the basal area to varying levels of 30, 40, and 50 square feet per acre. Woody biomass was removed from these treatments in the form of pulpwood and sawlogs. The biomass harvest was immediately followed by a silvicultural study to assess the effects of each treatment on understory growth of oak and non-oak species as well as the impact on regeneration abundance.

PURPOSE AND OBJECTIVES

The purpose of this study was to determine whether silvicultural techniques to remove sawlogs and biomass from forests stand are sustainable. The general objectives of this study are first, to understand the dynamics of height and basal diameter growth of oak and non-oak understory trees in response to single tree selection and shelterwood in strips treatments and, second, to understand the regeneration dynamics of understory reproduction in response to treatment.

This study will specifically: a) evaluate how over story density affects understory height and basal diameter growth; and b) evaluate how overstory density affects regeneration abundance.

HYPOTHESIS

This study tests the following hypotheses for upland oak/hickory forest in the Missouri Ozarks: a) Will the height and diameter growth of understory trees decrease as overstory density increases; and b) Will the abundance of regeneration of all hardwood species decrease with increasing overstory density?

CHAPTER 2
LITERATURE REVIEW

DEVELOPMENT OF OAK-HICKORY FOREST TYPE IN THE OZARKS

Oak (*Quercus*) represents one of the most dominant group of tree species in eastern North America's deciduous hardwood forests (Abrams, 1992). Oaks usually grow in areas prone to disturbance increasing the chance of recruitment of advance oak regeneration into the dominant and codominant canopy classes following disturbance (Johnson, 1977; Larsen et al., 1997). Consequently, the Ozark Highlands of Missouri harbor an abundance of forested areas dominated by the oak- hickory (*Quercus-Carya*) cover type which has developed through a variety of disturbance conditions (Abrams, 1992; Soucy et al., 2005). Historically the oak-hickory forests of the Ozark Highlands were subject to regular disturbance, with the type and degree of disturbance being influenced by either natural (e.g. tornado, fire, wind, ice) or anthropogenic (e.g. timber harvests, clearing, grazing) events (Abrams, 1992, Soucy et al. 2005). Fire seems to have been, historically, the most influential form of disturbance on the development of oak stands in the Ozark Highlands with low to intense wildfires occurring every 3-4 years prior to European settlement (Guyette and Cutter, 1991, Abrams, 1992). Oak reproduction is relatively intolerant to shade thus periodic disturbance ensures the accumulation of regeneration, and subsequently the perpetuation of the oak-hickory forest of the Ozarks (Abrams, 1992; Larsen et al., 1997; Larsen et al., 1999; Soucy et al., 2005).

Soil and climate conditions in the Ozark Highlands also play an important role in the development of oak stands (Kabrick et al., 2007). Oak species in the Ozarks have developed a tolerance to drought, due to xeric conditions, and therefore depend on the processes of shoot dieback and resprouting and the accumulation of advance regeneration in the understory. This process of recurrent dieback and resprouting often occurs over decades and is a species coping device to deal with limited water resources (Larsen et al., 1997, Larsen and Johnson, 1998; Kabrick et al., 2007). Oaks have become dependent upon exploiting these factors giving them an advantage over other species and allowing them to out-compete other drought intolerant species when drought conditions are encountered (Larsen and Johnson, 1998). The advantage of drought tolerance accompanied with the rapid height growth of advance regeneration following release, allows oaks to make up a large proportion of the tree species composition observed in mature stands in the Ozark Highlands (Green, 2007). However, an understanding of basic forest stand dynamics is critical to fully appreciate the development of oak regeneration and recruitment in the Ozark Highlands

The relationship of forest succession and stand development is an important key in understanding the dynamics of regeneration, understory development and overstory crown expansion in the oak dominated forests of the Ozark Highlands. Forests in general undergo four developmental stages as described by Oliver (1981) which serve as a beneficial tool in comprehending stand dynamics. The four stages described by Oliver (1981) are: stand initiation stage, stem exclusion stage, understory reinitiation stage and old forest complex stage. These stages are useful when predicting the future development of an oak stand in the Ozark Highlands following a disturbance.

The stand initiation stage (Oliver and Larson, 1996) is caused by a major disturbance that kills most or all of the large, over story trees but can impact or leave the forest floor undisturbed, depending on the type of disturbance, and usually lasts 20 years for eastern oak species. Types of large scale disturbance in the Ozark Highlands may include: tornadoes, intense fire, timber harvest, etc. A large- scale disturbance my radically change forest floor environments by altering chemical and biological processes within the forest soil, increasing light availability to the forest floor and providing increased growing space for pioneer species and advance oak regeneration. Tree regeneration from a germinated seed or advance regeneration from seedling and stump sprouts are the typical forms of regeneration following a disturbance (Oliver and Larson, 1996; Johnson et al., 2009). In the Missouri Ozarks for example, oaks rely heavily on the sprouting of seedling and stump sprouts following a disturbance (Liming and Johnston, 1944; Johnson, 1979; Dey et al., 1996).

The newly opened growing space is quickly exploited by the fastest growing species which can occupy the site for many years to decades (Oliver and Larson, 1996). The advantage to quickly occupying the growing space allows species to dominate and/or exclude other competing species from that growing space, sometimes until the next disturbance (Oliver and Larson, 1996). Good examples of stand replacing disturbances in the Ozark Highlands today are in the form of man-made clearcuts, shelterwoods and single- tree selections. Oak advance regeneration has the advantage to quickly respond to a thinning of the overstory and appear to have a positive response to these types of silvicultural treatments (Roach and Gingrich, 1968) allowing them to quickly out-compete other species (Sander et al., 1984).

The stem exclusion stage (Oliver and Larson, 1996) occurs approximately 20 years after a stand initiating disturbance (Johnson et al. 2002). During this stage growing space is fully occupied by young, fast growing trees which consequently prevent new trees from regenerating and causing some stems to die thus eliminating them from the stand. Species that can compete well during this stage begin to express distinguished growth patterns causing varying developmental patterns within the stand. Trees that are not able to compete well eventually yield to inferior crown positions or mortality. Stand characteristics become evident during this stage as trees rapidly form into four distinguished crown classes: dominant, codominant, intermediate and suppressed (Oliver and Larson 1996). Trees are in constant competition as their canopies continue to expand and either dominate or are dominated by the other trees (Oliver and Larson 1996). Peet and Christianson (1987) refer to this phenomenon as natural thinning or self-thinning.

The understory reinitation stage (Oliver and Larson 1996) occurs when new shrubs, herbs, trees and other woody plants begin to colonize the forest floor. These species are generally shade tolerant and slow growing. Photosynthesis is reduced in these species since the overstory canopy reduces the amount of available sunlight that reaches the forest floor (Oliver and Larson 1996). This stage begins approximately 80 to 120 years after the stand initiation stage for oak species in eastern North America and will typically last 10 to 20 years. Extensive studies as to why stems appear during this stage rather than earlier in a stand's age have not been conducted and little is understood about the understory reinitiation stage (Oliver and Larson 1996). The reinitiated understory may remain relatively small and distinct from the older trees for many years and could be considered in a literal sense a second cohort. However, reinitiated understory trees are considered a part of the original cohort until they become older and larger (Oliver and Larson 1996).

The old growth or complex forest stage (Oliver and Larson 1996) is no longer prone to large scale disturbance events but rather more small scale events such as tree mortality caused by old age or accumulated effects of pathogens, drought or insects (Oliver and Larson 1996). As large, older trees die in the Ozarks they open up small gaps within the canopy. Underneath these gaps trees in the understory reinitiation stage are gradually recruited to the over story. In essence the forest complex stage may contain different age and size classes of trees with both large and small trees growing in separate and intermixed patches (Oliver and Larson 1996). A true "old growth" or forest complex stage is rarely reached because the probability of a large-scale disturbance increases as the stand becomes older (Oliver and Larson 1996).

OAK REGENERATION IN THE OZARKS

All oaks begin their life cycle as an acorn with most oak species producing good acorn crops 1 year in every 3 or 4 (Olson, 1974; Johnson et.al, 2009). Weather related factors directly influence the flowering process of oaks with other natural factors affecting the later stages of oak development (Johnson et.al, 2009). However, site factors such as topography, soil nutrients and site index appear to have little or no influence on acorn production (Tryon and Carvell, 1962; Wolgast, 1972; Johnson et.al, 2009). Some oaks trees never produce acorns, even while inhabiting excellent growing space and occupying superior crown positions, suggesting that environment, genetics and the interactive effects of all these factors are potential determinants in acorn production for a site (Johnson et. al, 2009).

The most abundant member of the White Oak family at the research site was white oak (*Quercus alba* L). Acorn production for white oak can be prolific but good crops are irregular and occur usually every 4 to 10 years (Rogers, 199; Johnson et. al, 2009). Open grown white oaks can produce more than 23,000 acorns during a good year; however, the average production for forest grown white oaks during a good year is no more than 10,000 acorns for a mature tree (Rogers 1990) Studies have indicated that only a small percent of the total acorn crop (18 percent) will have the potential to develop into seedlings with the remaining 82 percent being damaged or destroyed by animals and insects. The 18 percent that survives damage has a successful germination capacity from 50 to 99 percent (Olson 1974) and will quickly germinate in the fall soon after dropping (Rogers 1990).

White oak will reproduce sufficiently from seed given that soil and climate conditions are favorable yet studies have again shown that despite adequate amounts of sound acorns, the number of new white oak seedlings is relatively low when compared to other oak species (Carvell and Tryon, 1961; Rogers, 1990). However, these seedlings have the ability to persist in the understory for many years by continually dying back and resprouting with a gradual buildup of advance regeneration in the understory (Rogers, 1990; Larsen et al., 1997). When observed under ideal growing conditions it is not uncommon for white oak seedlings to grow 2 feet or more a year. However it is rare to witness newly established white oak seedlings being of value to stand reproduction directly following over story removal due to their slow growth and are eventually outcompeted by the faster growing advance regeneration (Roger,s 1990; Oliver and Larson, 1996; Larsen et al., 1997).

The most abundant member of the Red Oak family at the research site was black oak (*Quercus velutina* Lam). In a forest setting black oak will begin to produce acorns at about 20 years of age with optimum production occurring at 40 to 75 years (Sander, 1972). Black oak will consistently produce seed with good crops occurring every 2 to 3 years with the average number of mature acorns per tree generally being higher for black oaks than for other oaks (Sander, 1972). However the number of seeds that become available for regeneration is relatively low, even in good years, due to damage from animals and insects (Sander, 1972). Black oak acorns germinate in the spring, requiring a cold period to germinate, and seedlings tend to be similar in drought tolerance as white oak seedlings (Seidel, 1972). As with white oak it is rare to witness newly established black oak seedlings being of value to stand reproduction directly following overstory removal owing to the fact that they are too slow growing and eventually outcompeted by the faster growing advance regeneration (Sander, 197; Oliver and Larson, 1996; Larsen et al., 1997).

The best results for acorn germination for all oak species occur on sites with loose soil and an adequate humus layer (Carvell and Tryon, 1961). Soils that have been compacted and have a humus layer less than one inch in depth are not conducive to seed germination since the acorn will be pushed around as the radicle tries to penetrate the soil and will eventually desiccate and die from exposure. The humus layer adds support and reduces moisture loss during seedling establishment and helps maintain a loose, porous soil surface thus reducing interference with the radicle as it penetrates the soil (Carvell and Tryon, 1961). If the soil and climate conditions are favorable for germination, oak will reproduce adequately from seed when: large seed trees are within 200 feet; litter cover is light to moderate; and light reaching seedling level is at least 35 percent of full sunlight (Rogers, 1990). However, acorns that do germinate under high over story densities have a lower survival rate than acorns that germinate under lower over story densities. Typically acorns that germinate and develop into seedlings in the understory seldom remain true seedlings because drought, low light levels, fire or animals kill the tops back to the root collar. A dormant bud near the root collar will then produce a new shoot leading to what is typically known as a seedling sprout or advance regeneration (Sander and Clark, 1971).

Seedling sprouts are defined as sprouts arising from stumps that are less than 1 inch in diameter generally with only one sprout arising from the stump which have died back and resprouted one or more times (Oliver and Larson, 1996; Johnson et al, 2009). They are often the predominant form of oak reproduction growing beneath the forest canopy (Johnson et. al, 2009). Understory oak trees of some species in the Ozarks characteristically grow very little for 10 to 15 years in the understory, dies back to the root collar and re-sprouts a new stem. This stem will then grow for another 10 to 15 years and then die back again to be followed by another sprout. This in turn stimulates the development of a large root system rather than a large stem (Oliver and Larson 1996, Dey et al., 1996). These understory oaks can persist for decades in a "suspended growth" stage and display very little height and diameter growth for many years to decades. It is not uncommon for a root collar to be over 30 years older than the sprout growing from it (Oliver and Larson, 1996). These distinguishing traits give oaks a competitive advantage over other tree species following a disturbance. Oak trees originating from advance regeneration can exhibit rapid height and diameter growth following a release giving these oaks a higher probability of becoming canopy dominants and co-dominants.

Oaks have another successful form of asexual regeneration known as stump sprouting. This form of regeneration is the development of sprouts from dormant buds at the base of severed trees following a disturbance or can arise from the bases of trees top killed by fire (Oliver and Larson, 1996; Johnson et.al, 2009). In the Central Hardwood Region stump sprouts are defined as those originating from a stump 2 inches or larger in diameter (Roach and Gingrich, 1967; Johnson et.al, 2009).

A study conducted by Weigel and Dey, 2007, on the development of stump sprouts over a 15- year period for 5 oak species, 4 of which were red oak species, indicated that after 5 years of growth all of the oak species, which included white oak and black oak, averaged over four sprouts per stump. By year 10 all species, except white oak which had fewer than 3 sprouts per stump, had less than four sprouts per stump. By year 15 there was no difference in sprout density for all species, however white oak sprouts tended to be shorter than sprouts from the other oak species. They concluded that white oak stump sprouts may need assistance to be released from surrounding competition in order to remain competitive with black oak stump sprouts during the early stages of stand development. However, care should be taken to not remove too much of the competition due to the possibility of releasing faster growing competitors (Weigel and Dey, 2007). The results from this study can be used by foresters to more quantitatively evaluate the contribution oak stump sprouts have on the sustainability of oak species in future forests (Weigel and Dey, 2007).

Stump sprouts can provide an exceptional method for foresters or land owners to reinitiate a stand without the expenses of artificial regeneration. Seed broadcasting or transplanting nursery rootstock can become expensive and take a long time to establish whereas natural stump sprouts can grow rapidly and quickly occupy freed growing space. However the vigor of sprouts depends heavily on species and the time of year in which the parent stem was removed (Oliver and Larson, 1996). Commonly, trees that are harvested at the peak of the growing season can exhibit substantially less growth and vigor due to the exhaustion of photosynthetic reserves in the root system caused by the elongation of new shoots (Oliver and Larson, 1996).

New shoots that develop below the point of cutting on stems are the most desirable because rot from the parent stump will less readily enter the new stem which in turn can lead to unsound growing stock (Oliver and Larson, 1996). Stumps of large, older trees commonly produce fewer if any sprouts when compared to smaller stumps of younger, more vigorous trees. Sprouts from vigorous stumps can begin growing immediately following a disturbance due to well established roots systems and food reserves and can readily out-compete other trees (Oliver and Larson, 1996). Knowing the best time to cut trees in order to achieve the maximum quantity of vigorous stump sprouts and identifying preferred types of stump sprout can assist foresters and landowners on when to harvest and also give them an idea of what to look for following the harvest.

FACTORS THAT AFFECT OAK REPRODUCTION ABUNDANCE AND UNDERSTORY HEIGHT GROWTH

Oak regeneration is a recurrent process involving the birth and death of seedlings, continual shoot growth and dieback, and the development, accumulation and recruitment of advance regeneration and stump sprouts from cut trees (Sander; 1971, Larsen et al,. 1997). The most common forms of oak regeneration in the Ozark Highlands are seedlings from newly germinated acorns, seedling sprouts and stump sprouts (Larsen et al. 1997). Oak forests in the eastern United States rely heavily on natural regeneration and the accumulation of decades of advance regeneration underneath the parent stand in order to perpetuate the stand following a disturbance (Larsen et al., 1997; Larsen and Johnson, 1998; Larsen et al., 1999). Post-harvest forest structure can be influenced by the establishment and survival of oak seedlings in the understory. In order to achieve successful results following silvicultural treatment extra attention should be paid to stand composition and structure before harvesting in order to determine or control the amount of trees that will be recruited into the over story following a harvest.

Disturbance of various types and magnitude is the key factor for over story reduction and the recruitment of regeneration in the upland oak/hickory forests of the Ozarks. Disturbances can range in magnitude from relatively small, such as the death of a single tree from disease or blow-down, to very large caused by fire, wind or timber harvests (Larsen et al., 1999). Over story density has been found to have a direct effect on regeneration abundance and a proportion of oak regeneration must be recruited into the dominant and codominant canopy classes in order for regeneration to be successful. Carvell and Tryon (1961) found that the percent sunlight that reached the forest floor exhibited a significant positive correlation with the amount of oak regeneration present.

Similarly they found that if a stand had been thinned, grazed or lightly burned two decades prior to their study that these stands exhibited a greater amount of oak regeneration than undisturbed stands. The regression equation relating oak regeneration to percent sunlight that was developed for this study indicated a greater amount of sunlight reaching the forest floor increased the number of oak seedlings.

It is unusual to observe oaks being actively recruited into the over story without reduction or removal of the over story first and recruitment of advance regeneration is primarily obtained when the over story has been reduced by at least 50% (Dey et al., 1996; Dey and Parker, 1997; Larsen et al. 1999). A study conducted by Larsen et al. (1997) examined the effect over story density had on the abundance of oak and non-oak species in uneven-aged forests. The main focus of their study was to develop success criteria for oak regeneration and determine if pre-harvest regeneration abundance would meet those criteria under differing over story densities. Once the success criteria were defined and probabilistic models were developed they found that the probability of success for all species and oaks increased as over story density decreased. They also found once over story density exceeded 87 ft^2/ acre that none of the species met the size or density requirements confirming the importance of over story removal if successful regeneration is desired.

In another study by Loftis (1990) on the effects of a shelterwood treatment on red oak advance regeneration in the southern Appalachians found that by reducing the overstory from below with herbicide increased the chance of survival for red oak advance regeneration. He increased the growing space and competitive advantage of the advance regeneration by eliminating the possibility of stump sprouts with herbicides. He found that the survival rates of advance regeneration was also dependent upon site index and suggests that a higher residual basal area could remain in a stand with a higher site index because of the increase in site quality. Loftis indicates that because of the high variability of sites in the Appalachians that basal area should be removed according to site index. Subsequently, he found that reducing the basal area too heavily on any site increased the chance that the new growing space would be quickly exploited by shade-intolerant, undesirable species. For this he suggests retaining a slightly higher residual basal area in the shelterwood treatments in order to suppress shade-intolerant, undesirable species while favoring the more shade-tolerant red oak advance regeneration. Because of the high variability of site quality in the Ozark Highlands a similar approach to Loftis' shelterwood treatments could be applied in the Ozarks.

Dey and Parker (1997) found that underplanted red oaks in an uncut stand experienced a 90 percent survival rate after two years. However, these underplanted red oaks experienced negligible or negative annual growth in height and basal diameter. They state further that underplanted red oaks in a shelterwood experienced a significantly higher amount of growth in height and basal diameter and a 99 percent survival rate after 2 years. Dey and Parker indicate that underplanted red oaks will be at significant disadvantage if planted under a forest intended for a shelterwood harvest 2 years prior to the harvest. Seedlings and seedling sprouts, already present in the stand, together with stump sprouts are crucial for regenerating the stand whereas the size, not necessarily the abundance, of the reproduction is the critical factor for adequate growth and stocking when the over story is removed (Sander, 1972). Sander et al. (1976, 1984) developed a method to adequately evaluate advance oak reproduction before a harvest which would ensure adequate stocking levels of oak reproduction following a clearcut. In order to be adequately stocked, at least 30% of the stand must be stocked with oaks that have a mean diameter of 3 inches. This is based on Gingrich's (1976) stocking diagrams of upland hardwood species. Sander et al. (1976) concluded that a minimum of 443 trees per acre that are 4.5 feet tall or taller is the required amount to ensure a future stocking of the stand of at least 221 dominant and codominant trees per acre on a site with a 50- year site index curve.

CHAPTER 3
METHODS

STUDY SITE DESCRIPTIONS

The study was conducted on 36 acres of a mixed, oak-hickory, upland forest in northeastern Butler County, Missouri. The site is characterized as a physiological sub-region called "flatwoods" and is located on the 7,000 acre University Forest Conservation Area north of State Highway KK. These "flatwoods" form a transition between the Ozark uplands and the Mississippi River flood plain and are characterized by gently rolling terrain. The site had a northern/northeastern aspect with a slope that ranged from 0 to 5 percent. It was estimated that the site index was 55 to 60 feet, slightly higher than the average Ozark upland forest site.

The site is located on soils of the Loring-Captina-Clarksville association (Graves 1983, Dwyer 1988) with a silt loam cap approximately 5 to 6 inches. The soils are moderately well-drained and have a fragipan at a depth of approximately 33 inches with water permeability significantly decreasing once the fragipan is encountered. The Captina soils have a cherty fragipan at a depth of 16 to 20 inches in contrast to the Loring soils which do not have chert in the fragipan. The Loring soil fragipan ranges at a depth from 26 to 35 inches. Rooting depth for trees in these soils ranges from 28 to 33 inches due to the presence of a fragipan in both soils. Below this depth root development is restricted because of the compaction of the fragipan (Dwyer 1988).

Overstory trees at the site were comprised primarily of mature oak and hickory species that ranged in age from 80 to 115 years old. Mature trees with 2 to 3 main stems indicated that past timber harvests occurred at the site. These multi-stemmed trees, also known as coppice or stump sprouts, originated from dormant buds at ground level on cut stumps after the tree was harvested. Groups of younger trees were present throughout the site which was the result of natural canopy openings and past, small scale timber harvests. The predominant overstory species at the site were white oak (*Quercus alba*), scarlet oak (*Quercus coccinea*), post oak (*Quercus stellata*), black oak (*Quercus velutina*), and southern red oak (*Quercus falcata*), Minor species present at the site include hickory (*Carya spp.*), black cherry (*Prunus serotina*), red maple (*Acer rubrum*), slippery elm (*Ulmus rubra*), green ash (*Fraxinus pennsylvanica*), blackgum (*Nyssa sylvatica*), sweetgum (*Liquidambar styraciflua*), and sassafras (*Sassafras albidum*).

PRE-TREATMENT EXPERIMENTAL DESIGN

This study was conducted on the University Forest Conservation area along state highway KK and had a north to northeast aspect. Each replicate consisted of three, 3- acre, single- tree selection treatments (Treatments 1, 2, and 3), four, 0.75- acre, shelterwood in strips treatments (Treatment 4), two, 1.5- acre, shelterwood in strips treatments (Treatment 5) and one, 3- acre, Control (Figure 2. Two replications of the treatments were implemented at the research site. The corners of each treatment plot were marked with four permanent steel corner posts and an aluminum tag indicating replication and plot number was nailed to a tree in close proximity to the corner posts. The plot boundaries were marked with red blazes painted at breast height on boundary trees. All treatments had a 75- foot buffer zone between them and the next treatment. Each replication was approximately 18 acres in size with an approximate total of 36 total acres for both replications and approximately 15 acres of timber harvested from each replication (Table 1).

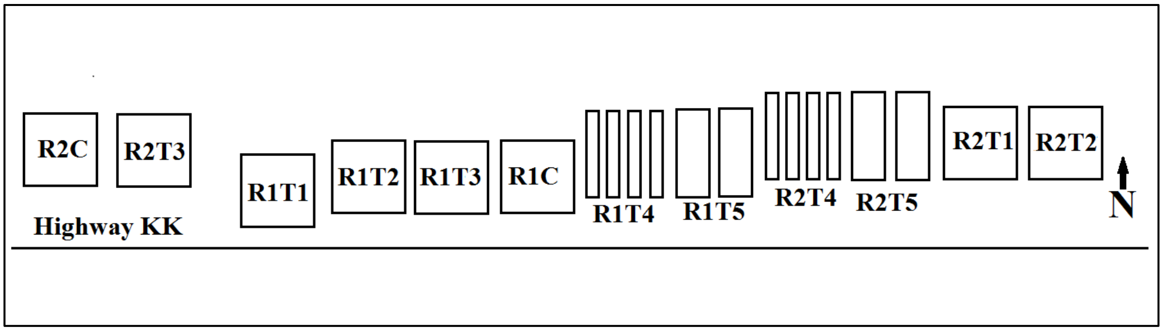


Figure 1. Schematic map of the treatment layout(R=replication number, T=treatment number and C=control). Square plots are 3 acres and represent the single tree selection treatments and controls. The narrow plots are the shelterwood in strip treatments, either 0.75 acres or 1.5 acres.

Table 1. List of treatment plots with target basal area and acres harvested

Treatment	Basal Area	Number of Sample plots	Area(acres)
Treatment 1	30 sq. ft.	2	5.87
Treatment 2	40 sq. ft.	2	5.91
Treatment 3	50 sq. ft.	2	5.74
Treatment 4	40 sq. ft.	8	6.9
Treatment 5	40 sq. ft.	4	6.24
Control	No harvest	2	5.95
Total		20	36.61

Pre-treatment Data Sampling

Preliminary over story and understory measurements were collected in the spring of 2009 in order to obtain base line stand information for the research site. Four, variable- radius prism plots were established for each 3- acre treatment using a 10-factor angle gauge to determine the basal area for that particular plot. The limiting distance was calculated in the case of a border-line tree to determine whether the tree was considered in or out of the plot. The diameter, species, crown class and height were recorded for all over story trees that fell within the variable radius plot. A complete inventory of trees greater than 5 inches at breast height (4.5 feet above the ground) was conducted. The diameter distribution of pre-harvest stand conditions is presented in Figure 1. The pre-treatment basal area density for the entire site averaged 89.7 square feet and ranged from as low as 70.0 square feet and as high as 220 square feet co-collected with Saunders, 2010.

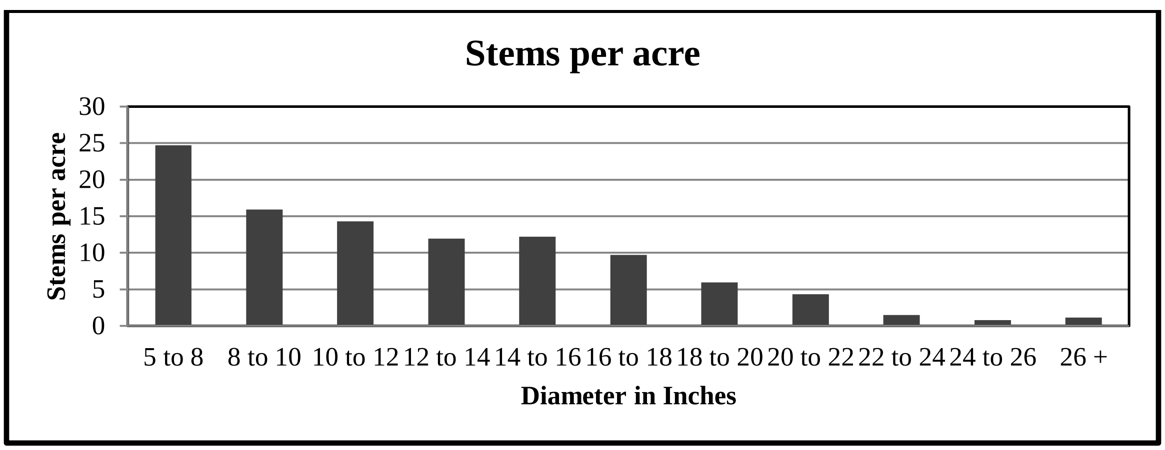
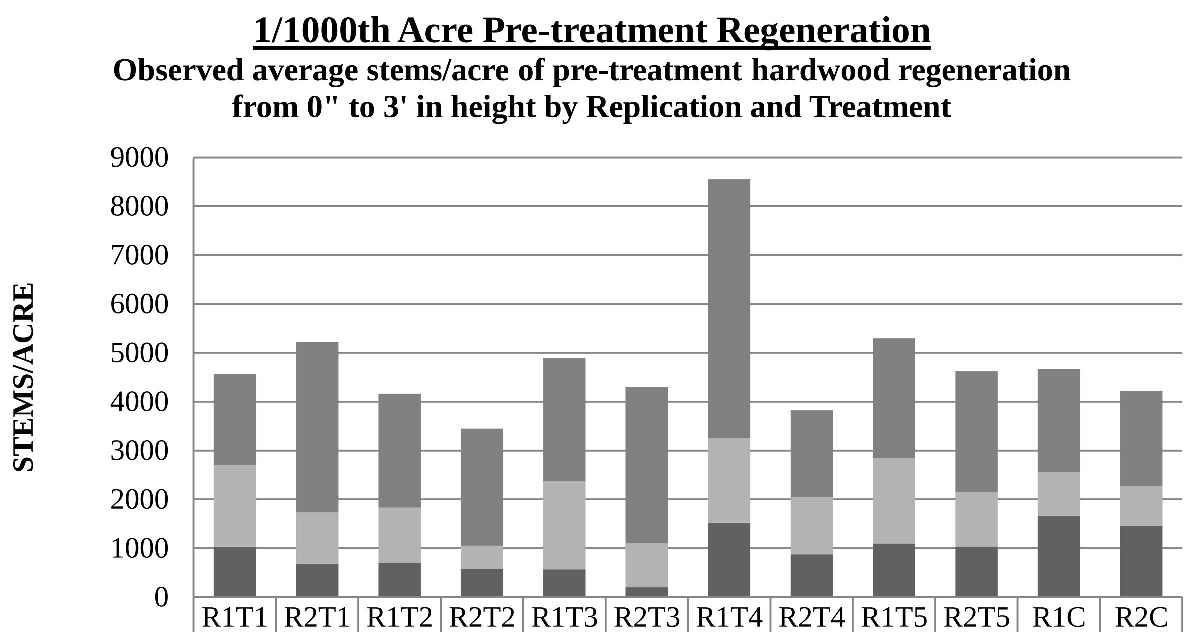


Figure 2. Pre-treatment diameter distribution of the trees per acre developed by Saunders 2010

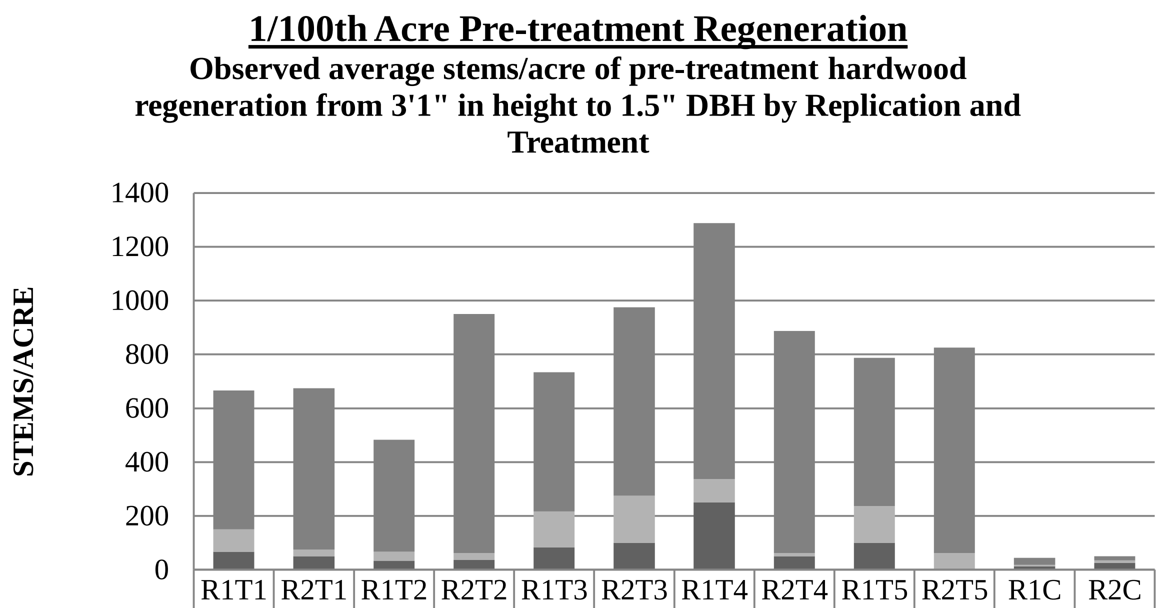
Pre-harvest understory and regeneration information was also collected in the spring of 2009. For each 3- acre treatment replicate, 40, 1/1000th -acre fixed area regeneration plots were chosen at random. A total of 480 1/1000th-acre fixed area plots were sampled on the entire research site. The 1/1000th -acre fixed area plots had a radius of 3 feet, 8.7 inches in which all woody regeneration up to 3 feet in height was recorded by species. Eight 1/100th -acre, fixed area plots with a radius of 11 feet, 9.3 inches were also chosen at random for each 3- acre treatment replicate with a total of 96 plots sampled on the research site. Every tree within the 1/100th -acre fixed area plot that was >3 feet in height to 1.5 inches diameter at breast height was recorded by species. Finally, eight 1/20th -acre fixed area regeneration plots with a radius of 26 feet, 4 inches were chosen at random for each 3- acre treatment replicate with a total of 96 plots sampled on the research site. All understory trees within the 1/20th acre plots that were from 1.5 inches to 5.0 inches diameter at breast height were recorded by species.

Figure 3 (1/1000th acre plots) represents the observed number of pre-treatment stems per acre of regeneration up to 3 feet in height for all treatments. Figure 4 (1/100th acre plots) represents the observed number of pre-treatment stems per acre of regeneration from 3 feet 1 inch in height to 1.5 inches diameter at breast height (DBH). Figure 5 (1/20th acre plots) represents the observed number of pre-treatment stems per acre of regeneration from 1.6 to 5 inches DBH. The graph represented in each figure can be interpreted by observing the *x* and *y* axis. The *y* axis indicates the number of stems per acre observed for white oaks, red oaks and non-oaks with each species group having a separate identifying color. Columns are located on the *x* axis and underneath each column is a code category. Each code category identifies the replicate number (R1=replicate 1 or R2=replicate 2) and treatment number (T1=treatment 1 or T2=treatment 2) in which the datum was collected. Under each code are 3 sets of numbers indicating the number of stems per acre for white oaks, red oaks and non-oaks corresponding to what treatment category they are under.



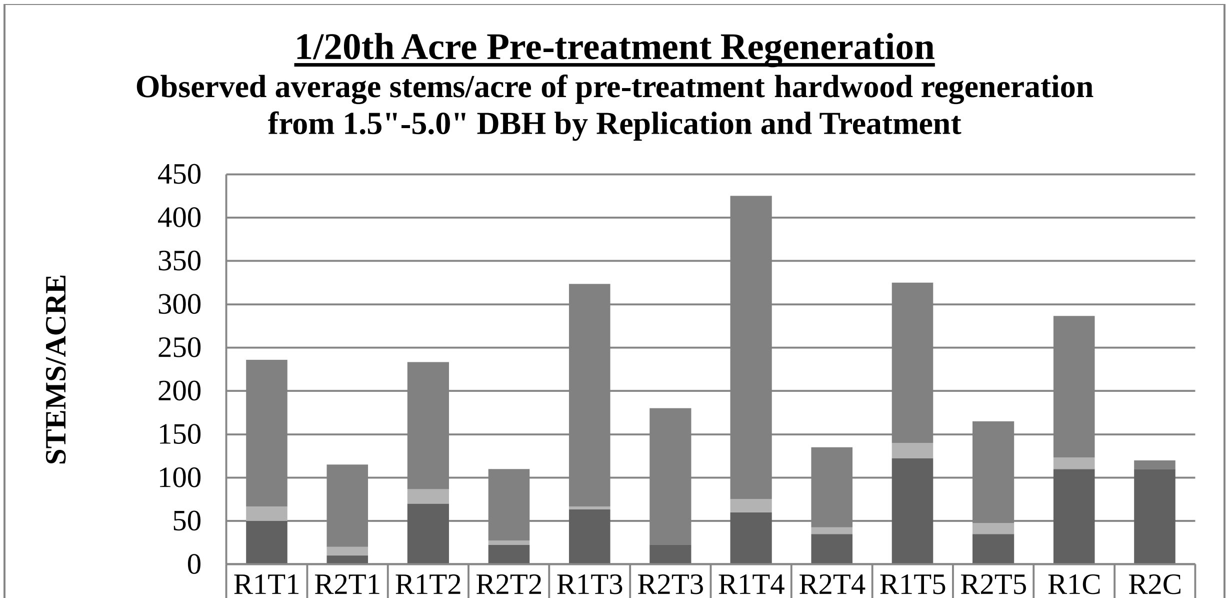
	R1T1	R2T1	R1T2	R2T2	R1T3	R2T3	R1T4	R2T4	R1T5	R2T5	R1C	R2C
Non-oaks	1867	3488	2333	2400	2533	3200	5300	1775	2450	2475	2100	1955
Red Oaks	1667	1049	1133	475	1800	900	1725	1175	1750	1125	900	800
White Oaks	1033	683	700	575	567	200	1525	875	1100	1025	1667	1465

Figure 3. Observed average stems/acre of pre-treatment hardwood regeneration from 0” to 3” in height by Replication and Treatment (R=Replication number, T= Treatment number, C=Control).



	R1T1	R2T1	R1T2	R2T2	R1T3	R2T3	R1T4	R2T4	R1T5	R2T5	R1C	R2C
Non-oaks	517	600	417	888	517	700	950	825	550	763	26	15
Red Oaks	83	25	33	25	133	175	88	13	138	63	5	10
White Oaks	67	50	33	38	83	100	250	50	100	0	13	25

Figure 4 Observed average stems/acre of pre-treatment hardwood regeneration from 3.1" in height to 1.5" DBH by Replication and Treatment (R=Replication number, T= Treatment number, C=Control).



	R1T1	R2T1	R1T2	R2T2	R1T3	R2T3	R1T4	R2T4	R1T5	R2T5	R1C	R2C
Non-oaks	169	95	147	83	257	158	350	93	185	118	163	10
Red Oaks	17	10	17	5	3	0	15	8	18	13	13	0
White Oaks	50	10	70	23	63	23	60	35	123	35	110	110

Figure 5. Observed average stems/acre of pre-treatment hardwood regeneration from 1.5" to 5.0" DBH by Replication and Treatment (R=Replication number, T= Treatment number, C=Control).

Equation for estimating Stems Per Acre (SPA)

The number of stems per acre (SPA) for each regeneration size class by treatment was calculated using the following equation:

1. *SPA*=(Total number of stems per species**EF*)/Number of Plots
2.

Where;

SPA is the stems per acre,

EF is the expansion factor (the size of the plot relative to one acre), and the Number of Plots is the number of observed plots in which the specific hardwood regeneration data was collected.

For example, all stems recorded in the 1/1000th -acre regeneration size class were totaled by treatment and species, multiplied by the expansion factor (EF) of 1000 (being that the observed plots were 1/1000th of an acre in size) and in turn divided by 40 (40 being the number of 1/1000th acre fixed area plots per treatment). The final product of this equation is the observed average number of stems per acre (SPA) of woody regeneration by species up to 3 feet in height for each treatment (Figure 3). The same equation was used for the 1/100th and 1/20th acre fixed area regeneration plots, however the expansion factor for the 1/100th acre fixed area plots was 100 and the number of observed plots was 8 (Figure 4) and the expansion factor for the 1/20th acre fixed area plots was 20 and the number of observed plots was 8 (Figure 5).

SILVICULTURAL DESIGN

Two different silvicultural treatments, single- tree selection and shelterwood in strips, were applied to the research site and were designed to reduce the over story density and basal area of the existing stand. The central goal of both treatments was to encourage the recruitment of a fresh cohort of advance regeneration and stump sprouts and to promote the development of a more diverse herbaceous layer on the forest floor. Scarlet oak and black oak were targeted for harvest due to their close proximity to the end of their expected lifespan and the presence of oak decline among the red oak species whereas white oak, post oak and hickory species were favored as leave trees because of their higher value and longer life expectancy. Snags and cull trees were also preferential as leave trees for their importance to forest structure and wildlife benefits. Small diameter nurse trees, because of their role in reducing the potential for epicormic sprouting along the boles of the leave trees, were also marked to keep. All leave trees were marked with a ring of blue paint at breast height in order to distinguish them for the loggers.

Single-Tree Selection Design

The goal of the single tree selection treatments (Treatments 1, 2 and 3) was to observe the response of oak/hickory advance regeneration and stump sprouts under three different single- tree selection treatments with differing over story densities. Each replication had one of each single- tree selection treatment, for a total of two of each treatment for the entire experiment. Treatment 1 had a target residual basal area of 30 square feet per acre, Treatment 2 had a target residual basal area of 40 square feet per acre and Treatment 3 had a target residual basal area of 50 square feet per acre. The total area of each single- tree selection treatment (Treatments 1, 2, and 3) was approximately 3 square acres in size with the dimensions of 360 feet in length by 360 feet in width respectively. The residual trees in these Treatments 1, 2, and 3 were spaced homogenously across the three acre treatment area in order to achieve 30, 40 or 50 square feet per acre of residual basal area. In actuality the final residual basal area after trees were marked for Treatment 1 for both replications was approximately 38 square feet per acre, Treatment 2 for both replications was approximately 46 square feet per acre and Treatment 3 for both replications was approximately 58 square feet per acre. The response of advance regeneration and stump sprouts to each treatment was then successively monitored following the treatment harvest in order to collect height and diameter growth results from the data. In the next 10 to 20 years the initial leave trees from Treatments 1, 2, and 3, designated in the summer of 2009, will gradually be harvested to provide gap openings in the canopy. Gap openings will be used in order to mimic natural small-scale disturbances. This will recruit trees from the recently initiated cohort into the over story and to encourage the growth of advance regeneration and stump sprouts. This method of only harvesting a select few leave trees per year will assist in the progression of the stand to a more uneven- age condition and provide higher quality crop trees for future harvests.

Shelterwood in Strips Design

The goal of the shelterwood in strips treatments (Treatments 4 and 5) was to observe the response of oak/hickory regeneration under two different shelterwood conditions. Two different shelterwood in strip treatments were developed for the site in order to determine the impact of two different shelterwood widths on understory height and diameter growth as well as the response of regeneration to the treatment. The first shelterwood design (Treatment 4) had the dimension of 75 feet in width and 450 feet in length with a total area of 0.75 acres per strip. These dimensions were chosen in order to keep the treatment more contained rather than having one long strip running for a quarter of a mile through the woods. A total of four, 0.75- acre shelterwood strips were designated per replication totaling eight 0.75- acre shelterwood strips between replicate 1 and 2, with a total area of approximately 3 acres for Treatment 4 per replication. The second shelterwood design (Treatment 5) had the dimensions of 150 feet in width and 450 feet in length with a total area of 1.5 acres per strip. A total of two 1.5- acre shelterwood strips were designated per replication totaling four 1.5 acre shelterwood strips between replicate 1 and 2, with a total area of approximately 3 acres for Treatment 5 per replication.

The area within both Treatments 4 and 5 was thinned to a target residual basal area of 40 square feet per acre with a 75- foot buffer area of unharvested trees between each shelterwood strip. The intention of the shelterwood treatments was to serve the dual purpose of removing some of the older over story trees to recruit advance regeneration and root sprouts into the over story while leaving enough residual over story to create a protective or “sheltering” environment for the establishment of new regeneration (Smith et al. 1997). After 15 to 20 years a secondary harvest will ensue to remove the initial leave or “shelter” trees from Treatments 4 and 5, and release the cohort of younger trees growing beneath them. A final harvest 15 to 20 years after the secondary harvest is planned for the future for the original Treatments 4 and 5. This final harvest will release the new cohort that formed under the “shelter” trees and increase the growing space for crop trees in Treatments 4 and 5. This silvicultural treatment will promote an even- aged cohort and provide quality crop trees for future harvests.

POST-TREATMENT EXPERIMENTAL DESIGN

Immediately following the completion of the biomass harvest in July 2009, 300 permanent plots were established across the research site. These sub-plots were nested within 1/100th acre plots with a total of one hundred fifty per replication. The sub-plots were used for monitoring the ingrowth, upgrowth and mortality of regeneration and for monitoring the growth of the tagged understory trees. Steel rebar was used to mark plot center for each subplot along with an aluminum tag indicating the treatment and subplot number. A total of 25 monitoring sub-plots were established in Treatments 1, 2, 3 and the Control in a 60- foot by 60- foot grid. Establishing the sub plots in this grid pattern allowed for minimal interference between sup plots, such as the same over story trees influencing different sub plots, while allowing for maximum sampling within these treatments.

Due to the long and narrow design of Treatment 4 in Replicate 1 and 2 adjustments had to be made in order to accommodate 25 sub plots for the entire treatment. Three of the 0.75 acre shelterwood strips had 6 sub plots in a 33 foot by 75 foot grid pattern with the remaining 0.75 acre shelterwood strip having 7 subplots laid out in the same grid pattern. This allowed for a total of 25 sub plots to be established for the entire 3 acres of Treatment 4. Treatment 5 in Replicate 1 and 2 had the same 33- foot by 75- foot grid that was used to space the 25 sub plots as was used in Treatment 4. For both treatment 5 replications one of the 1.5 acre strip plots had 12 sub plots and the other plot had had 13 sub plots for a total of 50 plots (both replicates) for the entire 13.1 acres. This was duplicated for both replications

Post treatment data sampling

Located at each sub plot was a 1/100th acre fixed area plot with a radius of 11 feet 7 inches from plot center. Two understory trees, originating either from seed, advance regeneration in the form of a seedling sprout, or from a stump sprout immediately following harvest, were tagged for monitoring. The tree tags were marked with either Tree 1 or Tree 2 in order to keep the trees separate on the data sheets. The treatment and subplot number along with the date that the trees were tagged were also marked on the tags. The height and basal diameter growth of the tagged trees was monitored over two consecutive growing seasons directly following the harvest. The height of the tagged, understory trees were measured in inches using a yard stick and the basal diameter was measured in inches using digital calipers (Figure 6).

Figure 6. Left: Digital calipers used to measure basal diameter. Right: Biltmore stick used to measure height of understory trees.

Acceptable trees for monitoring had to be in the form of advance regeneration (seedling sprout), a root sprout or a newly germinated seedling, and must have been established directly following the timber harvest. Each tree was then assigned a number of 1, 2 or 3 (Figure 7) identifying which form of regeneration it was; 1 - a stump sprout, 2- a seedling sprout, and 3 - a newly germinated seedling. Identifying characteristics of each form of regeneration were utilized to differentiate between them. Stump sprouts generally had an old stump present with more than two sprouts originating from the severed stump. Seedling sprouts generally had a much thicker root collar than the single stem growing from it and usually the dead stem that had died back was still present. Newly germinated seedlings tended to be very small, only a couple of inches in height and usually still had the acorn attached to it. The numbering system was used in order to differentiate between the growth rates of the three forms of regeneration in the data analysis. The height and basal diameter of each tagged tree was collected in the fall of 2009, 2010 and 2011 after they had begun to senesce. Measuring in September of 2009 allowed for a base line measurement to be collected on the tagged understory trees (>1.5 - ≤ 5.0 ins. dbh) followed by two full growing seasons of monitored growth.

Figure 7. Three types of trees tagged for monitoring. Starting in top left moving clockwise: Stump sprout (1), stump sprout (1), newly germinated seedling (3), and seedling sprout (2).

Also located within and sharing the same plot center as the 1/100th -acre fixed area plot was a 1/1000th -acre fixed area plot with a radius of 3 feet 6 inches from plot center established for monitoring the number stems per acre of oak and non-oak species. The species and location of each stem of regeneration as it occurred within each 1/1000th -acre plot were recorded on circle diagram sheets. This allowed for relatively easy monitoring of each 1/1000th -acre plot from year- to- year to determine which stems died (mortality), which stems grew into the next regeneration size class from 3.1 inches in height to 1.5 inches DBH (upgrowth) and which stems were new (ingrowth). Every hardwood species that was less than 3 feet in height was recorded. Trees that became established within the plot after the fall 2009 base-line recording were marked as "in" for ingrowth. Trees that grew taller than 3 feet in height from 2009 to 2010 were marked as "up" for upgrowth. A tally of white oak, red oak and non-oak species occurring within the 1/1000th acre plot was collected in the fall of 2009 and 2010.

DATA ANALYSIS

Methods for Evaluating the Response of Understory Height Growth to Over Story Density

One of the primary objectives of this study was to evaluate the trends in height growth of understory trees based on differing over story densities. The method used to determine the probability of success was similar to the method used by Larsen et al. (1997) and Green (2008). A total sample size of 530 tagged understory trees which included white oaks, red oaks and non-oaks was used for this analysis. A PROC LOGISTIC (SAS 9.2, 2008) regression model was used based on the stochastic or predictable nature of an oak/hickory forest following a disturbance. The analysis of the model estimated the probability of obtaining height growth based on the surrounding over story density (basal area) as a determining factor. The following logistic regression equation was used:

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

Where;

P_s is the probability of the obtaining the minimum height growth of the understory tree, BA is the over story density (basal area),

and the coefficients b_o and b_1 are parameter estimates collected from the data set.

In order to run the logistic regression analysis the data had to be converted into a binomial format using an if/then statement in Microsoft © Excel. This enabled the dependent variable data, P_s, to be constrained to either a 0 (failure) or 1 (success). Mean annual height growth thresholds were determined to facilitate data analysis. The annual height thresholds used were; ≥0 inches, ≥ 2 inches, ≥ 4 inches,≥ 6 inches, ≥ 8 inches, ≥10 inches, and ≥ 12 inches of average annual growth for the first growing season following harvest, For the second growing season the height growth thresholds were; ≥0 inches, ≥ 6 inches, ≥ 12 inches, ≥ 18 inches, ≥ 24 inches, ≥ 30 inches ≥ 36 inches, ≥ 42 inches and ≥48 inches. The species groups (white oaks, red oaks and non-oaks) were then regressed for each mean annual height growth threshold. The over story density was measured using basal area per acre and was determined from the live basal area present at each sub plot after the completion of the harvest in 2009. The basal area was calculated using a 10-factor angle gauge. If a tree was a border tree the limiting distance was calculated for said border tree to determine whether it was considered in or out of the plot. Basal area was the parameter chosen to explain the impact that over story density had on the development of the average annual height growth trends of the understory trees. The basal area densities ranged from 0 sq. ft./acre to 250 sq. ft./acre.

Analysis of the height growth data used reproduction that either resprouted or were established from seed directly following treatment in 2009. Individual trees were used in this analysis rather than the treatment average to make the subplots independent of their treatment in order to analyze the probabilities of individual trees' response to the immediately surrounding basal area rather than the average basal area of the treatment. The annual height growth of understory trees were examined over a 2- year growing period (2009 – 2011) with height growth sample size observations for 211 understory white oaks, 238 red oaks and 101 non-oak species. No assumptions were made about growth in 2009 since it is known that the trees began height growth at the treatment year. A tree was removed from the analysis if it fell under any of the following criteria:

1) Trees that were not a newly sprouted root or seedling sprout directly following harvest.
2) Recently germinated seeds established before the harvest.
3) A tree that died back after the first or second growing season thus exhibiting negative height growth.
4) All tree or shrub species that rarely develop into the over story (i.e. sassafras, black gum, flowering dogwood, red maple, black cherry and elm spp.).

Methods for Evaluating the Response of Hardwood Regeneration to Over Story Density

A total of 300, 1/1000th -acre fixed area regeneration plots (25 subplots per replicate) were used in the analysis of the response of hardwood regeneration to the harvest treatment. At each subplot the species and location of each stem of regeneration as it occurred within each 1/1000th acre plot were recorded on circle diagram sheets. This allowed for relatively easy monitoring of each 1/1000th acre plot from year- to- year to determine which stems died (mortality), which stems grew into the next regeneration size class (upgrowth) and which stems were new (ingrowth). Every hardwood species that occurred within the 1/1000th -acre fixed area regeneration plot that was less than 3 feet in height was recorded. Trees that became established within the plot after the fall 2009 base-line recording were marked as “in” for ingrowth. Trees that grew taller than 3 feet in height from 2009 to 2010 were marked as “up” for upgrowth since they had grown into a new regeneration size class. A tally of white oak, red oak and non-oak species occurring within the 1/1000th -acre plot was collected in the fall of 2009 and the fall of 2010. A similar equation used for determining the pre-treatment stems per acre of regeneration was used to determine the post-treatment stems per acre of ingrowth, upgrowth and mortality for each treatment. However, the equation (1.) had to be altered to accommodate for the 25 permanent, post-treatment 1/1000th -acre fixed area regeneration subplots established for each treatment. The expansion factor (EF) is 1,000 and the denominator (number of plots) is 25. All stems measured and recorded in the 1/1000th acre regeneration size class in the fall of 2009 and 2010 included; 1) stems which remained in the subplot from 2009 to 2010, 2) t stems which were ingrowth from 2009, 3) stems which were upgrowth from 2009, and 4) stems which died from 2009.

These categories of regeneration were totaled by treatment and species, multiplied by the expansion factor (EF) of 1000 (being that the observed plots were $1/1000^{th}$ - acre in size) and divided by 25 (the number of $1/1000^{th}$ -acre fixed area subplots per treatment) to calculate the observed average number of stems per acre (SPA) of trees present in the above categories.

Analysis of variance

An analysis of variance (ANOVA) was used to evaluate the differences in height growth based on the following criteria:

1) Differences in height growth between stump sprouts (1), seedling sprouts (2) and newly established seedlings (3) by species across both replications as a function of treatment response.
2) Differences in basal diameter growth between stump sprouts (1), seedling sprouts (2) and newly established seedlings (3) by species across both replications as a result of treatment.

A 2 x 6 factorial analysis of variance was used, which accounts for variance due to treatment differences and growing season measurements. This analysis tested the differences at the protection level of $\alpha = 0.05$ using least squared differences for mean separations. The main effects of mean annual height and diameter growth by treatment were examined. The analysis offered a comparison between the different forms of regeneration by harvest treatment, red oaks versus white oaks and all oaks versus non-oaks as the result of the effect of harvest treatment on height and basal diameter growth.

CHAPTER 4
RESULTS

THE EFFECT OF OVER STORY DENSITY ON UNDERSTORY HEIGHT GROWTH FOR SEASONS ONE AND TWO

Growing seasons one and two were evaluated separately for this particular section of the analysis. The purpose of the separate analysis was to compare and contrast the same trees using the same average annual height growth thresholds from season one and season two. This allowed for an easy comparison as to how the trees responded to surrounding basal area from season one to season two. It was noted that a decrease in the frequency of tagged understory trees that met annual height-growth thresholds occurred as over story density increased. The use of logistic regression helped identify growth trends which resulted from the effect over story density had on mean annual height growth of understory trees. Table 2 represents the logistic regression model parameters for growing season one and Table 3 represents the logistic regression model parameters for growing season two.

Table 2: Logistic regression parameters for estimating the probability of obtaining an average annual height growth on a 1/100th acre plot for the first growing season following a timber harvest.

Reproduction mean annual height growth (in) for the first growing season	Model coefficients			
	b_0	*SE*	b_1	*SE*
White oak understory (n=194)				
≥0.0"	2.5886	(0.5028)	-0.001	(0.0057)
≥2.0"	2.507	(0.3481)	-0.017	(0.0036)
≥4.0"	1.61	(0.3064)	-0.016	(0.0037)
≥6.0"	0.8605	(0.2922)	-0.013	(0.0037)
≥8.0"	0.3124	(0.303)	-0.012	(0.004)
≥10.0"	0.2629	(0.3495)	-0.013	(0.005)
≥12.0"	-0.012	(0.3824)	-0.012	(0.0055)
Red oak understory (n=217)				
≥0.0"	2.984	(0.4463)	-0.007	(0.0041)
≥2.0"	2.1786	(0.3044)	-0.019	(0.0034)
≥4.0"	1.319	(0.2783)	-0.015	(0.0034)
≥6.0"	0.6337	(0.281)	-0.014	(0.0036)
≥8.0"	-0.22	(0.3171)	-0.012	(0.0043)
≥10.0"	-1.156	(0.3715)	-0.008	(0.0049)
≥12.0"	-1.183	(0.3928)	-0.01	(0.0054)
Non-oak understory (n=95)				
≥0.0"	2.7254	(0.9526)	0.0032	(0.0119)
≥2.0"	1.4654	(0.4457)	-0.008	(0.0049)
≥4.0"	0.871	(0.4181)	-0.008	(0.0049)
≥6.0"	-0.06	(0.4093)	-0.003	(0.0048)
≥8.0"	-0.885	(0.4365)	0.0009	(0.005)
≥10.0"	-1.327	(0.4791)	0.0014	(0.0055)
≥12.0"	-1.401	(0.506)	3E-05	(0.0059)

Note: The values in parentheses are the SE of the parameter estimates

*For the model $P_s = \exp(b_0+b_1\text{BA})/(1+\exp(b_0+b_1\text{BA}))$

Table 3: Logistic regression parameters for estimating the probability of obtaining an average annual height growth on a 1/100th acre plot for the second growing season following a timber harvest

Reproduction mean annual height growth (in) for the second growing season	Model coefficients			
	b_0	*SE*	b_1	*SE*
White oak understory (n=205)				
≥0.0"	2.0959	(0.449)	0.00102	(0.00535)
≥2.0"	2.0727	(0.3392)	-0.0098	(0.0035)
≥4.0"	2.1632	(0.3321)	-0.0175	(0.00371)
≥6.0"	1.4324	(0.3036)	-0.0144	(0.00365)
≥8.0"	1.0553	(0.302)	-0.0143	(0.00384)
≥10.0"	0.9112	(0.3215)	-0.0169	(0.00441)
≥12.0"	0.5242	(0.3163)	-0.0143	(0.00432)
Red oak understory (n=235)				
≥0.0"	2.4272	(0.3998)	-0.0037	(0.00398)
≥2.0"	2.8309	(0.3438)	-0.0216	(0.00349)
≥4.0"	2.3784	(0.3197)	-0.0208	(0.00354)
≥6.0"	2.1578	(0.3199)	-0.0224	(0.00387)
≥8.0"	1.2404	(0.295)	-0.0178	(0.0038)
≥10.0"	0.7847	(0.3056)	-0.0174	(0.00417)
≥12.0"	0.4114	(0.3327)	-0.018	(0.00482)
Non-oak understory (n=98)				
≥0.0"	3.0389	(0.8493)	-0.0039	(0.00891)
≥2.0"	2.1468	(0.511)	-0.0104	(0.00524)
≥4.0"	1.6397	(0.4584)	-0.0103	(0.00499)
≥6.0"	1.2295	(0.4353)	-0.0099	(0.00496)
≥8.0"	0.4188	(0.4121)	-0.0048	(0.00479)
≥10.0"	0.0294	(0.4155)	-0.0039	(0.0049)
≥12.0"	-0.2192	(0.4315)	-0.0046	(0.00519)

Note: The values in parentheses are the SE of the parameter estimates
*For the model $P_s = \exp(b_0+b_1\mathrm{BA})/(1+\exp(b_0+b_1\mathrm{BA}))$

Table 4 represents the number of trees in the white oak, red oak or non-oak categories which were above or below the average annual height growth thresholds for the first growing season. The white oak, red oak and non-oak trees presented in Table 4 refer to all categories of regeneration which include: seedling sprouts, stump sprouts and newly germinated seedlings. It is observed that as the height growth thresholds increased the number of trees that surpassed the threshold decreased while the number of trees that fell below the threshold increased (Table 4). There were 211 individually tagged white oak trees, 238 individually tagged red oak trees and 101 individually tagged non-oak trees across the entire research site. At the end of the first growing season there were 56 (26.5%) white oak trees that had grown equal to or above 12 inches in annual height, 52 (21.8%) red oak trees that had grown equal to or above 12 inches in annual height and 25 (24.7%) non-oak trees that had grown equal to or above 12 inches in annual height.

Table 4. Observed numbers of trees above or below the specified average annual height growth threshold for the first growing season following a timber harvest

Mean average annual height growth threshold (in/yr)	Observed number of trees: Below threshold	Observed number of trees: Above or equal to threshold
White oak seedlings (n=211)		
≥0.0"	0	211
≥2.0"	35	176
≥4.0"	67	144
≥6.0"	92	119
≥8.0"	116	95
≥10.0"	143	68
≥12.0"	155	56
Red oak seedlings (n=238)		
≥0.0"	0	238
≥2.0"	60	178
≥4.0"	90	148
≥6.0"	121	117
≥8.0"	158	80
≥10.0"	183	55
≥12.0"	186	52
Non-oak seedlings (n=101)		
≥0.0"	0	101
≥2.0"	26	75
≥4.0"	38	63
≥6.0"	52	49
≥8.0"	65	36
≥10.0"	73	28
≥12.0"	76	25

Table 5 represents the number of trees in the white oak, red oak and non-oak categories which were above or below the average annual height growth thresholds for the second growing season. The same average annual height growth thresholds were used for this portion of the analysis of the second years' worth of growth in order to compare to the first season. It is observed again that as the height growth thresholds increased the number of trees that surpassed the threshold decreased while the number of trees that fell below the threshold increased (Table 5). Some of the tagged trees succumbed to mortality, animal damage or the tag was lost leading to a decreased number of observed tagged trees for the second growing season. For growing season two there were 205 individually tagged white oak trees, 235 individually tagged red oak trees and 98 individually tagged non-oak trees across the entire research site. At the end of the second growing season there were 100 (48.7%) white oak, 96 (40.8%) red oak trees and 42 (42.8%) non-oak trees that had grown equal to or above the maximum average annual height growth threshold of 12 inches which was an increase from year one.

Table 5. Observed numbers of trees above or below the specified average annual height growth threshold for the second growing season following a timber harvest

Mean average annual height growth threshold (in/yr)	Observed number of trees: Below threshold	Above or equal to threshold
White oak seedlings (n=205)		
≥0.0"	0	205
≥2.0"	23	182
≥4.0"	42	163
≥6.0"	63	142
≥8.0"	80	125
≥10.0"	95	110
≥12.0"	105	100
Red oak seedlings (n=235)		
≥0.0"	0	235
≥2.0"	38	197
≥4.0"	53	182
≥6.0"	68	167
≥8.0"	97	138
≥10.0"	119	116
≥12.0"	139	96
Non-oak seedlings (n=98)		
≥0.0"	0	99
≥2.0"	15	84
≥4.0"	24	75
≥6.0"	32	67
≥8.0"	42	57
≥10.0"	50	49
≥12.0"	57	42

Figure 8 represents the probability of 211 tagged understory white oak trees achieving a certain height growth threshold for the first growing season immediately following the harvest. This was based on observed annual height growth. The two species of white oaks observed at the site were; white oak and post oak with both species being combined together under the title *White oaks*. These white oaks were located randomly across the 300 1/100th acre regeneration plots established across the entire study and are the tagged trees mentioned in the *Post-harvest experimental design* section.

The white oak trees were composed of newly regenerated seedling sprouts, stump sprouts and germinated acorns which became established after the harvest. All forms of regeneration were combined for this evaluation across the entire harvest site. The X-axis in Figure 8 represents the increments of basal area (square feet/acre) observed for each of the 211 white oak trees and the Y-axis represents the probability (0-100%) that the tagged trees have of achieving a certain average annual height growth threshold at a given basal area. The average annual height growth thresholds are located on the right side of the graphic in Figure 8 and correspond to a trend-line on the graph. The trend-lines are made up of 211 individual percent probabilities representing each tree predicted by the PROC LOGISTIC (SAS 9.2, 2008) regression model for each average annual height growth threshold.

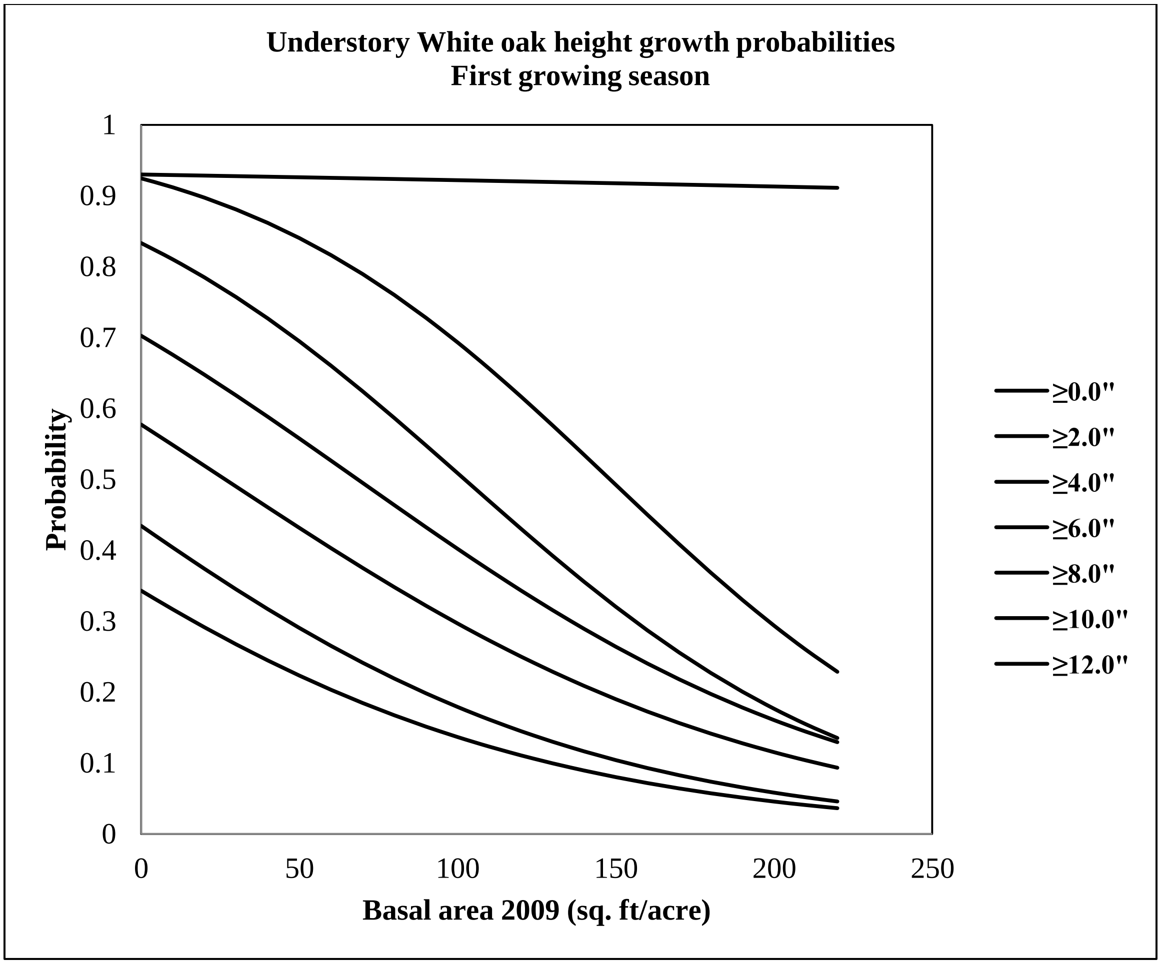


Figure 8: The estimated probability that understory white oak trees will have at least 2, 4, 6, 8, 10, or 12 inches of mean annual height growth for a given over story basal area one year following harvest

After the first growing season the white oak group had approximately a 91 percent probability of achieving 0-1.99 inches of average annual height growth regardless of the surround basal area (Figure 8). However it is indicated in Figure 8 that as the average annual height growth thresholds and basal area increase the probability of the white oak trees achieving higher annual height growth thresholds significantly decreases. This is especially evident once the surrounding basal area reaches 50 square feet per acre, where the probabilities represented by the trend lines begin to steeply decline as a response to increasing basal area.   White oaks only had a 35 percent chance of achieving 12 or more inches of annual height at 10 square feet of basal area per acre. This percentage rapidly decreases to less than a 20 percent probability at 50 square feet of basal area and less than 4 percent probability at 220 square feet of basal area.

Figure 9 represents the probability of the same white oak trees achieving the same average annual height growth thresholds for the second growing season. When Figure 9 is compared to Figure 8 it is evident that white oaks had a higher probability of achieving the ≥4”,6”, 8”, 10” and 12”average annual height growth thresholds after the second growing season than they did in the first season. Results from season one indicate that the probability of white oaks achieving 4-5.99 inches of growth was 83 percent whereas in the second season they had an 88 percent probability. This is the same for the remaining higher average annual height growth thresholds for the second growing season. Similar to year one, however, the probability of white oaks achieving a certain height growth threshold continued to significantly decrease once the surrounding basal area surpassed 50 square feet per acre.

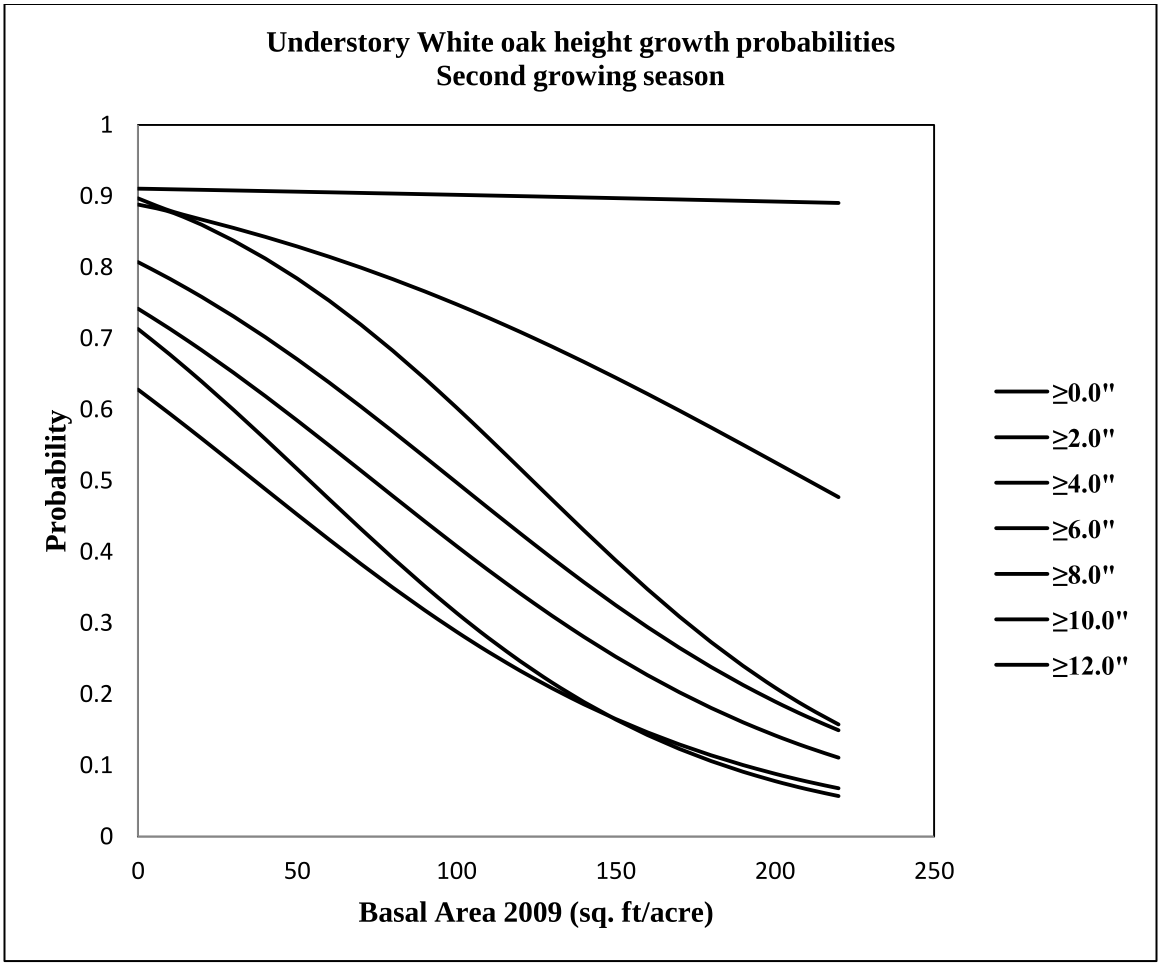


Figure 9: The estimated probability that understory white oak trees will have at least 0, 2, 4, 6, 8, 10, or 12 inches of mean annual height growth for a given over story basal area for the second growing season following harvest.

Figure 10 represents the probability of 238 tagged understory red oak trees achieving a certain average annual height growth threshold for the first growing season immediately following the harvest based on observed annual height growth. The three species of red oaks observed at the site were; black oak, scarlet oak, and southern red oak with all three species being combined together under the title *Red oaks.* Like the white oaks the red oaks were located randomly across 300 1/100th acre regeneration plots established across the entire study. The red oak trees were composed of newly regenerated seedling sprouts, stump sprouts and germinated acorns which became established after the harvest. All forms of regeneration were combined for this evaluation across the entire harvest site.

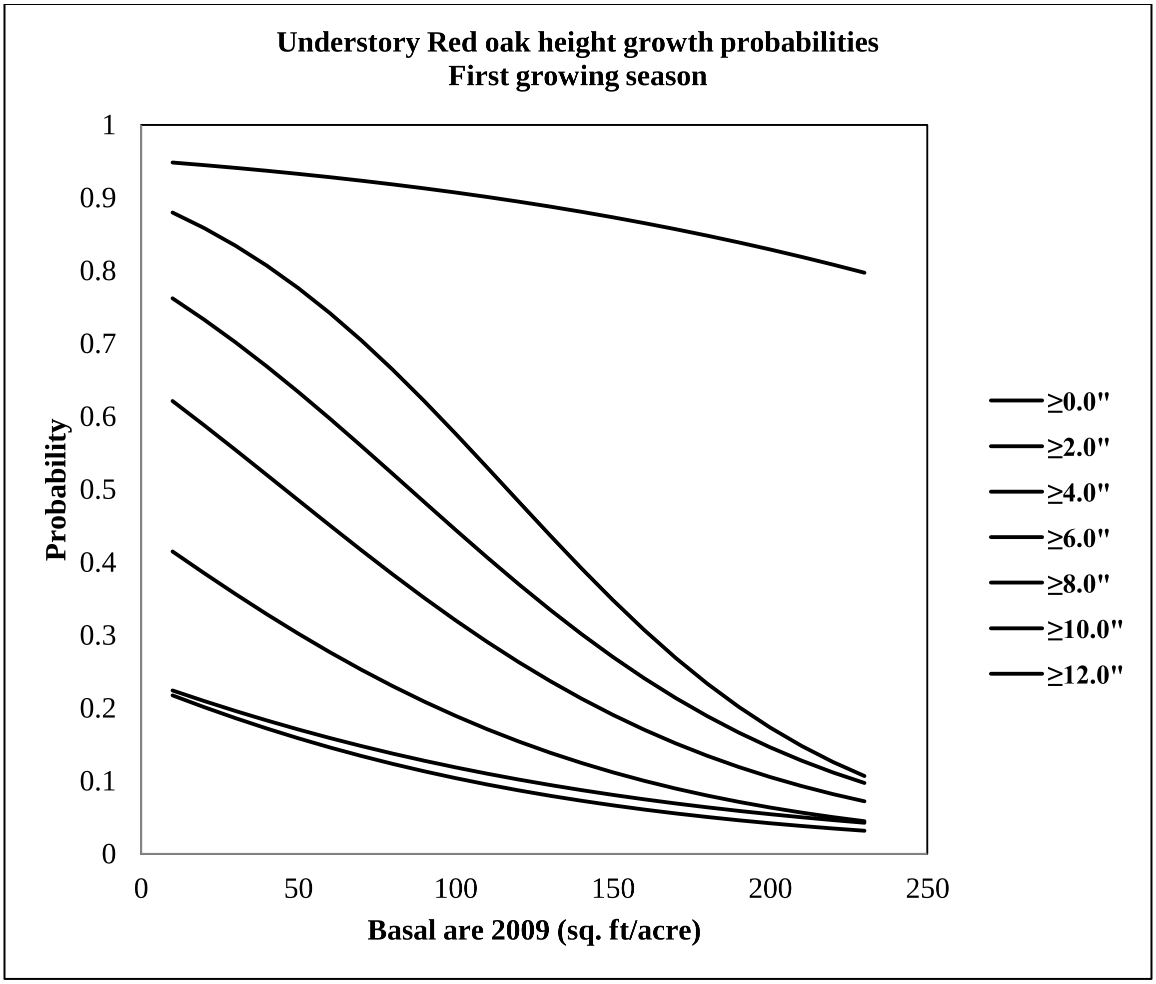


Figure 10: The estimated probability that understory red oak trees will have at least 0, 2, 4, 6, 8, 10, or 12 inches of annual height growth for a given basal area one year after harvest.

The probability of understory red oak trees achieving 0-1.99 inches of growth at 10 square feet per acre of basal area was approximately 95 percent for the first growing season. However, unlike the probability of white oak trees which maintained a constant 91 percent probability of achieving 0-1.99 inches of annual height growth for all basal area categories (Figure 8), red oaks decreased to 85 percent probability at 220 square feet of basal area (Figure 10). Similar to white oaks however, the probability of red oaks achieving a certain average annual height growth threshold began to decrease as basal area increased, especially once basal area surpassed 50 square feet per acre. It is apparent that understory red oaks have a lower probability of achieving successful height growth (Figure 10) as over story increases when compared to white oaks (Figure 8). This is an indication that red oak species are less tolerant to over story competition than white oak species.

Figure 11 represents the probability of the same red oak trees achieving the same average annual height growth thresholds for the second growing season. When Figure 11 is compared to Figure 10 it is evident that red oaks had a higher probability of achieving the same average annual height growth thresholds after the second growing season than they did in the first with the exception of 0-1.99 inches threshold which slightly decreased in year two. Similarly, however, the probability of red oaks achieving a certain height growth threshold continued to significantly decrease once the surrounding basal area surpassed 50 square feet per acre. When the second year of growth for white oaks (Figure 9) is compared to the second year of growth for red oaks (Figure 11) it appears that the probability of success for achieving certain average annual height growth thresholds is comparable to white oak success until once again, 50 square feet per acre of basal area is surpassed. This again indicates that red oaks tend to be less tolerant of over story density, especially once it surpasses 50 square feet per acre.

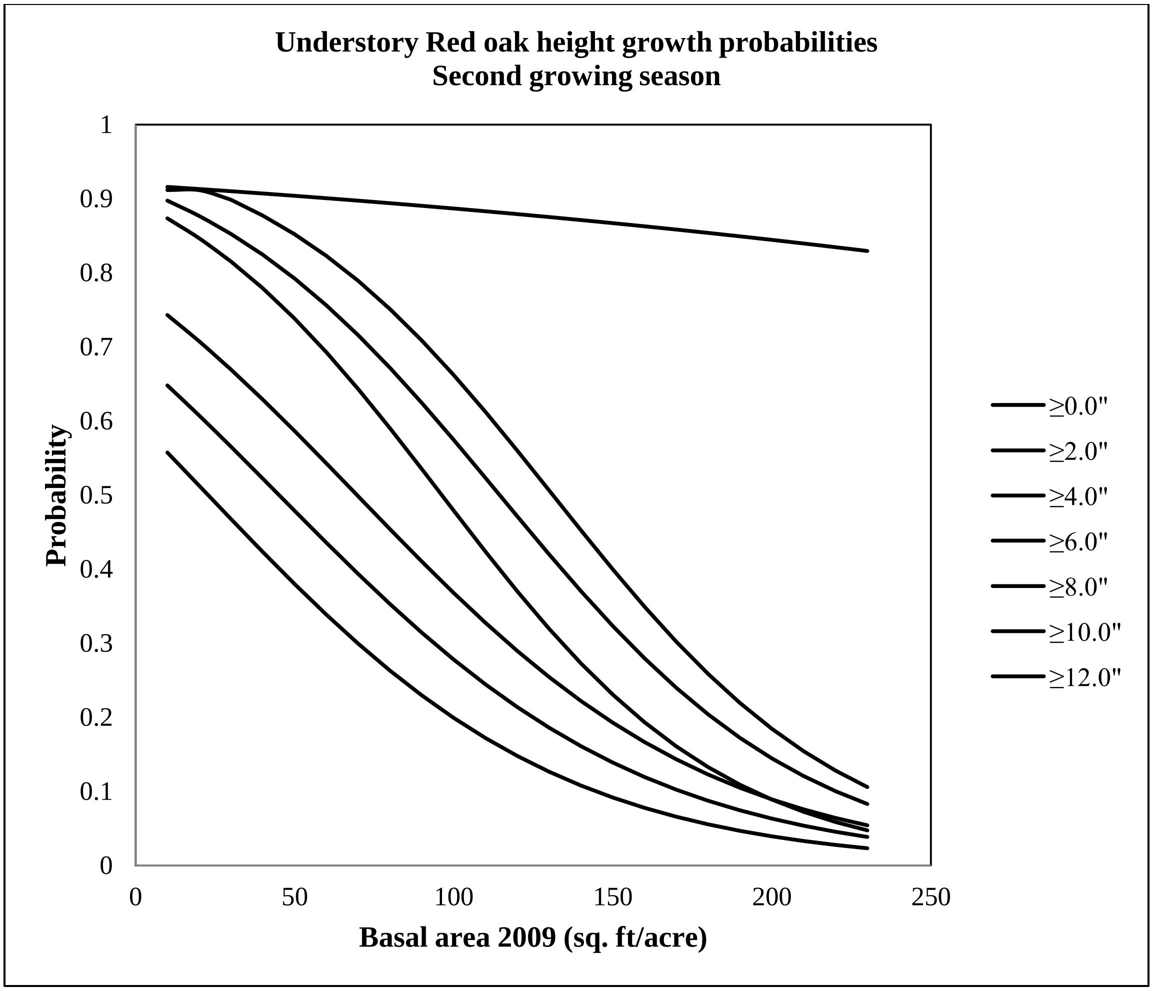


Figure 11: The estimated probability that understory red oak trees will have at least 0, 2, 4, 6, 8, 10, or 12 inches of mean annual height growth for a given over story basal area for the second growing season following harvest.

Figure 12 represents the probability of 101 tagged understory non-oak trees achieving a certain average annual height growth threshold for the first growing season immediately following the harvest based on observed annual height growth. The species of non-oak observed at the site were predominately hickory species, red maple, and green ash with all non-oak species being combined together under the title *Non-oaks.* Like the white oaks and red oaks the non-oaks were located randomly across 300 1/100th acre regeneration plots established across the entire study. The non-oak trees were composed of newly regenerated seedling sprouts, stump sprouts and germinated acorns which became established after the harvest. All forms of regeneration were combined for this evaluation across the entire harvest site.

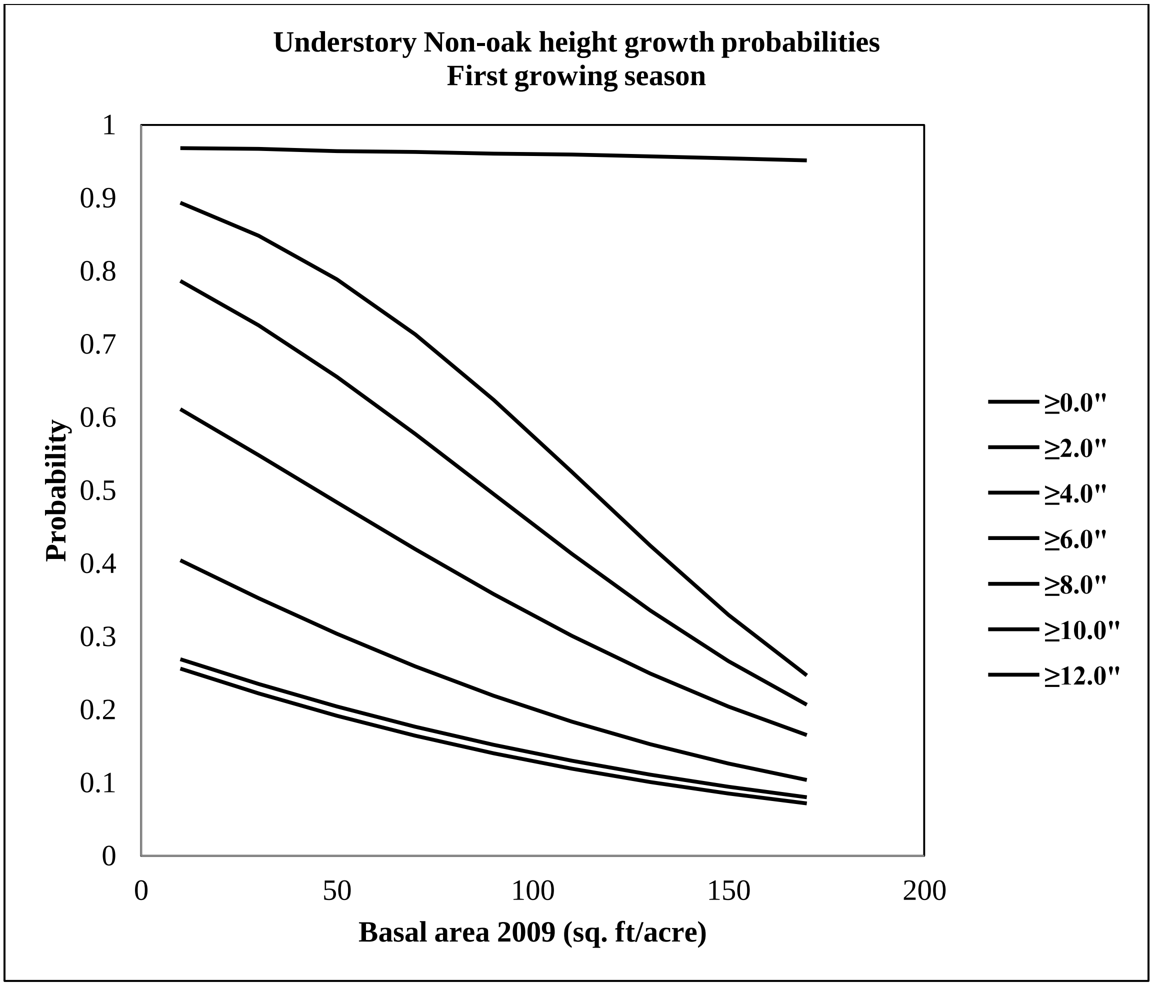


Figure 12. The estimated probability that understory non-oaks will have at least 2, 4, 6,8, 10, or 12 inches of mean annual height growth for a given over story basal area one year following harvest

The probability of understory non-oak trees achieving 0-1.99 inches of growth at 10 square feet per acre of basal area was approximately 97 percent for the first growing season. Non-oaks maintained a constant probability for this average annual height growth threshold across all basal area categories. For the first year non-oaks exhibit a higher probabilitiy of achieving at least 0-1.99 inches of annual height growth when compared to the probabilities of white oaks (Figure 8) and red oaks (Figure 10) from the first growing season. However, non-oaks tended to respond more similarly to the red oaks once average annual height growth thresholds and basal area began to increase. This is an indication that similar to the red oak species that non-oak species are less tolerant to overstory competition than white oak species.

Figure 13 represents the probability of the same non-oak trees achieving the same average annual height growth thresholds for the second growing season. When Figure 13 is compared to Figure 12 a big difference is seen between the trend lines from year one to year two. Figure 13 indicates that the non-oaks experienced a significantly less amount of observed average annual height growth than did the white oaks and red oaks. A large drop off in the success probabilities is indicated by the steep slope of the trend lines. This may indicate that the non-oaks are responding poorly to the surrounding competition from the white oak and red oak regeneration since basal area has not changed. Figure 13 is a good indication that non-oaks will not dominate the stand in the future due to their intolerance to vegetative and over story competition and their lower probabilities of achieving higher average annual height growth thresholds than white and red oaks.

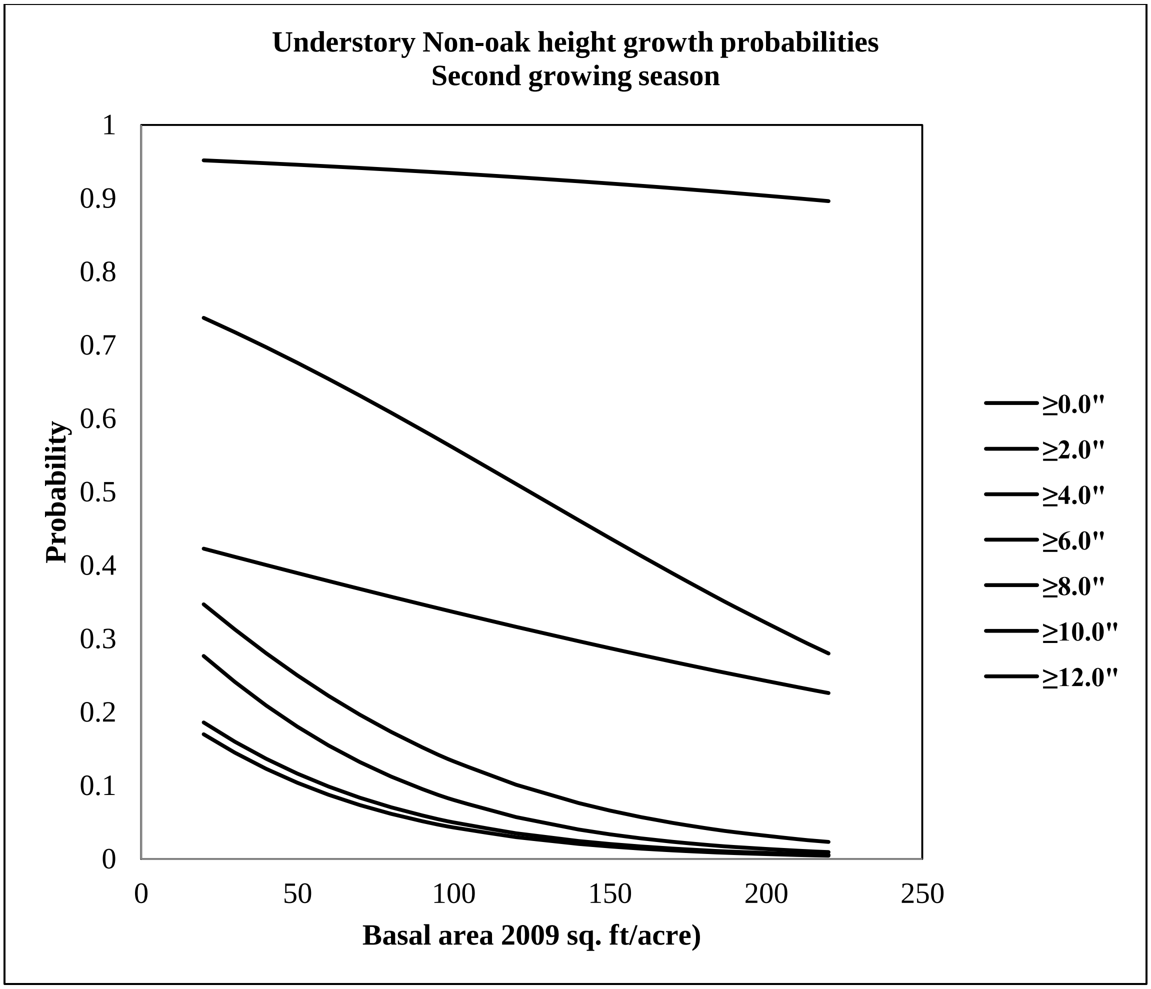


Figure 13: The estimated probability that understory non-oak trees will have at least 0, 2, 4, 6, 8, 10, or 12 inches of mean annual height growth for a given over story basal area for the second growing season following harvest.

THE EFFECT OF OVER STORY DENSITY ON UNDERSTORY HEIGHT GROWTH FOR THE DURATION OF THE EXPERIMENT

In order to determine probabilities representative of the accumulative growth made during both growing seasons, the average annual height growth thresholds were increased to ½- foot increments for the second growing season's data to accommodate for the increased height growth of the tagged trees. The logistic regression models again illustrate that the probability of all species groups that met the average annual height growth thresholds decreased as over story density increased. Additionally, the proportion of understory trees that met a given average annual height growth threshold decreased as over story density increased for all species.

Table 6 represents the number of trees in the white oak, red oak or non-oak categories which were above or below the average annual height growth thresholds for the for the duration of the study (two growing seasons). Table 7 represents the logistic parameters for predicting the probability of the mode. The purpose of this analysis was to evaluate the probability that white oaks, red oaks and non-oaks will have of achieving increased height growth after a two year period based on observed data. It is identified that as the height growth thresholds increased the number of trees that surpassed the threshold decreased while the number of trees that fell below the threshold increased (Table 6). Some of the tagged trees succumbed to mortality, animal damage or the tag was lost leading to a decreased number of observed tagged trees for the second growing season. For growing season two there were 205 individually tagged white oak trees, 235 individually tagged red oak trees and 99 individually tagged non-oak trees across the entire research site. At the end of the entire study there were 27 (13%) white oak , 31

(13%) red oak trees and 9 (9%) non-oak trees that had grown equal to or above the maximum average annual height growth threshold of 48 inches.

Table 6. Observed numbers of trees above or below the specified average annual height growth threshold for the second growing season following harvest

	Observed number of trees	
Understory mean annual height growth threshold (in/yr)	Below threshold	Above or equal to threshold
White oak seedlings (n=205)		
≥0.0"	0	205
≥6.0"	63	142
≥12.0"	105	100
≥18.0"	143	62
≥24.0"	156	49
≥30.0"	163	42
≥36.0"	165	40
≥42.0"	174	31
≥48.0"	178	27
Red oak seedlings (n=235)		
≥0.0"	0	235
≥6.0"	68	167
≥12.0"	139	96
≥18.0"	173	62
≥24.0"	193	42
≥30.0"	197	38
≥36.0"	199	36
≥42.0"	203	32
≥48.0"	204	31
Non-oak seedlings (n=99)		
≥0.0"	0	99
≥6.0"	32	67
≥12.0"	57	42
≥18.0"	73	26
≥24.0"	79	20
≥30.0"	84	15
≥36.0"	85	14
≥42.0"	89	10
≥48.0"	90	9

Table 7: Logistic regression parameters for estimating the probability of obtaining an average annual height growth on a 1/100th acre plot for the2-year duration of the study

Reproduction mean annual height growth (in) for the second growing season	Model coefficients			
	b₀	*SE*	*b₁*	*SE*
White oak understory (n=194)				
≥0.0"	2.0959	0.449	0.001	0.0054
≥6.0"	1.4324	0.3036	-0.014	0.0037
≥12.0"	0.5242	0.3163	-0.014	0.0043
≥18.0"	-0.1981	0.4187	-0.018	0.0066
≥24.0"	-0.7648	0.4756	-0.017	0.0075
≥30.0"	-1.3475	0.507	-0.013	0.0076
≥36.0"	-1.4524	0.5313	-0.013	0.008
≥42.0"	-2.1849	0.71	-0.012	0.0108
≥48.0"	-2.0596	1.0213	-0.024	0.0185
Red oak understory (n=217)				
≥0.0"	2.4272	0.3998	-0.004	0.004
≥6.0"	2.1578	0.3199	-0.022	0.0039
≥12.0"	0.4114	0.3327	-0.018	0.0048
≥18.0"	-0.1151	0.4786	-0.025	0.008
≥24.0"	-1.5494	0.5763	-0.015	0.0089
≥30.0"	-1.5138	0.7203	-0.021	0.0121
≥36.0"	-1.5803	0.8046	-0.023	0.0139
≥42.0"	-2.3676	0.9143	-0.017	0.0148
≥48.0"	-1.9022	1.159	-0.029	0.0215
Non-oak understory (n=95)				
≥0.0"	3.0674	0.8431	-0.004	0.0088
≥6.0"	1.2295	0.4353	-0.01	0.005
≥12.0"	-0.2192	0.4315	-0.005	0.0052
≥18.0"	0.5242	0.3163	-0.014	0.0043
≥24.0"	-0.5928	0.7257	-0.018	0.0113
≥30.0"	-1.1078	0.8825	-0.018	0.0141
≥36.0"	-1.2064	0.9392	-0.019	0.0151
≥42.0"	-2.9224	1.0605	-0.003	0.0132
≥48.0"	0.7954	2.1433	-0.084	0.0502

Figure 14 represents the probability of 205 tagged understory white oak trees achieving a certain average annual height growth threshold for duration of the study based on observed annual height growth. After the duration of the two year study the white oak group had approximately a 91 percent probability of achieving 0-5.99 inches of average annual height growth regardless of the surround basal area (Figure 14). However it is indicated in Figure 14 that as the average annual height growth thresholds and basal area increase the probability of the white oak trees achieving higher annual height growth thresholds significantly decreases. This is especially evident once the surrounding basal area reaches 50 square feet per acre, where the probabilities represented by the trend lines begin to steeply decline as a response to increasing basal area. White oaks only had an 11 percent probability of achieving 48 or more inches of annual height at 10 square feet of basal area per acre. This percentage rapidly decreases to less than a 5 percent probability at 50 square feet of basal area and a zero percent probability at 220 square feet of basal area.

White oak regeneration did exhibit the ability to grow in excess of 48 inches in just two years following a timber harvest but as indicated in in Figure 14 and Table 8 the probability for white oak regeneration to achieve this is relatively low. White oaks tended to have a higher probability of success for the lower average annual height growth thresholds. However, basal area again appears to play a significant role when it comes to the probability of white oaks achieving significant height growth after 50 square feet of basal area per acre (Figure 14).

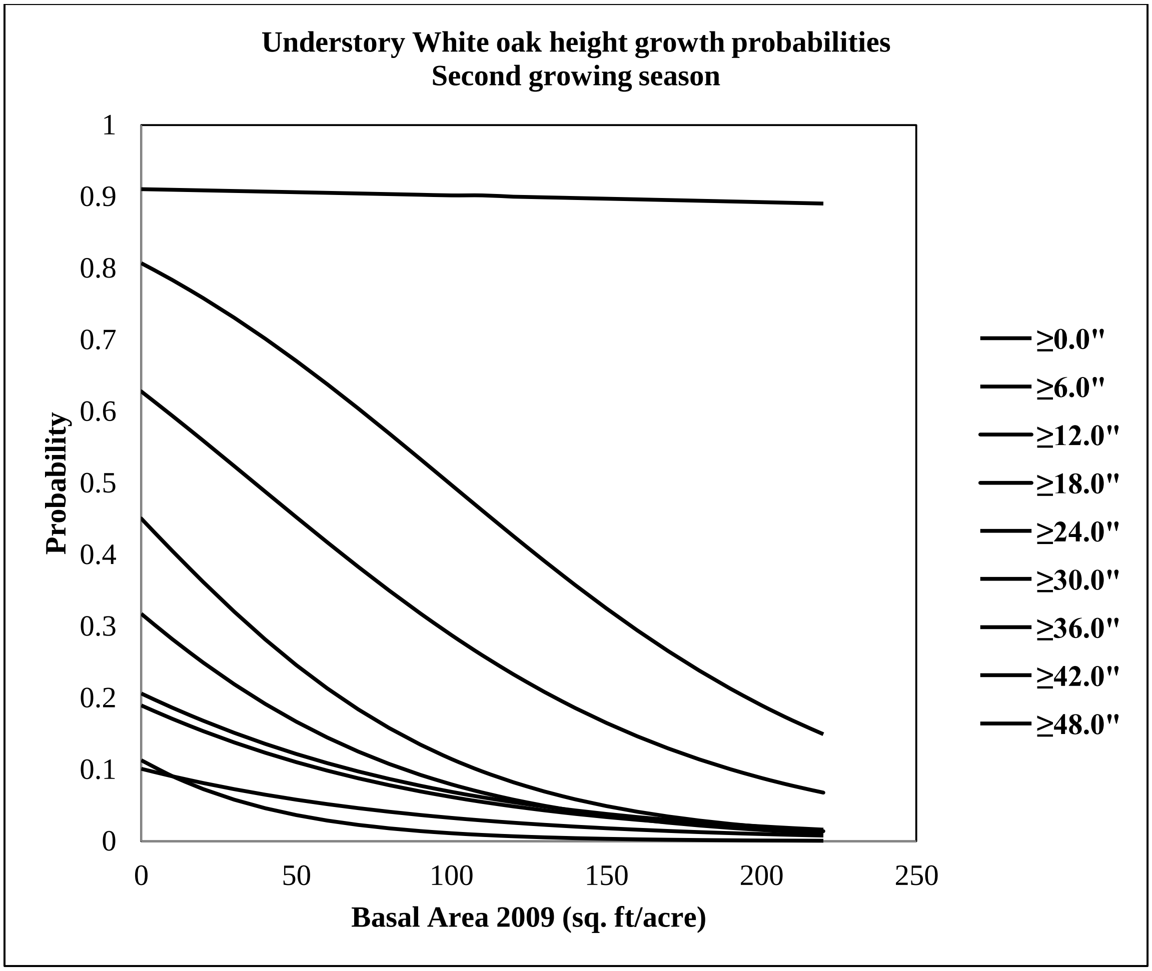


Figure 14: The estimated probability that understory white oak trees will have at least 0, 6, 12, 18, 24, 30, 36, 42 or 48 inches of mean annual height growth for a given over story basal area for the second growing season following harvest.

Figure 15 represents the probability of 235 tagged understory red oak trees achieving a certain average annual height growth threshold for duration of the study based on observed annual height growth. The probability of understory red oak trees achieving 0-5.99 inches of growth at 10 square feet per acre of basal area was approximately 91 percent for the duration of the study. However, unlike the probability of white oak trees which maintained approximately a constant 91 percent probability of achieving 0-5.99 inches of annual height growth for all basal area categories (Figure 14), red oaks decreased to 82 percent probability at 220 square feet of basal area (Figure 15). Red oaks only had a 6 percent probability of achieving 48 or more inches of annual height at 10 square feet of basal area per acre. This percentage rapidly decreases to less than a 4 percent probability at 50 square feet of basal area and a zero percent probability at 220 square feet of basal area.

Red oak regeneration did exhibit the ability to grow in excess of 48 inches in just two years following a timber harvest but as indicated in in Figure 15 and Table 8 the probability and actual number of red oak trees that achieved this is relatively low. White red tended to have a lower probability of success after the average annual height growth threshold increased past 12 inches of growth per year. However, basal area again appears to play a significant role when it comes to the probability of red oaks achieving significant height growth after 50 square feet of basal area per acre (Figure 15). This is similar to white oaks when compared to red oaks with both oak groups tending to exhibit lower probabilities once a basal area of 50 is reached. It is apparent that understory red oaks have a lower probability of achieving successful height growth (Figure 15) as over story increases when compared to white oaks (Figure 14) for the duration of the study.

This is helps to reinforce that red oak species are less tolerant to over story competition than white oak species.

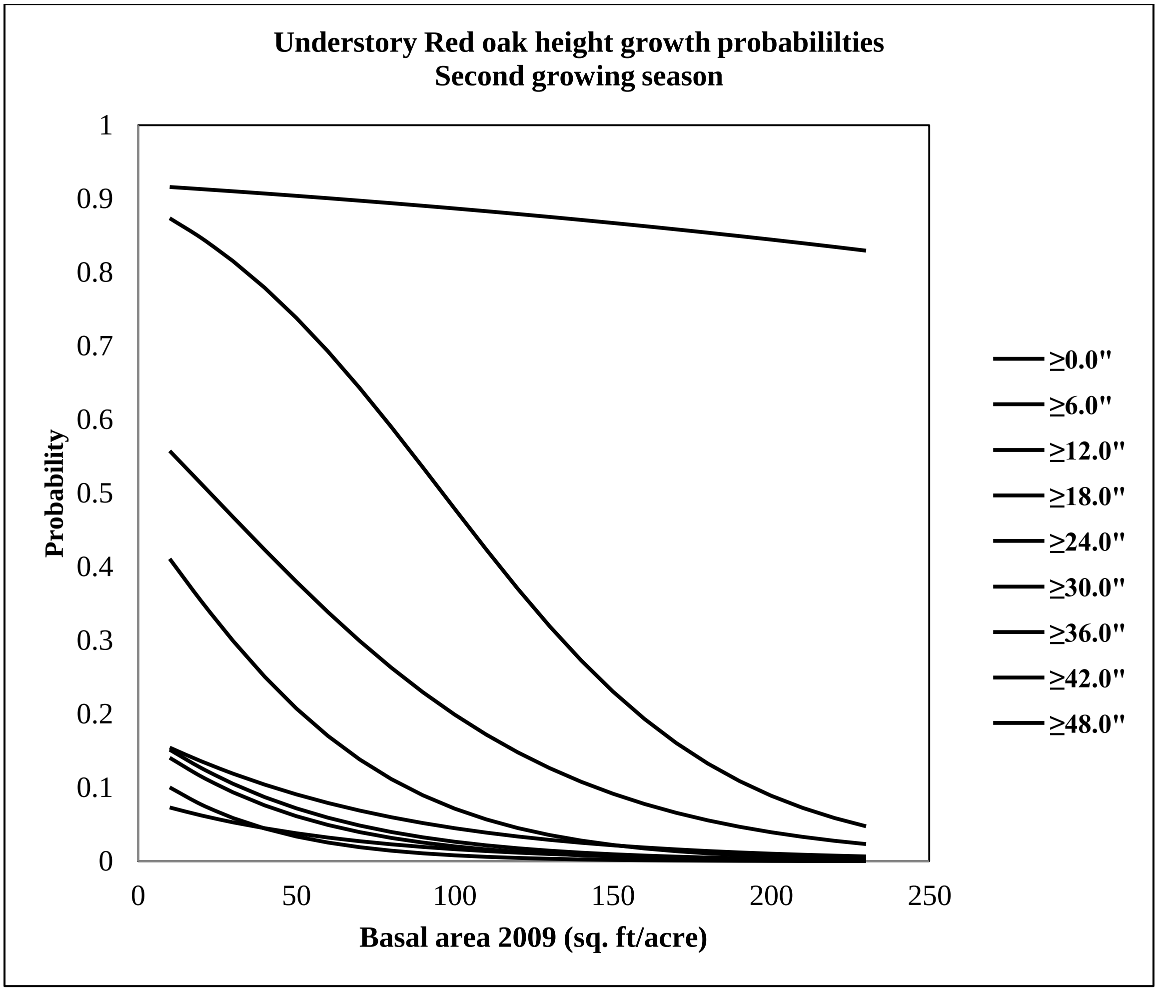


Figure 15: The estimated probability that understory red oak trees will have at least 0, 6, 12, 18, 24, 30, 36, 42 or 48 inches of mean annual height growth for a given over story basal area for the second growing season following harvest.

Figure 16 represents the probability of 99 tagged understory non-oak trees achieving a certain average annual height growth threshold for duration of the study based on observed annual height growth. The probability of understory non-oak trees achieving 0-5.99 inches of growth at 20 square feet per acre of basal area was approximately 94 percent but decreased to 89 percent as basal area increased to 220 square feet per acre. Similar to year one, non-oaks exhibit a higher probability of achieving at least 0-5.99 inches of annual height growth for the duration of the study when compared to the probabilities of white oaks (Figure 14) and red oaks (Figure 15). However, non-oaks began to exhibit a lower probability of success as the average annual height growth thresholds and basal area increased when compared to white oaks (Figure 14) and red oaks (Figure 15).

Figure 16 again indicates that the non-oaks experienced a significantly less average annual height growth than did the white oaks and red oaks. A large drop off in the success probabilities is indicated by the steep slope of the trend lines. This may indicate once again that the non-oaks are responding poorly to the surrounding competition from the surrounding white oaks and red oaks regeneration since basal area has not changed. Figure 16 is a good indication that non-oaks will not dominate the stand in the future due to their intolerance to vegetative and over story competition and their lower probabilities of achieving higher average annual height growth thresholds than white and red oaks.

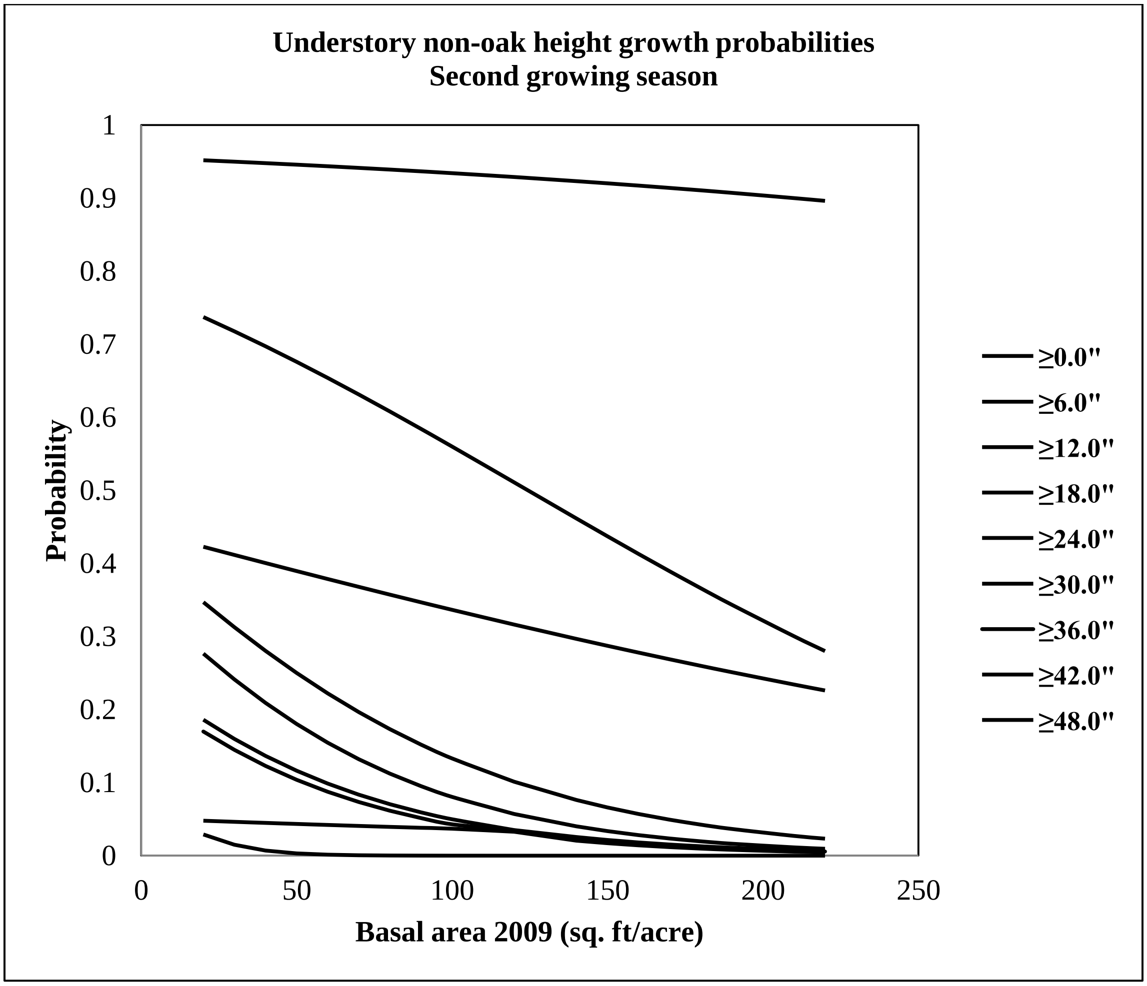


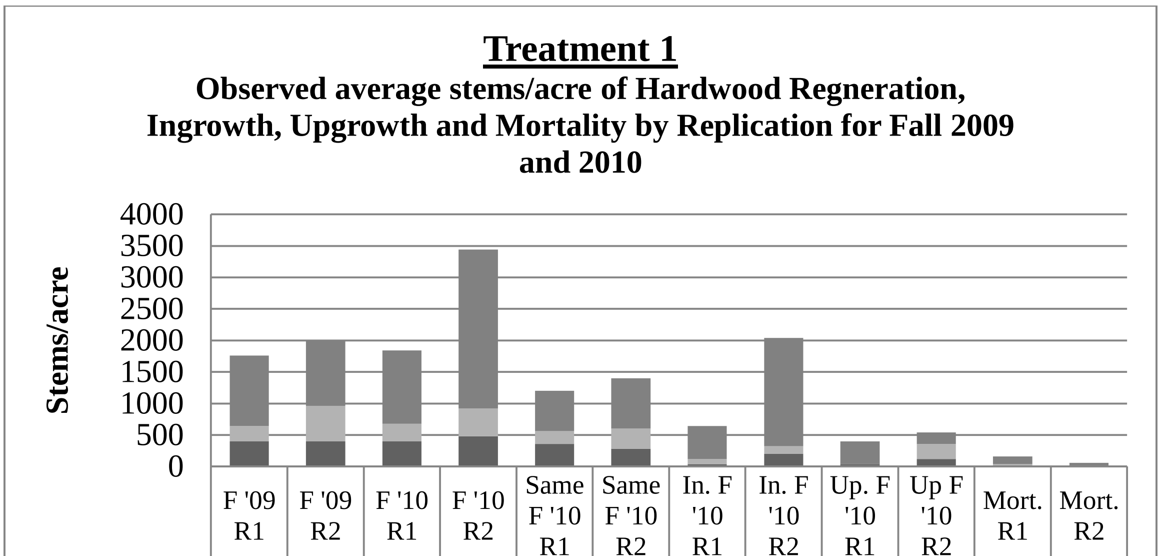
Figure 16: The estimated probability that understory non-oak trees will have at least 0, 6, 12, 18, 24, 30, 36, 42 or 48 inches of mean annual height growth for a given over story basal area for the second growing season following harvest

EVALUATION OF HARDWOOD REGENERATION ABUNDANCE BY TREATMENT

The analysis of the stems per acre (SPA) of hardwood regeneration, ingrowth, upgrowth and mortality up to 3 feet in height by treatment yielded similar results as the logistic regression analysis of the height of understory oaks and non-oaks; as basal area for the treatments increased the amount of regeneration decreased. Figures 17 through 22 represent the observed number of regeneration up to 3 feet in height for all treatments. The graph represented in each figure can be interpreted by observing the *x* and *y* axis. The *y* axis indicates the number of stems per acre observed for white oaks, red oaks and non-oaks with each species group having a separate identifying color. Columns are located on the x axis and underneath each column is a code category. Each code category identifies the season (F=fall) the year ('09=2009 or '10=2010), and the replicate number (R1=replicate 1 or R2=replicate 2) in which the datum was collected. The code category SAME is representative of the number of stems that remained in the 1/1000th acre plot from 2009 to 2010, the code category IN is representative of ingrowth or the number of new stems observed in 2010, the code category UP is representative of upgrowth or the number of stems that grew into the next size class of regeneration and the code category MORT is representative of the number of stems that died between 2009 and 2010. Under each code are 3 numbers indicating the number of stems per acre for white oaks, red oaks and non-oaks corresponding to what code category they are under.

Figure 17 represents the single tree selection treatments (Treatments 1, 2, and 3) and was observed that Treatment 1 (T1), in Replicates 1 and 2 (R1 and R2) had similar results for observed white oak stems per acre for 2009 and 2010 (400 SPA for R1T1 vs. 400 SPA for R2T1 for fall 2009 and 400 SPA for R1T1 vs. 480 SPA for R2T1 for fall

2010) (Figure 17). However white oaks in Treatment 1, replicate 2 had higher observed stems per acre of ingrowth and up-growth for 2010 than did Treatment 1 of Replicate 1 (Figure 17). Similar results are seen for red oak and non-oak regeneration for Treatment 1 for both replications (Figures 17). Treatment 1 for both replications had the highest observed stems per acre of ingrowth, upgrowth and least mortality for all species for the Single-tree Selection treatments (Treatments 1, 2 and 3).



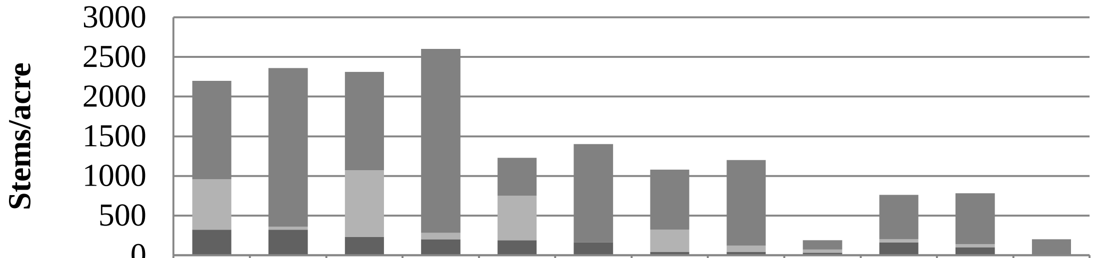
	F '09 R1	F '09 R2	F '10 R1	F '10 R2	Same F '10 R1	Same F '10 R2	In. F '10 R1	In. F '10 R2	Up. F '10 R1	Up F '10 R2	Mort. R1	Mort. R2
Non-oaks	1120	1040	1160	2520	640	800	520	1720	360	180	120	60
Red Oaks	240	560	280	440	200	320	80	120	0	240	40	0
White Oaks	400	400	400	480	360	280	40	200	40	120	0	0

Figure 17. Stacked graph of observed average stems/acre of hardwood regeneration, ingrowth, upgrowth and mortality for Treatment 1 by Replication(F=Fall, R=Replication number, Same= regeneration that remained in the plot between Fall '09 and Fall '10, In.=Ingrowth, Up.=Upgrowth into next regeneration size class of 3.1 inches in height to 1.5 inches DBH, Mort.=Mortality).

Treatment 2 of the single- tree selection treatments had the lowest stems per acre of observed ingrowth and up-growth for 2010 for both replications (Figure 18). Treatment 3, the lightest thinned of the single-tree selection treatments (58 ft^2 BA) had the second highest average observed stems of ingrowth per acre for all species and Single-tree Selection treatments for the fall 2010 (Figure 19). All species in Treatment 3 for both replications, however, had lower observed stems per acre of up-growth of regeneration into the next size class for 2010 which can be contributed to a higher over story density, and a relatively low mortality when compared to the other single-tree selection treatments.

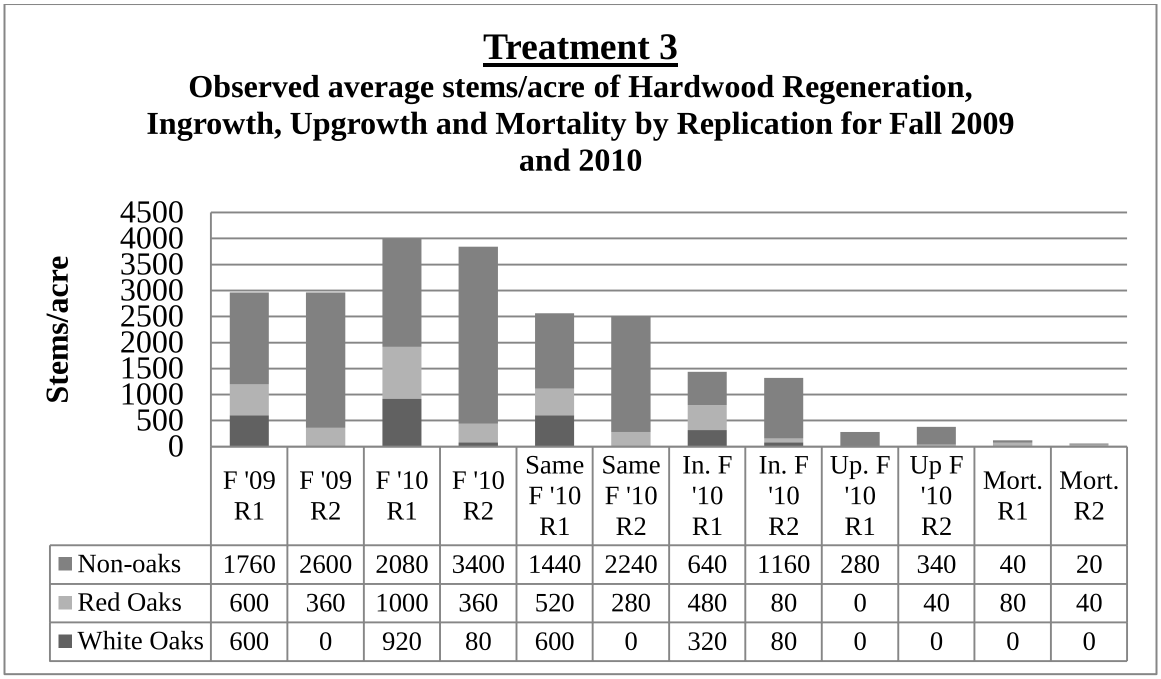
Treatment 2

Observed average stems/acre of Hardwood Regeneration, Ingrowth, Upgrowth and Mortality by Replication for Fall 2009 and 2010



	F '09 R1	F '09 R2	F '10 R1	F '10 R2	Same F '10 R1	Same F '10 R2	In. F '10 R1	In. F '10 R2	Up. F '10 R1	Up F '10 R2	Mort. R1	Mort. R2
Non-oaks	1240	2000	1240	2320	480	1240	760	1080	120	560	640	200
Red Oaks	640	40	840	80	560	0	280	80	40	40	40	0
White Oaks	320	320	230	200	190	160	40	40	30	160	100	0

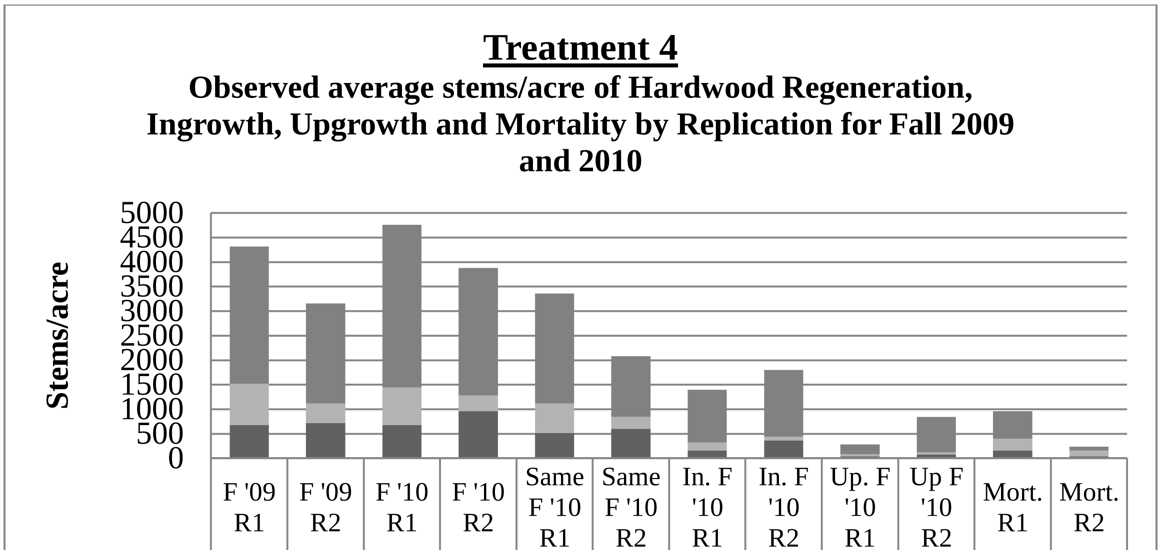
Figure 18. Stacked graph of observed average stems/acre of hardwood regeneration, ingrowth, upgrowth and mortality for Treatment 2 by Replication (F=Fall, R=Replication number, Same= regeneration that remained in the plot between Fall ‘09 and Fall ‘10, In.=Ingrowth, Up.=Upgrowth into next regeneration size class of 3.1 inches in height to 1.5 inches DBH, Mort.=Mortality).



	F '09 R1	F '09 R2	F '10 R1	F '10 R2	Same F '10 R1	Same F '10 R2	In. F '10 R1	In. F '10 R2	Up. F '10 R1	Up F '10 R2	Mort. R1	Mort. R2
Non-oaks	1760	2600	2080	3400	1440	2240	640	1160	280	340	40	20
Red Oaks	600	360	1000	360	520	280	480	80	0	40	80	40
White Oaks	600	0	920	80	600	0	320	80	0	0	0	0

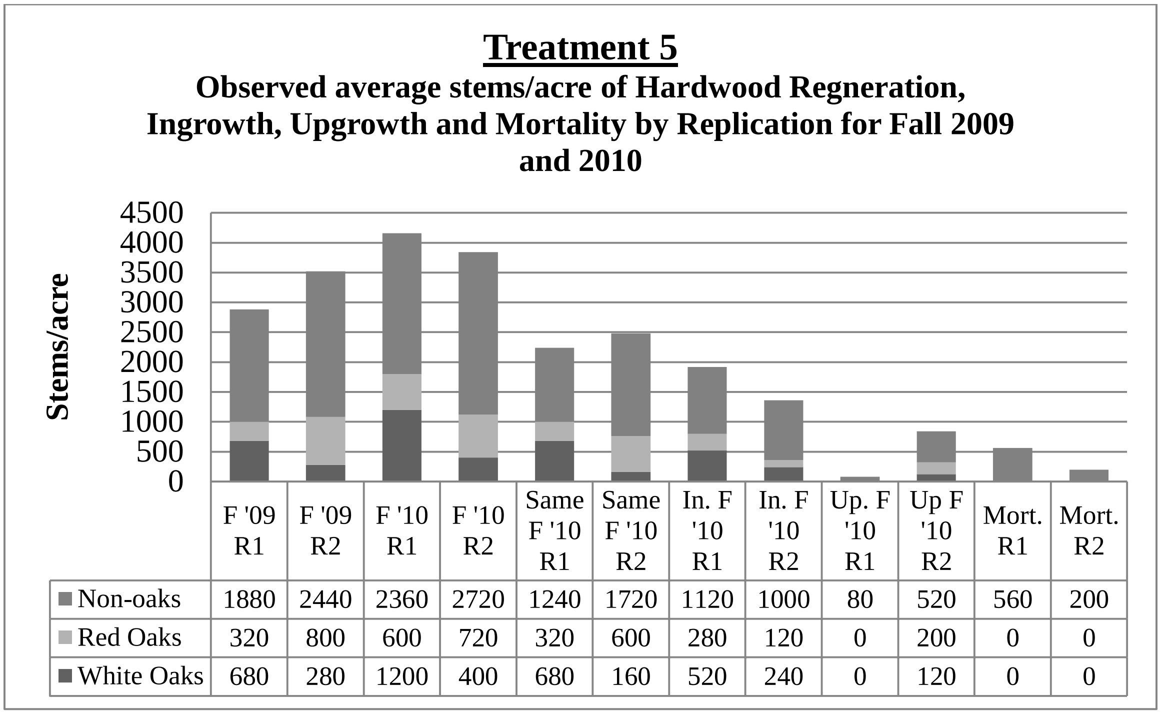
Figure 19. Stacked graph of observed average stems/acre of hardwood regeneration, ingrowth, upgrowth and mortality for Treatment 3 by Replication (F=Fall, R=Replication number, Same= regeneration that remained in the plot between Fall ‘09 and Fall ‘10, In.=Ingrowth, Up.=Upgrowth into next regeneration size class of 3.1 inches in height to 1.5 inches DBH, Mort.=Mortality)

Treatments 4 and 5, the shelterwood in strips (residual BA of 40 ft^2) had similar results to each other in observed stems of ingrowth, up-growth and mortality for all species in 2010 (Figures 20, 21). Treatments 4 and 5 had higher overall observed stems per acre of ingrowth, and up-growth for all species when compared to Treatments 1, 2, and 3 but generally had similar numbers of stems per acre of mortality of all species as Treatments 1, 2, and 3.



	F '09 R1	F '09 R2	F '10 R1	F '10 R2	Same F '10 R1	Same F '10 R2	In. F '10 R1	In. F '10 R2	Up. F '10 R1	Up F '10 R2	Mort. R1	Mort. R2
Non-oaks	2800	2040	3320	2600	2240	1240	1080	1360	200	720	560	80
Red Oaks	840	400	760	320	600	240	160	80	40	40	240	120
White Oaks	680	720	680	960	520	600	160	360	40	80	160	40

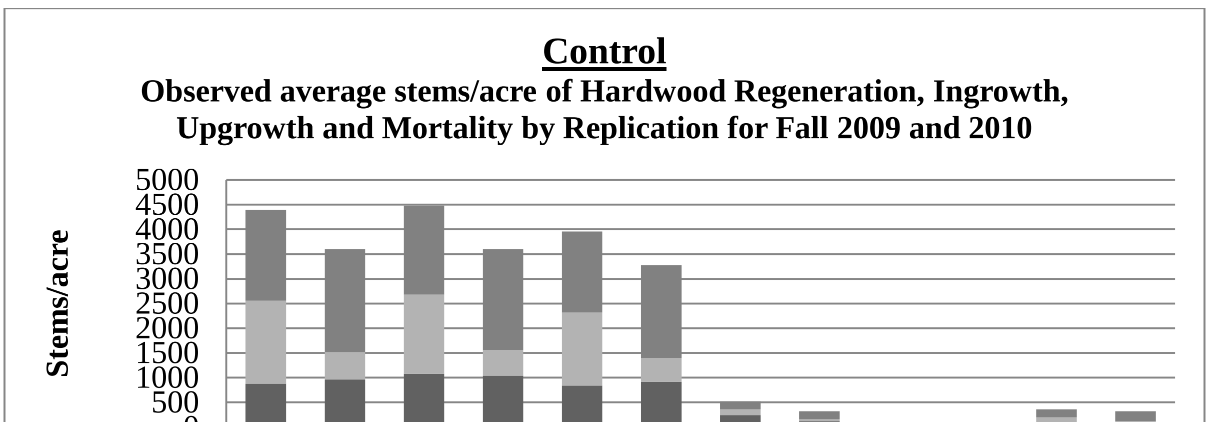
Figure 20. Stacked graph of observed average stems/acre of hardwood regeneration, ingrowth, upgrowth and mortality for Treatment 4 by Replication (F=Fall, R=Replication number, Same= regeneration that remained in the plot between Fall ‘09 and Fall ‘10, In.=Ingrowth, Up.=Upgrowth into next regeneration size class of 3.1 inches in height to 1.5 inches DBH, Mort.=Mortality).



	F '09 R1	F '09 R2	F '10 R1	F '10 R2	Same F '10 R1	Same F '10 R2	In. F '10 R1	In. F '10 R2	Up. F '10 R1	Up F '10 R2	Mort. R1	Mort. R2
Non-oaks	1880	2440	2360	2720	1240	1720	1120	1000	80	520	560	200
Red Oaks	320	800	600	720	320	600	280	120	0	200	0	0
White Oaks	680	280	1200	400	680	160	520	240	0	120	0	0

Figure 21. Stacked graph of observed average stems/acre of hardwood regeneration, ingrowth, upgrowth and mortality for Treatment 5 by Replication (F=Fall, R=Replication number, Same= regeneration that remained in the plot between Fall '09 and Fall '10, In.=Ingrowth, Up.=Upgrowth into next regeneration size class of 3.1 inches in height to 1.5 inches DBH, Mort.=Mortality).

The Control (Figure 22) had higher overall observed stems per acre of regeneration than any of the other treatments; however minimal if any upgrowth was observed in 2010 along with relatively low ingrowth. The higher observed stems per acre can be attributed to the fact that the Control was never harvested. Many of the stems of regeneration in the Control had remained in a state of suspended growth for the duration of the study with minimal height and basal diameter growth. The leading cause of this is the fact that the Control is over stocked with minimal sunlight reaching the forest floor to stimulate growth of understory regeneration that has accumulated there.



	F '09 R1	F '09 R2	F '10 R1	F '10 R2	Same F '10 R1	Same F '10 R2	In. F '10 R1	In. F '10 R2	Up. F '10 R1	Up F '10 R2	Mort. R1	Mort. R2
Non-oaks	1840	2080	1800	2040	1640	1880	160	160	40	0	160	200
Red Oaks	1680	560	1600	520	1480	480	120	40	0	0	200	80
White Oaks	880	960	1080	1040	840	920	240	120	40	0	0	40

Figure 22. Stacked graph of observed average stems/acre of hardwood regeneration, ingrowth, upgrowth and mortality for the Control by Replication (F=Fall, R=Replication number, Same= regeneration that remained in the plot between Fall ‘09 and Fall ‘10, In.=Ingrowth, Up.= Upgrowth into next regeneration size class of 3.1 inches in height to 1.5 inches DBH, Mort.=Mortality).

ANALYSIS OF VARIANCE

The ANOVA produced results similar to the logistic regression for the first two years of growth for all species. Treatment 1 (the heaviest thinned) provided the maximum average height growth (Table 8) and basal diameter growth (Table 9) of the understory trees for white oak, red oak and non-oak seedling sprouts and stump sprouts (Table 8). However red oak seedling sprouts, according to the p-value on Table 8, were significantly taller than and non-oak seedling sprouts for Treatment 1. The mean annual height growth for red oak seedling sprouts was 17 inches taller than non-oak seedling sprouts for Treatment 1. White oak seedling sprouts were also significantly taller than non-oak seedlings sprouts and were 15.4 inches taller than non-oak seedling sprouts for Treatment 1 (Table 9). Similarly Treatment 1 yielded the most significant difference in basal diameter increase with white oak stump sprouts being significantly larger in basal diameter than non-oak stump sprouts. The other treatments exhibited differences between species and origin (stump sprouts and seedling sprouts) but nothing of a large significance in difference as Treatment1. Treatment 1 appeared to have been thinned to a residual basal area that supported the maximum increase in growth of advance regeneration and may yield the best results for future growth and survival for oak species.

Table 8: Least squared comparison of white oak, red oak, and non-oak height growth for the duration of the study across varying harvest treatments. The Difference Estimate is the difference between Column A and Column B

		Species Comparison (A-B)					
Trt.	Origin	A	B	Difference Estimate	Error	t-value	Pr >|t|
1	Stump	Non-oak	Red Oaks	-6.4594	6.5894	0.98	0.3276
1	Stump	Non-oak	White Oaks	-8.3761	5.2217	1.6	0.1096
1	Stump	Red Oaks	White Oaks	1.9167	5.1888	0.37	0.7121
1	Seedling	Non-oak	Red Oaks	-15.4234	3.7445	4.12	<.0001*
1	Seedling	Non-oak	White Oaks	-17.3063	4.2546	4.07	<.0001*
1	Seedling	Red Oaks	White Oaks	1.8829	3.2027	0.59	0.557
2	Stump	Non-oak	Red Oaks	-4.4933	6.7306	-0.67	0.5048
2	Stump	Non-oak	White Oaks	-2.8000	5.0840	-0.55	0.5822
2	Stump	Red Oaks	White Oaks	1.6933	6.7306	0.25	0.8015
2	Seedling	Non-oak	Red Oaks	4.6882	3.5826	1.31	0.1915
2	Seedling	Non-oak	White Oaks	-1.5438	4.0770	-0.38	0.7052
2	Seedling	Red Oaks	White Oaks	-6.2320	3.2994	-1.89	0.0597*
3	Stump	Non-oak	Red Oaks	0.7841	5.1547	0.15	0.8792
3	Stump	Non-oak	White Oaks	-1.2262	5.1511	-0.24	0.812
3	Stump	Red Oaks	White Oaks	-2.0104	3.1789	-0.63	0.5275
3	Seedling	Non-oak	Red Oaks	0.0252	4.1527	0.01	0.9952
3	Seedling	Non-oak	White Oaks	-1.6370	4.1613	-0.39	0.6943
3	Seedling	Red Oaks	White Oaks	-1.6622	2.9405	-0.57	0.5722
4	Stump	Non-oak	Red Oaks	-0.6997	3.5205	-0.2	0.8426
4	Stump	Non-oak	White Oaks	-5.4063	3.6229	-1.49	0.1365
4	Stump	Red Oaks	White Oaks	-4.7067	3.0689	-1.53	0.126
4	Seedling	Non-oak	Red Oaks	8.8259	3.8006	2.32	0.0208*
4	Seedling	Non-oak	White Oaks	6.9312	3.9279	1.76	0.0785
4	Seedling	Red Oaks	White Oaks	-1.8947	2.8657	-0.66	0.5089
5	Stump	Non-oak	Red Oaks	2.2237	3.4456	0.65	0.5191
5	Stump	Non-oak	White Oaks	-2.3457	3.5467	-0.66	0.5088
5	Stump	Red Oaks	White Oaks	-4.5694	3.6936	-1.24	0.2169
5	Seedling	Non-oak	Red Oaks	8.5585	4.1467	2.06	0.0398*
5	Seedling	Non-oak	White Oaks	6.9562	4.0842	1.7	0.0894
5	Seedling	Red Oaks	White Oaks	-1.6023	2.7629	-0.58	0.5623
6	Stump	Non-oak	Red Oaks	-13.3063	5.3732	-2.48	0.0137*
6	Stump	Non-oak	White Oaks	-40.1172	6.3028	-6.36	<.0001*
6	Stump	Red Oaks	White Oaks	-26.8109	7.3904	-3.63	0.0003*
6	Seedling	Non-oak	Red Oaks	10.4174	2.5834	4.03	<.0001*
6	Seedling	Non-oak	White Oaks	3.5605	2.7141	1.31	0.1904
6	Seedling	Red Oaks	White Oaks	-6.8570	2.0233	-3.39	0.0008*

Note: * Indicates significance (< α=0.05)

Table 9: Least squared comparison of white oak, red oak, and non-oak diameter growth for the duration of the study across varying harvest treatments. The Difference Estimate is the difference between Column A and Column B

		Species Comparison (A-B)					
Trt.	Origin	A	B	Difference Estimate	Error	t-value	Pr >|t|
1	Stump	Non-oak	Red Oaks	-0.1693	0.0711	2.38	0.0179*
1	Stump	Non-oak	White Oaks	-0.2325	0.0564	4.12	<.0001*
1	Stump	Red Oaks	White Oaks	0.0631	0.0560	1.13	0.2604
1	Seedling	Non-oak	Red Oaks	0.0928	0.0404	2.3	0.0222*
1	Seedling	Non-oak	White Oaks	0.1147	0.0459	2.5	0.0129*
1	Seedling	Red Oaks	White Oaks	0.0219	0.0346	0.63	0.5266
2	Stump	Non-oak	Red Oaks	0.0308	0.0727	0.42	0.6715
2	Stump	Non-oak	White Oaks	0.0164	0.0549	0.3	0.7653
2	Stump	Red Oaks	White Oaks	-0.0144	0.0727	-0.2	0.8425
2	Seedling	Non-oak	Red Oaks	0.0043	0.0410	0.11	0.9153
2	Seedling	Non-oak	White Oaks	-0.0194	0.0462	-0.42	0.6742
2	Seedling	Red Oaks	White Oaks	-0.0237	0.0356	-0.67	0.5046
3	Stump	Non-oak	Red Oaks	0.018	0.0557	0.32	0.7464
3	Stump	Non-oak	White Oaks	0.0225	0.0556	0.4	0.6865
3	Stump	Red Oaks	White Oaks	0.0045	0.0343	0.13	0.8968
3	Seedling	Non-oak	Red Oaks	0.0018	0.0448	0.04	0.968
3	Seedling	Non-oak	White Oaks	-0.0406	0.0449	-0.9	0.3666
3	Seedling	Red Oaks	White Oaks	-0.0424	0.0318	-1.34	0.1824
4	Stump	Non-oak	Red Oaks	-0.0084	0.0380	-0.22	0.8258
4	Stump	Non-oak	White Oaks	-0.0353	0.0391	-0.9	0.3673
4	Stump	Red Oaks	White Oaks	-0.0269	0.0331	-0.81	0.4168
4	Seedling	Non-oak	Red Oaks	0.0522	0.0410	1.27	0.2046
4	Seedling	Non-oak	White Oaks	0.0422	0.0424	0.99	0.3209
4	Seedling	Red Oaks	White Oaks	-0.0099	0.0309	-0.32	0.7468
5	Stump	Non-oak	Red Oaks	-0.0183	0.0372	-0.49	0.6223
5	Stump	Non-oak	White Oaks	-0.0364	0.0383	-0.95	0.3422
5	Stump	Red Oaks	White Oaks	-0.018	0.0399	-0.45	0.6505
5	Seedling	Non-oak	Red Oaks	0.0504	0.0448	1.12	0.2615
5	Seedling	Non-oak	White Oaks	0.0355	0.0441	0.8	0.4215
5	Seedling	Red Oaks	White Oaks	-0.0149	0.0298	-0.5	0.6184
6	Stump	Non-oak	Red Oaks	-0.2731	0.0580	-4.71	<.0001*
6	Stump	Non-oak	White Oaks	-0.2458	0.0681	-3.61	0.0003*
6	Stump	Red Oaks	White Oaks	0.02734	0.0798	0.34	0.7321
6	Seedling	Non-oak	Red Oaks	0.112	0.0279	4.02	<.0001*
6	Seedling	Non-oak	White Oaks	0.0144	0.0293	0.49	0.6229
6	Seedling	Red Oaks	White Oaks	-0.0976	0.0218	-4.47	<.0001*

Note: * Indicates significance (< α=0.05)

CHAPTER 5
DISCUSSION

One of the most important factors in the development of oak/hickory forests is survival and height growth of the understory trees. Trees that can grow the tallest will eventually overwhelm and out-compete their surrounding competitors. Disturbance is crucial in an oak/hickory forest in the Ozarks, allowing the young, understory trees to perpetuate the stand into the future. Oaks are well adapted to varying degrees of the intensity and frequency of disturbance and have developed specific adaptations to survival and exploitation of disturbances. As shown in Figures 3, 4, and 5, white oak was the most dominant species in the pre-treatment regeneration assessment of the research site due to its higher tolerance of shade which allows this species to persist in the understory for longer periods of time. Oaks in the Ozarks have the ability to die back and resprout which helps them develop larger root systems. This adaptation of shoot dieback and resprouting might give oak a competitive edge once the over story has been removed, allowing for rapid juvenile height and diameter growth. An oak seedling with a well-developed root system may be more effective, competitively, in capturing and rapidly occupying freed growing space.

The results from this study indicate that the probability of obtaining a given height growth one and two years after treatment for understory oaks and non-oaks decreases as over story density increases. Oaks and hickory species were favored for this study as trees to monitor for height and basal diameter growth due to the presence of these species as canopy dominants and codominants in Ozark forests. The results of the logistic regression indicate that oaks species at this site have the ability to out-compete the non-oak species across all height growth classes. Similarities in success were seen after the first growing season, with the majority of all oak and non-oaks obtaining the annual height threshold of ≥0 inches (up to 1.9 inches) of annual height growth. This may indicate that one year after a timber harvest, it is relatively easy for all species to obtain a height growth of up to 2 inches. However, it is remiss to say that trees that grow an average of 2 inches a year would have the ability to compete well enough to eventually be recruited into the over story canopy. In the remaining categories oaks, especially oaks regenerating from stump sprouts had a higher probability of obtaining a height growth success than non-oaks. This supports the hypothesis that non-oaks less frequently become dominant trees within the canopy, especially in the Ozarks. It could be assumed that non-oak species may dominate the forest composition, when considering the higher abundance of non-oak species versus oak species present at the research site following treatment. However, the annual height growth for oak species tends to exceed annual height growth when compared to non-oak species, at least for 2 years following a harvest.

In the Ozarks, it is typically uncommon for oaks to be recruited into the over story without the occurrence of disturbance to open the canopy. Annual height growth becomes an important aspect in terms of determining the probability of a tree reaching dominant or codominant status following the removal of the over story. Therefore, in accordance with the results from the logistic regression analysis, the over story should be reduced below 50 square feet of basal area per acre allowing for the recruitment of understory trees into dominant and codominant crown classes. Oaks and non-oaks exhibited the highest height growth within Treatment 1, and little to no height growth within the Control for both replications. The target residual basal for Treatment 1 was 30 ft^2/ acre while both controls were not harvested and exceeded 130 ft^2/acre. In order to achieve recruitment of oak into the over story when practicing uneven and even-age management the stand density must be reduced below the B-level (50% or less) stocking following harvest (Gingrich, 1967; Larsen et. al, 1997; Green, 2008).

Results from the logistic regression analysis can be used by private land owners or forest managers to estimate the probability of achieving various height growth thresholds at varying over story densities. This information can be used to estimate the height growth of understory oak and non-oak trees for a wide variety of silvicultural treatments. The results also illustrate the general trends observed for understory tree height growth under varying over story densities.

It is apparent when examining the comparisons of height and basal diameter growth between white oak, red oak and non-oak stump sprouts and seedling sprouts (Tables 8 and 9) that Treatment 1 provided the overall best results for achieving maximum height and basal diameter growth of understory trees. As basal area increased for Treatment 2 and 3 understory white oaks, red oaks and non-oaks began to decrease in their differences in height and basal diameter growth. However, Treatments 4 and 5 yielded similar results in height and basal diameter growth of understory. The Control, which was not harvested, yielded the poorest results in terms of height and basal diameter growth. Sometimes exceeding 200 square feet per acre of basal area, the control exhibited the least growth in height and basal diameter, with many tagged understory trees remaining in a suspended state with no measurable growth. One of the consequences of retaining a high over story basal area is a significant decrease in height and basal diameter growth of understory oak trees, even though it is rare to observe non-oaks dominating the landscape in the Ozarks. Because of this it is important to take into consideration stand dynamics which plays a crucial role in determining future over story species dominance.

For example, the height and basal diameter growth of understory trees may be indicative of their proximity to gap openings and orientation to over story trees. It can be expected that the closer an understory tree is to the center of a gap opening the better it can fare in terms of survival and growth thus exhibiting the greater annual height and basal diameter growth. This can be attributed to greater light availability and less competition from the over story and surrounding trees. However, understory trees that are located farther from the center of the gap opening and oriented closer to competing over story trees may experience a decrease in height and basal diameter growth because of these competing factors. Treatments 1, 2, and 3 may most likely function in a comparable mode, due to the intention of utilizing these treatments as an uneven-aged management practice by creating gap openings thus stimulating understory height and diameter growth. The ANOVA regrettably was not able to explain this situation due to its use of plot averages rather than individual plots. An examination of the understory at an individual level instead of a plot or average level may better reveal this scenario. Factors such as over story density, proximity to competing over story trees and spatial location are crucial when examining understory trees and determining their potential for height and basal diameter growth.

A low overstory basal area may be an contributing factor as to why non-oaks appear to dominate a stand during the early phases of stand re-initiation. Low overstory density may also allow non-oaks to readily compete with oak species. However, it appears that red oaks stump sprouts and seedling sprouts were significantly larger than white oak and non-oak stump and seedling sprouts in height and basal diameter when examining the results from the ANOVA for Treatment 1 (Table 8). White oak stump sprouts and seedling sprouts also exhibited a significant difference in height and basal diameter growth when compared to non-oaks but were, however, smaller than stump and seedling sprouts of red oaks for Treatment 1 (Table 8). This may indicate that understory red oak stump and seedling sprouts may have a competitive edge over white oak and non-oak stump and seedling sprouts when the residual basal area is reduced to 40 square feet per acre or lower. However, an increase from 40 square feet per acre in over story basal area seemed to favor the production of white oak seedling and stump sprouts in the understory although this was not statistically different. Red oaks are primarily known as pioneer or early succession species following a disturbance and tend to be less shade tolerant than white oaks and non-oaks which may be what is indicated by the ANOVA results. Therefore white oak and non-oak understory trees may be the favored species for height and basal diameter growth over red oak species as over story density increases beyond 40 square feet per acre.

THE EFFECT OF TREATMENT ON REGENERATION ABUNDANCE

The results of this study indicated that Treatment 1, (basal area 37 ft^2/acre) , and Treatments 4 and 5, the shelterwood in strips treatment(basal area of 40 ft^2 acre), yielded the best results of observed average stems per acre of oak and non-oak regeneration, ingrowth, upgrowth and mortality when compared to Treatments 2 and 3 and the Control. However, the oaks were less abundant as a group than the non-oaks. Non-oak species such as sassafras and black gum appeared to be the more dominant species seen in the regeneration counts following harvest in 2009 but it should be noted that many of these non-oak species will not become canopy dominants even though they can quickly colonize growing space. Non-oak species generally rely on other survival strategies such as prolific seed production and fast growth rather than the development of large root systems and tend to compete poorly for light and resources once the growing space around them has been occupied. Even though these species were more abundant than oaks following the harvest, they will eventually be out-competed by oaks and hickories due to their observed absence in the over story during the pre-treatment assessment of the research site.

Oaks are well adapted to disturbance in the Ozark Highlands and it is rare to witness non-oak species dominating the over story. Due to their adaptations to fire, drought tolerance, and their ability to sprout, oaks are better able to compete for newly freed growing space and overtake their non-oak competitors. However it is important to consider that this dataset only examines a 2- year period of growth directly following a harvest which may not be sufficient amount of time to examine these adaptations and changes in forest structure. Two years is an extremely short amount of time to obtain definitive results but this study showed that oak and non-oak advance regeneration and root sprouts have the potential to grow in excess of 4 feet in just two years. These results are extremely important in examining and understanding the immediate response of trees to various silvicultural treatments.

Understory regeneration abundance is dependent upon growing space and adequate levels of sunlight. Therefore, in accordance with the Gingrich stocking chart, the over story should be reduced below the B-level stocking allowing for adequate numbers of oak regeneration (Gingrich 1967). Once the over story is reduced below the B-line stocking level enough sunlight will be available to penetrate to the forest floor in order to stimulate regeneration of oak species in the understory.

CHAPTER 6
CONCLUSIONS

UNDERSTORY GROWTH IS DEPENDENT ON OVER STORY DENSITY

The height and basal diameter growth of understory oak and non-oak trees is highly dependent on the density of the over story. As indicated in the logistic regression models, understory height and basal diameter growth increases as over story density decreases. This trend is consistent for all species. The regression models provide basic information that illustrate the average expected outcomes of understory height and diameter growth at a given over story density. Height and basal diameter growth was almost at an absolute minimum in the unharvested Control. However, regeneration growth was observed in the Control treatment when located near the center of a gap opening which occurred due to blowdowns or snags. This strongly suggests that disturbances which reduce the over story density is needed for growth of understory regeneration. With this mentioned, height and basal diameter growth of understory oaks and non-oaks is dependent on their relative vicinity to over story trees and openings in the canopy. It can be expected that the closer an understory tree is to the center of a gap opening the better it can fare in terms of survival and growth thus exhibiting increased chances of obtaining higher annual height and basal diameter growth. Understory trees that are not in close proximity to a gap opening or that are occurring under a closed canopy situation may yield minimal height and basal diameter growth and may not be able to compete well under those situations.

In the case of this study, the treatment that would best mimic natural canopy openings and disturbance scenarios experienced by oaks in the Ozarks and produced the best results for height and diameter growth of understory oaks would be Treatment 1. Treatment 1 was the heaviest thinned of all the treatments and yielded the highest observed growth for understory trees. However, Treatments 4 and 5, the shelterwood in strip treatments might be a better alternative when considering which treatment may be the most productive for future biomass harvests. Treatments 1, 2, and 3 were methods designed to create uneven-aged stands whereas Treatment 4 and 5 were methods designed to produce an even- aged stand structure. Treatments 4 and 5 would be overall more conducive to a biomass harvest due to even-age, small diameter trees that could be harvested with relative ease. The single-tree selection treatments, while producing positive results, may not be as conducive to a biomass harvest due to the uneven-aged state of the stand, making the harvest of small diameter trees more difficult in amongst a mixed stand of different size and age class trees.

SUSTAINABLE OAK REGENERATION IS DEPENDENT ON THE REGULATION OF OVER STORY DENSITY

Successful regeneration of oak species is highly dependent on the density of the over story. Sander et al. (1976, 1984) developed a procedure to adequately evaluate advance oak reproduction before a harvest which would ensure adequate stocking levels of oak reproduction following a clearcut. His definition of adequate stocking specified that at least 30% of the stand must be stocked with oaks that have a mean diameter of 3 inches at 20 years of age. This is based on Gingrich's (1976) stocking diagrams of upland hardwood species. Sander et al. (1976) concluded that a minimum of 443 trees per acre that are 4.5 feet tall or taller is the required amount to ensure a future stocking of the stand of at least 221 dominant and codominant trees per acre on a site with a 50- year site index. Controlling the abundance of oak regeneration is dependent on management efforts to reduce the over story density. To ensure adequate levels of regeneration foresters should concentrate on controlling the amount of over story density. The tables presented for the observed average stems per acre for each treatment can provide guidelines that illustrate the average expected regeneration abundance at differing silvicultural treatments, at least for this site in the Ozarks.

FUTURE RESEARCH

Several opportunities exist for future research and monitoring of this site. As mentioned before, this experiment only examined the results of understory height and basal diameter growth and regeneration abundance for a two- year period directly following the timber harvest. This is a relatively short time period and further monitoring of the tagged understory trees should be re-evaluated in at least 10 years. Due to the stochastic nature of this dataset, the evaluation of future species composition, height and basal diameter growth and regeneration abundance are crucial for developing proper forest management decisions. And so, it is vital that this site be remeasured at least every 10 years to determine how stand dynamic processes are functioning at this site.

CHAPTER 7
LITERATURE CITED

Abrams, Marc D. 1992. Fire and the development of oak forests. Bioscience, 42(5):346-343.

Bowman M. J. S, Balch, J.K., Artaxo P., Bond, W.J., Carlson, J.M., Cochrane, M.A., D'Antonio, C.M., DeFries, D.S., Doyle, J.C., Harrison, S.P., Johnston, F.H., Keeley, J.E., Krawchuk, M.A., Kull, C.A., Marston, J.M., Moritz, M.A., Prentice, I.C., Roos, C.I., Scott, A.C., Swetnam, T.W., Van der Werf, R.S. Pyne S.J., 2009. Fire in the Earth System.*Science* 324, 481 (2009);

Carvell K. L. and E. H. Tryon. 1961. The effect of environmental factors on the abundance of oak regeneration beneath mature oak stands. Forest Science, 7(2):98-105.

Dey, Daniel C., Paul S. Johnson, and H. E. Garrett. 1996. Modeling the regeneration of oak stands in the Missouri Ozark Highlands. Canadian Journal of Forest Research, 26:573-583.

Dey, Daniel C. and William C. Parker. 1997. Overstory density affects field performance of underplanted red oak (*Quercus rubra* L.) in Ontario. Northern Journal of Applied Forestry. 14(3):120-125

Dwyer, John Patrick. "Evaluation of the Long-Term Silvicutural and Economic Effects of Thinning and Pruning Treatments on a Scarlet and Black Oak Timber Stand in Southeastern Missouri." Diss, university of Missouri, 1988.

Gingrich, Samual F. 1967. Measuring and evaluating stocking and stand density in upland hardwood forests in the Central States. Forest Science, 13:38-53.

Graves, L.H. Jr. 1983. Soil survey of Butler County and part of Ripley County Missouri. USDA Soil Conservation Service. U.S. Government Printing Office. Washington, D.C. 141p.

Green, Jason Lee. "Overstory Density and its Effect on Oak Regeneration Abundance and Oak Understory Height Growth in the Missouri Ozark Highlands." MA Thesis. University of Missouri, 2008. Print

Guyette, Richard P. and Bruce E. Cutter. 1991. Tree-ring analysis of fire history of a post oak savanna in the Missouri Ozarks. Natural Areas Journal, 11:93-99.

Johnson, Paul S. 1977. Predicting oak stump sprout probabilities and sprout development in the Missouri Ozarks. Forest Service Research Paper, NC-149. United States Department of Agriculture, Forest Service, North Central Experiment Station, St. Paul, MN.

Johnson, Paul S., Stephen R. Shifley, and Robert Rogers. 2002. *The Ecology and Silviculture of Oaks*. CABI Publishing, New York, New York.

Johnson, Paul S., Stephen R. Shifley, and Robert Rogers. 2009. *The Ecology and Silviculture of Oaks. Second Edition.* CABI Publishing, New York, New York.

Kabrick, John M., Erick K. Zenner, Daniel C. Dey, David Gwaze, and Randy Jensen. 2007. Using ecological land types to examine landscape-scale oak regeneration dynamics. Forest Ecology and Management, 225:3051-3062

Larsen, David R. and Paul S. Johnson. 1998. Linking the ecology of natural oak regeneration to silviculture. Forest Ecology and Management, 106:1-7.

Larsen, David R., Edward F. Loewenstein, and Paul S. Johnson. 1999. Sustaining recruitment of oak reproduction in uneven-aged stands in the Ozark Highlands. Gen. Tech. Rep. NC-203. United States Department of Agriculture, Forest Service.

Larsen, David R., Monte A. Metzger, and Paul S. Johnson. 1997. Oak regeneration and overstory density in the Missouri Ozarks. Canadian Journal of Forest Research, 27:869-875.

Liming, F.G. and Johnston, J.P. 1944. Reproduction in oak-hickory forest stands of the Missouri Ozarks. Journal of Forestry 42:175-180

Loftis, David L. 1990. A shelterwood method for regenerating red oak in the southern Appalachians. Forest Science, 36(4):917-929

Oliver, Chadwick D. 1981. Forest development in North America following major disturbances, *Forest Ecology and Management* 3:153-168

Oliver, Chadwick D. and Bruce C. Larson. 1996. *Forest Stand Dynamics*. John Wiley and Sons, Inc. 520 pp.

Olson, David F., Jr. 1974. Quercus L. Oak. In Seeds of woody plants in the United States p. 692-703. C.S. Schopmeyer, tech. coord. U.S. Department of Agriculture, Agriculture Handbook 450. Washington D.C.

Peet, Robert K. and Norman L. Christensen. 1987. Competition and tree death. Bioscience, 37:586-595.

Roach, Benjamin A. and Samuel F. Gingrich. 1968. Even-aged silviculture for upland central hardwoods. Agricultural Handbook 355. United States Department of Agriculture, Forest Service.

Sander, Ivan L. and Bryan F. Clark. 1971. Oak regeneration in the central states. Agric. Handb. 405. United States Department of Agriculture, Forest Service.

Sander, Ivan L. 1972. Size of oak reproduction: key to growth following harvest cutting. Forest Service Research Paper, NC-79. United States Department of Agriculture, Forest Service, North Central Experiment Station, St. Paul, MN.

Sander, Ivan L. 1979. Regenerating oaks with the shelterwood system. In Proceedings, Regenerating Oaks in Upland Hardwood Forests. John S. Wright Forestry Conference. p. 54-60. Purdue University, West Lafayette, IN.

Sander, Ivan L., Paul S. Johnson, and Robert Rogers. 1984. Evaluating oak advance reproduction in the Missouri Ozarks. Research Paper, NC-251. United States Department of Agriculture, Forest Service, North Central Experiment Station, St. Paul, MN.

Saunders, Adam M. "Economic Analysis of Woody Biomass Harvesting in the Missouri Ozarks." MA Thesis. University of Missouri, 2010. Print

Seidel, Kenneth W. 1972. Drought resistance and internal water balance of oak seedlings. Forest Science 18(1):34-40

Smith, David M., et al. *The Practice of Silviculture: Applied Forest Ecology.* Ninth Edition. New York: John Wiley and Sons, 1997. Print

Soucy, Rick D. Eric Heitzman and Martin A. Spetich. 2005. The establishment and development of oak forests in the Ozark Mountains of Arkansas. Canadian Journal of Forest Research, 35:1790-1797.

Stupak, Inge. Brenna Lattimore, Brian D. Titus, C. Tattersall Smith. 2011. Criteria and indicators for sustainable forest fuel production and harvesting: A review of current standards for sustainable forest management. Biomass and Bioenergy 35:3287-3308

Tryon, E. H. and K. L. Carvell. 1958. Regeneration under oak stands. West Virginia University Agricultural Experiment Station, Bulletin 428T.

Weigel, Dale R. Daniel C. Dey. "Fifteen years of stump sprout development for five oak species in southern Indiana." *2007 Proceedings of the 15th Central Forest Conference, Knoxville, TN.* Ed. Buckley, David S., Clatterbuck, Wayne K. Washington, D.C: Department of Agriculture, 2007.

Wolgast, L.J. "Mast production of scrub oak (*Quercus ilicifolia*) on the coastal plain in New Jersey." Diss. Rutgers Universtity, Princeton, New Jersey. 1972. Print

Vanguelova, Elena, Rona Pitman, Jukaa Luiro, Heljä-Sisko Helmisaari. 2010. Long term effects of whole tree harvesting on soil carbon and nutrient sustainability in the UK. Biogeochemistry 101:43-59