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EFFECTS OF MIDSTORY REMOVAL AND SHOOT CLIPPING ON THE GROWTH AND DEVELOPMENT OF THREE OAK SPECIES

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EFFECTS OF MIDSTORY REMOVAL AND SHOOT CLIPPING ON THE GROWTH AND DEVELOPMENT OF THREE OAK SPECIES

THESIS

By

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Lexington, Kentucky

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2012

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ABSTRACT OF THESIS

EFFECTS OF MIDSTORY REMOVAL AND SHOOT CLIPPING ON THE GROWTH AND DEVELOPMENT OF THREE OAK SPECIES

Problems developing tall oak seedlings of high abundance have become a concern throughout many eastern hardwood forests. The decline in oak seedling recruitment into canopy positions is often attributed to the increasing abundance of shade tolerant midstory species, especially red maple (Acer rubrum L.). Studies have shown that increasing light to the understory by way of a midstory removal has the ability to favor oak seedlings over competitors. The majority of studies to date have examined northern red (Quercus rubra L.) and cherrybark oak (Quercus pagoda Raf.) on productive sites, but relatively little is known about the effects of midstory removal on white (Quercus alba L.) and black (Quercus velutina L.) oaks, which are valuable species commercially and for wildlife. This study tests the effect of a midstory removal on oak seedlings and red maples six years after treatment implementation. In addition to seedling growth, survival, and competitiveness, the study also illustrates the changes in canopy structure and light transmittance resulting from the midstory removal. Basal clipping response of white oak seedlings following six years under a midstory removal is also examined as a method for regenerating more vigorous oaks. Results from this study support implementation of midstory removal as a method for improving oak regeneration.

KEYWORDS: Quercus, Oak regeneration, Shelterwood, Underplanting, Red maple

Jared Matthew Craig

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EFFECTS OF MISTORY REMOVAL AND SHOOT CLIPPING
ON THE GROWTH AND DEVELOPMENT OF THREE OAK SPECIES

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CHAPTER ONE: INTRODUCTION

Oaks \(Quercus\) spp. L.) have historically been one of the most important hardwood genera in the U.S. from both an economic and ecological standpoint. Because of their wide availability and high market price when compared to many other hardwood species, oaks have come to dominate the hardwood market in the eastern U.S. In the south-central states (TX, LA, AR, MS, AL, TN, and KY), oaks currently comprise 55% of the total U.S. hardwood sawtimber market in terms of volume (Luppold and Bumgardner 2008). In addition to their economic importance, oaks are an invaluable wildlife food source. Throughout their range, oaks provide a primary source of hard mast for deer, birds, and rodents (Korschgen 1962; Goodrum et al. 1971; Barnett 1977; McShea and Schwede 1993; McShea 2000).

Numerous factors such as resource availability, soil type, climate, and competing vegetation play a role in determining the success or failure of oak seedlings (Kolb et al. 1990; Collet et al. 1998; Clinton 2003; Dillaway and Stringer 2006; Lhotka and Loewenstein 2009). Adequate light levels are often considered one of the most important components to promoting successful oak regeneration. Because oaks typically have intermediate shade tolerance, designing silvicultural practices that create optimal light levels for oak seedlings has been difficult.

At the time of European settlement, oaks of all size classes were likely abundant in eastern broadleaf forests, but events such as increased deer browse, gypsy moth introduction, and especially the suppression of fire have hindered the ability of oak species to establish and be recruited into the overstory (Lorimer 1993; Abrams 1998). Perhaps the biggest problem impeding the success of oaks is the increasing abundance of
shade tolerant species such as red maple (*Acer rubrum* L.), sugar maple (*A. saccharum* Marsh.), and American beech (*Fagus grandifolia* Ehrh.). Given their ability to proliferate under low light conditions, these shade tolerant species have entered oak dominated stands and created dense midstories that severely limit the light received by understory oak reproduction.

Before European settlement, red maple was rarely found comprising more than 6% of trees in most eastern forests (Abrams 1998). Since that time, the physical range of red maple has expanded considerably and can now be found in nearly every eastern forest habitat (Abrams 1998). Recent U.S. Forest Service Forest Inventory and Analysis (FIA) data have also shown that red maple density is increasing in most states (Fei and Steiner 2007), while oak density is widely decreasing (Fei et al. 2011). Sugar maple, another shade tolerant oak competitor, is also of concern because of its competitive ability to outcompete red maple under mesic conditions. It is more commonly found on rich sites as well as in traditional prairie soils throughout Illinois and Missouri where red maple is not native (Abrams 1998). In Kentucky, however, the co-occurrence of red and sugar maple is common.

The lack of sufficient oak recruitment in many stands is often attributed to advance reproduction that is of inadequate density, size, or distribution prior to disturbance (Sander 1971; Sander and Clark 1971; Sander 1972; Sander 1979; Loftis 1983, 1990a; Lorimer 1993; Loftis 2004; Steiner et al. 2008). Studies have estimated that 247 to 1074 oak seedlings per hectare are needed for successful regeneration (Sander 1979; Spetich et al. 2004), and the seedlings should be at least 90 (Belli et al. 1999; Brose et al. 2008) to 137 cm (Sander 1972) at the time of final release to increase competitive
ability. In instances where density of oak advance reproduction is deficient, underplanted seedlings have been used with success (Johnson 1984, 1988; Bardon and Countryman 1993; Dey and Parker 1997b; Lhotka and Loewenstein 2009).

Several factors influence whether or not a forest will contain enough oak seedlings of adequate size. From the time acorns reach the ground, they are preyed on by deer, rodents, birds, insects, and other animals (Crow 1988). The seeds that avoid predation and desiccation on the forest floor will then have the opportunity to germinate given acceptable conditions. Ideal conditions vary among species, but primarily rely upon light levels, soil moisture, and leaf litter depth (Barrett 1931; Beck 1993; Ashton and Larson 1996). In some years, upwards of 90 percent of acorns may be lost (Lorimer 1993); however, in higher mast years, many acorns are often able to survive. Of the surviving acorns that are undamaged, it is possible to see germination rates of over 75 percent (Olson Jr and Boyce 1971).

Even when forests do have adequate oak seedling numbers, their growth can be greatly hindered by other species competing for limited resources, primarily light. In central Kentucky, the main oak competitors are either shade tolerant maples or shade intolerant species such as yellow-poplar (*Liriodendron tulipifera* L.). However, any shade tolerant midstory species can pose a problem. Tolerant or intolerant seedlings can outcompete oaks using different growth strategies. Shade tolerant maples compete by first becoming established in the understory. Since they are able to maintain a positive carbon balance under the low light conditions of a dense hardwood forest (usually <8 percent), they slowly begin to overtop oaks of intermediate tolerance, which put on little height growth under the low light levels. Following a canopy disturbance, shade tolerant
maples are in a better position to utilize the additional light and eventually fill canopy positions all the while keeping oaks suppressed to lower height classes.

Shade intolerant species work much the opposite. These species use a shoot-first growth strategy in which they grow little in the understory, but when a canopy gap occurs, they put on significant height growth in a short period of time. Although they use a different growth mechanism, shade intolerant species still overtop slower growing seedlings following canopy disturbance and create low light levels for oak seedlings which perpetuates the regeneration problem.

Site quality is also considered to be an important factor in the success of oak regeneration following a harvest. In general, oaks are able to perpetually sustain canopy dominance in areas with a site index of 60 or less, because species such as red maple or yellow-poplar are not as vigorous on the poorer soils (Lorimer 1993). Oaks’ adaptability to drought also makes them more competitive on less productive sites (Hodges and Gardiner 1993; Rebbeck et al. 2011). On better sites, however, oaks are often outcompeted by both shade intolerant and tolerant species (Smith 1993) following the mechanisms outlined above. Loftis (1990a) even found site index to be a significant predictor of red oak advance regeneration height growth following shelterwood harvesting.

As has been alluded to, one of the most important factors affecting regeneration is the amount of direct sunlight reaching the forest floor. Because of light’s importance to oak seedling growth, altering the canopy structure to increase understory light availability is one of the most common silvicultural prescriptions. This is also a viable approach for the fact that stand structure—as compared to site quality or climate—is one of the few
conditions that can be manipulated by forest managers. Removing portions of the
overstory must be done carefully, however, so as to create a canopy structure (and
resulting understory light environment) that yields light levels low enough to limit shade
intolerant species’ growth but high enough to encourage oak growth over that of shade
tolerant species.

Over the past 100 years, numerous silvicultural practices have been implemented
in an attempt to favor oaks over competitors, and trials have been met with varied levels
of success. Even-aged regeneration methods, such as clearcuts and shelterwoods,
achieved some positive results in terms of oak regeneration (Boring et al. 1981; Johnson
and Jacobs 1981; Loftis 1990b; Kabrick et al. 2008) but most also witnessed oaks facing
serious competition from shade intolerant species like yellow-poplar and black locust
(Sander 1979; Loftis 1983; Beck and Hooper 1986; Loftis 1990b). This competition was
primarily attributed to poor advance oak reproduction size and increased light levels that
favored the shoot-first growth strategy of shade intolerant species.

At the other end of the spectrum, uneven-aged systems have also been met with
mixed results. Kabrick (2008) found that white oak species in the Ozarks responded well
to single-tree and group selection methods; however, other studies have observed oaks
being suppressed by shade tolerant midstory species (Lorimer 1984; Della-Bianca and

For enhanced oak seedling growth, several studies have found that stands should
have at least 20 percent of full sunlight reaching the forest floor (Jarvis 1964; Phares
1971; Gottschalk 1994; Guo et al. 2001; Dillaway and Stringer 2006) compared to the 1
to 8 percent of full sunlight found in an unaltered oak stand (Gottschalk 1994; Dey and
Parker 1996; Dillaway and Stringer 2006; Lhotka and Loewenstein 2009). To achieve this goal, Loftis (1983) suggests a midstory removal technique in which stems of increasing diameters are removed from the understory until a target basal area removal has been achieved.

The purpose of a midstory removal is to serve as a pre-treatment for an even-aged regeneration method, typically a shelterwood or clearcut. Roughly five to ten years before overstory removal, the midstory canopy is removed to increase understory light availablity. The increased light levels should be enough to stimulate oak growth over shade tolerant species while inhibiting the release of shade intolerant species. By the time of final overstory removal, enough oak seedlings should have reached an acceptable size to ensure recruitment into the overstory following release.

Several studies have implemented midstory removals with high levels of success; however, most of these studies have been performed with northern red oak (Loftis 1983; Lorimer et al. 1994; Miller et al. 2004) and cherrybark oak (*Quercus pagoda* Raf.) (Deen et al. 1992; Lockhart et al. 2000; Lhotka and Loewenstein 2006; Lhotka and Loewenstein 2008; Lhotka and Loewenstein 2009). Within the Cumberland Plateau and Knobs physiographic regions, forest canopies are primarily composed of white and black oaks, of which there have been few studies. Parrott (2011) found that, although midstory removal was able to slightly increase oak growth, it had a much larger effect on red maple, which was still posed to dominate stands following future disturbances.
OBJECTIVES

Given the limited information concerning white oak as well as the importance of both white and red oak species throughout the Central Hardwood Forest Region, this study examines how white, northern red, and black oaks as well as a primary competitor, red maple, interact in the understory of unaltered stands and following midstory removal. Specifically, this study consisted of two primary objectives and a number of more detailed research questions aimed at better understanding the factors that may influence the growth and development of seedlings following midstory removal.

Objective 1: Six growing seasons following a midstory removal, assess potential environmental factors such as canopy structure and understory conditions that contribute to the growth and development of white, northern red, and black oak as well as red maple.

Research questions:
1. Does the presence of midstory canopy significantly affect the height, basal diameter, survival, and competitiveness of oaks and red maples after six growing seasons?
2. For individual oak species, does seedling type (natural or artificially regenerated) affect growth over six growing seasons?
3. How does stand structure differ between midstory removal plots and untreated controls?
4. What are the possible relationships between structural and environmental stand components including light transmittance, vertical and horizontal canopy
structure, and competitor positions to six-year height and diameter growth of
naturally regenerated oak and maple seedlings as well as underplanted oaks?

5. How do stand conditions affect seedling survival and competitiveness over six
growing seasons?

6. Are there differences between significant growth factors when examining the
larger treatment-level data compared to more specific within-treatment plot
variations?

**Objective 2:** Characterize six-year effects of a midstory removal on white oak growth
and biomass allocation and accumulation, and identify potential correlates between
midstory removal and seedling response one growing season following shoot clipping.

Research questions:

1. What effect does a midstory removal treatment have on the size of oak seedling
   height, diameter, and biomass accumulation and allocation over six growing
   seasons?

2. What is the first-year sprouting response of white oak seedlings after basal
   clipping?

3. What relationships exist between seedling size and biomass accumulation and
   allocation?

4. In terms of forest management, what are the most useful correlates between
   pre- and post-clipping growth?
CHAPTER TWO: EFFECTS OF MIDSTORY REMOVAL ON THE GROWTH AND DEVELOPMENT OF WHITE, NORTHERN RED, AND BLACK OAK

INTRODUCTION

Over the past century, oak-dominated forests of the eastern United States have experienced a notable decline in the successful recruitment of several oak species into canopy positions (Clark 1993). Several theories have been posed for this decline, but the true source of the oak regeneration problem is most likely a combination of factors including fire suppression, increased deer herbivory, disease outbreaks, and climate change (Mackey Jr and Sivec 1973; Abrams 1998; McEwan et al. 2007). These alterations to historic conditions are responsible for allowing shade tolerant species like red maple (Acer rubrum L.), sugar maple (Acer saccharum Marsh.), and American beech (Fagus grandifolia Ehrh.) to become well established in the understories of oak dominated stands. Red maple, in particular, has even extended its historic range into new areas throughout the eastern United States (Abrams 1998).

The proliferation of shade-adapted species in the understory causes major problems in terms of recruiting oaks of intermediate shade tolerance to the overstory. Before the widespread suppression of fire in the late 18th and early 19th centuries, disturbance effects of fire were thought to have kept maple populations in check and provided proper conditions for oak growth and overstory succession (Abrams 1992; Abrams 1998). After fire was eliminated over much of the eastern landscape, however, shade tolerant species were able to establish much easier in oak-dominated forests.
The growth strategies of the two species groups also benefit maples over oaks when found together in a forest. Oaks may go through a series of growth, die back, and resprouting stages that develop strong root systems for the trees and prepare them for a canopy disturbance (Lorimer 1993). Shade tolerant species, on the other hand, can persist in the understory and grow continuously for many years once they become established (Lorimer 1993). Eventually, many forests will result in a midstory of nearly all shade tolerant species while oak seedlings remain suppressed below. Once a disturbance is created, it is the shade tolerant species that are in the best position to utilize the increased light reaching the forest floor. Meanwhile, the oaks are outcompeted and stay shaded. To further the problem, increased light to the forest floor may also stimulate the germination and rapid growth of shade intolerant species such as yellow-poplar (*Liriodendron tulipifera* L.) that can overtop oak seedlings in a short period of time.

To generate more suitable conditions for the growth of oak advance reproduction, several silvicultural techniques have been proposed that focus on increasing light transmittance to a point where oaks can compete with maples while the growth of shade intolerant species like yellow-poplar is limited. In stands lacking sufficient oak advance reproduction, these considerations rule out the use of clearcuts that often result in shade intolerant species outcompeting oaks (Beck and Hooper 1986; Kolb et al. 1990). Additionally, single tree selection has been found to favor the recruitment of shade species into the canopy (Lorimer 1984; Della-Bianca and Beck 1985; Lorimer 1993).

Several studies examining the optimal light levels for oak growth have found that silvicultural prescriptions should attempt to create conditions where at least 20 percent of total sunlight reaches the forest floor (Jarvis 1964; Phares 1971; Gottschalk 1994; Guo et
al. 2001; Dillaway and Stringer 2006). In a typical oak-dominated forest with a shade tolerant midstory, understory light availability can be as low as 1 to 8 percent of total full sunlight (Gottschalk 1994; Dey and Parker 1996; Dillaway and Stringer 2006; Lhotka and Loewenstein 2009). Midstory removal has been suggested as one method of achieving the higher light levels needed to promote oak seedling growth (Loftis 1983, 1990b; Miller et al. 2004; Lhotka and Loewenstein 2009). The removal of midstory vegetation should create enhanced light conditions that favor oak seedlings over shade tolerant species while also limiting the growth of fast-growing, shade intolerant seedlings (Loftis 1990b).

Even with improved light conditions, a midstory removal treatment will be unsuccessful without an adequate number of large oak seedlings with the potential to survive and eventually reach the canopy. A number of studies have found that naturally regenerated seedlings may be too few in number to successfully replace an entire oak stand (Loftis 1990a; Lorimer 1993; Loftis 2004). To compensate for the lack of natural regeneration, underplanted seedlings have been used with success in several studies (Johnson 1984, 1988; Bardon and Countryman 1993; Dey and Parker 1997b; Lhotka and Loewenstein 2009).

In the majority of studies to date, the main species of interest have been northern red (Quercus rubra L.) and cherrybark oak (Quercus pagoda Raf.). While these trees are important species throughout their ranges, white oak (Quercus alba L.) is the dominant canopy species throughout significant portions of the Central Hardwood Forest Region, but relatively few studies have closely examined white oak response to light manipulation. Additionally, the studies performed to date that have included a midstory
removal have examined seedling response across an entire treatment; however, forests are complex systems with higher variance in horizontal and vertical canopy structure, and a midstory removal treatment does not result in a homogenous light environment across an entire stand.

The objectives of this study can be divided into three main components. First, we assessed the effect of midstory removal treatment and seedling stock type on the overall height and diameter growth, total size, survival, and competitiveness of seedlings after six growing seasons. To get a better idea of the forest structure resulting from midstory removal, we next quantified the within-plot variations in terms of canopy height and openness. Finally, we created a series of models that may help explain how variation of canopy structure within plots could affect the growth and development of the selected species. In each case, underplanted and naturally regenerated seedlings of white, northern red, and black oak (*Quercus velutina* Lam.) were examined as well as naturally regenerated seedlings of their main competitor, red maple.

METHODS

Study Sites

In January of 2005, three study sites were established in Berea College Forest (37° 32’ N, 84° 14’ W) in Madison County, Kentucky, which is located on the western edge of the northern Cumberland Plateau physiographic region. The sites were named Water Plant, Pigg House, and Fentress Spur. Major soil types for each site were from the Weikert and Shelocta series. Both of these series are acidic, well-drained silt loams common to the region. At the time of treatment implementation, basal areas of the sites
ranged from 24.5 to 27.9 m²ha⁻¹. Dominant and codominant canopy positions were
primarily composed of white oak, black oak, chestnut oak, and hickories (Carya spp. L.).
The understory was mainly dominated by shade tolerant species such as red maple, sugar
maple, and American beech.

Average canopy top height was found to be 27.9 meters, and site indices ranged
from 19.8 to 21 m at age 50. Although a complete record of management activities was
unavailable, tree cores taken from the sites show the average age to be 111 years old and
suggest that no major disturbance events have taken place over the last century.

Study Design

At each site, two areas of similar slope and aspect were chosen with one being
randomly designated as the control plot and the other as the removal. In the control plot, a
0.2 ha square (45m per side) was located, and the corners were marked with fiberglass
posts. In the second area, the midstory removal treatment was applied over a 0.4 ha
square (63 m per side). Within this square, a 0.2 ha square was nested in the center to
serve as the study plot. The nesting approach resulted in a 9 m buffer on all sides of the
plot to minimize the impact of edge effects. To accomplish the midstory removal, a 20
percent basal area reduction was performed by mechanically felling with a chainsaw all
trees of 2.6 cm dbh and working upward in diameter sizes until the target basal area had
been removed. This treatment effectively removed overtopped and intermediate crown
class trees while keeping all dominant and codominant trees intact. Pre- and post-
treatment basal areas of each site are presented in Table 2.1. To facilitate monitoring of
the plots, felled trees were cut into smaller pieces, and slash was carried outside plot
boundaries. Immediately following treatment, cut stumps were sprayed with 100% Roundup Pro® (Monsanto Company, St. Louis, MO) to prevent sprouting. The control areas were left undisturbed.

Each treatment area (control or midstory removal) was divided into 36 square cells measuring 7.5 m on each side. Cell corners were marked with 46 cm fiberglass posts. From the 36 cells, white, black, and northern red oak seedlings were each underplanted in six cells per plot. In each of these cells, twelve, 1-0 bareroot seedlings of the selected species were planted in a grid with an approximate 0.5 m spacing. In six other randomly selected cells per plot, oak and maple advance reproduction at the time of treatment was recorded. The remaining twelve cells were not pertinent to this study and did not influence the cells included in the analyses presented here.

Data Collection

Prior to the 2005 growing season, total height and ground line diameter of all natural (oak and maple) and underplanted (oak) seedlings were measured in the sampling cells. Seedlings were given a pin flag with a unique number to facilitate long-term monitoring. After six growing seasons (summer 2010), total height and diameter of each seedling were again recorded. Seedling height was determined by holding a meter stick at the base of a seedling perpendicular to the ground. Height readings were recorded to the nearest 0.5 cm, and seedlings were left in their natural position to better assess true competitive height. Diameters were taken using digital calipers held perpendicular to the stem at ground level. Readings were recorded to the nearest 0.1 mm. Two measurements
were made at 90 degree angles to each other, and these were averaged to represent the final seedling diameter.

An assessment of seedling competitors was also taken in summer 2010. In the center of each treatment cell, a 0.0002 ha square (1.4 m) was established, and all woody vegetation present within the square was recorded by species and height class. Height classes included seedlings ≤10 cm, 10 to 49.5 cm, and in 50 cm increments thereafter. The tallest height class included vegetation >250 cm. After competitor height data were collected, the density of competitors in each treatment was calculated.

Competitiveness of each observed natural and underplanted oak seedling was determined using a procedure similar to that presented by Morrissey et al. (2010). Competitive seedlings were considered to be those seedlings whose total height in 2010 was ≥80% of the height of directly competing seedlings in that cell. To determine the height threshold for each cell, the seedling competitor data were compiled, and the top quartile of competing seedlings were identified. The average height of this top quartile was identified as the competitive threshold, and tagged seedlings ≥80% of this number were considered competitive.

Several additional measures were also taken during the sixth growing season to characterize the horizontal and vertical canopy structure of the plots. To assess the vertical components of the stand, a measure to the top and bottom of the canopy was taken at the center of each cell. The lower canopy readings were taken using a TruPulse™ 360 laser rangefinder (Laser Technology, Centennial, CO) on the vertical distance setting. The rangefinder was positioned 137 cm off of the ground to avoid low vegetation interference and was pointed directly upward. A reading was then taken, and
137 cm was added to this reading to determine the height to the bottom of the canopy. The height to the top of the canopy was also measured using the same rangefinder on the height setting. To take these readings the tree closest to the cell’s center was identified. Horizontal distance to the tree as well as degrees incline to the top and bottom of the tree were taken, and the rangefinder output total tree height. For more accurate measures, the horizontal distance was always taken at least 15 m from the tree. To obtain a measure of canopy depth, the total tree height was subtracted from the height to the bottom of the canopy.

The percent of visible sky from each cell was determined from hemispherical photographs. Photographs were taken from the center of each cell on using a Nikon CoolPix 8400 camera equipped with a Nikon FC-E9 180° fisheye lens. All pictures were taken on July 21, 2010 during overcast conditions where the solar disk was not visible. These photographs were then analyzed using HemiView © software (Delta-T Devices, Cambridge, UK). Four readings of visible sky were calculated for each picture that represented a 180, 120, 90, and 60 degree view angle from a point directly above the camera.

During the seventh growing season, photosynthetically active radiation (PAR) measurements were taken to assess light transmittance in the plots. This was done using an Accupar PAR ceptometer (Decagon Devices, Inc., Pullman, WA) on May 15, 2011. All readings were taken within two hours of solar noon when the solar disk was not visible. In each cell, three readings were taken at breast height (1.37 meters) in each of the cardinal directions away from the technician’s shadow. The three readings were averaged to get a measurement for each cell. The ceptometer was then calibrated with an open-sky LiCor quantum sensor (LI-190SB, Li-Cor, Lincoln, NE) connected to a datalogger (CR1000,
Regression equations were then developed between the two devices to estimate percent light transmittance into the cells. Since only one set of measurements was taken, no statistical analyses were performed to check for significant differences between treatments.

Data Analysis

To assess whether average seedling size was similar at the time of treatment, two-way analysis of variance (ANOVA) was performed for each species to compare initial seedling heights and diameters between treatments (control and midstory removal) and seedling type (natural and underplanted) (Table 2.3). It was found that for white oak and red maple, there was no significant difference between initial heights of underplanted and advance regeneration seedlings (p>0.05). Heights of northern red and black oak underplanted seedlings were larger than advance regeneration seedlings. As for initial diameters, underplanted white and black oaks had larger average basal diameters (p<0.05) compared to their naturally regenerated counterparts. There were no cases in which seedlings of identical species and type differed between treatments at the beginning of the study.

Following initial size analysis, two-way ANOVA by species was used to determine if seedling size, survival, and competitiveness measurements differed among the midstory removal treatments and (or) seedling types after six growing seasons. To avoid pseudoreplication, each ANOVA test used means of the six treatment plots by species and regeneration type. It is important to note that analyses used the mean of the
seedlings in each cell rather than comparing individual seedlings as done in related studies by Dey and Parker (1997a) and Lhotka and Loewenstein (2009).

Once ANOVA results were found, the following step was to assess the effects of within-treatment plot canopy structure variation on seedling growth. To capture the heterogeneity of canopy structure within treatment plots and identify individual factors that may have affected seedling development, individual cells were used as experimental units to develop regression equations. In the first set of models, ordinary least squares regression was applied to total seedling height and diameter growth after six growing seasons. Possible effects included in the models were initial total height and diameter, treatment, distance to the top and bottom of the canopy, canopy depth, and visible sky. For the visible sky measures, only the 120 and 90 degree angles were included as variables as they best represented the true heterogeneity of the canopy. The 180 and 60 degree angles were not used as these extremes biased the visible sky measures by underestimating or overestimating the values, respectively. For the models, each seedling species and regeneration type (natural or underplanted) was analyzed individually. The factors influencing the six-year height of surrounding competitors were also analyzed using the same process.

To choose the best indicators of seedling growth and competitor height, the R-squared selection method was used. Various models were then tested to determine the most significant combination (p<0.05) of variables. In cases where the data did not meet assumptions of normality or homogeneity of variance, a Box-Cox transformation was applied (SAS Institute Inc. 2008). Seedling survival and competitiveness were analyzed using logistic regression. For the survival models, total height and diameter were omitted
as it was found that these measures disproportionately affected logistic model selection due to the small range of initial observations.

RESULTS

Treatment-Level Effects

Analysis of variance of six-year total height and diameter growth for each of the four species found significant treatment and seedling type differences (Table 2.4), but no interaction between the two main effects (treatment and seedling type) was found for any species. For each species, planted seedlings growing under a midstory removal saw the greatest average height growth. Black oak was the only species that did not experience significantly higher height growth under a midstory removal although all seedling types experienced at least a 200 percent increase in height on average over the six growing seasons. Of the other two oak species, white oak was the only one to show a difference between both seedling type and treatment. Among white oaks, planted seedlings in the removal treatments grew the most (46.4 cm and 422 percent increase in initial height). Advance reproduction white oaks in the controls experienced the lowest average growth of any species/treatment/type combination (15.7 cm and 161 percent increase). The greatest overall growth in terms of average total height, height growth, and percent increase was observed among underplanted northern red oaks (91.8 cm, 75.4 cm, and 460 percent, respectively). Because there were no underplanted red maples, seedling type differences could not be tested, but it was found that average height growth of red maples in removal treatments was 56.1 cm (449 percent increase), which was larger than the height growth of all seedlings except underplanted northern red oaks.
For diameter growth, all three oaks species differed significantly between treatments but not between seedling type. As with height, the most diameter growth was observed among seedlings in removal treatments. Northern red oaks in midstory removal plots experienced the largest average diameter growth. Advance regeneration seedlings grew 5.23 mm (107 percent) on average with underplanted seedlings growing 4.51 mm (79 percent). For two underplanted species (white and black oak), no net diameter growth was recorded after six growing seasons, and diameter growth of northern red oaks was only 0.59 mm. While there was a fourfold difference between the mean diameter growth of red maple in the control versus midstory removal (0.77 cm and 3.21 cm, respectively), no significant difference was present between treatments (p=0.07).

An assessment of average total heights and diameter after six growing seasons found results similar to growth analysis (Table 2.5). Both treatment and seedling type were found to be significant factors affecting total height of white and northern red oak, while black oak and red maple did not display any differences between factors. The tallest average seedlings after six growing seasons were planted northern red oaks in the removal treatment (91.8 cm) followed by red maples in removals (68.6 cm). The smallest seedlings were advance reproduction white oaks in the controls (25.6 cm on average). For diameter, all oaks in the removal treatments were significantly larger than in the control. Underplanted northern red oaks under midstory removals were again the largest seedlings in total size with an average diameter of 10.21 mm. The smallest average seedlings were white oaks in controls with diameters of 3.05 mm, on average. Red maples were again not found to be significantly different between treatments; however, p-values for total
height and diameter approached the significance threshold (p=0.0506 and p=0.0550, respectively).

The two-way ANOVA of survival found differences between survival rates for white oak and red maple seedlings (Table 2.8). In the case of white oak, planted seedlings experienced higher mortality than naturally regenerated seedlings (40 percent and 1 percent, respectively); however, there was no difference between treatments. This was not the case with red maple where seedlings experienced higher survival in midstory removal plots (54 percent control and 86 percent removal). For black and northern red oak, survival of advance reproduction seedlings was extremely high (98 percent), but this may have been influenced by low sample size. Highest mortality in both treatments was observed among underplanted black oaks (64 percent controls and 45 percent removals).

For competitiveness, analysis of variance found treatment to be a significant factor affecting each species (Table 2.10). In the case of red oak species, seedlings were less competitive in removal treatments than in controls with the exception of planted northern red oaks. In control treatments, white oaks were the least competitive seedlings (26 percent competitive), while black oaks were the least competitive in removal treatments (37 percent). Red maples experienced an opposite trend with seedlings being more competitive under midstory removals than in controls (64 percent versus 42 percent).

Stand Structure

As expected, removing 20 percent of the initial basal area from the treatment plots created a structural variation across the plots that was still present after six growing
seasons. Figure 2.1 shows the difference between visible sky measurements in the two treatments taken during the sixth year. Although the unaltered controls have a lower average amount of visible sky (18 percent) compared to the midstory removals (23 percent), there is some overlap between the two treatments. Figure 2.2 shows the distribution of height to forest canopy across the two treatments. Again, a trend can be observed with both sets of data covering a wide range of observations. For this measure, the average height to canopy is nearly twice as high in the removal treatments as in the controls (16.4 m and 9 m, respectively). In both cases, the majority of midstory removal observations fall near the median of the overall observations rather than being skewed toward higher levels which helps to demonstrate the variability that can be found among plots.

Trends in the light transmittance levels (Table 2.2)(Figure 2.3) also had a noticeable pattern in the control and removal treatments. In the controls, the average light transmittance was 2.9 percent full sunlight, while in the removal treatments, the average percent transmittance was 18.5. Although the overlap between treatments was not as pronounced as with visible sky or bottom canopy height, the removal of midstory did not create conditions that were always distinct from control cells. In some cells within the midstory treatment, transmittance numbers as low at 3% were seen. This was often caused by one of two events. In one case, a yellow-poplar seedling had a strong response to the increased light levels, thereby shading some parts of the forest floor. In other instances, heavy epicormic branching from overstory trees shaded portions of the understory. As for the higher limits of light transmission, this was caused by newly created gaps in the canopy. Immediately after the initial treatment, a large canopy tree at
the Water Plant site was blown down by wind creating a large single-tree gap. In other cases, the removal of the midstory, exposed small, natural spaces in the canopy and allowed more of the light to reach the seedling layer.

Within-Treatment Plot Effects

The assessment of stand structure variables indicates that the midstory removal treatment did indeed create different conditions when compared to the controls. The ANOVA findings show that the midstory removal conditions often favored seedlings over their counterparts in the control treatments. These results and the observed variation in horizontal and vertical canopy structure justified moving forward and using regression equations to evaluate how the various structural characteristics among experimental plots may have influenced the growth and development of seedlings. When looking individually at each species and regeneration type, every group yielded a unique set of growth indicators to describe the relationship between six-year growth and canopy structure characteristics.

It was found that for height growth, initial seedling height and midstory removal treatment were the most important variables, and only two structural measures (visible sky and canopy depth) were significant factors in some models (Table 2.6). For each advance reproduction oak species, initial height was a significant predictor of six-year growth. A similar trend was evident among underplanted oak species where the midstory removal treatment was always one of the indicators of future height growth. In contrast to all species of advance reproduction oaks, black oaks are the only underplanted species for which initial height was a significant indicator of future success. Similar to white oak
advance reproduction, red maple’s most significant height growth factor was midstory treatment. Canopy depth and visible sky were also observed in the models for planted black oak and red maple, respectively.

Analysis of diameter growth was much more consistent among species and regeneration types (Table 2.7). The most notable finding was that diameter increase was significantly affected by treatment in every case. This is consistent with ANOVA results that found treatment to be a significant factor for each oak species. When comparing height and diameter growth equations, no trends were found among the groups with the exception of midstory being the most influential factor for both sets. One point to take note of from both height and diameter equations, though, was that initial diameter was never a significant indicator of future growth.

Survival and Competitiveness

Significant models for survival were able to be created for five seedling types, and trends were seen among these groups (Table 2.9). For underplanted seedlings, height of competing vegetation always had a significant effect on survival rates. Patterns among survival equations also seemed to point largely toward overstory structure being influential factors as visible sky and canopy position were components of three models each. Advance reproduction black oaks could not be fitted with a regression considering all traceable seedlings were still alive in 2010. No significant predictors were found for northern red oak advance regeneration, either. The inability to develop predictive equations for black and northern red oak could have been caused by low sample size (n=52 and n=63, respectively).
Regression equations of competitiveness are shown in Table 2.11. In these models, initial size was included and was found to be significant in four models. The equations also suggest that midstory presence has a strong effect, especially for white oaks. Average competitor height is the most common variable, and was found to be significant in each model. This is unsurprising since the measure of competitiveness was related to competing seedlings in a given cell. Because of this, an analysis of factors affecting competitor height was performed and found that height to the top of the canopy and midstory treatment were the most significant factors contributing to competitor heights.

DISCUSSION

Seedling Growth

While several studies have observed positive growth effects following midstory removal, few studies have looked at the specific stand characteristics resulting from the treatment. However, variances in canopy and stand characteristics can be expected within treatment areas. Furthermore, some canopy characteristics were shown to have a significant effect on the growth and development of oak seedlings and their competitors.

Between both underplanted and advance reproduction seedlings, the presence or absence of midstory treatment was the most significant factor in all but two models, but there were slight differences between seedling stock types. Each of the advance reproduction models included initial height as a significant factor, and this was the only factor for black and northern red oak. This may indicate differences between the two seedling types. One possible explanation for this comes from the original variance
associated with the advance reproduction seedlings compared to the underplanted. As shown in Table 2.3, with the exception of planted white oak, the standard errors of the advance reproduction seedlings were higher than underplanted. This would indicate that advance regeneration seedlings covered a wider range of initial heights.

According to the models produced for advance reproduction oaks, taller seedlings at the time of treatment were more likely to experience larger absolute height growth over six years. One could imagine that the larger advance reproduction seedlings at the time of treatment possessed increased vigor compared to smaller seedlings, which would put them in a better position to utilize any increased resources following treatment. Therefore, taller seedlings at the time of treatment would be more likely to experience larger height growth. From the standpoint of forest management, it would be helpful to know the life history of seedlings at the time of treatment. One might initially expect that the taller initial seedlings were simply a product of older age; however, Dillaway et al. (2007) found that older seedlings actually contained lower levels of soluble carbohydrates and concluded that these seedlings may not be as vigorous following midstory and overstory treatments as would younger seedlings. Because Dillaway et al. (2007) only examined seedlings after one year post-treatment and since roots were not analyzed in our study, it is impossible to know whether this trend continued or if older seedlings may experience a lag phase before producing soluble carbohydrates to stimulate shoot growth.

Although red maples were also naturally regenerated, initial height did not play a significant role in their height growth. This may be explained by maple’s physiology and growth habits which allow maples to more easily increase height growth under low light
conditions (Walters and Reich 1996). Since red maple was well established in the understory at the time of treatment, perhaps most of the seedlings were at a point where roots were well developed enough so that the plants could focus light resources into shoot (i.e., height) growth.

Underplanted oaks had a similar response to the midstory as red maple, but the mechanisms behind their height growth are likely different. In contrast to maples, oaks utilize a root-first growth strategy. Since the underplanted oak seedlings were only one year old, their root systems were relatively small and probably experienced transplant shock until fine roots were able to develop (Struve 1990). In order to overcome this transplant shock, seedlings would have needed to allot significant portions of their light resources toward roots rather than shoots. The negligible average diameter growth of underplanted seedlings growing in control treatments suggests that light levels were inadequate to sustain growth resulting in death. This seems more probable when considering that at least 40 percent of all underplanted seedlings were dead after six years and underplanted seedlings in the removal treatments experienced higher diameter growth and survival. Given that many of the underplanted seedlings would have put on height growth following shoot die-back, it follows that midstory treatment rather than initial height would have played a more important role in future height growth.

Relatedly, diameter growth over the six growing seasons was found to be almost solely based on midstory treatment. The observed diameter growth could be linked to light through root growth. As previously mentioned, increased light levels typically equate to more below-ground biomass for oak species (Phares 1971; Kolb et al. 1990; Dillaway et al. 2007), and increased root size is related to diameter size. In the controls,
where understory light was limited, the majority of light resources likely were spent for basic survival rather than growth. In the case of underplanted seedlings with smaller root systems than advance reproduction seedlings, there was very little growth, and mortality was high. Although the age of advance reproduction seedlings is unknown, Dillaway et al. (2007) found the average age of white oak roots in adjacent sites to be about nine years old. Because most of these oak seedlings would have had more time to develop root systems, it follows that they would have been able to exhibit some diameter growth, but this growth was still significantly less than that experienced by seedlings in the removal treatments. Given this information, it is reasonable to assume that increased light levels associated with the removal of midstory helped the seedlings develop larger root systems that spurred diameter growth.

The negative diameter growth reported for underplanted white and black oak seedlings may have had two causes. It is possible that some seedlings which died during over the six growing seasons were able to sprout and had a diameter in 2010 that was smaller than the initial diameter. Additionally, there would have been measurement error associated with the readings taken in the two years that could cause growth to appear negative.

Perhaps the most surprising finding from the growth analysis is that none of the equations found initial diameter as a significant indicator of future height or diameter growth. When looking at the relationship between a growth variable and initial diameter by itself (not presented), the diameter measure was only significant in two instances. This suggests that diameter was not just removed from equations with the addition of more variables. The lack of a diameter variable is contrary to other studies that examined
diameter growth following midstory removal (Lhotka and Loewenstein 2009; Motsinger et al. 2010).

The fact that initial diameter was not significant in the models is not to say that diameter growth itself was insignificant. Instead, what it suggests is that other factors were more influential for diameter growth during the study period. A possible explanation for a lack of the initial diameter variable in the equations could be a direct effect of the seedlings’ light environments. The inclusion of the treatment variable is evidence for this hypothesis. For seedlings in which midstory vegetation was present, one would expect light conditions to be low, and this is evidenced by the ceptometer data from Table 2.2. At the light levels observed under midstory vegetation, the oaks and red maple seedlings could be achieving less than half of their total photosynthetic capacity (Loach 1967). Decreased levels of photosynthate production would mean less overall growth of stem diameters. Conversely, without midstory trees to intercept large portions of light, trees would likely experience higher levels of photosynthesis (Loach 1967; Teskey and Shrestha 1985; Barton and Gleeson 1996). The extra photosynthetic production from increased light could explain why presence or absence of midstory was more related to diameter growth than initial diameter.

Other possible explanations can be derived from the statistical analysis of the experiment. First, many seedlings died and resprouted over the six growing seasons resulting in negative growth for some species. This could greatly affect the predictive power of the initial diameter variable. Also, this study analyzed average initial diameters rather than individual seedlings as done by Dey and Parker (1997b) and Lhotka and Loewenstein (2009).
Considering the models together, the final equations were efficient indicators of growth. As displayed in Tables 2.6 and 2.7, the $R^2$ values for the height growth equations ranged from 0.23 to 0.56 while diameter growth $R^2$ values were between 0.29 and 0.64. A similar study by Lhotka and Loewenstein (2008) on cherrybark oak looked at two year height growth as a function of stand structure, but found a generally lower $R^2$ of 0.26. Additionally, while Lhotka and Loewenstein (2008) found initial height to be a significant predictor of growth, initial diameter was more significant. Our findings here suggest that both initial height and treatment are highly significant indicators of height growth but not initial diameter.

Given that the height and diameter growth model results showed few trends outside of what could be seen by a simple ANOVA procedure, it appears that the strength of the relationship between structural variables and growth is not as important as midstory alone. This does not indicate that structure is unimportant, however. Implementation of a midstory removal undoubtedly alters the structure of a stand, but the results suggest that rather than a specific characteristic of the resulting midstory removal being significant, it is the cumulative suite of effects that is most important. However, when looking at the models for seedling survival and competitiveness, the importance of specific canopy structure variables to long-term seedling success becomes much more apparent.

Survival and Competitiveness

The survival model variables can be divided into three general categories – treatment effect, canopy structure, and competitive height. Whereas basic trends could be
observed among height and diameter growth, the survival equations are unique to each species and seedling type.

In each instance, presence of midstory is negatively correlated to survival, which is expected. Decreased light to the understory results in seedlings that have fewer resources to photosynthesize. Given the low light levels observed in the controls, the majority of seedlings would have been well below their maximum level of photosynthesis. This theory is supported by other studies linking increased basal area and midstory vegetation to decreased survival (Schuler et al. 2005; Lhotka and Loewenstein 2008; Lhotka and Loewenstein 2009).

Canopy structure, as described by Aussenac (2000), can have several effects on understory conditions ranging from increased light transmittance to altered microclimates. Lhotka and Loewenstein (2008) also found height to the bottom of the canopy to be a significant predictor of cherrybark oak survival after two growing seasons. In our models, visible sky was a significant variable in all but one equation and was positively correlated to survival. The presence of top and bottom canopy heights also indicates the importance of vertical canopy structure to survival.

The height of competitors was the only significant predictor of survival not directly related to stand structure, but this variable was only present for underplanted seedlings. The fact that competitor height was significant only among underplanted seedlings may again be related to initial root size. Taller competitors near black and white oak seedlings may have resulted in decreased survival through light interception or resource uptake (Collet et al. 1998). Since the majority of underplanted seedlings likely did not have the same level of root development as advance reproduction seedlings, the
underplanted seedlings would have had more trouble initially acquiring nutrients and water (Struve 1990). Given instances of taller competitors, those seedlings would receive less light and have had a harder time developing initial root systems to overcome transplant shock resulting in higher mortality. In the case of advance reproduction seedlings, however, shading by competitors may not have been a significant cause of dieback since the root systems could be assumed to be strong enough to overcome the competition.

The survival rates reported by other studies vary greatly depending on species, regeneration type, treatment, and age. In Ontario with northern red oak, Dey and Parker (1997b) saw over 90 percent survival of planted seedlings over two years in both a shelterwood and undisturbed stand. For pin oaks, Motsinger et al. (2010) had approximately 75 percent survival of 1-0 bareroot seedlings and 45 percent survival of advance reproduction seedlings after three years. In midstory removal studies, Lhotka and Loewenstein (2009) reported 73 to 95 percent survival of two-year old, planted cherrybark oak. Finally, Dillaway (2005) saw 85 and 65 percent survival of 1-0 bareroot seedlings of white and black oak, respectively, in midstory removal plots, while control plots had 15 percent lower rates of survival. The lower overall rates of survival we noticed may have been related to the age of the study. In a five-year study of northern red oaks, Morrissey et al. (2010) had 40 to 65 percent survival of bareroot seedlings under various size group selections.

Among underplanted northern red oak seedlings, we observed that competitor height was positively correlated to survival. What this may suggest is that, given northern red oak is more shade intolerant than the other oak species, it was able to grow at a
similar rate as competitors. If fewer red oaks were overtopped by competitors due to these factors, it would follow that they experienced lower mortality.

As with survival, competitiveness of seedlings was less a factor of treatment than other conditions. In the case of the black oaks and advance reproduction northern red oak, initial height was the variable most related to competitiveness. Initial diameter was present for white oak advance reproduction. These initial growth measures logically suggest that the larger a seedling is at the time of treatment, the better prepared it will be to compete for light and nutrient resources.

For the remaining four seedling groups, there was an indirect measure of light availability. Among underplanted northern red oak, an increase in the percentage of visible sky around seedlings increased the probability of an individual being competitive. The presence of midstory was found to be a factor that decreased the competitive ability of both white oak stock types as well as red maples. This was likely through the shading of leaves.

An assessment of the factors that affect competitor height found the average height to be related to midstory treatment and canopy height, which are both linked to light transmittance. Although it is not surprising that competitor height was a significant variable in each model, it is important from the standpoint of forest management keep in mind the tradeoffs that occur following a midstory removal. While light availability will be increased to oak seedlings, competitors will also benefit. Results on adjacent sites by Parrott (2011) concluded that, although a midstory removal did increase the height growth of oaks, the same effect was seen among red maples, which were in position to pose a threat to oaks following future disturbance.
Management Implications

One of the key uses for the information derived from this study is as a tool to manage regeneration in oak-dominated forests. Although the equations presented are not meant to produce a perfect model for the response of every oak species, they do provide an effective overview of the many variables working together to influence seedling development. A forest manager must realize that both the horizontal and vertical components of a stand create a wide array of light and microclimate conditions that can affect seedling growth, survival, and competitiveness.

As previously mentioned, one of the most important keys for managing an oak stand is regenerating a large number of seedlings that are able to reach a competitive height. This study has found the height growth consideration to be very strongly influenced by the presence of midstory vegetation. Our results along with the results of other midstory removal studies would suggest that this treatment is an effective means of increasing oak seedling growth (Lockhart et al. 2000; Lhotka and Loewenstein 2009; Motsinger et al. 2010; Parrott 2011).

To generate a large number of seedlings that are competitive within their cohort, our results have suggested that limiting the height or reducing the number of surrounding competitors is of major importance for every species. This study also found that the same factors that influenced oak growth also benefited red maple. This suggests that midstory removals should also be accompanied by competitor removal in some form. Because experimenting with competitor removal was beyond the scope of this project, we can only hypothesize about which methods may be effective for favoring oaks over other species.
Since fire is historically thought to have played a role in perpetuating oak forests, prescribed burns have been suggested as means of controlling competing vegetation and improving oak regeneration (Abrams 2005). Throughout the Central Hardwoods region, however, prescribed burns have yielded a wide range of results. In most cases, fire is found to initially top-kill a large portion of midstory vegetation (Barnes and Van Lear 1998; Franklin et al. 2003; Chiang et al. 2005; Hutchinson et al. 2005; Blankenship and Arthur 2006); however long-term success is less certain. Studies have found a range of results including an increase in oak and maple regeneration (Arthur et al. 1998; Kuddes-Fischer and Arthur 2002), no effect on oak (Reich et al. 1990; Hutchinson et al. 2005; Albrecht and McCarthy 2006), an increase in only oak (Elliott et al. 1999), and a decrease in maples (Reich et al. 1990; Kruger and Reich 1997; Elliott et al. 1999). Conclusions of studies examining fire’s effect on the competitiveness of oaks following a burn have also been mixed (Swan 1970; Brose et al. 1999; Hutchinson et al. 2005; Alexander et al. 2008).

One of the main conclusions for many of the studies mentioned thus far is that fires do not remove enough of the midstory for a long enough period of time to stimulate growth. In Brose et al. (1999) and Brose (2010), however, a shelterwood treatment was implemented along with varying fire regimes and found that oaks were able to dominate future stands under certain conditions. Other studies have also suggested that repeated fires are probably necessary to increase the success of oaks over longer temporal scales (van Lear and Watt 1993; Hutchinson et al. 2005; Albrecht and McCarthy 2006). Given previous studies and the conclusions found in our study, further research into combinations of midstory removal, burning intensity, and burning timing are warranted.
Table 2.1. Density and basal area of stands by species pre and post midstory removal treatment

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<th>Species</th>
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<th>Post-treatment</th>
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<td>Relative abundance (%)</td>
<td>Basal area (m² ha⁻¹)</td>
<td>Relative abundance (%)</td>
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<tr>
<td>Hickories</td>
<td>6.3</td>
<td>6.3</td>
<td>12.8</td>
<td>16.4</td>
</tr>
<tr>
<td>Black gum</td>
<td>3.5</td>
<td>3.5</td>
<td>1.9</td>
<td>2.5</td>
</tr>
<tr>
<td>Ash</td>
<td>1.9</td>
<td>1.9</td>
<td>1.7</td>
<td>2.2</td>
</tr>
<tr>
<td>Yellow-poplar</td>
<td>0.9</td>
<td>0.9</td>
<td>0.8</td>
<td>1.1</td>
</tr>
<tr>
<td>Other hardwoods</td>
<td>5.8</td>
<td>5.8</td>
<td>1.8</td>
<td>2.3</td>
</tr>
<tr>
<td>Total</td>
<td>100.0</td>
<td>100.0</td>
<td>78.3</td>
<td>100.0</td>
</tr>
</tbody>
</table>

* Greater than 2.5 cm dbh.
Table 2.2 Average, minimum, and maximum stand structure variables by treatment

<table>
<thead>
<tr>
<th>Variable*</th>
<th>Control</th>
<th>Removal</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Average</td>
<td>Min</td>
<td>Max</td>
</tr>
<tr>
<td>Light transmittance (%)*</td>
<td>2.9 ± 0.12</td>
<td>0.6</td>
<td>6.2</td>
</tr>
<tr>
<td>Canopy top height (m)</td>
<td>28.4 ± 0.4</td>
<td>14.7</td>
<td>35.7</td>
</tr>
<tr>
<td>Canopy bottom height (m)</td>
<td>9.4 ± 0.8</td>
<td>0.5</td>
<td>27.7</td>
</tr>
<tr>
<td>Visible sky 90°</td>
<td>0.18 ± 0.007</td>
<td>0.10</td>
<td>0.28</td>
</tr>
<tr>
<td>Visible sky 120°</td>
<td>0.16 ± 0.006</td>
<td>0.10</td>
<td>0.25</td>
</tr>
</tbody>
</table>

*Light transmittance taken during seventh growing season. All other measures taken during year six.
Table 2.3. Average initial total height and ground line diameter (±SE) of advance reproduction and underplanted white oak, northern red oak, black oak, and red maple

<table>
<thead>
<tr>
<th>Species</th>
<th>Type</th>
<th>Total height (cm)</th>
<th></th>
<th>Ground line diameter (mm)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Control</td>
<td>Removal</td>
<td>Control</td>
<td>Removal</td>
</tr>
<tr>
<td>White oak</td>
<td>Adv. Rep.</td>
<td>9.8 ± 0.58</td>
<td>9.6 ± 0.54</td>
<td>2.94 ± 0.15</td>
<td>3.14 ± 0.05</td>
</tr>
<tr>
<td></td>
<td>Planted</td>
<td>10.9 ± 0.93</td>
<td>11.0 ± 0.38</td>
<td>5.18 ± 0.17</td>
<td>5.10 ± 0.26</td>
</tr>
<tr>
<td>N. red oak</td>
<td>Adv. Rep.</td>
<td>13.6 ± 0.93</td>
<td>12.9 ± 0.90</td>
<td>5.05 ± 0.86</td>
<td>4.74 ± 0.61</td>
</tr>
<tr>
<td></td>
<td>Planted</td>
<td>17.2 ± 0.42</td>
<td>16.4 ± 0.98</td>
<td>6.19 ± 0.27</td>
<td>5.70 ± 0.32</td>
</tr>
<tr>
<td>Black oak</td>
<td>Adv. Rep.</td>
<td>12.4 ± 1.85</td>
<td>9.5 ± 0.71</td>
<td>4.18 ± 0.58</td>
<td>3.63 ± 0.29</td>
</tr>
<tr>
<td></td>
<td>Planted</td>
<td>12.6 ± 0.46</td>
<td>13.5 ± 0.83</td>
<td>4.99 ± 0.15</td>
<td>4.98 ± 0.19</td>
</tr>
<tr>
<td>Red maple</td>
<td>Adv. Rep.</td>
<td>12.7 ± 0.65</td>
<td>12.5 ± 0.40</td>
<td>4.37 ± 0.25</td>
<td>4.11 ± 0.05</td>
</tr>
</tbody>
</table>

Similar letters represent no significant difference between seedling type or treatment for an individual species at p=0.05
Table 2.4. Six-year average height and diameter growth of white oak, northern red oak, black oak, and red maple seedlings

<table>
<thead>
<tr>
<th>Species</th>
<th>Type</th>
<th>Total height (cm)</th>
<th>Ground line diameter (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Control</td>
<td>Removal</td>
</tr>
<tr>
<td>White oak</td>
<td>Adv. Rep.</td>
<td>15.7±2.01</td>
<td>29.3±3.17</td>
</tr>
<tr>
<td></td>
<td>Planted</td>
<td>27.6±2.42</td>
<td>46.4±5.66</td>
</tr>
<tr>
<td>N. red oak</td>
<td>Adv. Rep.</td>
<td>34.1±4.96</td>
<td>47.2±10.45</td>
</tr>
<tr>
<td></td>
<td>Planted</td>
<td>42.2±2.32</td>
<td>75.4±10.61</td>
</tr>
<tr>
<td>Black oak</td>
<td>Adv. Rep.</td>
<td>34.9±8.56</td>
<td>32.0±4.21</td>
</tr>
<tr>
<td></td>
<td>Planted</td>
<td>25.5±0.96</td>
<td>39.6±3.28</td>
</tr>
<tr>
<td>Red maple</td>
<td>Adv. Rep.</td>
<td>30.0±4.43</td>
<td>56.1±5.1</td>
</tr>
</tbody>
</table>

Similar letters represent no significant difference between seedling type or treatment for an individual species at p=0.05.
Table 2.5. Average total height and diameter of white oak, northern red oak, black oak, and red maple seedlings after six growing seasons

<table>
<thead>
<tr>
<th>Species</th>
<th>Type</th>
<th>Total height (cm)</th>
<th>Ground line diameter (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Control</td>
<td>Removal</td>
</tr>
<tr>
<td>White oak</td>
<td>Adv. Rep.</td>
<td>25.6 ± 2.26</td>
<td>38.9 ± 3.46</td>
</tr>
<tr>
<td></td>
<td>Planted</td>
<td>38.5c ± 2.53</td>
<td>57.4d ± 5.57</td>
</tr>
<tr>
<td>N. red oak</td>
<td>Adv. Rep.</td>
<td>46.8a ± 5.50</td>
<td>59.5b ± 10.94</td>
</tr>
<tr>
<td></td>
<td>Planted</td>
<td>59.3c ± 2.33</td>
<td>91.8d ± 10.70</td>
</tr>
<tr>
<td>Black oak</td>
<td>Adv. Rep.</td>
<td>47.9a ± 10.23</td>
<td>42.3a ± 4.92</td>
</tr>
<tr>
<td></td>
<td>Planted</td>
<td>38.3a ± 1.10</td>
<td>53.0a ± 3.48</td>
</tr>
<tr>
<td>Red maple</td>
<td>Adv. Rep.</td>
<td>42.7a ± 4.39</td>
<td>68.6a ± 5.11</td>
</tr>
</tbody>
</table>

Similar letters represent no significant difference between seedling type or treatment for an individual species at p=0.05
Table 2.6. Six-year height growth model coefficients and fit statistics by species

<table>
<thead>
<tr>
<th>Six-year height growth model</th>
<th>( b_0 )</th>
<th>( b_1 )</th>
<th>( b_2 )</th>
<th>( b_3 )</th>
<th>( R^2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \text{BO}<em>{\text{AdvRep}} = b_0 + b_1 \text{Ht}</em>{\text{Initial}} )</td>
<td>2.82</td>
<td>2.82</td>
<td>–</td>
<td>–</td>
<td>0.50</td>
</tr>
<tr>
<td>( \text{BO}<em>{\text{Planted}} = -b_0 - b_1 \text{Midstory} + b_2 \text{Ht}</em>{\text{Initial}} + b_3 \text{CanDep} )</td>
<td>2.45</td>
<td>17.16</td>
<td>2.79</td>
<td>0.48</td>
<td>0.52</td>
</tr>
<tr>
<td>( \text{NRO}<em>{\text{AdvRep}} = b_0 + b_1 \text{Ht}</em>{\text{Initial}}^* )</td>
<td>2.34</td>
<td>0.16</td>
<td>–</td>
<td>–</td>
<td>0.27</td>
</tr>
<tr>
<td>( \text{NRO}_{\text{Planted}} = b_0 - b_1 \text{Midstory}^* )</td>
<td>1.93</td>
<td>0.08</td>
<td>–</td>
<td>–</td>
<td>0.26</td>
</tr>
<tr>
<td>( \text{WO}<em>{\text{AdvRep}} = -b_0 - b_1 \text{Midstory} + b_2 \text{Ht}</em>{\text{Initial}} )</td>
<td>9.42</td>
<td>14.84</td>
<td>4.04</td>
<td>–</td>
<td>0.56</td>
</tr>
<tr>
<td>( \text{WO}_{\text{Planted}} = b_0 - b_1 \text{Midstory}^* )</td>
<td>13.48</td>
<td>3.95</td>
<td>–</td>
<td>–</td>
<td>0.23</td>
</tr>
<tr>
<td>( \text{RM}<em>{\text{AdvRep}} = b_0 - b_1 \text{Midstory} + b_2 \text{VisSky}</em>{90}^* )</td>
<td>2.48</td>
<td>0.30</td>
<td>2.05</td>
<td>–</td>
<td>0.51</td>
</tr>
</tbody>
</table>

* Model has been Box-Cox transformed

\( \text{Ht}_{\text{Initial}} \) = initial seedling height (cm); \( \text{Midstory} \) = presence or absence of midstory following treatment (0 = midstory absent and 1 = midstory present); \( \text{CanDep} \) = Depth of canopy; \( \text{VisSky}_{90} \) = Visible sky at photo angle 90
Table 2.7. Six-year diameter growth model coefficients and fit statistics by species

<table>
<thead>
<tr>
<th>Six-year diameter growth model</th>
<th>$b_0$</th>
<th>$b_1$</th>
<th>$b_2$</th>
<th>$R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$BO_{AdvRep} = b_0 - b_1\text{Midstory} + b_2\text{Ht}_{\text{Initial}}$</td>
<td>4.15</td>
<td>2.65</td>
<td>0.40</td>
<td>0.64</td>
</tr>
<tr>
<td>$BO_{Planted} = b_0 - b_1\text{Midstory}^*$</td>
<td>1.29</td>
<td>0.18</td>
<td>–</td>
<td>0.40</td>
</tr>
<tr>
<td>$NRO_{AdvRep} = b_0 - b_1\text{Midstory}^*$</td>
<td>1.18</td>
<td>0.12</td>
<td>–</td>
<td>0.31</td>
</tr>
<tr>
<td>$NRO_{Planted} = b_0 - b_1\text{Midstory}^*$</td>
<td>1.72</td>
<td>0.35</td>
<td>–</td>
<td>0.52</td>
</tr>
<tr>
<td>$WO_{AdvRep} = b_0 - b_1\text{Midstory}^*$</td>
<td>1.48</td>
<td>0.18</td>
<td>–</td>
<td>0.29</td>
</tr>
<tr>
<td>$WO_{Planted} = b_0 - b_1\text{Midstory}$</td>
<td>6.05</td>
<td>2.28</td>
<td>–</td>
<td>0.31</td>
</tr>
<tr>
<td>$RM_{AdvRep} = b_0 - b_1\text{Midstory}^*$</td>
<td>2.95</td>
<td>0.72</td>
<td>–</td>
<td>0.40</td>
</tr>
</tbody>
</table>

* Model has been Box-Cox transformed

Midstory = presence or absence of midstory following treatment (0 = midstory absent and 1 = midstory present); $\text{Ht}_{\text{Initial}}$ = initial seedling height (cm)
Table 2.8. Survival of oaks and red maple by seedling type and treatment

<table>
<thead>
<tr>
<th>Species</th>
<th>Type</th>
<th>Alive</th>
<th>Dead</th>
<th>Percent survival</th>
<th>Control</th>
<th>Alive</th>
<th>Dead</th>
<th>Percent survival</th>
<th>Removal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Black oak</td>
<td>Adv. Rep.</td>
<td>23</td>
<td>0</td>
<td>100.0&lt;sup&gt;a&lt;/sup&gt;</td>
<td>100.0&lt;sup&gt;a&lt;/sup&gt;</td>
<td>29</td>
<td>0</td>
<td>100.0&lt;sup&gt;a&lt;/sup&gt;</td>
<td>54.8&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td></td>
<td>Planted</td>
<td>66</td>
<td>115</td>
<td>36.5&lt;sup&gt;a&lt;/sup&gt;</td>
<td>100.0&lt;sup&gt;a&lt;/sup&gt;</td>
<td>102</td>
<td>84</td>
<td>54.8&lt;sup&gt;a&lt;/sup&gt;</td>
<td></td>
</tr>
<tr>
<td>N. red oak</td>
<td>Adv. Rep.</td>
<td>20</td>
<td>0</td>
<td>100.0&lt;sup&gt;a&lt;/sup&gt;</td>
<td>95.7&lt;sup&gt;a&lt;/sup&gt;</td>
<td>45</td>
<td>2</td>
<td>79.9&lt;sup&gt;a&lt;/sup&gt;</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Planted</td>
<td>117</td>
<td>80</td>
<td>59.4&lt;sup&gt;a&lt;/sup&gt;</td>
<td>59.4&lt;sup&gt;a&lt;/sup&gt;</td>
<td>115</td>
<td>29</td>
<td>79.9&lt;sup&gt;a&lt;/sup&gt;</td>
<td></td>
</tr>
<tr>
<td>White oak</td>
<td>Adv. Rep.</td>
<td>97</td>
<td>1</td>
<td>99.0&lt;sup&gt;a&lt;/sup&gt;</td>
<td>98.7&lt;sup&gt;a&lt;/sup&gt;</td>
<td>149</td>
<td>2</td>
<td>70.4&lt;sup&gt;b&lt;/sup&gt;</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Planted</td>
<td>88</td>
<td>88</td>
<td>50.0&lt;sup&gt;b&lt;/sup&gt;</td>
<td>50.0&lt;sup&gt;b&lt;/sup&gt;</td>
<td>114</td>
<td>48</td>
<td>70.4&lt;sup&gt;b&lt;/sup&gt;</td>
<td></td>
</tr>
<tr>
<td>Red maple</td>
<td>Adv. Rep.</td>
<td>111</td>
<td>96</td>
<td>53.6&lt;sup&gt;a&lt;/sup&gt;</td>
<td>85.3&lt;sup&gt;b&lt;/sup&gt;</td>
<td>145</td>
<td>25</td>
<td>85.3&lt;sup&gt;b&lt;/sup&gt;</td>
<td></td>
</tr>
</tbody>
</table>

Similar letters represent no significant difference between seedling type or treatment for an individual species at p=0.05.
Table 2.9. Six-year seedling survival model coefficients and fit statistics by species

<table>
<thead>
<tr>
<th>Six-year survival model</th>
<th>$b_0$</th>
<th>$b_1$</th>
<th>$b_2$</th>
<th>$b_3$</th>
<th>c-statistic</th>
</tr>
</thead>
<tbody>
<tr>
<td>$BO_{AdvRep} = \text{No model}$</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>$BO_{Planted} = \frac{1}{1 + \exp(-b_0 - b_1 \text{VisSky}_{90} - b_2 \text{CompHt})}$</td>
<td>-1.44</td>
<td>10.56</td>
<td>-0.02</td>
<td>-</td>
<td>0.67</td>
</tr>
<tr>
<td>$NRO_{AdvRep} = \text{No model}$</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>$NRO_{Planted} = \frac{1}{1 + \exp(-b_0 - b_1 \text{Midstory} - b_2 \text{CanTop} - b_3 \text{CompHt})}$</td>
<td>-2.47</td>
<td>-1.18</td>
<td>0.11</td>
<td>0.03</td>
<td>0.69</td>
</tr>
<tr>
<td>$WO_{AdvRep} = \frac{1}{1 + \exp(-b_0 - b_1 \text{CanBot} - b_2 \text{VisSky}_{120} - b_3 \text{Midstory})}$</td>
<td>-0.38</td>
<td>-0.005</td>
<td>26.42</td>
<td>1.39</td>
<td>0.65</td>
</tr>
<tr>
<td>$WO_{Planted} = \frac{1}{1 + \exp(-b_0 - b_1 \text{VisSky}_{120} - b_2 \text{CanBot} - b_3 \text{CompHt})}$</td>
<td>-3.06</td>
<td>20.83</td>
<td>0.05</td>
<td>-0.02</td>
<td>0.73</td>
</tr>
<tr>
<td>$RM_{AdvRep} = \frac{1}{1 + \exp(-b_0 - b_1 \text{Midstory} - b_2 \text{VisSky}_{120})}$</td>
<td>-0.10</td>
<td>-1.37</td>
<td>10.21</td>
<td>-</td>
<td>0.72</td>
</tr>
</tbody>
</table>

$\text{VisSky}_{90} =$ Visible sky at photo angle 90; $\text{CompHt} =$ Average height of immediate competitors (cm); $\text{Midstory} =$ presence or absence of midstory following treatment (0 = midstory absent and 1 = midstory present); $\text{CanTop} =$ Height to top of canopy; $\text{CanBot} =$ Height to lowest vegetation directly above seedlings; $\text{VisSky}_{120} =$ Visible sky at photo angle 120
Table 2.10. Number of competitive seedlings by species, seedling type, and treatment

<table>
<thead>
<tr>
<th>Species</th>
<th>Type</th>
<th>Control</th>
<th></th>
<th></th>
<th>Removal</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Competitive</td>
<td>Non-competitive</td>
<td>Percent</td>
<td>Competitive</td>
<td>Non-competitive</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>competitive</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Black oak</td>
<td>Adv. Rep.</td>
<td>12</td>
<td>11</td>
<td>52.2&lt;sup&gt;a&lt;/sup&gt;</td>
<td>6</td>
<td>23</td>
</tr>
<tr>
<td></td>
<td>Planted</td>
<td>32</td>
<td>34</td>
<td>48.5&lt;sup&gt;a&lt;/sup&gt;</td>
<td>43</td>
<td>59</td>
</tr>
<tr>
<td>N. red oak</td>
<td>Adv. Rep.</td>
<td>13</td>
<td>7</td>
<td>65.0&lt;sup&gt;a&lt;/sup&gt;</td>
<td>17</td>
<td>28</td>
</tr>
<tr>
<td></td>
<td>Planted</td>
<td>60</td>
<td>57</td>
<td>51.3&lt;sup&gt;c&lt;/sup&gt;</td>
<td>77</td>
<td>38</td>
</tr>
<tr>
<td>White oak</td>
<td>Adv. Rep.</td>
<td>15</td>
<td>82</td>
<td>15.5&lt;sup&gt;a&lt;/sup&gt;</td>
<td>51</td>
<td>98</td>
</tr>
<tr>
<td></td>
<td>Planted</td>
<td>33</td>
<td>55</td>
<td>37.5&lt;sup&gt;c&lt;/sup&gt;</td>
<td>73</td>
<td>71</td>
</tr>
<tr>
<td>Red maple</td>
<td>Adv. Rep.</td>
<td>47</td>
<td>64</td>
<td>42.3&lt;sup&gt;a&lt;/sup&gt;</td>
<td>93</td>
<td>52</td>
</tr>
</tbody>
</table>

Similar letters represent no significant difference between seedling type or treatment for an individual species at p=0.05
Table 2.11. Seedling competitiveness model coefficients and fit statistics by species at year six

<table>
<thead>
<tr>
<th>Six-year competitiveness model</th>
<th>$b_0$</th>
<th>$b_1$</th>
<th>$b_2$</th>
<th>$b_3$</th>
<th>$b_4$</th>
<th>c-statistic</th>
</tr>
</thead>
<tbody>
<tr>
<td>$BO_{AdvRep} = \frac{1}{1 + \exp(-b_0 - b_1 H_{\text{Initial}} - b_2 \text{CompHt})}$</td>
<td>-1.89</td>
<td>0.43</td>
<td>-0.10</td>
<td>-</td>
<td>-</td>
<td>0.87</td>
</tr>
<tr>
<td>$BO_{Planted} = \frac{1}{1 + \exp(-b_0 - b_1 H_{\text{Initial}} - b_2 \text{CompHt})}$</td>
<td>-6.95</td>
<td>0.47</td>
<td>-0.09</td>
<td>-</td>
<td>-</td>
<td>0.83</td>
</tr>
<tr>
<td>$NRO_{AdvRep} = \frac{1}{1 + \exp(-b_0 - b_1 H_{\text{Initial}} - b_2 \text{CompHt})}$</td>
<td>-0.02</td>
<td>0.35</td>
<td>-0.12</td>
<td>-</td>
<td>-</td>
<td>0.86</td>
</tr>
<tr>
<td>$NRO_{Planted} = \frac{1}{1 + \exp(-b_0 - b_1 \text{VisSky}_{90} - b_2 \text{CompHt})}$</td>
<td>2.55</td>
<td>13.82</td>
<td>-0.12</td>
<td>-</td>
<td>-</td>
<td>0.86</td>
</tr>
<tr>
<td>$WO_{AdvRep} = \frac{1}{1 + \exp(-b_0 - b_1 \text{CompHt} - b_2 \text{Midstory} - b_3 \text{CanTop} - b_4 \text{Dia}_{05})}$</td>
<td>3.79</td>
<td>-0.14</td>
<td>-1.50</td>
<td>-0.19</td>
<td>1.63</td>
<td>0.83</td>
</tr>
<tr>
<td>$WO_{Planted} = \frac{1}{1 + \exp(-b_0 - b_1 \text{Midstory} - b_2 \text{CompHt})}$</td>
<td>3.23</td>
<td>-0.95</td>
<td>-0.10</td>
<td>-</td>
<td>-</td>
<td>0.79</td>
</tr>
<tr>
<td>$RM_{AdvRep} = \frac{1}{1 + \exp(-b_0 - b_1 \text{Midstory} - b_2 \text{CompHt})}$</td>
<td>3.63</td>
<td>-1.41</td>
<td>-0.08</td>
<td>-</td>
<td>-</td>
<td>0.79</td>
</tr>
</tbody>
</table>

$H_{\text{Initial}} =$ initial seedling height (cm); $\text{CompHt} =$ Average height of immediate competitors (cm); $\text{VisSky}_{90} =$ Visible sky at photo angle 90; $\text{Midstory} =$ presence or absence of midstory following treatment (0 = midstory absent and 1 = midstory present); $\text{CanTop} =$ Height to top of canopy; $\text{Dia}_{05} =$ initial seedling ground line diameter (mm)
Figure 2.1. Distribution of visible sky across treatment cells based on hemispherical photographs with a photo angle of 90 degrees
Figure 2.2. Distribution of height to canopy bottom in meters across treatment cells
Figure 2.3. Distribution of full sunlight transmittance to the understory in percent across treatment cells.
CHAPTER THREE: SIX-YEAR EFFECT OF MIDSTORY REMOVAL ON WHITE OAK GROWTH AND BIOMASS AND SEEDLING RESPONSE ONE YEAR POST-CLIPPING

INTRODUCTION

Oak regeneration has become a problem throughout much of the eastern United States. Many of the issues have appeared over the past century. These problems are often attributable to the increasing presence of shade tolerant species such as red maple (*Acer rubrum* L.), sugar maple (*Acer saccharum* Marsh.), and American beech (*Fagus grandifolia* Ehrh.) in the midstory of oak-dominated stands (Lorimer et al. 1994).

In the case of both oaks and shade tolerant species, seedlings persist in the understory until a canopy disturbance is created. Under the low light conditions created by an intact midstory, maples and other shade tolerant are able to gain an important height advantage over oak seedlings. Oaks have been found to have a higher maximum photosynthetic rate than shade tolerants in high light conditions (Barton and Gleeson 1996); however, maples have a lower light compensation point than oaks (Loach 1967; Teskey and Shrestha 1985). This difference allows maples to come closer to reaching their maximum photosynthetic capacity at lower light levels. Some researchers have even suggested that oaks growing in the understory of shaded stands may photosynthesize similar or greater overall amounts of sugars than shade tolerant species, but much of the photosynthate produced is allocated toward below-ground biomass rather than toward height growth (Hodges and Gardiner 1993; Abrams 1996).
Due to oaks favoring root growth under low light, seedlings often reach a point in which enough resources are not devoted to sustaining above-ground biomass, and the seedling will eventually die back and resprout the following year (Merz and Boyce 1956; Hodges and Gardiner 1993). Although some seedlings may experience true mortality, numerous growth and die-back stages in surviving oak seedlings may eventually develop a strong root system that allows a seedling to respond quickly following increased light from a canopy disturbance (Hodges and Gardiner 1993). Shade tolerant species are typically able to grow continuously in the understory and persist until a disturbance occurs. At the time of disturbance, maples, which have been growing continuously, are often taller than oaks. This size advantage allows them to effectively utilize increased light availability and be recruited into the canopy while continuing to shade the oaks below.

Competition from shade tolerant species may not have always been a problem for oaks. The rapid increase in shade tolerant tree density is often attributed to the suppression of fire throughout much of the United States (Abrams 1992; Abrams 1998; McEwan et al. 2007). Given this successional pattern, many oak regeneration studies have suggested the implementation of fire as a method of creating competitive oak seedlings (van Lear and Watt 1993; Albrecht and McCarthy 2006; Dey et al. 2008; Brose 2010). The thought is that introducing fire could eliminate a large portion of the midstory while destroying the above-ground portion of maples. Because of their potential for developing large root systems, oak seedlings should be able to create vigorous sprouts that are able to compete with maples. In practice, though, studies have found mixed results in terms of fire and oak success.
Throughout the Central Hardwood and Appalachian regions, prescribed fire studies have generated a range of results. In some cases, oaks have benefited by a significant reduction in midstory trees and positive growth response (Elliott et al. 1999; Iverson et al. 2008). Other studies, however, have found oak seedlings either remain at pre-burn densities or decrease in numbers (Reich et al. 1990; Hutchinson et al. 2005). Various other findings have been reported that showed red maples both increasing and decreasing following fire (Arthur et al. 1998; Kuddes-Fischer and Arthur 2002; Albrecht and McCarthy 2006). Finally, in many studies where a large number of midstory trees were top-killed by fire, it was found that elevated light levels only remained for short periods of time, and most likely did not help oaks reach competitive status (Arthur et al. 1998; Chiang et al. 2005; Hutchinson et al. 2005; Alexander et al. 2008).

Findings from previous studies suggest that prescribed fires should be performed following other silvicultural treatments that could remove midstory competition for longer periods of time and enhance oak root development. At this point, however, very few studies have actually combined the two treatments. In studies performed by Brose et al. (1999) and Brose (2010), a fire treatment was combined with a shelterwood treatment and was found to enhance oak growth over a period of 11 years. Additional studies involving fire and stand manipulation have also yielded positive results for oak seedling success (Lanham et al. 2002; Albrecht and McCarthy 2006; Iverson et al. 2008).

The objective of this study was to mimic the top-kill effect of fire through shoot clipping and combine this with a midstory removal treatment. The rationale was that removing the midstory should enhance oak vigor through increased light resources. Over six growing seasons, the oaks would have the ability to grow and develop more biomass
compared to seedlings in an unaltered stand. After the sixth growing season, the seedlings were clipped and allowed to resprout. We then assessed the first year growth of the new white oak sprouts and attempted to relate sprout response to a range of physical attributes including initial size, leaf area, and root and shoot biomass. Besides simply identifying the factors related to seedling response, we also assessed the treatment effect over six years and created a set of models that document what pre-clipping characteristics of seedlings may be the most important in predicting post-clipping growth as well as biomass allocation and sprouting probability.

METHODS

Study Sites and Design

The sites used for this study were established in 2005 in the Berea College Forest located in Madison County, Kentucky. The three sites: Water Plant, Pigg House, and Fentress Spur, are located on the western edge of the northern Cumberland Plateau physiographic region. The main soil series located at the sites are Weikert and Shelocta, which are acidic, well-drained silt loams.

Before treatment, basal area ranged from 24.5 to 27.9 m²ha⁻¹ with dominant and codominant species being white oak, chestnut oak, black oak, and hickories. Understory vegetation was primarily shade tolerant species such as red maple, sugar maple, and American beech. Average site index for white oak at age 50 was found to be 20 meters, and average tree age was 111 years.

At each site, a pair of square, 0.2 ha plots were chosen that had similar slope and aspect. One location was randomly selected to receive a midstory removal treatment,
while the other was designated as the control. Starting with trees equal to 2.54 cm and working upward in size, stems were mechanically felled until 20 percent of the initial basal area was removed at each site. Large stems were cut to smaller lengths, while slash was removed from the plots to facilitate movement. Controls were left unaltered.

Data Collection and Analysis

At the time of treatment, height and ground line diameter measurements of naturally regenerated white oak seedlings were taken in the experimental plots as part of the Chapter 2 analyses. These seedlings were selected from six random locations throughout each plot. Height was measured using a meter stick held vertically at the base of the stem while leaving the seedling in its natural position. Measurements were made to the nearest 0.5 cm. For diameter, two perpendicular measurements were taken at the intersection of the stem and ground using digital calipers to the nearest 0.1 mm. The two readings were averaged to determine the final diameter. At the time of midstory treatment, there were found to be no significant differences between white oak seedlings in the control and removal treatments. The average height of seedlings was 9.7 cm, and average diameter was 3.04 mm (Table 3.1).

After the 2010 growing season, 30 white oak seedlings independent of the seedlings measured in 2005 were randomly chosen per plot to receive a basal clipping treatment. The selected seedlings, however, were stratified based upon the year six diameter distribution of the advance regeneration seedlings. The range of diameters of the original seedlings was divided into five equal size classes for each plot. The proportion of original seedlings that fell into each size class determined the number of seedlings from
each class that would be chosen for clipping. This was done to ensure that the clipped seedlings adequately represented the population of white oak seedlings in each plot. For each of the 30 newly selected seedlings, height and ground line diameter were recorded as described above.

In addition to height and diameter, leaf area was collected for ten of the 30 seedlings. These ten seedlings also followed the previously mentioned distribution. Leaf area was determined by measuring the midrib length of each leaf and using the following equations derived from adjacent plots (Parrott 2011):

$$\ln LA = -0.97 + 1.93\ln \text{Midrib}$$

where $LA=$individual leaf area in cm$^2$ and $\text{Midrib}=\text{length of leaf midrib in cm}$.

After using leaf midribs to determine the total leaf area of the ten sampled trees, a relationship was then found to exist between height, basal diameter, and total leaf area as follows:

$$LA = (-0.8556 + 0.1353Ht + 4.1078Dia)^2$$

$R^2 = 0.9568$

where $LA=$total seedling leaf area in cm$^2$, $Ht=$initial seedling height in cm, and $Dia=$initial seedling diameter in mm.

This equation was then used to estimate the leaf area of the remaining 20 trees per plot.

In February 2011, each randomly selected white oak seedling was clipped approximately one inch above the ground line. The tops were collected and oven-dried to measure total above-ground biomass. In 2011, at the end of one growing season, the height and diameter of sprouts were recorded using the previously described methodology.
To estimate the below-ground biomass of the clipped seedlings, 80 additional white oak seedlings were selected from adjacent midstory removal and control plots during the summer of 2010 (40 from each treatment). The treatment plots, described by Parrott (2011), received a 20 percent midstory removal treatment identical to that performed on these sites. The selected seedlings were also chosen to represent the range of diameter distribution present. Height, diameter, and leaf area of all 80 seedlings were collected using the previously described methods. In February 2011, the seedlings were extracted, and the root systems were left intact. Above- and below-ground portions were then separated, oven-dried, and weighed. Finally, a root biomass regression equation was derived from the roots of the destructively sampled seedlings to estimate the root weight of the clipped seedlings as follows:

\[
\text{Biomass}_{\text{below}} = (0.27482 + 0.29794\text{Dia} + 0.71499\sqrt{\text{Biomass}_{\text{above}}})^2, \quad R^2 = 0.8822
\]

where Biomass_{\text{below}}=total below-ground biomass in g, Dia=initial seedling diameter in mm, and Biomass_{\text{above}}=above-ground seedling biomass in g.

Once the necessary values were calculated for each clipped seedling, a series of t-tests were performed to test the effect of the midstory removal treatment on seedling growth and biomass. For each of the eight variables (initial and post-clipping height and diameter, leaf area, above- and below-ground biomass, and total biomass) comparisons were made between seedlings in the removal treatments compared to the controls. Whether midstory treatments affected either the proportion of biomass found above and below ground or the relative growth of seedlings was also of interest to this study and was tested using t-tests as described above.
In order to identify whether any variables were significantly correlated with the probability of seedlings sprouting, logistic regression was used. Each of the measured variables was included in models, and the stepwise selection method was used to identify which variables were significantly related to the probability that a seedling sprouted after the first growing season.

The next step in analysis was to use least squares regression to formulate various models that could be used to better understand what seedling characteristics were the most important to the success of white oaks one year following clipping. The first test examined the relationships between each of the variables before clipping treatment. To accomplish this, sets of direct comparisons were performed between one variable and the remaining seven variables using regression. This was done to demonstrate the correlation observed between the different growth measurements. The second regression analysis created single and multivariate models that could be used to suggest the most influential factors to sprout height and diameter growth following the clipping treatment.

RESULTS

It was found that seedlings growing in the midstory removal treatment were significantly larger in all aspects than seedlings in the control (Table 3.2). Removal treatment seedlings were nearly 1.5 times as tall and had twice the diameter as those in the control. While the control seedlings grew an average of 14.5 cm over the six growing seasons, those in the removed plots grew 26.4 cm. A small diameter growth increment was seen in the control plots (0.05 mm), but those in the removal treatments grew 1.73
mm, on average. Additionally, the average leaf area of a seedling in the removal treatment was nearly 850 cm$^2$ larger than in the control.

We also investigated whether implementation of a midstory removal would significantly affect above- and below-ground biomass totals, which is important, since larger root systems have been linked to more vigorous shoot growth (Dillaway et al. 2007). A comparison of biomass totals found significant differences between the two midstory treatments. When looking at above-ground biomass, removal treatments were over four times as large ($p=0.001$), while root weights in the removals were three times as large as in the controls ($p=0.009$). Total mass of the control (5.21 g) was also significantly smaller than the removal (18.47 g) ($p<0.0001$) (Figure 3.1). Even though overall seedling biomass was much higher in the removal treatments, it was found that biomass allocation did not significantly differ between treatments ($p=.4520$) (Figure 3.2). In both treatments, the above- and below-ground biomass percentages were roughly 25 and 75 percent, respectively.

The final t-test analysis examined the first year height growth of seedlings relative to height the year before clipping. This test found that, on average, seedlings that sprouted grew to 66% of their initial height and 60% of their initial diameter. There was no significant difference between relative height ($p=0.8340$) or diameter ($p=.2796$) growth between the two treatments.

Analysis of seedling sprouting probability yielded no significant variables, but the lack of significant variables may be a result of a high overall sprouting probability. In this study, 148 of the 173 seedlings measured (85.5 percent) resprouted after clipping with half of the failures occurring in the midstory treatment (Table 3.3). Visual observations of
clipped seedlings showed that large as well as small seedlings failed to resprout in some cases.

The first goal of the regression analysis was to identify any relationships among pre-clipping variables. Single comparisons between individual variables to find which two factors were most well-correlated with each other were all highly significant (p<0.0001) in every case; however, some trends emerged when examining fit statistics (Table 3.4). For the height and diameter measures in the year before clipping, it was found that below-ground biomass was the best overall predictor of size with R² values of 0.8546 and 0.9593, respectively. Total seedling leaf area, which was taken before clipping, was most highly correlated with initial diameter (R²=0.9460), but also had strong relationships to both biomass variables and initial height. The strongest relationship between any two variables was seen between above- and below-ground biomass. There was a very strong relationship in which over 97 percent of variation could be explained by the opposite biomass measure, although this may be partially explained by the fact that above-ground biomass was included in the equation to predict below-ground biomass. When looking at the second most correlated values for each biomass variable, it was found that above-ground biomass and below-ground biomass were strongly linked to leaf area and initial diameter, respectively.

The second part of the regression analysis aimed to find the best single and multivariate models for post-clipping total height and diameter. From Table 3.4, it can be seen that the post-clipping size variables were found to be most well-correlated with each other rather than any biomass measures (R²=0.6754). Unfortunately, this information has little informative value for making predictions of future growth. Instead, pre-clipping
diameter seems to be the best overall indicator of post-clipping height and diameter (Table 3.5). When including all pre-clipping variables in multivariate model selection, the outcome remains the same that diameter the year before clipping is the most significant predictor of future size for both height and diameter.

DISCUSSION

One of the primary findings of the study performed here is that implementation of a midstory removal treatment does have a significant effect on the overall size and biomass accumulation of seedlings. This is important for several reasons. First, the fact that six years of growth in the treatment resulted in larger overall seedling is important not just for clipping studies, but provides validity to the use of midstory removals as a silvicultural treatment to increase oak growth prior to harvest. Also, as all of the models from this study have suggested, seedlings that are larger at the time of clipping should, on average, have increased height growth in the first growing season. While future growth is still unknown, if oak seedlings are able to continue similar growth rates into subsequent years, the largest seedlings would reach competitive heights exponentially faster than the smallest seedlings.

To date, most clipping studies have looked at either northern red oak (Quercus rubra L.) or cherrybark oak (Quercus pagoda Raf.). In these studies, the general purpose has been to test the effect of shoot clipping after planting or directly following a silvicultural treatment. The majority of these studies have found that shoot clipping does have an immediate effect on the growth rate of seedlings allowing them to grow faster than unclipped seedlings under similar conditions (Johnson 1984; Janzen and Hodges
1986; Crunkilton et al. 1989; Zaczk et al. 1997; Lockhart et al. 2000). Results published by Zaczek et al. (1997) and Lockhart et al. (2000) examining northern red oak and cherrybark oak, respectively, have found that, although sprouts do experience rapid growth during the first years after clipping, this growth eventually slows after three to four years to a point where seedlings are again growing at the same rate as unclipped seedlings.

One area of the literature that is lacking is the response of advance oak reproduction to clipping. Besides Lockhart et al. (2000) with cherrybark oak under a midstory removal, Kittredge et al. (1992) have experimented with clipping northern red oak advance reproduction in an intact forest. In their study, they found, as have others, that initial growth was extremely rapid during the first growing season, but that clipped trees remained at nearly equal heights as unclipped trees following the second growing season. What no known studies have examined is the effect of clipping after seedlings have been allowed to develop for six years under a midstory removal before clipping. As seen in our study, seedlings allowed to grow under the midstory removal were much larger than control seedlings even though initial size at the time of treatment was the same. This was especially true for leaf area, which is directly responsible for photosynthesizing light and stimulating plant growth. Perhaps with the additional biomass reserves obtained over the six years, these seedlings will be able to overcome the growth rate threshold that has been observed in other studies.

Although little is known about the exact development of historic oak forests in the presence of fire, this study may better simulate what an historic fire regime may have accomplished. Arthur et al. (In press) propose that besides having regular fire to remove...
midstory vegetation, oak forests must also have sustained periods without fire to allow oaks to reach sizes that will make them less susceptible to damage from future fires. In our study, the six years following midstory removal could be analogous to a period of regular fire that allowed oak seedlings to increase in size; therefore, the clipping would signify the last fire before a sustained fire-free phase in which seedlings could grow to competitive heights. What our study does not replicate, however, is the removal of surrounding competing vegetation that would theoretically be experienced following fire. At this point, it is unknown whether this vegetation will inhibit oak growth and to what extent. The answer to this question lies primarily in future growth rates of the oak seedlings. An additional point to consider is that, as seedlings age, other variables may become more important to growth.

Although we did not control for competing vegetation, we can speculate on how it may affect oak success in the future. Increased below-ground biomass should result in larger sprouts within the first year of growth as evidenced by the models. This is furthered by the fact that seedlings experienced 66 percent relative height growth after the first year, which would have relied largely on below-ground carbohydrates. Additionally, the models showed that seedlings which were larger at the time of clipping remained the largest sprouts after clipping. If our white oak seedlings experience the slowed growth patterns as seen by Kittredge et al., however, it could mean that seedlings will still not be tall enough to compete with surrounding vegetation. Long term results will be needed to test the final outcome, but previous studies have suggested that a large number of oak seedlings with a height of 137 or 90 cm are needed before overstory treatments will result in sufficient oak recruitment to the overstory (1992).
Since the seedlings in this study were only observed for one growing season after clipping, it is still unknown whether the rapid growth observed will continue in future growing seasons. If clipped seedlings in the midstory removal treatments can continue at their current annual rate of growth (21 cm), it will take four years to reach 90 cm. This would equate to a total time of ten years between midstory implementation and overstory release. Although this timeframe would be acceptable in most circumstances, maples and other competitors will continue to grow along with the oaks. If the oaks are not among the tallest class of seedlings at the time of overstory removal, it is less likely they will be recruited into the new canopy gaps.

Management Implications

The results obtained from this study, specifically the size variable models, have several possible uses for forest managers tasked with sustaining or increasing competitive oak regeneration. Given that we found initial diameter to be the variable most associated with future sprout height and diameter, practitioners interested in using clipping to stimulate future growth should target seedlings with larger diameters rather than other characteristics. The reason behind this finding is that diameter and below-ground biomass are very strongly correlated ($R^2=0.9593$). Seedlings with larger initial diameters should have, on average, larger roots that will generate bigger seedlings in terms of height and diameter after clipping.

One of the major benefits of using clipping as compared to fire is that clipping can be done quickly over relatively small areas and with little equipment. Also, clipping is a nonintrusive treatment both in terms of producing smoke or disturbing wildlife
habitat. These benefits are especially important considering that the vast majority of forestland in Kentucky and surrounding states is owned by nonindustrial private landowners who generally own small parcels of land where burning could be time consuming, costly, and (or) socially unacceptable.

As mentioned, one of the issues that is still uncertain is how competing vegetation will affect the success of the sprouts. Future monitoring of seedlings will be important to determine whether surrounding plants negatively influence growth. Additional avenues of research could also test the effect of clipping on underplanted seedlings on the same sites.
Table 3.1. Average white oak seedling height and diameter prior to midstory removal (2005) by treatment based on advance reproduction seedlings

<table>
<thead>
<tr>
<th></th>
<th>Control</th>
<th>Removal</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial height (cm)</td>
<td>9.8 ± 0.58</td>
<td>9.6 ± 0.54</td>
<td>0.74</td>
</tr>
<tr>
<td>Initial diameter (mm)</td>
<td>2.94 ± 0.15</td>
<td>3.14 ± 0.05</td>
<td>0.28</td>
</tr>
</tbody>
</table>

Similar letters indicate no significant difference between treatments at p=0.05.
Table 3.2. Mean comparisons (t-test) (±SE) between treatments of average clipped seedling measurements with associated p-values

<table>
<thead>
<tr>
<th>Variable</th>
<th>Control</th>
<th>Removal</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial height (cm)</td>
<td>24.30 ± 1.17</td>
<td>36.00 ± 2.30</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Sprout height (cm)</td>
<td>15.20 ± 0.75</td>
<td>21.33 ± 1.33</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Initial diameter (mm)</td>
<td>2.99 ± 0.14</td>
<td>4.87 ± 0.30</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Sprout diameter (mm)</td>
<td>1.75 ± 0.10</td>
<td>2.68 ± 0.17</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Initial total leaf area (cm²)</td>
<td>239.30 ± 56.74</td>
<td>1087.10 ± 229.20</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Initial above-ground biomass (g)</td>
<td>1.39 ± 0.21</td>
<td>6.02 ± 1.35</td>
<td>0.008</td>
</tr>
<tr>
<td>Initial below-ground biomass (g)</td>
<td>4.20 ± 0.44</td>
<td>13.13 ± 2.05</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Initial total biomass (g)</td>
<td>5.21 ± 0.65</td>
<td>18.46 ± 2.92</td>
<td>&lt;0.001</td>
</tr>
</tbody>
</table>
Table 3.3. Clipped white oak seedling sprouting numbers and percentages by treatment one year after clipping

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Number with sprouts</th>
<th>No sprouts</th>
<th>Percent sprouted</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>74</td>
<td>13</td>
<td>85(^a)</td>
</tr>
<tr>
<td>Removal</td>
<td>74</td>
<td>12</td>
<td>86(^a)</td>
</tr>
</tbody>
</table>

Similar letters indicate no significant difference at \( p=0.05 \).
Table 3.4. $R^2$ fit statistics between individual growth and biomass variables

<table>
<thead>
<tr>
<th></th>
<th>$H_{\text{Pre}}$</th>
<th>$D_{\text{Pre}}$</th>
<th>$H_{\text{Post}}$</th>
<th>$D_{\text{Post}}$</th>
<th>$L_{\text{Pre}}$</th>
<th>$\text{Biomass-above}$</th>
<th>$\text{Biomass-below}$*</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H_{\text{Pre}}$</td>
<td>—</td>
<td>0.7922*</td>
<td>0.5025</td>
<td>0.4658</td>
<td>0.8417</td>
<td>0.8540</td>
<td>0.8546</td>
</tr>
<tr>
<td>$D_{\text{Pre}}$</td>
<td>0.7922</td>
<td>—</td>
<td>0.5837</td>
<td>0.6074</td>
<td>0.9460</td>
<td>0.8756</td>
<td>0.9593</td>
</tr>
<tr>
<td>$H_{\text{Post}}$</td>
<td>0.5025</td>
<td>0.5837</td>
<td>—</td>
<td>0.6754</td>
<td>0.5753</td>
<td>0.5485</td>
<td>0.5792</td>
</tr>
<tr>
<td>$D_{\text{Post}}$</td>
<td>0.4658</td>
<td>0.6074</td>
<td>0.6754</td>
<td>—</td>
<td>0.5181</td>
<td>0.5210</td>
<td>0.5744</td>
</tr>
<tr>
<td>$L_{\text{Pre}}$*</td>
<td>0.8417</td>
<td>0.9460</td>
<td>0.5753</td>
<td>0.5181</td>
<td>—</td>
<td>0.9310</td>
<td>0.9245</td>
</tr>
<tr>
<td>$\text{Biomass-above}$*</td>
<td>0.8540</td>
<td>0.8756</td>
<td>0.5485</td>
<td>0.5210</td>
<td>0.9310</td>
<td>—</td>
<td>0.9754</td>
</tr>
<tr>
<td>$\text{Biomass-below}$*</td>
<td>0.8546</td>
<td>0.9593</td>
<td>0.5792</td>
<td>0.5744</td>
<td>0.9245</td>
<td>0.9754</td>
<td>—</td>
</tr>
</tbody>
</table>

*For all comparisons, $p<0.0001$

**Square root of variable

$H_{\text{Pre}}$ = initial height (cm); $D_{\text{Pre}}$ = initial diameter (mm); $H_{\text{Post}}$ = height after one growing season (cm); $D_{\text{Post}}$ = diameter after one growing season (mm); $L_{\text{Pre}}$ = leaf area before clipping (cm²); $\text{Biomass-below}$ = root biomass (g); $\text{Biomass-above}$ = shoot biomass (g)
Table 3.5. Growth and biomass models as a function of size variables

<table>
<thead>
<tr>
<th>Growth model</th>
<th>$b_0$</th>
<th>$b_1$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H_{t\text{Post}} = b_0 + b_1 Dia_{2010}$</td>
<td>4.96</td>
<td>3.40</td>
</tr>
<tr>
<td>$Dia_{\text{Post}} = b_0 + b_1 Dia_{2010}$</td>
<td>0.42</td>
<td>0.46</td>
</tr>
</tbody>
</table>

$H_{t\text{Post}} = \text{height one growing season after clipping (cm)}$; $Dia_{\text{Post}} = \text{diameter one growing season after clipping (mm)}$
Figure 3.1. Total biomass allocation of clipped white oak seedlings by treatment.

Different letters represent a significant different between treatments (p<0.05)

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Below-ground (g tree⁻¹)</th>
<th>Above-ground (g tree⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Removal</td>
<td>5</td>
<td>5</td>
</tr>
</tbody>
</table>

The graph shows the total biomass allocation for the control and removal treatments, with different letters indicating a significant difference between treatments (p<0.05).
Figure 3.2. Proportion of biomass of clipped white oak seedlings by treatment. Different letters represent a significant different between treatments (p<0.05)
CHAPTER FOUR: CONCLUSIONS

As seen by both studies, removal of the midstory was shown to have a positive effect on the growth of both underplanted and naturally regenerated oak seedlings. With oak response, however, came a growth response from red maple, oaks’ primary competitor and the species most connected with oak regeneration issues in Kentucky. The increases in height and growth experienced by the three oak species studied were also not of the same magnitude as responses observed in some other studies.

Given that red maple was also able to effectively utilize the available light resources, it was found to be taller than each oak species and seedling type with the exception of underplanted northern red oaks grown under a midstory removal. Again excluding the underplanted red oaks, if the oaks continue to grow at the current rates observed, it would still be at least six more years until they would reach what may be considered a competitive height of 90 cm. Even then, if they are still overtopped by red maple, their height will be inconsequential. The success of underplanted northern red oaks is promising, but their abundance is much less than white oak, which is the dominant canopy tree in central Kentucky and throughout much of the Central Hardwood Region.

The clipping study arrived at similar conclusions. While the presence of a midstory removal is undoubtedly better for regenerating oak seedlings, it is unclear whether clipped seedlings will be able to effectively utilize all available resources given the high abundance of tall red maples.

A wide range of lighting conditions were identified over the three sites, and the 2.9% transmittance seen in the controls is consistent with other studies from oak
dominated forests (Gottschalk 1994; Dey and Parker 1996; Dillaway and Stringer 2006; Lhotka and Loewenstein 2009). While the average transmittance of the removal treatments (18.5%) was similar to other midstory removal studies (Lhotka and Loewenstein 2009), it was slightly below the minimum 20 percent level of transmittance suggested for oak seedlings (Jarvis 1964; Phares 1971; Gottschalk 1994; Guo et al. 2001; Dillaway and Stringer 2006).

Our results also found that, in terms of height and diameter growth, it is often simply whether midstory is present or absent in a stand that affects the future growth of seedlings. What this may suggest about this study is that the initial midstory removal of 20 percent of basal area was not quite enough to stimulate oak growth over rival maples while also inhibiting the growth of shade intolerant yellow-poplar. To better test what conditions are created within a stand following a midstory removal and how they relate to seedling development later on, future studies should implement midstory removal treatments of varying intensities greater than 20 percent to identify the levels at which 20 to 40 percent full sunlight is able to reach the forest floor. This research is especially important in the context of white oak since little is known about its response to varying light conditions, especially under midstory removal treatments.

While concurrently studying the growth of oak species, it will be important to monitor red maple and identify its competitiveness at varying treatment levels. Additional avenues of research could also address the implementation of fire as a way to control red maple regeneration while potentially benefiting oaks. While research is being done to address this issue, the results have been inconclusive. Using fire in conjunction with
silvicultural treatments has rarely been tried but may prove to be what is necessary to successfully regenerate competitive oaks.

Since no known studies have investigated the effects of basal clipping several years following a silvicultural treatment, there are many areas of future research that are in need of investigation. In regards to this study specifically, it will be important to continue monitoring seedlings for the next three to four years to assess whether growth rates have remained high or whether they have stagnated as in previous clipping studies. It is also unclear at this time how competing vegetation will affect the white oaks. If the oaks cannot continue growing at their current pace, they will likely be overtopped by other seedlings in their vicinity.

In the event that future monitoring of the clipped seedlings does suggest they could be competitive following release, it would be important to conduct similar experiments with other species such as northern red, black, and cherrybark oak and compare the results. If it is found that seedlings are not competitive, the most beneficial research may be to repeat the experiment while controlling for competitors through either herbicide or fire. Overall, though, the first year results of the white oak clipping seem promising and may aid with developing competitive oak seedlings prior to final overstory removal.
Appendix A. Distribution of visible sky across treatments based on hemispherical photographs with a photo angle of 90 degrees at Fentress Spur site.
Appendix B. Distribution of visible sky across treatments based on hemispherical photographs with a photo angle of 90 degrees at Pigg House site.
Appendix C. Distribution of visible sky across treatments based on hemispherical photographs with a photo angle of 90 degrees at Water Plant site
Appendix D. Distribution of height to canopy bottom in meters across treatment cells at Fentress Spur site
Appendix E. Distribution of height to canopy bottom in meters across treatment cells at Pigg House site
Appendix F. Distribution of height to canopy bottom in meters across treatment cells at Water Plant site
Appendix G. Distribution of full sunlight transmittance to the understory in percent across treatment cells at Fentress Spur site
Appendix H. Distribution of full sunlight transmittance to the understory in percent across treatment cells at Pigg House site
Appendix I. Distribution of full sunlight transmittance to the understory in percent across treatment cells at Water Plant site
Appendix J. Distribution of residuals for equation relating individual leaf area to midrib length.
Appendix K. Distribution of residuals for equation relating total seedling leaf area to initial total height and ground line diameter
Appendix L. Distribution of residuals for equation relating below-ground biomass of white oak seedlings to initial ground line diameter and above-ground biomass.
Appendix M. Black oak seedling competitive position by treatment and type
Appendix N. Northern red oak seedling competitive position by treatment and type

![Bar chart showing competitive position of seedlings by treatment and type.]

- **Advance Reproduction**
  - CON
  - REM

- **Underplanted**
  - CON
  - REM

Legend:
- **Suppressed**
- **Intermediate**
- **Free-to-Grow**
Appendix O. White oak seedling competitive position by treatment and type
Appendix P. Red maple seedling competitive position by treatment and type

![Diagram showing competitive position by treatment and type](image)
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Publications