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The Response of Naturally Regenerating Hardwood Seedlings to Post-Harvest Weed Control and Fertilization

Kevin Andrew Tomlinson

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**The Response of Naturally Regenerating Hardwood Seedlings to
Post-Harvest Weed Control and Fertilization**

Kevin Andrew Tomlinson

**Thesis submitted
to the Davis College of Agriculture, Natural Resources, and Design
at West Virginia University**

in partial fulfillment of the requirements for the degree of

**Masters of Science in Forestry in
Forest Resources Management**

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Division of Forestry and Natural Resources

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**Keywords: post-harvest management, hardwood regeneration, targeted application
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ABSTRACT

The Response of Naturally Regenerating Hardwood Seedlings to Post-Harvest Weed Control and Fertilization

Kevin A. Tomlinson

Current models to predict post-harvest success rely upon pre-harvest regeneration assessments, which rarely occur. Furthermore, these models lack management recommendations to improve regeneration success of naturally regenerating desired hardwood species following overstory removal. Factorial combinations of weeding and fertilization were randomly assigned to individual naturally regenerating black cherry (*Prunus serotina* Ehrh.), chestnut oak (*Quercus montana* Willd.), white oak (*Quercus alba* L.), and red oak (*Q. rubra* L., *Q. velutina* Lam., and *Q. coccinea* Muenchh.) seedlings in the spring of 2015, three growing seasons post-harvest. Factorial ANOVA models with size at treatment application as a covariate were developed and showed species-specific height, root collar diameter (RCD), and survival responses to treatment application. Additionally, these responses were influenced by pressures from white-tailed deer (*Odocoileus virginianus* Zimm.) and competing vegetation. Height growth responses suggest that weeding allows for crown expansion and increased herbivory occurrence which causes a decrease in height growth, particularly when taller stems were treated. Species-specific responses were observed for RCD growth when weeded and for height growth when fertilized. Regardless of species, fertilization increased average RCD growth by 0.7 mm ($p = 0.005$). The height and RCD growth responses suggest that nutrients were limiting growth, particularly for black cherry. Survival across all treatments and species for the duration of the study was 92%, suggesting that though nutrients were limiting growth, resources were not meaningfully limiting. As these resources become more limiting with canopy closure, the effect of weeding and fertilization is expected to become more pronounced.

Based on the species-specific responses to weeding and fertilization, predictive equations for second year height post-treatment were developed for each species. These equations provide managers with a useful tool to predict the height of naturally regenerating seedlings two growing seasons post-treatment in response to post-harvest weeding and fertilization treatments. In time, continued monitoring will enable the development of models that can predict dominance probabilities of the desired individual seedlings. These findings show that direct-application of weeding and fertilization may be effective to bolster the success and growth of young naturally regenerating seedlings and influence species composition.

DEDICATION

This thesis is dedicated to my late mother, Dr. Patricia Tolson Tomlinson, and my father, Edward Lee Tomlinson Jr. To my mother, for inspiring and encouraging my scientific pursuit, and inspiring countless others to do the same. And to my father, for ceaselessly enabling, encouraging and believing in me. And for being my rock. It is because of you both that I will never forget to *Keep Smiling*.

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1.0 Introduction

Historically, oaks have been a major part of the forests in the eastern portion of the United States (Griscom et al. 2011). In West Virginia, many of the forested areas have poor representation of desired regeneration in the understory (Griscom et al. 2011) due to a myriad of environmental and biological factors (Buckley et al. 1998; Griscom et al. 2011). Pressures from white-tailed deer (*Odocoileus virginianus* Zimm.) (Brenneman 1983; Tilghman 1989, Buckley et al. 1998), competition from woody and herbaceous vegetation (Gurevitch et al. 2000; Griscom et al. 2011), and harvest-related disturbances (Meier et al. 1995; Kraft et al. 2004) can reduce the growth and survival of desired hardwood regeneration. Fertilization (Newton et al. 2002; Berengeuer et al. 2009), weed control (McGill and Brenneman 2002; Ristau 2017), deer exclusion (Marquis and Grisez 1978; Kraft et al. 2004; Miller et al. 2016), and release (Pham 1987; Newton et al. 2002; Schuler and Robison 2006) treatments have all been implemented in naturally regenerating hardwood stands with the same goal in mind—accelerating growth and improving the survival of desirable hardwood seedlings.

Competition for light, water, nutrients, and space limit the growth and often decreases the survival of many hardwood seedlings. Many previous studies have focused on the effects of broadcast treatment applications (Auchmoody 1985; Pham 1987; Bowersox and McCormick 1997; McGill and Brenneman 2002; Schuler 2005). Broadcast application improves the conditions for competing species as well as the desired regeneration (Auchmoody 1983), but can result in increased mortality of shorter seedlings (0-20 cm) (Schuler and Robison 2006). Spot application may be a cost-effective and accurate method of controlling competing vegetation with little risk of impacting non-target species (Shepard et al. 2004; Nyland 2002).

Studies have been limited on spot treatment application to young seedlings, with most studies being performed on planted seedlings (Nelson et al. 2014; Self et al. 2013). However, Nix (2004) found that targeted release of young naturally regenerating bottomland oak seedlings can be effective means to increase height growth.

Many models have been developed to predict dominance probabilities or regeneration success based on pre-harvest regeneration assessments (Loftis 1990; Gould et al. 2006; Gould et al. 2007; Vickers et al. 2011). However, regeneration assessments have too commonly “taken the form of casual observation” (Carvell 1988). Plot-based regeneration surveys are rarely performed pre-harvest (Voss 2012) rendering the current predictive models irrelevant under most circumstances. Furthermore, these models do not evaluate responses of regeneration to post-harvest management which can influence the probability of regeneration success.

There is a limited window of opportunity where simple management practices can be applied in young stands before the stands become too dense to navigate, which leads to the question: can targeted, post-harvest management practices be implemented in young stands to improve the regenerative success of the desired naturally regenerating seedlings? The objectives of this study are 1) to determine if there are species-specific growth and survival responses to combinations of fertilizer and weed control application following overstory removal; and 2) to develop predictive equations for forest managers to determine regeneration success following harvest based on post-harvest regeneration assessments. Development of these predictive equations can provide forest managers with an effective tool to determine regeneration success of desired species in young stands, and furthermore, provide a means of

predicting potential improvements in regeneration success through implementation of timely management practices.

2.0 Literature Review

2.1 The Regeneration Process

The process of regeneration following overstory removal is dependent on numerous environmental and biological factors. Pressures from herbaceous competition, herbivory, and harvests can all influence the regeneration process (Buckley et al. 1998; Griscom et al. 2011). However, the geology, topography, and climate also play a crucial role in site quality and potential regenerative success (Trimble 1964; Carmean 1971; Nyland 2002; Griscom et al. 2011).

2.1.1 Site Quality Relationships with Regeneration

The amount of erosion, soil productivity, and the ability of stands to respond to silvicultural prescriptions are affected by the steepness of slopes, position on the slope, and aspect (Nyland 2002). Furthermore, as soil depth increases, so does the site quality (Trimble 1964). However, maintaining optimal nutrient and moisture levels in the upper soil profile can improve productivity due to the higher concentrations of roots in these shallow layers (Carmean 1971).

Aspect also directly impacts site quality and the species likely to colonize. Northeast-facing slopes are characterized by the coldest temperatures, higher water availability, and lower light intensity and duration. Southwest-facing slopes are characterized by hotter temperatures, lower water availability, and higher light intensity and duration (Nyland 2002). Additionally, stands on lower slopes are usually more productive due to the accumulation of

water, nutrients, and sediment from upper slopes (Johnson et al. 2009). In general, the best site qualities are associated with north and east aspects, and gentle, concave, lower slope positions (Carmean 1971; McNab 1989; Nyland 2002). However, simple measures of site index can leave large variance in dominant and codominant stems across a landscape due to heterogeneity in slopes shape, steepness, and position (McNab 1989).

2.1.2 Overstory removal

Overstory removal can have both negative and positive impacts on the understory vegetation. Harvests cause forest floor disturbance and compaction from machinery use, and depending on the intensity of harvest, can shift species composition toward shade intolerant species (Meier et al. 1995; Crow et al. 2002; Kraft et al. 2004). However, harvests also reduce root competition, which increases water availability and nutrient availability (Crow et al. 2002; Huebner et al. 2010).

Determining the appropriate harvest is dependent upon management objectives and initial site conditions (i.e., the antecedent status of desired regeneration in the understory). In general, shelterwood harvests aim to gradually improve the lighting regime to favor intermediate shade tolerant species, namely oak species if they are present (Miller et al. 2016). When clearcuts are performed shade intolerant species are favored (Graney and Rogerson 1985) and increased soil erosion is common resulting in lower soil fertility (Grigal 2000). However, soil condition will gradually improve to pre-harvest levels (Marshall 2000) and soil fertility differences present between mature and clearcut stands will no longer be present 20 years post-harvest (Gilliam 2002).

Implementation of shelterwood cuts can improve the regeneration status of oaks compared to clearcuts depending upon initial conditions. Graney and Rogerson (1985) assessed the five-year growth and density of regeneration in upland oak stands subjected to four overstory thinning regimes across various site indices. In this study, 60% residual density established the highest density of oak seedlings while still maintaining components of white ash (*Fraxinus americana* L.) and black cherry (*Prunus serotina* Ehrh.) (Graney and Rogerson 1985). However, at 40% residual density, white ash and black cherry had increased growth and density while growth of upland oak regeneration was not improved. Stands thinned to 80% residual overstory showed a general decrease in height growth of upland oaks, white ash, and black cherry (Graney and Rogerson 1985).

However, when clearcut harvests are performed, herbaceous layer cover was shown to be significantly higher after 20 years (Gilliam 2002). Additionally, weed interference has been shown to increase with decreasing harvest intensities (Leak 1988), which can reduce the growth and survival of natural regeneration (Romagosa and Robison 2003).

2.2 Factors Influencing Regeneration Success

Establishing regeneration post-harvest takes time; very little growth can be seen in the year immediately following overstory removal (Graney and Rogerson 1985). In many hardwood stands, establishment of raspberry species (*Rubus* spp.) plays an integral part in natural stand development (Horsley 1983; Gordon et al. 1995). It quickly colonizes following harvests, even through fern and grass cover, and is usually succeeded by fast-growing pioneer species (Horsley and Marquis 1983). Also, its presence reduces the density of fern and grasses which compete more aggressively with regenerating hardwood species (Marquis and Grisez 1978; Horsley

1983). Raspberry species are a preferred food source for white-tailed deer, as well (Krueger and Patterson 2009). However, when deer pressures are high, raspberry species cover can be sparse, increasing the ground cover of ferns and grasses which reduces seedling growth and survival (Marquis and Grisez 1978; Horsley 1993; Krueger and Patterson 2009).

Following initial floristics composition (Egler 1954), all species are present in the initial cohort that colonizes post-harvest. The early successional species, such as raspberries, are ultimately succeeded by the species to be present in the next overstory (Loftis 2004). As the stand develops, density dependent mortality occurs due to resources becoming more limiting, resulting in lower stem densities (Oliver 1980). However, depending upon the antecedent conditions, the species composition post-harvest can shift towards more mesophytic species (Vickers and Fox 2015) and namely towards red maple (*Acer rubrum* L.) (Fei and Steiner 2007).

2.2.1 Oak Regeneration

Oak regeneration follows four broad stages: (1) acorn production, (2) seedling establishment, (3) seedling development, and (4) capture of adequate space to ensure future dominance (Johnson et al 2009). Additionally, there are three possible sources of oak regeneration (Loftis 1989): (1) stump sprouts, (2) new germinants, and (3) advance reproduction.

Stump sprouts are not likely to provide a large component of the potential oak regeneration in harvested stands. Stump sprouting probabilities for oaks decrease as the diameter at breast height (DBH) increases (Loftis 1989; Keyser and Loftis 2015). Most of the trees harvested in commercial sales have larger diameters, and therefore, lower sprouting probabilities.

Newly germinated oak seedlings are generally considered an unreliable source of oak regeneration (Loftis 1989). Bumper acorn crops occur roughly once every three to four years (Olson 1974), but the acorns that are produced have a low and variable germination rate (Marquis et al. 1976). Of those that do germinate, many studies have noted the low survival probability of the small, newly germinated, oak seedlings (Beck 1970; Sander 1972; Loftis 1988; Loftis 1989).

Numerous studies have concluded that the re-establishment of oaks following clearcut harvests is proportional to the number and size of oak advance regeneration present at the time of harvest (Sander et al. 1984; Loftis 1990; Steiner et al. 2008; Johnson et al. 2009). However, the presence of substantial amounts of oak advance regeneration does not ensure its future dominance (Dey et al. 2009) due to any combination of biological and environmental factors (Lorimer et al. 1994; Brose 2011):

- Slow juvenile growth and low survival
- Predation by rodents (Marquis et al. 1976)
- Damage by pests (Galford et al. 1991)
- Browsing and defoliation of seedlings by deer (Kraft et al. 2004)
- Competition with forbs and other tree species (Romagosa and Robison 2003)
- Shifts in disturbance/fire regimes (Buckley et al. 1998)
- Invasive species (both flora and fauna) (Dey 2014)

Successful regeneration of oak is a tradeoff between these biotic and abiotic factors. Buckley et al. (1998) illustrated that the point of peak oak seedling success was a balance between competitive pressures, and the increased occurrence of browse and frost damage due

to removal of competition. To aid in the successful establishment of oak in the understory, competitive sources must be sufficiently released at the appropriate time (Loftis 2004). To increase oak regeneration potential, the competitiveness of the regeneration must be increased, the competitiveness of interfering vegetation must be reduced, or a combination of the two (Loftis 2004).

Oak species are disturbance resistant. Once oak seedlings are established they can survive in extremely low light conditions for several years (less than 5%), although with minimal growth (Brose and Rebbbeck, 2016). Growth is favored when light conditions exceed that of 20% full sun (Kolb et al. 1990; Gottschalk 1994; Brose 2011). Studies have shown that the maximum photosynthetic rate for northern red oak (*Quercus rubra* L.) occurs around 30% full sun with minimal increase with increasing light levels (Kolb et al. 1990; Rebbbeck et al. 2011; Rebbbeck et al. 2012), whereas white oak (*Quercus alba* L.) saw maximum photosynthetic rate at approximate 20% full sun (Rebbbeck et al. 2012). White oak tends to be categorized as more shade tolerant than red oaks (Johnson et al. 2009); however, there is some disagreement in literature (Brose 2011; Brose and Rebbbeck 2016). Despite this disagreement, increasing light intensity from 4% to 14% showed significant improvement in the growth of oak species (Brose 2011). Additionally, at 75% full sun northern red oak had increased growth compared to black oak (*Quercus velutina* Lam.), white oak, and chestnut oak (*Quercus montana* Willd.) (Brose and Rebbbeck 2016).

The responsiveness of oaks to slight improvements in lighting regime suggests the importance of controlling taller competing vegetation (Rebbbeck et al 2012). Interspecific competition is a major factor limiting oak species' ability to regenerate successfully (Buckley et

al. 1998). Specifically, tall understory/midstory tree species (e.g. maple [*Acer* spp.] and birch [*Betula* spp.]) pose a major obstacle to oak regeneration development as they compete more aggressively than low herbaceous plants and cause more mortality in desired oak regeneration (Loftis 1988; Lorimer et al. 1994).

2.2.2 Black Cherry Regeneration

Black cherry is a shade intolerant, early successional species that is an important forest species both for timber and wildlife (Horsley 1993). Though regeneration success is not often as problematic as oak species, black cherry seedlings also have barriers to regenerative success including (Auchmoody 1985):

- Seed predation
- Competition from undesirable regeneration
- Large numbers required to ensure regeneration
- High soil nitrogen and phosphorus demands

Though black cherry sprouts readily, especially in full sun, their primary source of regeneration following harvest are newly germinated seeds (Vickers and Fox, 2015; Atwood et al. 2011; Marquis 1990). Black cherry seedlings can survive in the understory in shade for 3-5 years (Horsley 1993). Seedling survival and growth improves with increasing intensity of overstory removal (Marquis 1979).

Due to the high nutrient demands of black cherry, unless nutrient deficiencies are relieved, stand development can be delayed by 6-8 years (Auchmoody 1985). Fertilization has been a useful tool to improve the regenerative success of black cherry following clearcuts (Auchmoody 1982). Growth of black cherry has also been shown to increase with increasing

harvest intensity (Marquis 1979). However, a two-cut shelterwood provides a balance between establishment of black cherry and its subsequent growth (Marquis 1979). Generally, smaller seedlings have higher survival when grown under a partial harvest before final overstory removal (Marquis 1982). Thus, survival and growth of black cherry seedlings following overstory removal is dependent upon their size and abundance pre-harvest.

2.3 Improving Regeneration

Competition for growth resources (i.e., light, water, nutrients, and space) limit the growth and often decreases the survival of many hardwood seedlings. To improve the availability of resources to the desired seedlings, and thus, improve growth and survival, several post-harvest management techniques can be implemented, including (Schuler, 2005):

- Nutrient Management (i.e., fertilization)
- Weed Control (i.e., herbicide and/or mechanical weeding)
- Stem density reduction (i.e., release treatments)
- Microsite modification treatments

Decreases in growth rates can cause increased rotation lengths (Griscom et al. 2011; Puettmann et al. 2015). Improving the availability of resources post-harvest can improve the potential for successful regeneration even in stands where the potential for successful regeneration is bleak (Romagosa and Robison 2003; Schuler 2005).

2.3.1 Fertilization

Of the 16 essential elements for plant nutrition, nitrogen, phosphorus, and potassium are generally considered the most limiting nutrients for plant growth (Lea et al. 1979; Stanturf et al. 1989; Auchmoody 1989; Long et al. 2009). Phosphorus availability becomes limiting only

after nitrogen demands have been met (Auchmoody 1982). Thus, nitrogen is generally considered to be the primary growth limiting nutrient (Auchmoody 1989; Fowler et al. 2015). Excessive nitrogen, however, will not yield an increase in growth (Klooster et al. 2012). Fertilization improves tree growth largely through increases in total leaf area allowing for increased light interception (Klooster et al. 2012).

Desired regeneration, as well as herbaceous competition, will respond to application of fertilizer at the proper rates, timing, and type (Auchmoody 1983). For fertilization to be effective, it must be applied to responsive species on nutrient deficient soils when there are no other growth limiting factors (i.e., water availability) (Auchmoody 1985). However, even within the same community, different plant species can be limited by different nutrients depending on their species-specific demands and physiology (Bigelow and Canham 2007; Klooster et al. 2012). In general, shade tolerant species tend to be less responsive to fertilizer application than shade intolerant species and younger stands tend to be more responsive than older stands (Auchmoody 1989). However, fertilization can interfere with the success of new seedling recruitment (Schuler and Robison 2006).

Young North Carolina Piedmont hardwoods were shown to respond favorably to fertilization with sustained and substantial increases in height, diameter, and volume (Berenguer et al. 2009; Schuler and Robison 2006; Schuler 2005). However, fertilization was shown to increase mortality in the smaller height classes (0-20 cm) due to competition and density-dependent mortality (Schuler 2005; Schuler and Robison 2006). A species-specific response was observed when release treatments were applied with fertilization, with little growth improvement evident above application of fertilization alone (Newton et al. 2002).

Fertilization with nitrogen and phosphorus was the most effective means to improve growth and development for deciduous hardwood seedlings (Auchmoody, 1982; Newton et al. 2002; Berenguer et al. 2009). Fertilization does not necessarily correspond to increased growth on forest soils. Some forest stands may not respond to fertilization due to nutrient saturation (May et al. 2005) or because growth is limited by another factor such as moisture availability or rooting depth (Auchmoody 1972). Furthermore, even with deficiencies present, responses to fertilization are not ensured. Once one nutrient deficiency is corrected, other nutrient demands may increase and deficiencies arise again (Gress et al. 2007). Failure to consider the potential nutrient interactions when applying fertilizers can result in incorrectly declaring soils nutrient sufficient when nutrients may actually be limiting growth (Auchmoody 1972).

2.3.2 Weed Control

Desired tree species regeneration competes with other vegetation for aboveground resources (i.e., light and space) and belowground resources (i.e., nutrients, water, and space) (Bowersox and McCormick 1987). Weed control treatments are designed to improve the lighting regime and improve nutrient availability to the desired regeneration. The fewer stems a resource is being allocated to, the better off the remaining stems will fair. In general, dryer sites show more benefit from weed control treatments due to water scarcity (Bowersox and McCormick 1987; McGill and Brenneman 2002; Huebner et al. 2010).

Planted hardwoods have been shown to perform better when competing vegetation is sufficiently controlled (McCormick and Bowersox 1997; Oswalt et al. 2007; Ezell et al. 2007) except under high deer browse pressures (Gordon et al. 1995). Simple mechanical removal of competing vegetation saw no improvement in growth of planted seedlings due to persistence

of root competition (Robison et al. 2004; Schuler and Robison 2010). Similarly, belowground competition was shown to reduce shoot growth in black cherry seedlings (Horsley 1983). Thus, sufficiently controlling vegetation consists of controlling both aboveground and belowground competition.

Competition can reduce the productivity of young naturally regenerating hardwood stands (Romagosa and Robison 2003; Schuler and Robison 2006; Oswalt et al. 2007; Steiner et al. 2008). However, weed control alone has shown varied effects causing both shifts in species composition and increased growth (Romagosa and Robison 2003) and no shift in species composition with limited growth response of seedlings (Schuler and Robison 2006) in similar study areas. However, weed control has been shown to be favorable for oaks and yellow-poplar (*Liriodendron tulipifera* L.) both with and without fertilization (Schuler 2005).

Different species in the understory can compete to varying extents with the desired regeneration (McCormick and Bowersox 1997; Steiner et al. 2008; Vickers et al. 2011). For example, the height of white ash and yellow-poplar seedlings were shown to be significantly different between grass cover and fern cover (McCormick and Bowersox 1997). Oswalt et al. (2007) showed that following overstory removal, Japanese stiltgrass (*Microstegium vimineum* Trin.) reduces species diversity and stem density. Furthermore, hay-scented fern (*Dennstaedtia penttilobula* Michx.) was shown to reduce growth of advance regeneration (Horsley 1993; Kaeser et al. 2008). Seedling susceptibility to pathogens is also increased due to the high humidity and low light microclimate created by the dense understory of hay-scented fern (Horsley 1993). Northern red oak seedling survival was 56% with a 1.1 m average height after four years in the presence of competing herbaceous growth. When competition was excluded

by glyphosate application the survival was increased to 85% with a 1.5 m average height after four years (McCormick and Bowersox 1997).

Brose (2011) evaluated the growth of acorn-origin oak seedlings over eight growing seasons following each of the four harvests associated with a two-cut shelterwood (i.e., uncut, preparatory, first removal, and final removal). This study showed that acorn-origin seedlings were not able to catch up to the growth of other tree species. Despite acorn-origin oaks reaching heights of 3 to 4 m, there were still no dominant oaks eight growing seasons after final overstory removal (Brose 2011). As such, these findings emphasize the need to control competing woody and herbaceous competition to aid in the establishment of competitive oak regeneration.

Weed control and fertilization treatments applied in tandem to seedlings were shown to have very minimal effects above that of only fertilization (Schuler 2005). Different species respond differently to treatment application, with their initial size playing a crucial role in their response (Schuler 2005). This suggests that fertilization allows for increased stem densities reducing density-dependent mortality effects of competition for the regenerating seedlings studied. The main benefit of weeding may not be the reduced competition for resources in the soil, but rather, improving the lighting regime (Schuler 2005).

2.4 Profile of Herbicides

Herbicides are commonly used as a means of reducing the interference of surrounding vegetative communities on desired forest regeneration. Since herbicides affect species differently through many different modes of action, the use of a combination of herbicides can affect and control a broader range of species. In the Appalachian hardwood region, a tank mix

of Round Up® (glyphosate) and Oust® (sulfometuron methyl) has been shown to allow for control of a broad range of species (Brose et al. 2008; Kochenderfer et al. 2012). However, without recurrent herbicide application, one-time herbicide treatments result in competing vegetation returning to pre-treatment levels two to four years after treatment (Ristau et al. 2011).

2.4.1 Glyphosate

Glyphosate is a foliage absorbed, systemic, non-selective herbicide that disrupts amino acid synthesis. It is used as a post-emergent herbicide (Holt 1983; Brose et al. 2008). Once in the soil, it is non-persistent and is readily absorbed as iron and aluminum complexes and thus has low soil activity and low animal toxicity (Holt 1983). Glyphosate is typically used to control most herbaceous plants; however, woody plants can also be controlled with late summer and early fall applications (Holt 1983; Brose et al. 2008). Using glyphosate to control competition, there was a significant increase in the two-year height of planted hardwood seedlings compared to control plots (Bowersox and McCormick, 1987). The recommended rate of application for controlling competition in Appalachian hardwood forests is 1-2% glyphosate solution (Kochenderfer et al. 2012).

2.4.2 Sulfometuron methyl

Sulfometuron methyl is a selective, pre-emergent herbicide with short soil persistence that disrupts mitosis in meristematic tissues (Holt 1983; Brose et al. 2008). It has been shown to effectively reduce the occurrence of raspberry species, hay-scented fern, and New York fern (*Thelypteris noveboracensis* L.) in various natural mixed hardwood stands (McGill and Brenneman 2002; Ristau 2017) with as little as 0.14 kg ha⁻¹ (2 oz ac⁻¹) (Brose et al. 2008; Ristau

2017). In recently harvested upland oak stands, over-the-top application of Oust® (sulfometuron methyl) at 0.2 kg ha⁻¹ did not increase mortality of northern red oak seedlings and reduced stem density of non-oak, woody, and herbaceous competition (Schuler and Stephens 2010). When applied at 0.45 g L⁻¹ as a directed spray, overspray of Oust® has been shown to cause no damage to northern red oak (Brose et al. 2008), but can cause 100% mortality of white oak (Ezell and Nelson 2001).

2.5 Herbivory

Herbivory can drastically reduce the survival and growth of desired regeneration (Gurevitch et al. 2000; Griscom et al. 2011), particularly following overstory removal (Buckley et al. 1998; Horsley et al. 2003; Schuler and Martin 2016). High white-tailed deer populations can heavily browse much of the desired regenerating species, namely oak species (Griscom et al. 2011) and increase abundance of black cherry (Horsley et al. 2003). Overstory removal often results in an increase browse potential due to the increase in succulent understory vegetation and the feeding habits of deer (Buckley et al. 1998).

Deer tend to browse preferentially upon certain species. Northern red oak, white oak, and chestnut oak are moderately palatable species that are occasionally damaged by deer browse, while black cherry is typically not damaged by deer browse (Horsley 1993; Krueger and Peterson 2009; Schuler and Martin 2016). Red oak species tend to be more heavily browsed when deer pressures are high (Stange and Shea 1998; Griscom et al. 2011) resulting in increased mortality (Brenneman 1983; Griscom et al. 2011; Miller et al. 2016).

Under high deer pressures the understory can become dominated by shrubs, forbs, ferns, and other undesired woody and herbaceous flora (Griscom, et al. 2011) many of which

act as recruitment barriers for desired regeneration (George and Bazzaz 1999). When deer pressures are high, most seedlings that are within reach of the deer will be browsed (Brenneman 1983; Crow 1992). This can cause mortality and delay the development of the regenerating stand (Horsley and Marquis 1983; Heubner et al. 2010; Schuler and Martin 2016).

Deer browse pressures may also be increased solely from weed control (Buckley et al. 1998; Stange and Shea 1998; Romagosa and Robison 2003). When herbivory pressures were high, the presence of competing herbaceous vegetation was associated with higher seedling survival (Griscom et al. 2011). This suggests that the competing vegetation provides an advantage of shielding the desired regeneration from herbivory pressures.

Even when deer populations are low, oak regeneration can still often be uncertain. Thus, herbivory is only one of several factors that could be limiting establishment of competitive oak seedlings following harvests (Lorimer et al. 1994). Exclusion of deer, however, can have its own negative consequences. Deer exclusion can decrease the abundance of raspberry species which can lead to re-establishment of the understory by herbaceous cover that competes more aggressively with regenerating seedlings (such as ferns and forbs) (Horsley and Marquis 1983; Tilghman 1989; Gordon et al. 1995).

Due to variable deer preference for species, high populations of deer can alter species composition to species less preferred by deer (Horsley et al. 2003; Huebner et al. 2010). Coincidentally, many high value timber trees are also preferred by deer, though black cherry is not preferred. High deer pressures in a forest stand can have drastic developmental consequences on regenerating forests, and thus, significant monetary effects. In fact, height growth of seedlings in stands with high deer density showed a 50% decrease in height of the

tallest seedlings after five years (Tilghman 1989). Browse can delay stand development and increase the rotation length, which can result in losses equivalent to a 50% yield reduction (Marquis 1981). Improving stand development by creating more competitive sources of regeneration may decrease stand rotation times and promote desired species composition and density by enabling the regenerating stems to be released from deer browse pressures more quickly.

2.6 Predicting Regeneration Success

Many models and guidelines have been created to describe the regeneration potential of oaks. These guides focus on a variety of regions including the Missouri Ozarks (Sander et al. 1984), the Southern Appalachians (Loftis 1990; Vickers et al. 2011), and the Central Appalachians (Steiner et al. 2008). Several other models have also described oak regeneration potentials in New England (Hibbs and Bentley 1983) and southern bottomland stands (Belli et al. 1999). The goal of these models is largely to determine if oak regeneration will be likely, and substantial enough, to dominate the new stand based on pre-harvest regeneration surveys. However, regeneration surveys are frequently performed as casual observation (Carvell 1988; Voss 2012) prior to overstory removal rather than plot-based quantification.

2.6.1 *Sander (1984) Method*

Sander et al. (1984) presented a model for evaluating oak regeneration based on oak growth and reproduction in site indices ranging for 15 to 20 m for black oak. Regeneration assessment gathered descriptive site information (i.e., aspect and slope position), as well as, quantitative measurements of regeneration size including ground line diameter class and the height of oak advance regeneration to estimate regeneration success probabilities. These

measurements were used on a per plot basis to determine stocking and the subsequent probability of success following overstory removal. Stump sprouts were also included in determining subsequent oak dominance by determining sprouting probabilities using DBH, species, and site index (Sander et al. 1984). As DBH increases and site index decreases, stump sprouting probabilities decrease. Oak species vary in their sprouting probabilities with white oak sprouting probabilities decreasing more quickly than red oak as DBH increases (Sander et al. 1984; Johnson et al. 2009).

In this model, competing vegetation was not directly considered when developing success probabilities. Additionally, small advance regeneration, less than 30 cm in height, was viewed conservatively, and do not contribute to the probability of future success. While they do have a low survival probability, in other locations (e.g. Pennsylvania), large numbers of small oak seedlings can still have an influence on the probability of oak dominance (Gould et al. 2006; Steiner et al. 2008).

2.6.3 Steiner (2008) Method

The Steiner (2008) guide was created based off information gathered in mixed oak stands of the Central Appalachians, specifically in the Ridge and Valley and Appalachian Plateau physiographic province of Pennsylvania with site indices ranging from 18 to 23 m. Similar to Sander et al. (1984), their guide also called for inventories of advance oak regeneration and overstory assessment for sprouting probabilities. Regeneration assessments consisted of quantifying all seedlings by height class within a 1.13 m radius (milacre) plot. Third decade dominance probabilities are deduced using this information and then are summed to determine an expected seed-origin stocking value (Steiner et al. 2008). This method is more

optimistic about the potential influence of smaller oak seedlings on stocking percent. Adding the seed-origin (Gould et al. 2006) and sprout-origin (Gould et al. 2007) third decade survival probabilities yields an expected stocking percent for the forest three decades after a harvest. The guide also incorporates a decision support system that directs management decisions based on stocking percentages and competing herbaceous vegetation (Steiner et al. 2008).

2.6.2 Loftis (1990) Model

The model created by Dr. David Loftis was designed to predict height growth and subsequent dominance probabilities for red oak regeneration. Measuring the ground line diameter (GLD) and height of individual oak stems, as well as the site index of the stand pre-harvest allowed for predictions of the height of oak regeneration eight years post-harvest. This yielded the following equation that accounted for 42% of the variation in the predicted eighth year height:

$$HT8 = 29.9656 - (2.2099/BD) - (3.2886/HT) - (688.8281/SI) \quad (\text{Eq. 1})$$

where,

HT = height of advanced red oak pre-harvest (ft)

HT8 = height of red oak eight growing seasons post-harvest (ft)

SI = oak site index in feet (base age 50 years)

BD = basal diameter (measured as GLD) of advanced red oak pre-harvest (in)

Apical dominance was measured pre-harvest and used alongside mortality to assess subsequent dominance probabilities of regeneration following overstory removal. The probability of dominance eight years post-harvest was extrapolated to 20 year probabilities by multiplying by 0.5 based on data from a prior study. This provides forest managers with the

capability of determining how many dominant or codominant stems will be present in their subsequent 20-year-old stand based on pre-harvest regeneration assessments (Loftis 1990).

2.6.4 The REGEN Expert System

The REGEN Expert System was developed based off the work of Dr. David Loftis in 1989 and 1990 in the Southern Appalachians. This program was designed to predict future compositions of a stand following a disturbance, including harvests. Other models (Sander et al. 1984; Steiner et al. 2008), solely describe the oak stocking, largely ignoring potential competition with both desirable and undesirable species. The REGEN Expert System attempts to generalize disturbance dynamics and predict regeneration responses based on initial floristics and silvics of the species present pre-disturbance (Boucugnani 2005).

Advance regeneration assessment is performed and stems placed into one of five categories. Any stems with a DBH greater than two inches and greater than four feet tall were considered overstory and calculated for their potential to produce stump sprouts. The program then uses these data as well as established REGEN knowledge bases (RKBs) to determine future stand species composition. When adapted for the Central Appalachians, the REGEN system was capable of predicting composition within 4% of actual. However, oaks and yellow-poplar had the largest variance between actual forest composition and the predicted composition (Vickers et al. 2011). Additionally, preliminary work on adapting the REGEN expert system for the Appalachian Plateau has been conducted (Vickers et al. 2013).

3.0 Methods

3.1 Site Descriptions

Seedlings were located at four sites in Preston County and Monongalia County, West Virginia. Three of the sites were in the West Virginia University Research Forest (WVURF) (Figure 1). These were the Archery Range (AR), Goodspeed Road (GS), and Johnson's Hollow (JH) sites. A shelterwood establishment cut was conducted on each site that removed approximately 60% of the overstory and retained mostly oak trees. The fourth site was in Preston County, WV, near Rowlesburg (RB). A clearcut harvest was conducted on this site in the fall of 2012 (Table 1). For each site, soil series was determined using WebSoilSurvey (Soil Survey Staff [Accessed 2017]). Site indices were determined by collecting a minimum of three cores from dominant or codominant northern red oak on each site (Carmean 1978).

The Archery Range site was 14.6 hectares and characterized by Dekalb loamy soils with moderate west-facing slopes and a site index of 21.4 m (Table 1). The pre-harvest inventory indicated that the overstory was dominated by northern red oak, red maple, and chestnut oak with $6.43 \text{ m}^2 \text{ ha}^{-1}$ (32%), $5.74 \text{ m}^2 \text{ ha}^{-1}$ (28%), and $4.59 \text{ m}^2 \text{ ha}^{-1}$ (22%) of the pre-harvest basal area, respectively. In the summer of 2012, a shelterwood establishment cut was performed removing $5.74 \text{ m}^2 \text{ ha}^{-1}$ (33%) of the northern red oak, $2.75 \text{ m}^2 \text{ ha}^{-1}$ (57%) of the chestnut oak, and $5.74 \text{ m}^2 \text{ ha}^{-1}$ (100%) of the red maple. The residual overstory retained $6.89 \text{ m}^2 \text{ ha}^{-1}$ (34%) with 49.4 trees per hectare (TPH) (20%) and was dominated by northern red oak with $4.36 \text{ m}^2 \text{ ha}^{-1}$ (63%). Herbaceous regeneration in the understory three years post-harvest was largely greenbriar species (*Smilax* spp.) with a large component of grass species, namely deertongue (*Dichanthelium clandestinum* L.) and Japanese stiltgrass. Additionally, casual observation

suggested that the most competitive understory tree species was red maple, predominantly of sprout-origin.

The Goodspeed Road site was a 22.5-hectare site characterized by Dekalb stony loams with mostly south-facing moderate slopes and some steep slopes (25-65%) with a site index of 20.9 m (Table 1). The pre-harvest inventory indicated that the overstory was dominated by northern red oak with 10.1 m² ha⁻¹ (33%) while other oaks comprised another 5.28 m² ha⁻¹ (17%). Red maple and yellow-poplar were well represented with 5.51 m² ha⁻¹ (18%) and 6.66 m² ha⁻¹ (21%), respectively. In the summer of 2012, a shelterwood establishment cut was performed removing 5.74 m² ha⁻¹ (38%) of the oaks, 5.51 m² ha⁻¹ (100%) of the red maple, and 6.20 m² ha⁻¹ (93%) of the yellow-poplar. The residual overstory retained 10.1 m² ha⁻¹ (33%) with 59.3 TPH (22%). Herbaceous regeneration was largely raspberry species and greenbriar species. Additionally, casual observation suggested that sweet birch (*Betula lenta* L.) was the most competitive understory tree species on the site.

The Johnson's Hollow site was characterized by Dekalb Channery loams with moderate west-facing slopes and a site index of 20.3 m (Table 1). The pre-harvest inventory indicated that the overstory was dominated by yellow-poplar with 19.9 m² ha⁻¹ (70%), while oaks comprised 12.1 m² ha⁻¹ (52%) of the pre-harvest basal area. Major oak species present on the site were northern red oak and chestnut oak, with 5.26 m² ha⁻¹ (19%) and 3.13 m² ha⁻¹ (11%) of basal area, respectively. In the summer of 2012, a shelterwood establishment cut was performed removing 18.2 m² ha⁻¹ (92%) of yellow-poplar and 6.29 m² ha⁻¹ (52%) of the oak species on the site. The residual overstory retained 7.8 m² ha⁻¹ (27%) with 8.0 TPH (21%) with northern red oak comprising 36% of the residual TPH. The herbaceous community is largely raspberry and

greenbriar species with a significant portion of deertongue. Additionally, casual observation suggested that yellow-poplar was the most competitive of the understory tree species. The plots utilized in this study were located on the upper portion of the 10.3-hectare site where the overstory prior to harvest was more concentrated with northern red oak.

The Rowlesburg site was a 4.5-hectare site characterized by Calvin silt loams with steep south-facing slopes (25-65%) and a site index of 23.7 m (Table 1). Since the site was clearcut, site index was determined by coring dominant yellow-poplar stems surrounding the harvest area (Schlaegel et al. 1969), and converting to northern red oak (Doolittle 1958). The overstory prior to harvest was dominated by white oak, black oak, and northern red oak. Yellow-poplar and red maple species were well represented, though were not dominant. The herbaceous community is dominated by dense raspberry species. Additionally, casual observation suggested that sweet birch tended to be the most prevalent of the competing understory tree species on the site.

3.1.1 Soil Nutrients

Soil samples were collected to determine nutrient status of the study sites. At each site three composite samples from 10 randomly located 7.6 cm deep soil cores. Each composited sample was blocked to control for potential spatial variability that could be present at the study site (e.g. slope position). Rocks, roots, and other major debris were removed before air drying. Samples were then sent to the West Virginia University Soil Testing Laboratory for analysis. Soils were analyzed using Mehlich-1 extractions for plant available phosphorus, potassium, calcium, and magnesium. Base saturation (BS), cation exchange capacity (CEC), and pH were also determined for the soils (Table 2).

3.2 Experimental Design

At each of the four sites, factorial combinations of weed control and fertilization treatments were applied to individual seedlings of black cherry, chestnut oak, white oak, and red oaks (northern red oak, black oak, and scarlet oak [*Quercus coccinea* Muenchh.]). All species were not represented at every site. RB did not have any chestnut oak recorded. Additionally, JH had only one white oak seedling and was not able to be fully represented with all treatments on that site. Therefore, the experimental design was a 4x2x2 factorial design with incomplete blocks where site is the random factor.

3.2.1 Measurement

Each seedling was flagged with a metal pin flag and given a numbered aluminum tag. To make relocation easier, a distance and azimuth from metal stakes to each seedling were recorded. Total height and root collar diameter of each seedling were measured in the fall of 2015, three growing seasons (GS) post-harvest. Each target seedling was on its own plot with a radius of 1.13 m (milacre). Treatments were randomly assigned by species and size at initial measurement. Treatments were either weed control, fertilization, weed control and fertilization, or no treatment (control). Treatments were applied in April to early-May, three years post-harvest immediately following initial measurements. The growth and survival of the individual seedlings were monitored for the two subsequent years of the study.

3.2.1 Treatment Application

Factorial combinations of weed control and fertilization were applied to each of the four study species in April to early-May of 2015. Weed control treatments consisted of cutting all competing vegetation within 1.13 m of the target seedling to minimize the likelihood of

herbicide damage to target seedling. The competing vegetation within the plot was then sprayed with a tank mix of 0.14 kg ha⁻¹ (2 oz ac⁻¹) of Oust XP™ (sulfometuron methyl) and 2% Round-Up (glyphosate) from a backpack sprayer as suggested by Kochenderfer et al. (2012).

Fertilization treatment consisted of scattering 45 g of Osmocote® Plus Smart-Release Plant Food fertilizer directly around the target seedling. This fertilizer was a 15-9-12 NPK six-month slow release granular fertilizer.

3.2.2 Deer Herbivory

Seedlings were evaluated for the severity of deer browse that had occurred during the GS. This was evaluated on a scale of 0 to 5 and recorded after the first and second GS. These measurements correspond to 20% intervals of the percentage of apical branches browsed upon such that: 0 represented 0% (none), 1 represented between 0 and 20% (minimal), 2 represented between 20 and 40% (low), 3 represented between 40 and 60% (moderate), 4 represented between 60 and 80% (high), and 5 represented between 80 and 100% (severe).

3.2.3 Competing Vegetation

To assess competitive pressures on the target seedling, the single largest woody or herbaceous individual within a cone extending vertically at a 45-degree angle above the terminal bud was identified as the “worst aggressor” (Figure 2). The worst aggressor species was recorded after the first and second GS. The worst aggressor was further categorized as either a fast-growing tree species, slow-growing tree species, herbaceous, woody non-arborescent species, or no aggressor. Delineations between fast and slow-growing tree species was based on their silvics obtained from the USDA Forest Service (Burns and Honkala 1990) and by competition rankings established for the REGEN Expert System (Vickers et al. 2011). Fast-

growing tree species were considered black cherry, sweet birch, black locust (*Robinia pseudoacacia* L.), red maple, tree-of-heaven (*Ailanthus altissima* Mill.), yellow-poplar, striped maple (*Acer pensylvanicum* L.), staghorn sumac (*Rhus typhina* L.), American chestnut (*Castanea dentata* Marsh.), and all tree sprouts. Slow-growing tree species were considered oaks, sassafras (*Sassafras albidum* Nutt.), American holly (*Ilex opaca* Ait.), blackgum (*Nyssa sylvatica* Marsh.), mountain laurel (*Kalmia latifolia* L.), and spicebush (*Lindera benzoin* L.). Herbaceous species encountered were asters (*Aster* spp.), bonesets (*Eupatorium* spp.), deertongue, ferns (*Polystichum* spp.), Japanese stiltgrass, broomsedge (*Andropogon virginicus* L.), and switch grass (*Panicum virgatum* L.). Woody non-arborescent species were raspberry species, greenbriar species, azaleas (*Rhododendron* spp.), and multifloral rose (*Rosa multiflora* Thunb.).

3.3 Statistical Analysis

Height and RCD data were ln-transformed to meet assumptions of normality. Additionally, the absolute value of the most negative growth measurement was added to each observation prior to transformation. Site was the blocking factor and treated as a random effect in all mixed-effect models. All other factors included in each model were fixed effects. Significance from all models was assessed at an alpha of 0.05 with all statistical analysis performed using R (R Core Team 2017) and RStudio (RStudio Team 2017).

3.3.1 Growth Analysis

Analysis of RCD and height growth were individually analyzed using linear mixed-effects models (R package: *lme4*, Bates et al. 2015). The best model was determined by removal of all non-significant interactions from a full model (Eq. 2) following the strong-heredity principle (Nelder 1998).

$$Y_{02} = F(Y_0, SPP, F, W, AG_2, BR_2) \quad (\text{Eq. 2})$$

where,

Y_{02} = Response (RCD or height) growth for two growing seasons post-treatment.

Y_0 = RCD or height at treatment application three years post-harvest.

SPP = The species of the seedling treated with 4 levels.

F = Fertilization treatment applied three years post-harvest with 2 levels.

W = Weed control treatment applied three years post-harvest with 2 levels.

AG_2 = Worst aggressor for second growing season post-treatment with 5 classes.

BR_2 = Deer browse for second growing season post-treatment with 6 levels.

Interactions considered in the models were between height at treatment application, species, fertilization, and weed control. Subsequent Tukey HSD comparisons were then performed on the model to determine where significant differences were observed between species and between treatments ($\alpha = 0.05$) (R package: *multcomp*, Hothorn et al. 2008; R package: *lsmeans*, Lenth 2016). Subset models were also analyzed for each individual species to determine species-specific responses to treatments based on their height at treatment application if present in the global model.

3.3.2 Survival Analysis

Survival analysis was performed using logistic regression using a binomial generalized linear mixed-effects model. Best models were determined utilizing the same procedure as growth analysis by removing non-significant interactions from the full model (Eq. 2). Worst aggressor or severity of browse factors were excluded due to the inability to measure these

terms for a dead seedling. Subsequent Tukey HSD comparisons were also performed as necessary.

3.3.3 Herbivory and Competition Analysis

Potential effects of treatment and species on proportion of deer herbivory and worst aggressor were evaluated using Chi-Squared analysis. Subsequent multiple comparisons were evaluated using sequential Bonferroni adjustments as described by Holm (1979) (Rice 1989; R package: *fifer*, Fife 2017).

3.3.4 Height Predictive Model

Predictive models were also developed using Dr. David Loftis' (1990) REGEN model equation (Eq. 1) based on results from growth analysis. The predictive models were linear regression equations predicting height two GS post-treatment based on height and root collar diameter at treatment application, site index, and additional treatment factors determined from significances in growth analysis. The coefficients from the predictive models were utilized to create a linear equation for replicable use for forest managers. These models were built using a 70-30 split-rule for model validation (McGarigal et al. 2000).

4.0 Results

A total of 1115 seedlings were measured and tagged in the spring of 2015. By species, 358 were black cherry, 267 were chestnut oak, 364 were red oak, and 126 were white oak. Of those initially tagged, 1073 (96%) were found (including mortality) two GS later (Table 3). Seedlings that were not found were removed from analysis. Of the seedlings found, 92% were found alive two GS post treatment with 90% of black cherries, 96% of chestnut oaks, 90% of red oaks, and 96% of white oaks surviving (Table 4).

4.1 Worst Aggressor

After the first GS the most frequently recorded worst aggressors were woody non-arborescent species, which aggressed 52.4% of all live seedlings (Table 5). Greenbriar species were the most abundant single species, which aggressed 38.5% of all live seedlings. Raspberry species were the second most abundant aggressor at 14.4%. Fast- and slow-growing tree species were not commonly recorded as aggressors (Table 5). The most abundant competing tree species was red maple. Stump sprouts of all species accounted for only 3.0% of total aggressors with oaks representing 19.4% of all sprouts. Only 31.4% of the stems were considered free-to-grow (Table 5).

Treatment application affected the proportion of stems aggressed after the first GS. Weeding reduced the proportion of tagged seedlings that were aggressed ($p < 0.001$). Fertilization had no effect on the proportion of stems aggressed ($p = 0.592$, Figure 3). By species, chestnut oak was less frequently aggressed than white oak ($p = 0.009$, Figure 4).

After the second GS the most abundant aggressors were also woody non-arborescent species which aggressed 55% of tagged seedlings (Table 6). Greenbriar species were the most abundant aggressor, which aggressed 34.8% of all live seedlings. Raspberry species aggressed 21.2% of all seedlings and was the second most abundant aggressor. Fast-growing tree species aggressed 14% of seedlings while slow-growing tree species aggressed 6.6% (Table 6). Stump sprouts aggressed 4.7% of target seedlings, with oaks representing 19.6% of the stump sprout aggressors. After two GS, only 21% of all stems were free-to-grow (Table 6).

Weeding still affected the proportion of seedlings aggressed after two GS ($p < 0.001$). The proportion of seedlings aggressed was not affected by fertilizer application ($p = 0.072$,

Figure 5). Among species, chestnut oak had a lower proportion of stems that were aggressed compared to all other species ($p = 0.002$, Figure 4).

4.2 Deer Herbivory

After the first GS, only 26% of tagged seedlings were browsed. Among species, 36% of chestnut oak was browsed (Table 7), which was more frequent than black cherry with 21% ($p = 0.003$) and white oak with 17% ($p = 0.003$, Figure 6). For all species combined, the proportion of stems browsed was increased by 23% with fertilization ($p = 0.014$) and by 41% for weed control ($p < 0.001$, Figure 7).

After the second GS, 25% of tagged seedlings had no browse damage. Among species, 13% of white oak seedlings were browsed (Table 8), which was less frequent than either red oak or chestnut oak, both with 30% of seedlings browsed ($p < 0.001$, Figure 6). For all species combined, weeding increased the proportion of stems browsed ($p < 0.001$). However, fertilization no longer affected browse frequency ($p = 0.510$, Figure 8).

4.3 Growth Analysis

4.3.1 Height Growth Analysis

The best model for predicting height growth two years after treatment included height at treatment application (HT_0 ; $p < 0.001$), species (SPP; $p = 0.123$), fertilization main effects (FERT; $p = 0.700$), weed control main effects (WEED; $p = 0.114$), second GS deer browse (BR_2 ; $p = 0.012$), second GS worst aggressor (AG_2 ; $p < 0.001$), and interactions between HT_0 and SPP ($p = 0.005$), HT_0 and WEED ($p = 0.022$), SPP and FERT ($p = 0.022$), and HT_0 , SPP, and FERT ($p = 0.010$).

With increasing HT_0 , weeding resulted in decreased height growth for all species combined (Figure 9). For red oaks, as initial height increased, fertilization decreased second GS height growth relative to unfertilized stems ($p < 0.001$). None of the other species had significant fertilization effects associated with changes in HT_0 (Figure 10). However, white oak and black cherry, on average, did show increased growth due to fertilization ($p = 0.046$ and 0.002 respectively, Figure 11).

4.3.2 RCD Growth Analysis

The best model for predicting root collar diameter (RCD) growth two years after treatment was predicted by RCD at treatment application (RCD_0 ; $p < 0.001$), species ($p = 0.966$), fertilization main effects ($p = 0.005$), weed control main effects ($p = 0.026$), second GS worst aggressor ($p < 0.001$), and interactions between RCD_0 and SPP ($p = 0.018$), SPP and WEED ($p = 0.024$), and RCD_0 , SPP, and WEED ($p = 0.002$).

Fertilized seedlings grew 5.6 mm in RCD compared to 4.9 mm for non-fertilized seedlings ($p = 0.005$). Weeded black cherry seedlings had increased RCD growth dependent upon their RCD at treatment application ($p = 0.005$, Figure 12). By contrast, white oak seedlings had reduced RCD growth when weed control treatments were applied to stems with larger RCD_0 relative to non-weeded seedlings (Figure 12). Chestnut oak and red oaks did not respond to weeding treatments when considering RCD_0 (Figure 12) or on average (Figure 13).

4.4 Survival Analysis

Seedling survival across all species and treatments after two GS was 92% (Table 4). Two-year survival was affected by HT_0 ($p < 0.001$), species ($p = 0.001$), FERT ($p = 0.463$), WEED ($p = 0.869$) and interactions between FERT x WEED ($p = 0.018$). A higher proportion of white oak

stems survived compared to red oaks ($p < 0.001$) and black cherry ($p < 0.001$), while chestnut oak had a higher survival probability relative to black cherry ($p < 0.001$, Figure 14). Fertilization increased survival only when stems were not weeded (Figure 15). Survival for all species and treatments combined increased with increasing HT_0 (Figure 16).

4.5 Height Predictions

Individual models for each species were developed using Dr. David Loftis's (1990) model equation (Eq. 1) as a foundation. Due to the unique response of each species to fertilization and weed control treatments, species-specific equations were created to predict height two-years post-treatment. Each equation was a function of height (HT_0) and RCD at treatment application, (RCD_0) site index (SI), and, based on growth response analysis, weed control (W) and fertilization (F) treatment application.

$$HT_2 = F(HT_0, RCD_0, SI, F, W) \quad (\text{Eq. 3})$$

where,

HT_2 = height two growing seasons after treatment application (in cm)

HT_0 = height at treatment application three years after overstory removal (in cm)

RCD_0 = height at treatment application three years after overstory removal (in mm)

SI = site index standardized for northern red oak, base age 50 (in m) (Carmean 1978)

F = fertilization treatment as binary: 1 = applied, 0 = not applied.

W = weed control treatment as binary: 1 = applied, 0 = not applied.

The equation for black cherry seedlings was:

$$HT_2 = \beta_0 + \beta_1 HT_0 + \beta_2 RCD_0 + \beta_3 SI + \beta_4 F + \beta_5 HT_0 W \quad (\text{Eq. 4})$$

which described 58% of the variance and was significant ($p < 0.001$). All parameters included in the model were also significant (Table 9). Simple cross-validation showed that the equation had an accuracy of 74%.

The equation for chestnut oak was:

$$HT_2 = \beta_0 + \beta_1 HT_0 + \beta_2 RCD_0 + \beta_3 SI + \beta_5 HT_0 W \quad (\text{Eq. 5})$$

which described 57% of the variance and was significant ($p < 0.001$). Neither RCD_0 ($p = 0.609$) nor site index (0.586) were significant predictors in the equation. However, all other parameters included were significant (Table 9). Simple cross-validation showed that the equation had an accuracy of 82%.

The equation for red oaks was:

$$HT_2 = \beta_0 + \beta_1 HT_0 + \beta_2 RCD_0 + \beta_3 SI + \beta_4 F + \beta_5 HT_0 W + \beta_6 HT_0 F \quad (\text{Eq. 6})$$

which described 49% of the variance and was significant ($p < 0.001$). All parameters included in the model were also significant (Table 9). Simple cross-validation showed that the equation had an accuracy of 67%.

The equation for white oak was:

$$HT_2 = \beta_0 + \beta_1 HT_0 + \beta_2 RCD_0 + \beta_3 SI + \beta_4 F + \beta_5 HT_0 W \quad (\text{Eq. 7})$$

which described 55% of the variance and was significant ($p < 0.001$). Site index was not a significant predictor in the equation ($p = 0.513$). However, all other parameters included were significant (Table 9). Simple cross-validation showed that the equation had an accuracy of 73%.

5.0 Discussion

Fertilization in previous studies improved growth of young naturally regenerating oaks (Schuler and Robison 2006; Newton et al 2002; Berenguer et al. 2009) and black cherries (Auchmoody 1982; Schuler and Robison 2006). Some studies have shown mixed effects of weeding on growth of seedlings (McGill and Brenneman 2002, Miller et al. 2016), though many show increases in growth (McCormick and Bowersox 1997; Romagosa and Robison 2003; Robison et al. 2004; Ezell et al. 2007). Results of this study broadly corroborate these findings by demonstrating species-specific growth and survival responses to targeted weeding and fertilization treatments in recently harvested West Virginia hardwood stands.

The targeted weeding treatment was effective at reducing the proportion of stems directly overtopped by competing vegetation even two years post-application (Figure 4), similar to broadcast application using the same herbicides (Ristau et al. 2011). Additionally, it was visually observed that the percent cover of competing vegetation above individual stems was reduced by weeding, even for the stems that remained overtopped.

5.1 Height Growth

Results indicated that for black cherry and white oak seedlings, height growth was increased due to fertilizer application (Figure 11). Black cherry seedlings are nutrient demanding (Marquis 1990) and respond positively to fertilization, particularly with N and P additions (Auchmoody 1982; Schuler and Robison 2006; Adams et al. 2007). The current study

showed that fertilization increased white oak height growth, but had no effect on chestnut oak seedlings as other studies have found (Schuler and Robison 2006; Berenguer et al. 2009). Though oaks would be expected to grow best on fertile, well-drained sites, chestnut oak is commonly found on infertile, xeric ridges (McQuilkin 1990), suggesting that the chestnut oak seedlings were not limited by nutrients.

Fertilization was effective at improving growth of black cherry and white oak seedlings regardless of their HT_0 . The effect of fertilization on height growth of red oak seedlings was dependent upon HT_0 (Figure 10). A previous study showed that slow-release fertilizer significantly reduced nine-year height growth of planted 1-0 northern red oak seedlings that were greater than 6 mm RCD at planting (Ponder et al. 2012). In the current study, red oak height growth was greater for fertilized seedlings less than 30 cm HT_0 , however, red oak seedlings that were greater than 30 cm HT_0 had increased height growth when seedlings were not fertilized (Figure 10). This may be partially explained by trends observed for herbivory pressures. After the second GS, 32% of fertilized red oaks taller than 30 cm were browsed compared to only 22% of the non-fertilized seedlings (Figure 6, 8). These findings align with previous studies that showed a deer preference for red oaks (Schuler and Martin 2016) and larger seedlings (Crow 1992; Kellner and Swihart 2017).

The weeding effect was not species-specific and was not found to be effective at improving height growth. In fact, weeding reduced height growth for seedlings with larger HT_0 (Figure 9). Mixed responses to weeding have been seen in previous studies with: no improvements of height growth due to weeding (Seifert and Woeste 2002; Miller et al 2016), improvements in height growth (Romagosa and Robison 2003, Schuler et al. 2004), and even

height growth reductions (Ponder and Sambeek 2012) being reported. Minimal growth responses have been seen for oak species growing under light intensities greater than 30% full sun (Rebbeck et al. 2011), which were likely achieved following the harvests performed. Weed removal effects would then be overshadowed by the influence of overstory removal (Buckley et al. 1998). Furthermore, the understory was dominated by raspberry and greenbrier— species that play an integral part in the development of harvested stands (Gordon et al. 1995). Though not quantified, removal of understory competition may have allowed for lateral expansion of seedling crowns while not improving on height growth, as noted in previous studies (Schuler 2005). For example, Rebbeck et al. (2011) showed an increased aboveground oak biomass in response to increasing light intensity from 18% to 25% full sun without increased height.

Additionally, the effectiveness of weed control may have also been reduced due to deer browse being more prevalent on released stems (Figure 7, 8), as other studies have found (Buckley et al. 1998; Stange and Shea 1998; Romagosa and Robison 2003). This suggests a balance between the pressures of competition and browse on early stand development (Buckley et al. 1998). Competition may serve to benefit desired regeneration by reducing herbivory pressures and training seedlings vertically if light is not limiting.

5.2 RCD Growth

The fertilization effect improved RCD growth of all species collectively, as previous studies have noted (Schuler 2005, Berenguer et al 2009). RCD growth improvements due to fertilization have been detected as early as two years following treatment application (Berenguer et al. 2009).

However, two years may be too early to detect meaningful increases in RCD due to weeding oak species (Figure 10, 11). Miller et al. (2014) noted no significant increase in RCD growth for red oak when competing vegetation was controlled with herbicide even 10 years after overstory removal. Weeding increased RCD of black cherry after two GS, which was observed as early as one GS elsewhere (Seifert and Woeste 2002). This aligns with shade tolerance of the species studied suggesting weed control, on these sites, primarily influenced growth through increased light availability rather than reducing potential water limitations. Additionally, this suggests that, in time, weeding may improve height growth once competition becomes more severe as the stand develops.

White oak RCD growth was improved by weeding for stems less than 5 mm in RCD, however, stems larger than this showed reduced RCD growth relative to non-weeded white oak seedlings. White oak was the most shade tolerant of the species studied, and has shown no RCD growth due to increasing light conditions above 18% (Rebbeck et al. 2011), which was likely met by the overstory removal. Reduced RCD growth may be influenced by a browse preference for larger white oak, particularly when weeded. About 8% of non-weeded white oak seedlings less than 5 mm RCD were browsed while 33% of the same size weeded stems were browsed. Though browse pressures were not a significant predictor of second GS RCD, weeding did expose the smaller white oaks and led to increased herbivory. Additionally, 49% of the white oak were on the clearcut site. Nix (2004) noted an RCD growth increase with broadcast herbicide application following a clearcut, but no improvement with targeted application of the same herbicides. Therefore, weeding only 1.13 m surrounding each stem in clearcuts may not

adequately release targeted species from the fast-growing understory, as suggested by a previous study (Woeste et al. 2004).

5.3 Survival

As demonstrated in other studies (Loftis 1990; Schuler 2005), there was an effect of HT_0 on survival, where taller seedlings have a higher probability of survival. Survival of species studied generally followed shade tolerance with white oak having the highest survival and black cherry the lowest (Figure 14).

Treatments applied attempted to ameliorate potential limiting factors (i.e., light, water, nutrients, and space). High survival across all treatments and all species suggests that the typical limiting factors were not so severe that survival was reduced following overstory removal. However, survival tends to be episodic (Johnson et al. 2009) and the short duration of this study may not have yet captured a mortality event. Over time, as competition becomes more severe, canopy closes, and understory density increases, the survival will likely decrease and potentially differentiate based on the targeted treatments.

5.4 Predictive Equations

Species-specific predictive equations developed show that for all species HT_0 and RCD_0 have positive effects on height after two GS. For all species studied, the coefficient for HT_0 by weed interaction was negative indicating a reduction of height growth.

However, the effect of site index varied by species. As site index increased, oak regeneration success is typically diminished due to increased competition from more taxa and faster growing species (Loftis 1990; Johnson et al. 2009). Negative coefficients for site index for red oak follow this trend (Table 9), though site index was not a significant predictor of chestnut

oak or white oak height growth. The positive coefficient for white oak and chestnut oak may be explained by these species only being present on three out of the four sites studied.

Additionally, the positive site index coefficient for white oak may further be explained by 49% of the stems studied being located on the clearcut site, which was the most productive site (Table 1). Black cherry, as an early successional species, is expected to compete well on sites with higher indices (Graney and Rogerson 1985), as indicated by a positive site index coefficient in the model (Table 9).

The accuracy found from the simple cross-validation confirms the equations developed. These equations can be applied to recently harvested stands throughout the Appalachian region, but only to evaluate stems of similar size at treatment application, described in this study (Table 10). Additionally, predictive accuracy will be greatest when competing vegetation is similar in composition (i.e., similar to the distribution observed in Figure 3(a) when not weeded) and there are similar deer densities (i.e., moderate densities; around eight deer km⁻²).

5.5 Conclusion

Height growth, RCD growth, and survival varied by species in response to fertilization and weeding treatments. Nutrients were a growth limiting factor for the sites studied. Meaningful and measurable positive impacts of competition control may be delayed until competition becomes more intense with canopy closure. Survival was high for the study duration, suggesting these resources were not meaningfully limiting. In time, as competition for light, water, nutrients, and space increase, effects of treatments on survival are expected. Broadly, fertilization and weed control treatments show potential for improving the regeneration success of young naturally regenerating hardwood stands.

Height growth of fertilized red oak was negatively influenced by HT_0 and potentially an artifact of deer preference for taller and fertilized red oaks. However, average height growth of red oak was not affected by fertilization for the two-year duration of this study.

Black cherry is a nutrient and light demanding species. As such, growth increases due to improving light and nutrient availability through targeted weeding and fertilization treatments were most pronounced for black cherry seedlings.

White oak, the most shade tolerant of the species studied, exhibited reduced RCD and height growth when weeded. White oak was underrepresented on shelterwood sites and larger stems were also more likely to be browsed, particularly when weeded.

The predictive models developed provide managers with an estimate of two-year response of desired seedlings to targeted early management practices. The influence of increasing site index on growth follows expected patterns related to the competitiveness of certain regenerating species on more productive sites. Continued monitoring will extend the predictive capabilities and lead to development of dominance probabilities in response to early, post-harvest management.

In general, shade intolerant species (i.e., black cherry, yellow-poplar, etc.) are expected to show the most immediate response to weeding, while shade intermediate species (i.e., oaks [*Quercus* spp.] and hickories [*Carya* spp.]) will likely experience a delayed growth response. Overall, results indicate a balance between the effects herbivory, overstory removal, and understory competition control. To improve regeneration potential of recently harvested stands, weeding 1.13 m plots directly surrounding the single desired stem is suggested for most species, particularly if deer populations are low and there is an abundance of vegetation

preferred by deer (e.g. *Rubus* spp.). Weeding white oak should only be applied to smaller stature white oaks, less than about 5 mm RCD or 25 cm HT₀, particularly on sites with more intense harvests where competing vegetation may be more dense. Targeted fertilization is also recommended overall, though nutrient demanding species (e.g. black cherry or yellow-poplar) show the best response. However, when deer pressures are high, fertilization should be applied with caution to red oak. In these situations, consider fertilizing red oak only when they are shorter than 25 cm HT₀. As the stand continues to develop, targeted weeding and fertilization treatments may more ubiquitously prove an effective way of improving regeneration of desired species and balancing the effects of biological constraints.

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Figure 1. Map of the site locations in Preston County and Monongalia County, West Virginia.

Figure 2. Schematic for the measurement for worst aggressor above the target seedling.

Figure 3. The proportion of stems that were aggressed one growing season following (a) weeding and (b) fertilization treatment. Lowercase letters denote significant differences.

Figure 4. The (a) first year and (b) second year proportion of stems that were aggressed by species. Lowercase letters denote significant differences between species obtained using Chi-Squared multiple comparisons with sequential Bonferroni adjustments.

Figure 5. The proportion of stems that were aggressed two growing seasons following (a) weeding and (b) fertilization treatment. Lowercase letters denote significant differences.

Figure 6. The (a) first year and (b) second year proportion of stems that were browsed by species. Lowercase letters denote significant differences in total browse between species obtained using Chi-Squared multiple comparisons with sequential Bonferroni adjustments.

Figure 7. The proportion of stems that were browsed the first growing season after (a) weeding and (b) fertilization treatment. Lowercase letters denote significant differences in total browse.

Figure 8. The proportion of stems that were browsed the second growing season after (a) weeding and (b) fertilization treatment. Lowercase letters denote significant differences in total browse.

Figure 9. The height growth of all seedlings in response to the weeding effect based on their initial height. Untransformed data used for visualization, analysis performed on transformed data.

Figure 10. Examination of species-specific responses to fertilization dependent upon height at treatment application. Sub-models for each species using sequential Bonferroni adjustments were utilized to determine individual species significances. Untransformed data used for visualization, analysis performed on transformed data.

Figure 11. The height growth two years post-treatment for each species in response to fertilization. Asterisks denote significant responses to fertilization using Tukey-Kramer adjusted pairwise comparisons. Untransformed data used for visualization, analysis performed on transformed data. Error bars represent one standard error.

Figure 12. Species-specific RCD growth response to weed control application dependent upon RCD at treatment application. Untransformed data used for visualization, analysis performed on transformed data.

Figure 13. Two-year RCD growth for each species in response to weed control. Asterisk denotes significant responses to weed control using Tukey pairwise comparisons. Untransformed data used for visualization, analysis performed on transformed data. Error bars represent one standard error.

Figure 14. Two-year survival probabilities for each species. Lowercase letters indicate significant differences in survival between species using Tukey comparisons. Error bars represent one standard error.

Figure 15. Two-year survival probabilities for seedlings based on treatment combinations that were applied. Error bars represent one standard error.

Figure 16. Two-year survival probabilities for all seedlings based on height at treatment application. Untransformed data used for visualization, analysis performed on transformed data.

Table 1. The general site description for each study site. (SW = shelterwood, CC = clearcut)

Site	Harvest	Pre-Harvest Dominants	Soil Series ¹	Slope	Aspect	Site Index (m)
Archery Range (AR)	60% SW	Red oaks ^a	Dekalb loam	3-25%	West	21.4
Goodspeed Road (GS)	60% SW	Red oaks ^a	Dekalb stony loam	8-15%	South	20.9
Johnson's Hollow (JH)	60% SW	Red oaks ^a	Dekalb Channery loam	8-15%	West	20.3
Rowlesburg (RB)	CC	White oak	Calvin silt loam	25-65%	South	23.7

^a Red oaks include northern red oak (*Quercus rubra* L.), black oak (*Q. velutina* Lam.), and scarlet oak (*Q. coccinea* Muenchh.).

¹Obtained from WebSoilSurvey.

Table 2. Soil nutrient status of each study site measured using Mehlich-1 extractions.

Site	pH	Nutrients				CEC	BS
		P	K	Ca	Mg	Total	Total
		----- ppm -----				-- MEQ 100g ⁻¹ --	--- % ---
Archery Range	4.1	13.4	198.7	567.3	94.0	23.3	6.3
Goodspeed Road	4.2	15.1	256.8	599.3	82.7	19.0	7.3
Johnson's Hollow	4.5	9.9	396.8	389.3	70.0	15.7	7.3
Rowlesburg	4.6	10.5	266.7	705.3	146.0	12.3	13.7

Table 3. Sample size of seedlings for each species/treatment combination found alive two growing seasons post-treatment application in the spring of 2015.

Species	Treatment				Total
	Control	Weeded	Fertilized	Weed + fert	
Black cherry	101	80	74	87	342
Chestnut oak	69	62	60	65	256
Red oaks ^a	100	84	81	86	351
White oak	35	31	30	28	124
Total	305	245	266	257	1073

^a Red oaks include northern red oak (*Quercus rubra* L.), black oak (*Q. velutina* Lam.), and scarlet oak (*Q. coccinea* Muenchh.).

Table 4. Percent of seedlings that survived two growing seasons post-treatment for each species/treatment combination.

Species	Treatment				Total
	Control	Weeded	Fertilized	Weed + fert	
Black cherry	88	91	95	86	90
Chestnut oak	94	98	98	94	96
Red oaks ^a	84	95	90	93	90
White oak	97	94	100	93	96
Total	89	95	95	91	92

^a Red oaks include northern red oak (*Quercus rubra* L.), black oak (*Q. velutina* Lam.), and scarlet oak (*Q. coccinea* Muenchh.).

Table 5. A summary of the worst aggressor groupings for the first growing season (2015) for each species/treatment combination.

Species	Treatment	Worst Aggressor Category					Total Aggressed*
		None	Woody non-arb.	Fast trees	Slow trees	Herb.	
		----- % -----					
Black cherry	Control	9.5	70.5	8.4	4.2	7.4	90.5
Chestnut oak	Control	11.8	73.5	8.8	1.5	4.4	88.2
Red oaks ^a	Control	8.5	69.1	7.5	6.4	8.5	91.5
White oak	Control	8.3	61.1	11.1	16.7	2.8	91.7
Average control		9.6	69.6	8.5	5.8	6.5	90.4
Black cherry	Weeded	57.5	30.0	3.8	3.8	5.0	72.5
Chestnut oak	Weeded	66.1	29.0	1.6	1.6	1.6	33.9
Red oaks ^a	Weeded	62.2	32.1	1.2	2.5	2.5	38.3
White oak	Weeded	32.3	54.8	6.5	6.5	0.0	67.7
Average weeded		57.9	33.5	2.8	3.1	2.8	42.1
Black cherry	Fertilized	7.9	72.2	4.2	5.6	8.5	93.0
Chestnut oak	Fertilized	8.3	66.7	10.0	3.3	10.0	91.7
Red oaks ^a	Fertilized	5.1	72.2	10.1	2.5	10.1	94.9
White oak	Fertilized	10.0	66.7	6.7	6.7	10.0	90.0
Average fertilized		7.1	71.1	7.9	4.2	9.6	92.9
Black cherry	Weed + fert	53.2	35.4	3.8	0.0	7.6	46.8
Chestnut oak	Weed + fert	61.9	25.4	6.4	3.2	3.2	38.1
Red oaks ^a	Weed + fert	49.4	35.3	11.8	1.2	2.4	50.6
White oak	Weed + fert	35.7	42.9	3.6	14.3	3.6	64.3
Average weed + fert		52.2	33.7	7.1	2.8	4.3	47.8
Cumulative weeded		55.0	33.6	4.9	3.0	3.5	45.0
Cumulative non-weeded		8.4	70.4	8.2	5.1	7.9	91.6
Grand Total		31.2	52.4	6.6	4.0	5.8	68.8

^a Red oaks include northern red oak (*Quercus rubra* L.), black oak (*Q. velutina* Lam.), and scarlet oak (*Q. coccinea* Muenchh.).

* Cumulative of woody non-arborescent, fast trees, slow trees, and herbaceous aggressors.

Table 6. A summary of the worst aggressor groupings for the second growing season (2016) for each species/treatment combination.

Species	Treatment	Worst Aggressor Category					Total Aggressed*
		None	Woody non-arb.	Fast trees	Slow trees	Herb.	
		----- % -----					
Black cherry	Control	5.7	55.7	25.0	9.1	4.6	94.3
Chestnut oak	Control	24.6	50.8	20.0	3.1	1.5	75.4
Red oaks ^a	Control	8.1	65.1	15.1	7.0	4.7	91.9
White oak	Control	11.8	50.0	11.8	20.6	5.9	88.2
Average control		11.7	56.8	19.1	8.4	4.0	88.3
Black cherry	Weeded	13.9	70.8	11.1	4.2	0.0	86.1
Chestnut oak	Weeded	37.7	47.5	6.6	6.6	1.6	62.3
Red oaks ^a	Weeded	32.9	51.9	7.6	6.3	1.3	67.1
White oak	Weeded	17.2	58.6	13.8	10.3	0.0	82.8
Average weeded		26.6	57.3	9.1	6.2	0.8	73.4
Black cherry	Fertilized	2.9	78.6	12.9	4.3	1.4	97.1
Chestnut oak	Fertilized	30.5	33.9	18.6	11.9	5.1	69.5
Red oaks ^a	Fertilized	9.7	62.5	19.4	4.2	4.2	90.3
White oak	Fertilized	13.3	56.7	13.3	13.3	3.3	86.7
Average fertilized		13.4	59.3	16.5	7.4	3.5	86.6
Black cherry	Weed + fert	29.3	53.3	8.0	2.7	6.7	70.7
Chestnut oak	Weed + fert	50.0	32.3	9.7	6.5	1.6	50.0
Red oaks ^a	Weed + fert	29.1	51.9	11.4	0.0	7.6	70.9
White oak	Weed + fert	19.2	42.3	19.2	15.4	3.9	80.8
Average weed + fert		33.5	46.3	10.7	4.1	5.4	66.5
Cumulative weeded		30.0	51.8	9.9	5.2	3.1	70.0
Cumulative non-weeded		12.5	57.8	17.9	7.9	3.4	87.5
Grand Total		21.1	54.9	14.0	6.6	3.4	78.9

^a Red oaks include northern red oak (*Quercus rubra* L.), black oak (*Q. velutina* Lam.), and scarlet oak (*Q. coccinea* Muenchh.).

* Cumulative of woody non-arborescent, fast trees, slow trees, and herbaceous aggressors.

Table 7. A summary of the deer browse classifications for the first growing season (2015) for each species/treatment combination.

Species	Treatment	Browse Rating						Total Browsed*
		None (0)	Minimal (1)	Low (2)	Moderate (3)	High (4)	Severe (5)	
----- % -----								
Black cherry	Control	89.5	5.3	3.2	0.0	2.1	0.0	10.5
Black cherry	Weeded	78.8	5.0	3.8	8.8	2.5	1.3	21.3
Black cherry	Fertilized	76.1	9.9	4.3	4.2	5.6	0.0	23.9
Black cherry	Weed + fert	70.9	6.3	3.8	6.3	10.1	2.5	29.1
Average black cherry		79.4	6.5	3.7	4.6	4.9	0.9	20.6
Chestnut oak	Control	73.5	10.3	2.9	5.9	5.9	1.5	26.5
Chestnut oak	Weeded	48.4	3.2	14.5	16.1	17.7	0.0	51.6
Chestnut oak	Fertilized	70.0	6.7	6.7	3.3	8.3	5.0	30.0
Chestnut oak	Weed + fert	61.9	9.5	9.5	7.9	7.9	3.2	38.1
Average chestnut oak		63.6	7.5	8.3	8.3	9.9	2.4	36.4
Red oaks ^a	Control	83.0	3.2	4.3	3.2	5.3	1.1	17.0
Red oaks ^a	Weeded	69.1	6.1	4.9	4.9	12.2	2.4	30.9
Red oaks ^a	Fertilized	73.4	5.0	3.8	7.5	6.3	3.8	26.6
Red oaks ^a	Weed + fert	62.4	7.1	5.9	10.6	7.1	7.1	37.6
Average red oaks ^a		72.3	5.3	4.7	6.5	7.7	3.5	27.7
White oak	Control	94.4	2.8	2.8	0.0	0.0	0.0	5.6
White oak	Weeded	80.1	9.7	6.5	3.2	0.0	0.0	19.4
White oak	Fertilized	90.0	6.7	3.3	0.0	0.0	0.0	10.0
White oak	Weed + fert	64.3	10.7	7.1	7.1	7.1	3.6	35.7
Average white oak		83.2	7.2	4.8	2.4	1.6	0.8	16.8
Grand Total		73.7	6.4	5.3	5.9	6.6	2.1	26.3

^a Red oaks include northern red oak (*Quercus rubra* L.), black oak (*Q. velutina* Lam.), and scarlet oak (*Q. coccinea* Muenchh.).

* Cumulative of minimal (1) to severe (5) browse measures.

Table 8. A summary of the deer browse classifications for the second growing season (2016) for each species/treatment combination.

Species	Treatment	Browse Rating						Total Browsed*
		None (0)	Minimal (1)	Low (2)	Moderate (3)	High (4)	Severe (5)	
----- % -----								
Black cherry	Control	80.7	3.4	9.1	2.3	2.3	2.3	19.3
Black cherry	Weeded	70.8	0.0	15.3	4.2	2.8	6.9	29.2
Black cherry	Fertilized	82.9	0.0	10.0	4.3	0.0	2.9	17.1
Black cherry	Weed + fert	74.7	4.0	4.0	6.7	6.7	4.0	25.3
Average black cherry		77.4	2.0	9.5	4.3	3.0	3.9	22.6
Chestnut oak	Control	87.7	4.6	3.1	1.5	3.1	0.0	12.3
Chestnut oak	Weeded	57.4	6.6	8.2	9.8	9.8	8.2	42.6
Chestnut oak	Fertilized	78.0	11.9	5.1	3.4	0.0	1.7	22.0
Chestnut oak	Weed + fert	58.1	8.1	8.1	11.3	6.5	8.1	41.9
Average chestnut oak		70.5	7.7	6.1	6.5	4.9	4.5	29.6
Red oaks ^a	Control	82.6	5.9	2.4	2.4	1.2	5.9	17.4
Red oaks ^a	Weeded	59.5	8.9	2.5	10.1	10.1	8.9	40.1
Red oaks ^a	Fertilized	76.4	4.2	6.9	4.2	4.2	4.2	23.6
Red oaks ^a	Weed + fert	63.3	10.1	10.1	3.8	3.8	8.9	36.7
Average red oaks ^a		70.5	7.3	5.4	5.1	4.7	7.0	29.5
White oak	Control	85.3	5.9	2.9	0.0	5.9	0.0	14.7
White oak	Weeded	93.1	3.4	3.4	0.0	0.0	0.0	6.9
White oak	Fertilized	96.7	0.0	0.0	0.0	0.0	3.3	3.3
White oak	Weed + fert	69.2	7.7	7.7	7.7	3.8	3.8	30.8
Average white oak		86.6	4.2	3.4	1.7	2.5	1.7	13.5
Grand Total		74.6	5.4	6.6	4.8	4.0	4.7	25.4

^a Red oaks include northern red oak (*Quercus rubra* L.), black oak (*Q. velutina* Lam.), and scarlet oak (*Q. coccinea* Muenchh.).

* Cumulative of minimal (1) to severe (5) browse measures.

Table 9. Linear functions predicting second-year heights (cm) by species in a recently harvested hardwood stand in response to treatment application per the general model:

$$HT_2 = B_0 + B_1(HT_0) + B_2(RCD_0) + B_3(SI) + B_4(F) + B_5(HT_0W) + B_6(HT_0F).$$

Species	N	β_0	β_1	β_2	β_3	β_4	β_5	β_6	p-value	Adj. R ²
Black cherry	305	-77.790	0.7681	8.2679	3.6518	19.208	-0.4365		<0.0001	0.5782
Chestnut oak	246	-56.288	2.2721	0.8682	2.8673		-0.2774		<0.0001	0.5681
Red oaks ^a	315	97.316	1.3832	5.1145	-4.4571	17.217	-0.3785	-0.5817	<0.0001	0.4881
White oak	34	-18.8618	0.7747	7.4230	1.0515	13.169	-0.3258		<0.0001	0.5549

^a Red oaks include northern red oak (*Quercus rubra* L.), black oak (*Q. velutina* Lam.), and scarlet oak (*Q. coccinea* Muenchh.).

Table 10. Range and means of height and RCD data used in development of the predicted linear functions.

Species	RCD range at treatment	Mean RCD at treatment	HT range at treatment	Mean HT at treatment	Mean HT 2GS post-treatment
	----- mm -----		----- cm -----		
Black cherry	0.3 – 15.9	4.5	3 – 197	44	71
Chestnut oak	0.6 – 11.8	4.2	9 – 98	34	78
Red oaks ^a	0.5 – 11.0	4.3	6 – 93	27	57
White oak	0.8 – 10.5	4.0	6 – 84	27	59

^a Red oaks include northern red oak (*Quercus rubra* L.), black oak (*Q. velutina* Lam.), and scarlet oak (*Q. coccinea* Muenchh.).