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Oak and Yellow-Poplar Response to Pre-Commercial Chemical Applications After Clearcutting A High-Graded Hardwood Stand on the Western Highland Rim of Tennessee

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To the Graduate Council:

I am submitting herewith a dissertation written by Stephen Eric Peairs entitled "Oak and Yellow-Poplar Response to Pre-Commercial Chemical Applications After Clearcutting A High-Graded Hardwood Stand on the Western Highland Rim of Tennessee." I have examined the final electronic copy of this dissertation for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Doctor of Philosophy, with a major in Natural Resources.

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Oak and Yellow-Poplar Response to Pre-Commercial Chemical Applications After Clearcutting A High-Graded Hardwood Stand on the Western Highland Rim of Tennessee

A Dissertation Presented for the
Doctor of Philosophy
Degree
The University of Tennessee, Knoxville

Stephen Eric Peairs
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DEDICATION

This work is dedicated to my late mother, Sue Nell Travis. She believed more in my ability to get this work completed than I had in myself. I owe her a tremendous amount for promoting within me a love for nature and the outdoors. She always supported me through life as a loving mother will do for her child. My mom did not get to see me complete this degree as she passed away in the Fall of 2016, but I know she would be proud of this accomplishment. This one’s for you Mom!

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ABSTRACT

The repetitious use of diameter-limit harvesting in upland hardwoods has led to low-valued stands with understory canopy layers containing mostly shade-tolerant species. Desirable, shade intolerant reproduction is limited to regenerate these stands. This study evaluated the effectiveness of post-harvest herbicides (glyphosate and sulfometuron methyl) and application methods to accelerate the growth of natural oak advance reproduction. Treatment areas received clearcut treatments in the late winter/early spring of 2014. Six treatment units were established using banded foliar sprays, radial release sprays, pre-emergent broadcast sprays, or combinations of methods, along with an untreated control. Permanent regeneration plots were measured pre-harvest and after harvest (fall 2014) to evaluate the regeneration response. Individual white and red oak species along with yellow-poplar seedlings were measured for ground line diameter and overall height. Second measurements were taken in the winter of 2017 (two growing seasons later) to determine diameter and height growth change. Yellow-poplar and oak species reproduction per acre estimates, for the 2017 measurements, for block A, B, and C were 850, 1,900, and 233 seedlings. Shade intolerant reproduction formed a greater abundance compared to the shade tolerant species. It is proposed that the larger shade tolerant reproduction present before harvest was completely removed during the timber harvest activity. Significant differences were found between herbicide applications for absolute ground line diameter change for combined seedlings ($P=0.0037$), absolute height change for combined seedlings ($P<0.0001$), diameter growth among species ($P=0.02988$), height growth among species ($P=0.0399$), diameter change for sprout reproduction ($P=0.0268$), height change in new germinant reproduction ($P=0.0245$), height change for sprout reproduction ($P<0.0001$). Change in ground line diameter for yellow-poplar new germinants was significant ($P=0.0161$). The change in height comparisons for the species with size class found yellow-poplar sprout reproduction ($P=0.0031$), white oak new germinant and sprout reproduction were different ($P=0.0152$ and $P<0.0001$, respectively). Sulfometuron methyl only treatments typically had the greatest growth responses while radial treatments using glyphosate performed the poorest. A dense coverage of grasses established following herbicide applications. The emergence of grass likely reduced growth rates due to altered microenvironments as well as competition for root zone growing space, soil moisture, and nutrients.

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1. STATEMENT OF THE PROBLEM

Diameter-limit harvesting is commonly practiced in the central hardwood region by timber companies, and the use thereof is supported by private landowners. In forested stands that have been indiscriminately cut over several times, the regeneration response of desirable species can be at best, compromised. An abundance of shade tolerant species typically persist in the midstory and understory canopy positions of these stands. Advanced oak reproduction stocking is minimal. The application of the silvicultural clearcut regeneration method is commonly the optimal prescription used to regenerate the stand with more desirable, shade intolerant species. Following the clearcut, seedling stocking density is high which affects juvenile growth rates. The application of herbaceous weed control in conjunction with directed foliar spray applications of glyphosate herbicide to reduce stocking density will improve growth of released seedlings. Targeted herbicide application may improve the slower- growing oaks' competitive status compared to faster-growing shade intolerant species, including yellow-poplar. A reduction in competing plant species around individual seedlings may also promote improved growth of preferred tree species. In addition, species could also be selected to alter the future stand's composition. Herbicide applications applied in the initial year following disturbance can be accomplished operationally to successfully improve stands by using precision targeting to minimize potential loss of beneficial stems. Such silvicultural activities will advance adequate stocking of desirable species that may reduce rotation age, increasing the financial rate of return relative to forest management. A high-graded stand results from the removal of the more valuable trees from the stand while retaining the poorer growing stock. Such stands may need a greater level of active management to successfully regenerate desirable shade intolerant species. This study examines whether adequate oak regeneration will establish and develop in a high-graded stand, by implementation of silvicultural clearcutting, and if early herbicide applications applied at the incipient stages of stand re-initiation can improve early growth of naturally regenerated oak and yellow-poplar seedlings. Initial hypotheses include 1) regeneration will favor shade tolerant species following disturbance and 2) greater growth responses will be directly related to increased intensity of herbicide applications. In other words, applications involving both sulfometuron methyl and glyphosate herbicides should maximize seedling growth. Sulfometuron is commonly used to release seedlings from herbaceous competition.

Glyphosate is a broad spectrum herbicide that can kill woody plants but is also utilized for seedling release.

2. <u>LITERATURE REVIEW</u>

Diameter Limit Harvesting

Sustainable forestry implies that desirable timber species can be commercially harvested, but are successfully regenerated to form future stands. Income derived from timber sales propels forest management. In the southeastern United States, higher financial values are associated with high-grade, shade intolerant trees. Proper silvicultural prescriptions coupled with sound timber harvesting methodology promotes the sustainability objective. Unfortunately, too often improper timber extraction in the form of diameter limit harvesting is conducted to maximize immediate economic return while minimizing logging costs. This practice involves removing only the larger sized stems above a threshold diameter from a forested stand. However, diameter-limit harvesting practices often result in impoverished stands (Fajvan 2006). The widespread implementation of this harvesting technique is a leading cause to the decreased true value of otherwise economically attractive timberland (Fajvan and others 1998). Noss and others (1995) proposed that high-quality oak/hickory forests are on the decline in areas across the central and southern Appalachians. The authors also suggest that degrade in quality is attributed to species composition shifts resulting from diameter-limit harvesting. The prevalence of shade tolerant tree species is less advantageous for forest management compared to stands with greater compositions of shade intolerant species. Trimble (1973) reported that repeated single-tree selection and diameter-limit harvesting lead to a higher proportion of shade tolerant species in the overall stand species composition along with a general reduction in species diversity. Often times, oak stem abundance is significantly reduced following such timber harvests due to the loss of desirable parent growing stock. The reduction in seed sources for preferred financially attractive species occurs as they are targeted for removal. It is well-documented that harvesting of timber used in the production of hardwood products is species and quality driven (Luppold and Pugh 2016). Fajvan and others (1998) observed that 36% of surveyed timber harvests in West Virginia in 1995 reduced the basal area of northern red oak (*Quercus rubra*), white oak (*Quercus alba*), yellow-poplar (*Liriodendron tulipifera*), ash (*Fraxinus sp.*), and black cherry (*Prunus serotina*) by more than 80%. Fajvan (2006) assessed ninety-nine timber harvests in West Virginia and observed that red maple regeneration density was almost three times greater than yellow-poplar at 4 – 5 years post timber harvest. The author suggested that red maple height growth is promoted over black cherry and yellow-poplar growth due to the shading created by the residual overstory in diameter limit harvest areas. Red oak species only comprised 1% of the codominant/dominant stems and were usually overtopped by other tree species. The original stands in their study contained an average stocking for northern red oak of 45 square feet of basal area per acre. The inability of oak reproduction to establish greater crown positions is of great concern amongst researchers and the implementation of diameter limit harvesting only compounds this problem (Schuler and others 2016).

Oak Regeneration Establishment

Establishment of adequate oak reproduction is problematic in undisturbed and properly managed hardwood stands. Oak (*Quercus* sp.) are some of the most difficult tree species to attempt to regenerate using common silvicultural practices and natural seed stock (Hannah 1987). Few acorns produced during a mast crop will germinate and form a seedling (Downs and McQuilkin 1944, Marquis and others 1976). Oak seedling establishment is typically dependent on masting events as most seeds are consumed during non-mast years (Lorimer 1993). Impacts from predation by insects and animals inhibit the establishment of oak reproduction (Marquis and others 1976, Galford and others 1991). Seed desiccation due to a loss of seed moisture content that occurs in the winter dormant season is a major cause of seed loss (Korstain 1927). Downs and McQuilkin (1944) reported that only about 18% of white oak acorns studied in their project were sound enough to germinate and further approximately 6% of these seedlings had at least a fair chance to survive. They also suggest that a minimum of eight seed trees per acre are needed to supply enough acorns for germination. For those acorns that do survive, adequate light must be available for the seedling to grow in size and become an overstory tree. Carvell and Tryon (1961) reported that oak's ability to become established was not related to environmental conditions, but to their ability to persist. The primary reason that oak reproduction fails to form dominance in the future stand is usually attributed to a lack of adequate, sizeable advanced reproduction present at disturbance (Sander 1971). Slow growth rates also contribute to less competitiveness by oak as compared to faster growing species, such as yellow-poplar, to capture available growing space. The abundance of shade-tolerant stems in the understory and midstory of oak-dominated stands has been linked to changes in disturbance regimes, changes in climate, changes in herbivore pressure, loss of native species, and the establishment of alien species (McEwan and others 2011). Introducing a process of disturbance via silviculture prescriptions that mimic those that resulted in oak-dominant stands has proved to be challenging across the east (Loftis 1990, Schweitzer and Dey 2011, Hutchinson and others 2016, Miller and others 2016, Schuler and others 2016). It has been hypothesized that historically, relatively open conditions in oak-dominated stands were maintained by frequent, low-intensity, surface fires that removed fire-sensitive species and favored fire-tolerant oak in the regeneration layer (Abrams 1992, Hanberry and others 2014, Stambaugh and others 2015). This explanation for the widespread and long-term dominance of oak is known as the fire and oak hypothesis (Abrams 1992, Arthur and others 2012). Many oak species are generally drought tolerant, have relatively thick bark, readily stump sprout, and compartmentalize wounds; all fire adapted traits (Abrams 1992, Stambaugh and others 2015)

The establishment of oak reproduction initially requires an abundance of viable acorns. Greenberg and Parresol (2000) found that on average years, 29% of oak stems in a given stand will produce acorns; whereas in a good year, between 70 – 90% of oak trees will yield acorns. Acorn production consistency typically ranges between species and individual trees (Downs and McQuilking 1944, Burns and others 1954, Gysel 1956, Sharp and Sprague 1967, Christisen and Kearby 1984, Koenig and others 1994, Sork and others 1993). Goodrum and others (1971) suggest that intrinsic features such as age or size influence acorn production. Others demonstrate some relationship between external conditions such as stand density and acorn production (Healy, 1997). Results of this study confirm Beck’s (1977) findings that on average, northern red and white oak are superior acorn producers. However, this study among others clearly illustrate the importance of maintaining mixed oak stands, since interspecific differences in temporal masting patterns often offset complete mast failures (Beck and Olson, 1968, Beck 1977, Chistisen and Kearby 1984, Koenig and others 1994). Further, the distinction between numbers versus green weight and dry, edible biomass of acorns produced is important for land managers who wish to maintain a specified mast capability in forest stands.

Given the enormous variation in fecundity among individuals, it is not surprising that larger trees produce more acorns; this is primarily by virtue of their proportionately larger crowns. Tree diameter alone contributed little to differences in fecundity among individual trees. Stems in the more dominant size classes supply the bulk of seed available. Downs and McQuilkin (1944) observed the best crops typically occur on sizeable trees with diameters at breast height of twenty inches or greater and having vigorous crowns. Burns and others (1954) observed that larger crowned oaks typically produced more mast in a given stand. These dominant stems are typically targeted for harvest during diameter limit harvests.

High variability in acorn production among individual trees obscures any potential relationship between tree size and the number of acorns/m^2 BA. The weak to non-existent relationship between tree BA alone and acorn productivity has been noted in other studies (Downs and McQuilken 1944, Burns and others 1954, Gysel 1956, Sharp and Sprague 1967, Chistisen and Kearby 1984, Koenig and others 1991, Sork and others 1993).

The loss of parent oaks is particularly problematic if advanced oak reproduction is not already established on the forest floor. In the case of mature upland hardwood stands that have remained undisturbed, advanced oak reproduction is usually lacking or near non-existent in understory positions (Hodges and Gardiner 1992). *Quercus* species are desirable, and a considerable body of work has been published detailing Quercus ecology and silviculture (Johnson and others 2009). Various scientists have advocated the use of selection (Loewenstein and others (2000), in xeric Quercus forests), shelterwood, and clearcut regeneration methods (Roach and Gingrich 1968, Sander 1977, Loftis 1990, Johnson and others 2009) to sustain *Quercus* dominated forests depending on the site quality, region and competing species. But failures to regenerate Quercus by these various methods also are commonly reported in the literature (refer to review by Johnson and others 2009).

Various silvicultural practices are typically required to enable oak to develop into competitive size classes. Even when an abundance of oak germinants occurs after a good seed crop, sheer numbers of small seedlings are not enough to ensure oak regeneration success to form the future stand (Janzen and Hodges 1987, Lockhart and others 2000, Stringer 2005. Sander 1979, Smith 1986, Hannah 1987, Loftis 1983, Loftis 1990, Beck 1991, Schweitzer and Dey 2011). Ward and Stephens (1994) suggested that oaks which show early dominance have the best chance to survive and establish a place of prominence in the upper crown classes once the stand reaches maturity. Sander (1971) suggested that advance reproduction is imperative for asexual reproduction via sprout growth following clearcutting. His study indicated that oak sprout growth was related to ground line diameter of the stem and that larger seedlings or saplings resprouted and grew at faster rates. Other studies also supported that stem diameter was a significant predictor of sprouting potential following timber harvest (Johnson 1977, Bruggink 1988, Weigel and Peng 2002). The most optimal stem size for sprouting were stems between one-half to one inch in diameter as these stems were able to attain a position in the dominant canopy and produced fewer sprouts per stem compared to regeneration greater than one inch. Oaks, however, lose their propensity for developing stump sprouts with increasing stump diameter or age (Johnson 1977, Johnson 1992, McGee and Bivens 1984, Weigel and Peng 2002). A pre-commercial crop tree release, which thins coppice oak sprouts down to one individual stem, will increase height, diameter at breast height and volume compared to stump sprouts with multiple stems (Lowell and others 1989, Dwyer and others 1993).

Various studies have provided acceptable stocking levels of advanced oak regeneration necessary to assure oak prevalence in future mature stands. Clatterbuck and Meadows (1993) estimate that a bottomland hardwood stand has fully regenerated to oak if it has at least 150 free-to-grow oak stems per acre three years after harvest. Similarly, Sander (1972) advocates having at least four hundred well-distributed, large (4½ feet tall) oak stems per acre. Resprouts from large seedlings of this size had the greatest height growth and were the only size of oak reproduction that obtained dominant or codominant crown class twelve years after overstory removal. Sprouts that originated from large advance reproduction grew almost three feet in height during each of the first two years following complete overstory removal (Sander 1972). Retention of some oak as residual stems could potentially serve as a regeneration source.
The use of diameter-limit harvesting as multiple entries over time often removes most all desirable parent trees that could supply seed for regeneration. Diameter-limit harvested areas typically contain a greater abundance of shade tolerant regeneration and low levels of established oak reproduction on the forest floor (Fajvan 2006, Heilegmann and Ward 1993, Heilegmann and others 1985, Smith and Miller 1987, Trimble 1973). At the point where a stand exhibits these conditions, the land manager's optimal solution is to provide more sunlight to create favorable environmental conditions for higher financially valued, shade intolerant species establishment. In some regions, such as the northeast, shade tolerant sugar maple may also be acceptable growing stock and could be targeted for management. These impoverished stands may then become successfully regenerated with desirable tree species at an acceptable stocking rate to form the future stand. The use of the clearcut regeneration method often maximizes the abundance of desirable natural hardwood regeneration compared to other regeneration methods (Clatterbuck and others 1999, Ward and Stephens 1999, Jensen and Kabrick 2008). Even-aged regeneration methods, including the clearcut and shelterwood harvest methods, usually have a high

reproduction establishment rate of 10,000 – 40,000 stems per acre (Johnson and Krinard 1988, Romagosa and Robison 2003).

Schweitzer and others (2006) observed that planted oak seedlings growing in full-sun within a clearcut were statistically taller and had greater leaf density and flushes after one growing season compared to oak seedlings grown in shaded conditions under a shelterwood harvest area. These researchers also discovered that after one growing season, the sun grown oak seedlings planted in a clearcut had greater basal area growth than oak seedlings in the shelterwood areas. Sander (1972) reported that complete overstory removal had significantly taller natural oak reproduction after two years than both partially cut and uncut plots. In this study, the seedlings within completely cut plots averaged almost twice the height of seedlings in uncut plots after twelve years. Miller and others (2006) also stated that shade intolerant reproduction has 30 – 40% greater basal area production, twenty years after disturbance, in clearcuts compared to shaded environments in two-aged and shelterwood harvested stands. These findings suggest that the clearcut method favors shade intolerant regeneration and oak development if an adequate number and size of oak advanced reproduction are present.

Natural regeneration is also the more economically attractive management option due to the inhibitive cost of establishing hardwood regeneration via artificial means (Duryea and Dougherty 1991, Minore and Laacke 1992). Greater growth may also be expected from relying on natural regeneration compared to artificial regeneration. A study conducted in east Tennessee concluded that natural oak regeneration in a clearcut harvest had significantly greater growth (94% for white oak and 228% for northern red oak) compared to hand planted oak seedlings (Jackson 2006) 36 years after establishment. Though oak reproduction recruitment is often elevated following a clearcut harvest, these seedlings and sprouts have slow growth rates and are rapidly overtopped by pioneer tree species and herbaceous vegetation (Hannah 1987, Nix 1989).

Clearcutting for Regeneration

Sunlight exposure is maximized following a clearcut harvest which stimulates a wide range of plant types. A high emergence of various vegetation including less desirable tree species, herbaceous weeds, and grasses can inhibit oak seedling development or even cause mortality (Robison and others 2003, Stringer and others 2009). Many oak stems in young stands succumb to competition for growing space and limited resources before, during, and after crown closure. Johnson and others (1989) documented that red oak density decreased by 69% between the ages of 5 – 11 years of age. Ward and Heilegmannn (1990) similarly reported oak density decreased by 92% during the initial 18 – 20 years after clearcutting. Future prevalence of northern red oak in dominant or codominant crown positions within a clearcut at age twenty is less than half of the northern red oak present in the upper canopy when the stand was at eight years of age (Loftis 1990).

Research findings suggest that supplying adequate sunlight by controlling competing vegetation is critical for keeping oaks dominant and free to grow (Abrams 1992, Hannah 1987, Loftis 1990, Dey and Parker 1996, Ward 2009). The majority of oak species are listed as either intolerant or intermediate in shade tolerance (Burns and Honkala 1990, Clatterbuck 2005). When overtopped by dense plant competition, oak stem height growth is suppressed and mortality can occur. Lorimer (1981) revealed that oaks must be in dominant or codominant crown positions to have acceptable survival for the initial forty years after a disturbance. Thus, some form of silvicultural activity, such as cleaning and weeding, may be necessary to keep oaks competitive. Early release treatments have also been suggested following a clearcut to maintain oak competitiveness; this may enable oak stems to eventually obtain a dominant canopy position (Beck 1970, Hannah 1987). Such releases should be applied when the regenerating stand is four to five years of age (Beck 1970), although Thompson and Nix (1992) advise an even earlier application prior to the extreme overtopping by competing vegetation. Without some form of silvicultural management, non-oak species grow into larger size classes and become more likely to outcompete the preferred oak regeneration (Beck and Hooper 1986, Johnson and others 1989, Ward and Heilegmannn 1990).

Thinning and Prescribed Fire to Favor Oak Reproduction

Prescribed fire and herbicide have been studied as methods to keep oaks competitive while suppressing unwanted competition from other tree species. The implementation of fire alone has not successfully suggested that this management tool will successfully establish advanced oak reproduction. The results of prescribed fire vary in part due to differing fire intensity related to the season of burn (Van Lear and others 2000). Hardwood resprouting ability is greatest when carbohydrates reserves within the roots are high. This is most evident in the dormant season (Van Lear and others 2000). Implementing growing season burns is suggested to reduce less desirable hardwoods (Brose and Van Lear 1998). In addition, fires of higher intensity have shown greater control levels of competing hardwood species. Brose and others (1999) state that an area that receives a high-intensity spring burn will develop into an oak dominated forest (75 – 80% of species composition) after just one prescribed burn. These researchers observed that oak seedlings were about three times more abundant in burned areas versus that found in unburned controls.

Generally, multiple fires conducted over a decade or more will be required to adequately regenerate oak (Hutchinson and others 2012). Numerous fires are needed to suppress the more rapidly growing shade intolerant tree species as well as other competitors such as red maple. Though fire may topkill multiple competing species, a significant proportion of these plants will resprout from root suckers or from the stump (Dey and Fan 2008, Albrecht and McCarthy 2006, Iverson and others 2017). Huntley and McGee (1981) found that red maple resprouted vigorously and increased in abundance following burning activity. The authors also revealed that the more desirable northern red oak did not resprout to the same degree as black, scarlet, white, or chestnut oak, and that the preferred species' regeneration abundance actually declined on site. Alternatively, Brose and Van Lear (1998) indicated that fire intensity was critical in controlling yellow-poplar reproduction and to improve the growth rate of sprouting oaks. They stated that yellow-poplar and other competing species did still occupy the site and that additional fires would likely be necessary to enable oaks to dominate the site. Brose and others (1999) proposed that areas receiving low intensity fires, regardless of season, will likely develop into stands containing primarily yellow-poplar stems.

The use of single fires will unlikely alter species composition in favor of oak (Huntley and McGee 1981); thus multiple prescribed burns will be necessary to attempt to achieve an acceptable species composition to form the future stand. Other studies (McGee 1979, Dey and Fan 2008, Albrecht and McCarthy 2006) suggest that single burns are less likely to result in long-term changes in the species composition in an upland hardwood stand. Each burn also has detrimental effects in the form of loss of growth and the potential to lower stand quality through burn damage to the bole. Alexander and others (2008) discovered that prescribed fire did not affect stocking of sassafras but did result in approximately twice the height and basal diameter growth for that species. Iverson and others (2017) witnessed sassafras had enhanced recruitment of large seedlings on xeric sites following fire. This response is problematic however as a dense understory of sassafras may suppress developing oak regeneration. Measurements in Iverson and others (2017) study indicate that annual height and basal diameter growth for sassafras was 1.5 – 2.5 times faster than oak. The researchers also observed that a single prescribed burn did not impact red oak survival but increased mortality to white oak seedlings almost twice as much as unburned controls. The authors suggest that the white oak seedlings were of smaller stature as compared to the red oaks, and that this led to the greater mortality rate.

Repeated burns have been observed to negatively affect survival rates for both red and white oak seedlings compared to the control treatments. Dey and Hartman (2005) observed that multiple fires resulted in topkill for multiple species, and the majority of advance regeneration was restricted to the smallest height class (one foot). Johnson (1974), along with Dey and Parker (1996), reported that a low intensity dormant-season burn can result in high mortality (>70%) of young oak seedlings less than three years of age. High intensity fire can kill most stems occupying midstory canopy positions; this is favorable for increasing sunlight penetration but can damage or even cause mortality in overstory trees (Brose and others 1999). The use of prescribed fire most often must be accompanied by some form of overstory disturbance to allow small oak seedlings to remain competitive with shade tolerant tree species on high quality sites (Dey and Fan 2008). A positive response may only result after multiple prescribed burns as well. This implies that multiple management applications will be necessary to establish the desirable reproduction. Given these various findings, it can be suggested that prescribed fire yields uncertain oak regeneration responses. The inability of fire or the need for multiple fires to assist in oak regeneration establishment potentially suggests that fire is an inadequate management option for promoting oak reproduction and development.

Chemical Competition Control

Other research has looked at chemical applications to improve the growth and survival of oaks in hardwood stands. Often, early survival of planted hardwoods can be low due to various biological factors including plant competition. Herbicide applications have been scientifically conducted at various stages of early development to alleviate high mortality and enhance early regeneration growth. Approximately ten or more years after regeneration is in place, pre-commercial thinnings or timber stand improvement may be used to enhance tree growth. Various studies (Hopper and others 1992, Ezell and Catchot 1997, Ezell and Hodges 2002, Ezell and others 2007, Self and others 2008) suggest that chemical release of planted hardwood seedlings improves early survival rates. The use of sulfometuron to control herbaceous weeds improved overall oak seedling survival in study plots receiving competition control by 20% or greater compared to untreated controls at the end of the growing season of the initial year (Ezell 2000, Ezell and others 2007). A survival rate of 80 – 90% is common for oak seedlings that receive chemical release during normal precipitation years (Grebner and others 2004). Likewise, post-emergent applications utilizing glyphosate improves height growth in hardwood species (Hopper and others 1992) in addition to oak seedling survival. Hilt and Dale (1987) concluded that increased intensity of pre-commercial thinning resulted in greater diameter growth in stands 13, 17 and 21 years of age.

A study by Thompson and Nix (1992) observed that early crop tree release within a four year old clearcut using various herbicides significantly decreased herbaceous and woody plant competition. This reduction in competition resulted in increased seedling ground line diameter growth but did not improve height growth compared to control treatments. Nix (2004) remeasured the released natural oak in the clearcut ten years after the initial chemical release treatments and reported that four herbicide treatments significantly increased diameter growth of released oak seedlings. The researcher suggests that applying herbicide release treatments assists in enabling desirable oak to form dominance in the overstory canopy.

Research has demonstrated that release treatments can improve seedling survival, diameter growth, and potentially ensure selected stems will obtain superior crown class (dominant or co-dominant) positions. Demchik and Sharpe (1999) observed that herbaceous vegetation control increased height growth of natural northern red oak regeneration. One study by Carlisle and others (2002) surmised that increased levels of competition control significantly resulted in greater height growth of various hardwood species. Conversely, a study by Schuler and Miller (1999) indicated that a wider five foot radial release of sheltered northern red oak reduced vertical height growth compared to lower levels of control and greater competition. Sweetgum seedlings that received a chemical release using a glyphosate herbicide had significant increases in both 5-year height and diameter growth (Zutter and others 1987). Self and others (2008) reported that a pre-emergent application of sulfometuron resulted in significantly greater total height growth for planted Nuttall and white oak seedlings compared to release applications using glyphosate. Robison and others (2003) surmised that both height and diameter growth significantly improved following competition control treatments in stands ranging from 1 – 13 years of age. The number of chemical applications can impact seedling development however. Self and others (2008) reported that repeated herbicide applications conducted routinely over a three-year period resulted in less growth compared to pre-emergent only and pre-emergent plus one time foliar release treatments. A growth response may also not be evident in the early years following oak seedling release from competition. Beck (1970) documented that oak seedling growth was not statistically significant until the fifth year following overstory removal and a low vegetation control treatment. A chemical release may shorten the normal length of rotation for oaks by 10 – 15 years (Clatterbuck and Hodges 1988). These studies indicate that an early chemical release may dictate the species composition of the future stand.

In some instances, chemical control may adequately suppress the initially targeted competing vegetation but may favor the establishment of another plant species that responds favorably to the removal of the initial plants. Ezell and Catchot (1997) observed that broomsedge and other grass species were problematic plants when using sulfometuron methyl to release planted hardwood seedlings. This same herbicide has also been shown to have negative results on some species of hardwoods. Horsley and others (1992) reported that both black cherry and white ash were sensitive to treatments applied during the active growing season following leaf expansion. The control of these species may be necessary when attempting to regenerate oak. Alternatively, the researchers found that northern red oak and black oak were not sensitive to applications of sulfometuron methyl (Oust XP®) alone.

Stocking Density Reduction

Reducing stocking density can also lead to enhanced diameter and volume growth. Previous research by Gingrich (1967) indicates that quadratic mean stand diameter increases with reduced stocking levels. Numerous research studies on planting and spacing depict greater average stand diameter with wider spacing or lower stand density (Kennedy and others 1987, DeBell and Harrington 2002, Kennedy 1993). Based on these findings, reducing natural regeneration stocking density will accelerate diameter growth and ultimately reduce the harvest rotation age. The incorporation of chemical release applied to desirable natural regeneration should also encourage dominance in the future stand by the released oak reproduction.

3. METHODS

Site Description

The study site is located on a private landholding in west-central Tennessee. The Houston/Humphreys County line dissects the area. Block A is physically located within Humphreys County; Blocks B and C are located within Houston County. The physiographic ecoregion is the Western Highland Rim – highly dissected plateau (Smalley 1986). The land is within the mixed-mesophytic forest region as described by Braun (1950) with white oak (*Quercus alba*), southern red oak (*Quercus falcata*), chestnut oak (*Quercus montana*), black oak (*Quercus velutina*), scarlet oak (*Quercus coccinea*), hickory (*Carya* spp.), blackgum (*Nyssa sylvatica*), red maple (*Acer rubrum*), sugar maple (*Acer saccharum*), black cherry (*Prunus serotina*) and yellow-poplar (*Liriodendron tulipifera*) forming the majority of the overstory species composition. Midstory and understory canopy layers also contained flowering dogwood (*Cornus florida*), sourwood (*Oxydendrum aboreum*), sassafras (*Sassafras albidum*), eastern hophornbeam (*Ostrya virginiana*), elm (*Ulmus* spp.), and American beech (*Fagus grandifolia*). The sites had at least one diameter limit harvest in the past as indicated by residual stumps. One or more additional diameter limit harvest(s) probably occurred within the area. The most recent harvest likely occurred between 1990 – 1995. Most undisturbed forestland in that region is dominated (80% or greater) by oak species. The soils on the study site were Bodine gravelly silt loams (5-40% slopes). Site index values for white oak are moderate (value of 75; base age 50).

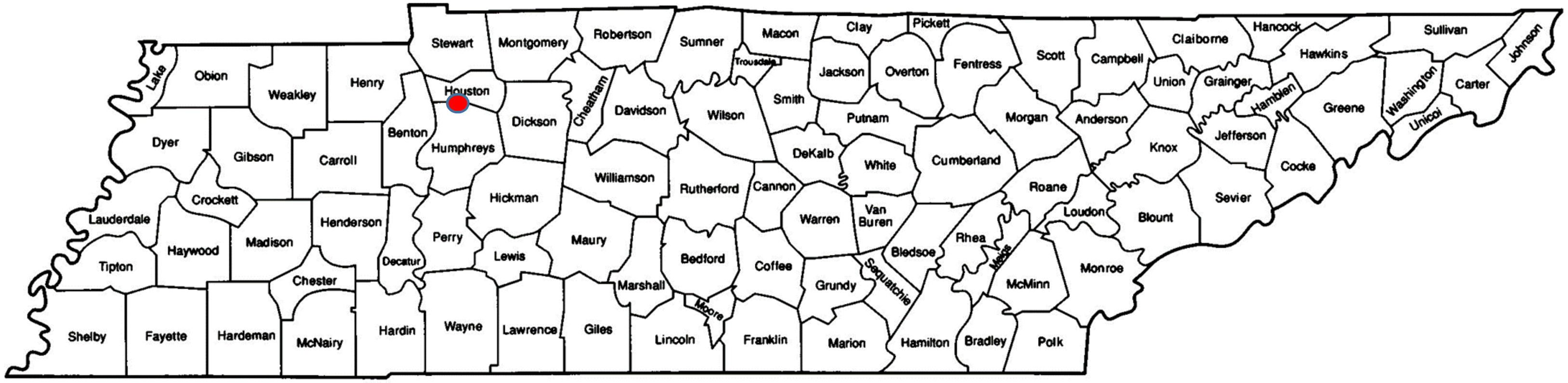

Figure 1. Research site location in the State of Tennessee

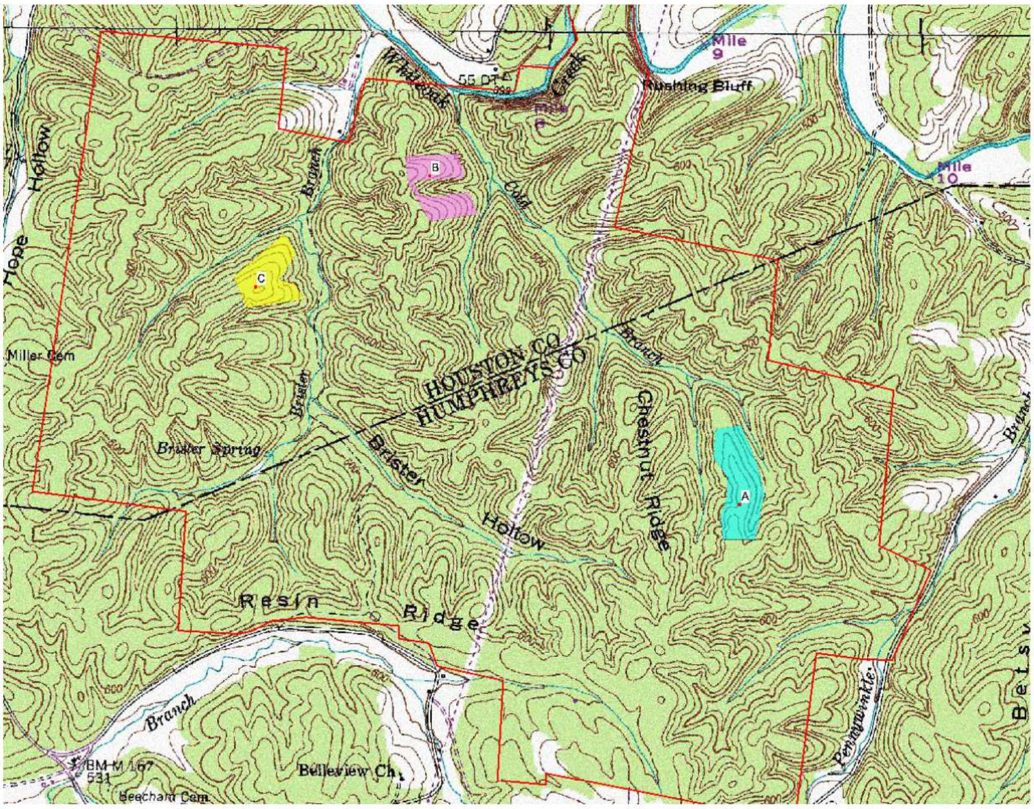

Figure 2. Research general and block locations for the degraded stand regeneration study located in west-central Tennessee.

Block Delineation

Four individual experimental blocks were chosen for the study to ensure an adequate amount of volume was available to improve feasibility of a timber harvest. Three of the four blocks were then selected to contain the replications for the actual research project. Each block was located on a similar aspect and soil type. Slope aspects for each block were north/northeast. Block borders extended from the ridge position downslope. Bodine cherty silt loam is the dominant soil type on each site. The potential block locations were selected using 7.5 topographical quad maps on GIS (Geographic Information Systems, Erin, TN) software. Corner position GPS (Global Positioning System) coordinates were derived using GIS software for each individual block. Blocks were approximately ten (10) acres. Waypoints (latitude/longitude coordinates) were established for each corner in any given block. Care was taken to clearly delineate the treatment areas; corner waypoints were downloaded into a handheld Garmin® (Olathe, KS) GPS unit, block perimeters were then traversed and marked with blue tree marking paint. To ensure confinement to the timber removal area, boundary stems were marked approximately six to seven feet above the ground surface and multiple spots on the stump. Forest woods roads already existed that enabled access to all the individual blocks. Figure 1 depicts the locations of the three blocks used for the research.

Two logging companies viewed each of the potential four blocks to determine feasibility and interest for harvest implementation (clearcut method). Each company had the ability to provide a chipping machine to process tree tops. The removal of logging slash was a requirement for the study as it enhanced accessibility across the sites for herbicide applications. Field visits were conducted with the logging company. After consideration of operativeness, one block was removed from the study due to excessive slope and poor road access.

Stand Inventory Plots

A pre-harvest stand inventory of all merchantable stems with a diameter at breast height (dbh) greater than four and one-half (4.5) inches was conducted. The three blocks were calculated at approximately ten acres each, prior to harvest. The inventory data were based on a 15% sample of the block areas using fixed plots distributed across the interior of each of the blocks. Thus, 15 fixed-radius plots were established in each block. A pre-harvest inventory on merchantable stems and advance reproduction were collected on tenth-acre plots to quantify merchantable timber and stand conditions (Figure 3). Data collected for all trees within the plots included diameter at breast height (DBH), ocular estimation of merchantable tree height, and a tally of all trees, by species, on each plot. Diameter measurements were taken to the nearest tenth of an inch using a d-tape. Merchantable height was ocular estimates to a four inch top for pulpwood and a ten inch top for sawtimber sized stems. Estimates for basal area by species, trees per acre, diameter distribution, volume estimates, and appraised financial value were derived using these plot measurements. Natural reproduction was estimated using 0.01-acre (tenth) plots nested in the larger plot. Polygons for each block were created in a GIS shapefile. Plots were created using a plot generator function tool. Any plots which landed within a dissecting road in the block were relocated within the forested area. Plot placement within the block resembled a “shotgun pattern” distribution. The following illustration shows the potential plot layout for any given 10+ acre block.

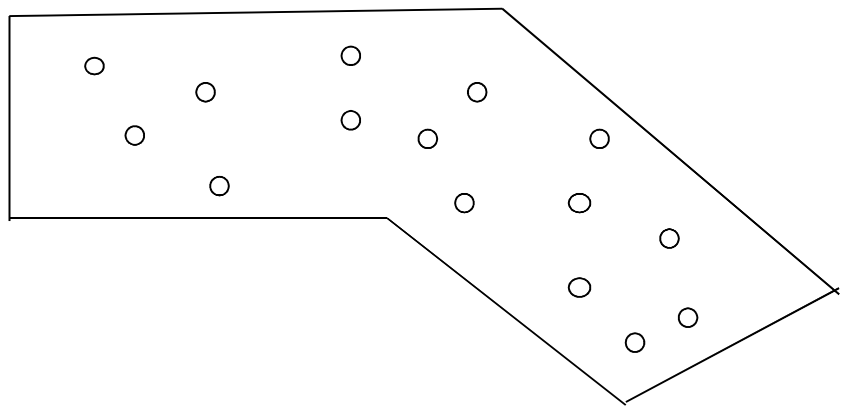

Figure 3. Diagram of measurement plots within a harvest unit for the hardwood response study in west-central Tennessee

Additional regeneration subplots were established at locations approximately 50 feet to the northeast (45° degrees) of all odd numbered plots to increase sample size. This equated to an additional eight regeneration subplots (23 total regeneration plots) on each block. Sample reproduction stems were tallied by species and height classes. Size classes included categories of 0-3 feet in height, 3-6 feet in height, greater than 1 inch ground diameter, greater than 3 inches ground diameter, greater than 6 inches ground diameter.

Plots were downloaded into handheld Garmin® 60 GPS unit from the GIS software. The handheld unit was then employed to install the plots on the site. Plot centers were marked using a seven-inch piece of polyvinyl chloride (PVC) pipe with paint applied to above ground portion. These PVC pieces were then driven into the ground to designate plot centers. Latitude/longitude coordinates were also collected at each plot location using a Garmin® handheld GPS unit. Three to four surrounding trees' trunk bases were also marked with tree paint, with the mark facing plot center. This marking enabled the triangulation of plot center when GPS coordinates proved unreliable during re-visitation.

Block Establishment and Harvesting

Once the pre-harvest inventory was completed, the two logging companies were contacted for availability to initiate the timber harvesting operation. Representatives from the two logging firms were taken to the sites for discussion of conducting logging operations. *Jarman Logging Company,* located in Vanleer, TN (Dickson County), was selected to conduct the logging operation based on both landowner preference and ability to implement timber cutting sooner in the initial year. Timber harvesting began in early March of 2014 on block A. One loading deck was established at the southern end of the opening adjacent to a permanent road. Trees were cut using a Caterpillar® (Caterpillar Incorporated, Deerfield, IL) 563 feller-buncher, moved upslope to this road, then a Caterpillar® 535 skidder transported materials to the loading deck. Tree tops were also processed at the loading deck in a wood chipper. Timber was extracted along the central ridge road that extended across the linear clearcuts. A total of eighteen (18) acres was actually harvested. Portions of the stand situated on the lower side slope where not harvested because of slope steepness. Harvesting of block B began near the beginning of April of 2014. A steep hollow within the central portion of block B was not harvested. The harvest created two large openings separated by the uncut steep hollow. Two loading decks were established at the upper slope positions on the west side of the two patch clearcuts. The trees were cut then skidded directly upslope using a centralized skid trail in each opening. The edge of the timber harvesting overlapped the boundaries marked with tree paint. This action was necessary for an adequate opening size to accommodate the study. Approximately ten (10) acres was harvested upon completion of block B. The timber harvesting on block C was completed in June of 2014. A portion of this block within a steep drain was also left unharvested. The harvest zone extended beyond the southernmost boundary of the block however resulting in approximately ten (10) acres of timber being removed. One loading deck was established at the top of the slope on the south side of the clearcut. All felled material was skidded directly upslope on a centralized skid trail along the western portion of the opening. The eastern portion of the clearcut had logs skidded directly to the loading deck without a centralized trail.

Treatment Unit Delineation and Establishment

Installation of individual treatment units followed the completion of harvest activity in each block. Six (6) treatment units were established within each experimental block. Units were established at least 50 feet from the boundary of the harvest to eliminate shading bias from the clearcut perimeter. An approximate 10-foot buffer strip was placed between individual treatments (measured seedling groups) to minimize spray drift impacting adjacent treatment units during herbicide applications. An individual treatment unit encompassed approximately three-quarters (¾) of an acre. Corner rebar markers were colored in blue tree paint and florescent orange spray paint in a horizontal stripe pattern. Distance between corners and rebar rows was measured using a 100’ tape and 75’ logger’s tape. A compass was also used to assist in maintaining line straightness. Shape of each treatment unit varied between blocks due to the uniquely shaped openings created from the timber harvesting operation. Physical randomization, by means of pulling numbers out of a hat, was used to determine treatment designation for each unit. Treatments included:

• control
• herbaceous/grass control herbicide only
• radial seedling release
• radial seedling release + herbaceous/grass control
• banded strip sprays
• banded strip sprays + herbaceous/grass control.

Unit layout design varied amongst each block because of the incomplete harvesting associated within the block (Figures 1 – 3). Steel rebar was placed at even intervals around the eastern/western perimeters of each treatment unit in order to serve as guidelines for spray applications. Twine was tied to each end of successive rebar. Banded sprays were conducted along the twine (approximate four foot width) to maintain uniform spray lanes. One exception to this rebar placement delineation was the banded spray treatment unit in Block C. Rebar within this particular unit was placed on the northern and southern perimeter. This unit had to be “fitted” in order to accommodate the opening size. Control and radial release units had rebar spacing of approximately twelve feet apart. Banded units were spaced approximately eight feet apart. Florescent flagging was also tied around the top of rebar sticks to enable visual determination of treatment types. Blue colored flagging denoted control units, orange flagging identified radial treatments, and pink flagging indicated banded treatments. Nylon twine was utilized within units that received banded spray treatments. The twine lines were attached to the rebar and served as guidelines to facilitate accurate spray applications. Placement of rebar and twine accomplished two objectives:

1. uniformly delineate spray paths for banded sprays
2. represent a row with a select number of seedlings to be measured following the clearcut harvests.

Figure 4. Treatment unit row delineation using flagged rebar (previous page); twine guide lines essential for conducting uniform banded spray applications (above) for the hardwood response study in west-central Tennessee.

Post-Harvest Plot Re-establishment

Previously established regeneration plots were reestablished and assessed following harvest. Measurements were made at the end of the first growing season post-harvest (October 2014). Plot centers were relocated using a handheld GPS unit. This methodology unfortunately was unreliable. Some plots were triangulated using the method of tree paint applied to individual tree trunk bases, but most were likely off from the exact point by some degree. Other plots remained undisturbed as they were located in the unharvested portions of the block. Plots that were situated within the unharvested areas of blocks B and C were omitted from the analysis because of the wide variation in tree size of the unharvested portions of block A versus the other two blocks. The unharvested trees that remained in block A were primarily large saplings (DBH greater than one inch, but less than 4.5 inches) and small poletimber (DBH greater than 4.5 inches, but less than 12 inches).

Blocks B and C received silvicultural clearcuts that removed all stems within the openings. Block A retained a greater percentage of sapling and poletimber sized trees in areas that were harvested because only sawtimber sized stems were removed. The density of residual stems in these areas was approximately 60 – 70 trees per acre. The area containing these residual stems was isolated along the lower slope positions and closer resembled a commercial clearcut (only merchantable stems removed) as opposed to a silvicultural clearcut (all stems removed). Residual stems on plots were mechanically treated within areas that had numerous residual saplings and midstory poletimber sized stems to increase sunlight penetration to levels that would approximate a silvicultural clearcut. Mechanical treatment radius around the regeneration plots were approximately thirteen feet extending from the plot centers. Thus, plots were "mechanically treated" to approximately twenty-six (26) feet in diameter. A Stihl® (Stihl Incorporated, Virginia Beach, VA) chainsaw was used to fell sapling sized stems and to girdle larger sized poletimber (primarily stems greater than 6 inches dbh) within this radius. Girdled trees received two girdles approximately 8 or more inches apart. Depth of girdles was 1 inch or greater.

Figure 5. Double girdling of small sawtimber stem (left); photograph of regeneration plot after mechanical treatment (right) for the hardwood response study in west-central Tennessee.

Regeneration was evaluated both pre and post-harvest to determine if the clearcut method adequately regenerated desirable tree species in a hardwood stand that likely had received multiple diameter-limit harvests. Regeneration plot remeasurement involved stem tallies that delineated individual samples by species and regeneration type, either a new germinant or a sprout. Numerous sapling sized stems appeared to have been uprooted during the harvest activity rendering the previous reproduction size class system unusable. Thus, seedlings were simply classified only as germinants or sprouts. Regeneration plots within treatments units that were sprayed with glyphosate solution were measured prior to or within a week of the application conductance. The control and sulfometuron methyl only treatment units were measured earlier in the spring of 2014 (Table 1).

Table 1. Research site timeline for all field activities

Activity	Month(s)	Year
Block perimeter marking	December	2013
Pre-harvest inventory	January – February	2014
Logging company visits	March	2014
Timber harvesting of three blocks	March – May	2014
Regeneration plot re-establishment	June – July	2014
Treatment unit establishment	April – June	2014
Herbicide spray applications	May – August	2014
Initial seedling measurements	October – November	2014
2-year seedling measurements	January – February	2017
Competing plant coverage estimation	January – February	2017

Experimental Treatments

Herbicide applications were conducted within the harvest blocks within a few months following harvest completion. The chemical treatments were applied to natural hardwood regeneration which had already broken dormancy by the middle of April. Oak and yellow-poplar seedlings were chosen as the preferred species to analyze for herbicide treatments due to their commercial value and management preference. No observable effect or mortality were observed for oak or yellow-poplar seedlings receiving this chemical application. Six treatments were analyzed during this study (Figure 6). Each individual block contains all six treatments (Figure 7). A total of eighteen (18) experimental units were located on the site with each treatment replicated three times. Treatment number one was a banded spray utilizing glyphosate herbicide. All glyphosate applications were conducted using Cornerstone® herbicide. The designated width of the bands was approximately four feet treated next to four feet untreated width. The treated/untreated bands alternated with one another across the experiment unit. Treatment number two was the banded spray plus a pre-emergent broadcast spray that used sulfometuron methyl herbicide. The trade name for this particular herbicide used was SFM 75®. The product was manufactured by the Alligare Company. Treatment number three incorporated individual radial stem release (five feet radius around oak and yellow-poplar seedlings only) that used glyphosate herbicide. Treatment number four was the radial stem release plus a pre-emergent broadcast spray that used sulfometuron methyl herbicide. Treatment number five was an untreated control. Treatment number six was a pre-emergent broadcast spray that used sulfometuron methyl herbicide only.

1. Radial + pre-emergent
2. Control
3. Banded
4. Radial
5. Control + pre-emergent
6. Banded + pre-emergent

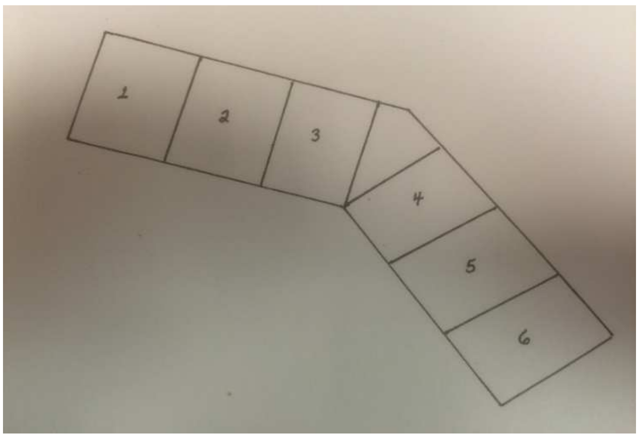

Figure 6. Schematic design of treatment units within a given block for the hardwood response study in west-central Tennessee.

Figure 7. Treatment unit design layout on all three blocks for the hardwood response study in west-central Tennessee

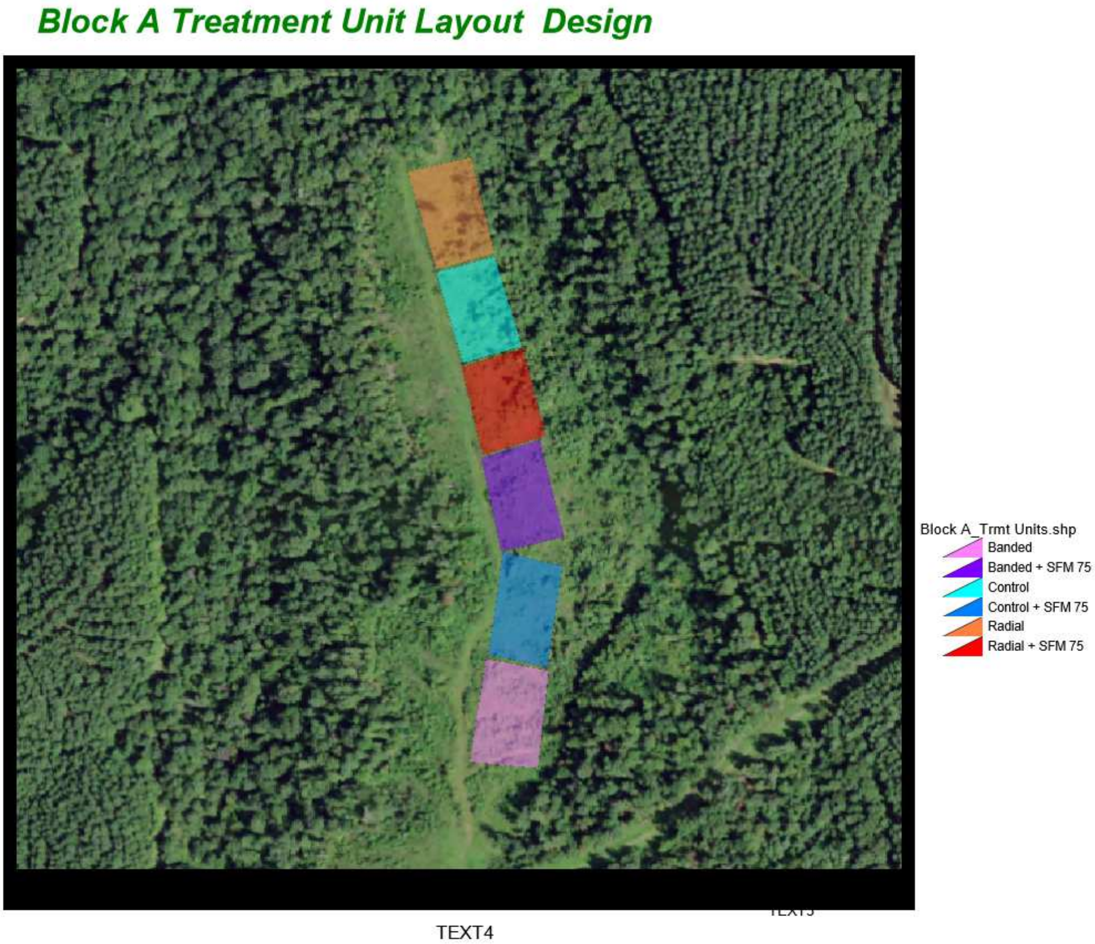

Figure 7. Continued

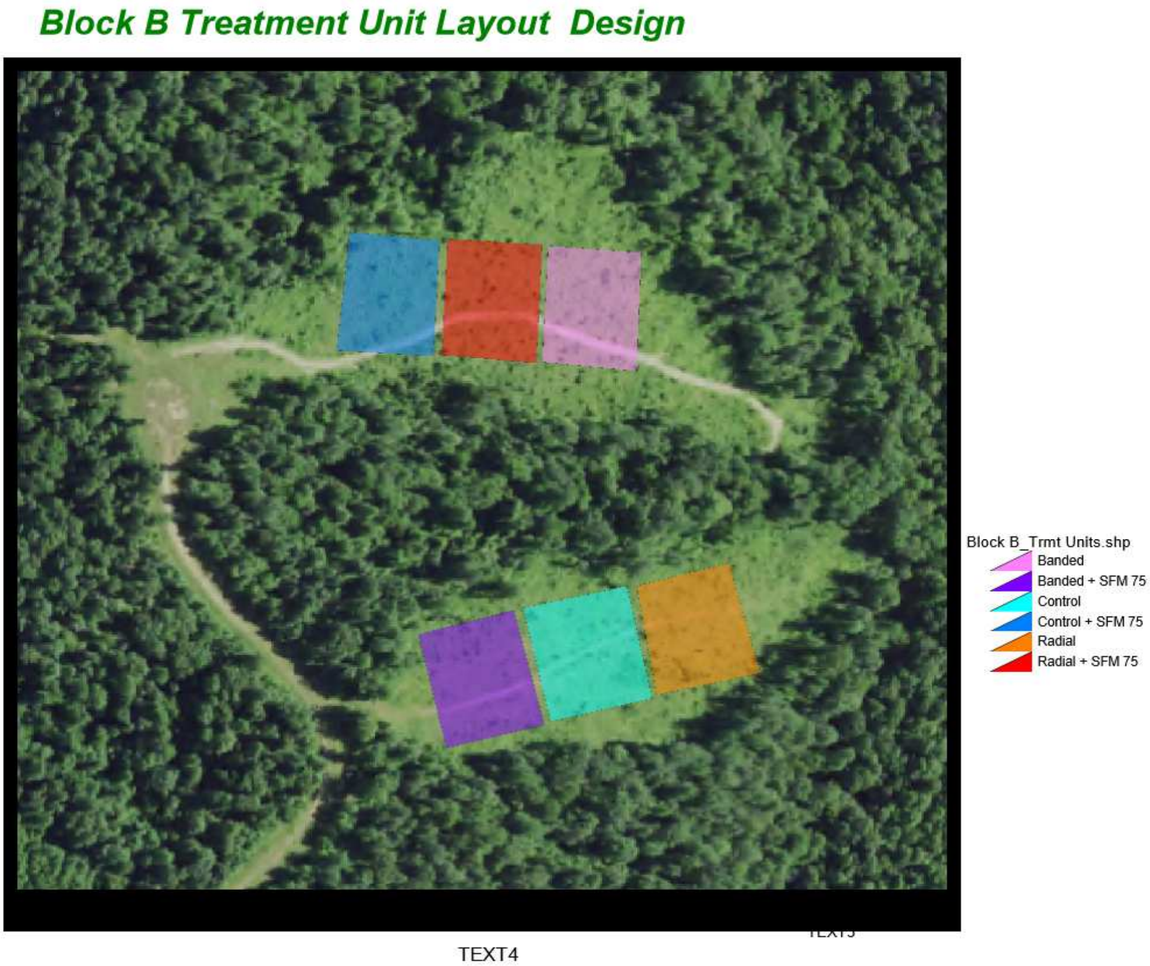

Figure 7. Continued

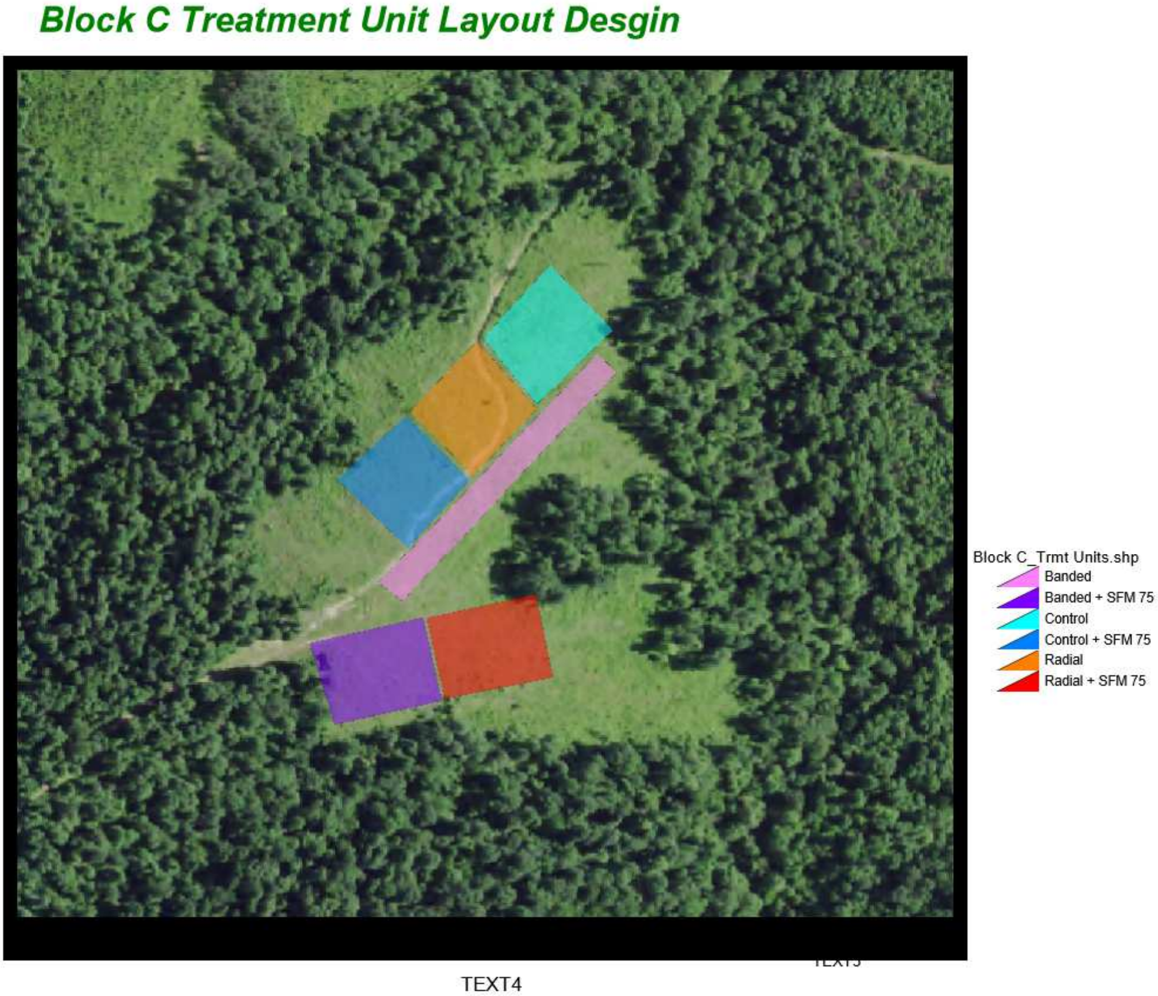

Figure 7. Continued

Competing Vegetation for Seedlings

The recently disturbed site had an influx on new plants emerge due to the maximized sunlight availability and bare ground exposure. The most frequent forb and grass competitors observed on the study site were garlic mustard (*Alliaria petiolata*), fireweed (*Erechtites hieraciifolia*), common ragweed (*Ambrosia artemisiifolia*), Dallisgrass (*Paspalum dilatatum*), crabgrass (*Digitaria sanguinalis*), and greenbriar (*Smilax* sp.) (Figure 7). Ground coverage by these species was estimated ocularly to be greater than ninety percent. Bare ground area were primarily deep ruts created by logging equipment and skid trails and existing forest roads within the blocks.

Garlic mustard

Fireweed

Common ragweed

Vervain

White snakeroot

Crabgrass

Greenbriar

Figure 8. Photographs taken onsite of common weed species within treatment units occurring prior to chemical applications on the study site in west-central Tennessee.

Herbicide Application Rates and Procedures

Application rates and procedures for each herbicide are as follows:

- Glyphosate treatments: 5% herbicide solution, ¼% surfactant with water applied as foliar spray covering at least 70% of foliage. Broadcast foliar applications were conducted in May – August.

- Sulfometuron methyl applications: 1.8 – 1.9 oz. per acre following bud swell (post-emergent broadcast application)

These application rates are commonly used for chemical seedling release prescriptions (Ezell and others 2007; Ezell and Self 2016). The herbaceous/grass control applications using SFM 75® herbicide (sulfometuron methyl – active ingredient) were implemented within 30 – 45 days following the completion of the timber harvest on the three designated treatments units within each given block. All herbaceous/grass control treatments were conducted following bud swell in either May or June. The ground cover was sparse at the time of herbicide application because of the short duration after the timber harvest and treatments were applied early in the growing season. Consultation with Dr. Andrew Ezell (personal communication, Department Head and George L. Switzer Professor of Forestry – College of Forest Resources, Mississippi State University, MS 39762) led to the decision to employ "over the top" applications, using no greater than an equivalent of two (2) ounces per acre of herbicide (sulfometuron methyl), on emerged hardwood regeneration. Approximately 1.8 – 1.9 ounces of granular herbicide was applied at 16 gallons of solution on half (total of 9 units) of all available three-quarter (¾) acre treatment units. A solo® (Solo Incorportated, Newport News, Virginia) 4-gallon backpack sprayer was used to conduct the application. To ensure adequate coverage and even distribution rate, individual units receiving the herbaceous/grass control were divided into four quadrants using pin flags. Each quadrant was treated one at a time until the entire unit was thoroughly treated. Prior to all applications, fire weather reports were reviewed from the National Oceanic and Atmospheric Administration (NOAA) website (https://www.weather.gov/fire) to ensure favorable conditions for application effectiveness and to avoid substantial environmental impacts. Preferred weather consisted of winds between 2 – 10 miles per hour, higher humidity (for this region low humidity is likely below 35%), and air temperatures between 65 – 85 degrees Fahrenheit, and a temperature inversion was not present (Accord® SP label – Dow Agrosciences

LLC, Indianapolis, IN). These weather variables can affect both drift and volitization of the pesticides. All herbaceous/grass control treatments were applied initially prior to subsequent radial and banded applications. The time span between sulfometuron methyl and glyphosate treatments was approximately 75 – 90 days.

Figure 9. Photograph depicting border of control treatment unit (right) and SFM 75 treated unit area (left) within two months after treatment in the hardwood response study in west-central Tennessee.

The application rate for glyphosate solution was 15 – 24 gallons per treatment block. Application rates differed due to size and abundance of vegetation on the particular site. Lesser spray volume was used on radial release treatments as compared to banded spray applications. Spot foliar spray method techniques involved covering greater than 70% of plant foliage in targeted spray areas. Applications on Block C were implemented later in the growing season (July/August 2014). Plants were able to develop for a longer period and were larger. A more commensurate application rate (24 gallons of solution) was thus required for the increased foliar volume.

Within the radial treatment units, approximately 132 – 150 oak (both red and white oak) or yellow-poplar seedlings were flagged with fluorescent tape prior to chemical spray application. Flagging the seedlings allowed applicators to reduce herbicide application time by pre-selecting crop stems to be released. The pesticide solution was administered at a minimum of five (5) foot spray radius around all marked seedlings. During application, marked stems were covered with stove-pipe (enclosed three (3) foot tall column with handle) and the immediate area of approximately a five (5) foot radius was treated. Care was taken to avoid herbicide solution contact with plants from the outer bottom of the stove pipe protection device. After treated vegetation had deadened, seedlings were permanently marked with an aluminum tag fastened at the base.

Figure 10. Photographs illustrate marked seedlings (note fluorescent flagging) which received radial release (post dessication) for the hardwood response study in west-central Tennessee.

Banded spray treatments were applied as treated (strips receiving spray solution) and non-treated (strips that did not receive spray solution) in an alternating pattern across the selected units. Both treated and non-treated strips were approximately four feet in width. Non-treated strips were centered on the previously placed rebar, spaced at eight foot intervals. Nylon twine was stretched between rebar on every other row to serve as visual guides during the spray application. Approximately two feet to each side of the twine was left untreated. The desired target width of treated strips was four feet. After treated vegetation had desiccated, up to 150 oak or yellow-poplar seedlings were marked with flagging and numbered with aluminum tags on each individual treatment unit.

Figure 11. Photographs depicting conditions post banded applications following dessication on the hardwood response study in west-central Tennessee

Control (untreated) and herbaceous/grass release only treatment units also had up to one hundred and fifty oak and yellow-poplar seedlings marked with fluorescent flagging and numbered using aluminum tags. Herbicide application timing varied over the 2014 growing season (Table 2).

Table 2. Timing of herbicide applications for the hardwood response study in west-central Tennessee

Block	Herbicide Applied	Month	Year
A	SFM 75 (sulfometuron methyl)	May	2014
B	SFM 75	May	2014
C	SFM 75	June	2014
A	Cornerstone (Glyphosate)	July	2014
B	Cornerstone	July	2014
C	Cornerstone	August	2014

*each individual herbicide, regardless of application procedure, was applied to all designated treatment units in a given block within the time period of one week.

4. MEASUREMENTS

Sample Seedling Measurements

Post-harvest reproduction was measured on established plots/subplots (69 plots total). Natural reproduction was evaluated by species and regeneration form. Individual seedling records included whether the sample was a germinant seedling or of sprout origin. The original size classification system was not used for post-harvest measurements due to removal of and damage to saplings during harvest and the indistinguishable diameter size of stump sprouts. The indistinguishable nature is derived from sprouting that occurs from below ground root stock which could not be measured.

Ground line diameter and height measurements were recorded for marked natural regeneration after completion of herbicide applications. Approximately 150 stems per acre were measured on each individual treatment unit. A few units on Block C contained slightly less than the desired 150 oak or yellow-poplar seedlings. Numbered seedlings on all treatment units were measured for ground line diameter using a digital caliper and for total height in inches using a standard English ruler. Individual stem ground line diameters were measured to the hundredth of an inch. Height measurements were taken to the nearest ½ – inch. First year (at the completion of one full growing season) measurements were recorded in the fall (October – December 2014) following the timber harvest which occurred at the beginning of the growing season in the same year. The second year seedling measurement for ground line diameter and total height were collected in January – February of 2017, two years after treatment and three growing seasons after harvest. Two complete growing seasons (2015 and 2016) along with a portion of the growing season (2014) had elapsed between seedling measurements. The same methodology was implemented during the second measurement period in 2017 as was for the initial measurements recorded in 2014. A robust response of broomsedge grass and Nepalese browntop made locating seedlings extremely difficult during the second seedling measurement period. A Teknetics® (Teknetics, El Paso, TX) Delta 4000 metal detector was used in an attempt to locate “hidden” marked seedlings located beneath heavy grass vegetation. Only a portion of marked seedlings were found again in the winter of 2017. All re-measured seedlings were re-flagged with fluorescent (blue) flagging tape and the aluminum tags were moved higher on the stems. Some additional growing space (between the wire and stem) was given to limit future girdling by the tag wire.

Competing Vegetation Estimation

Competing vegetation density was also quantified through ocular estimation. Four points within each treatment unit were used to estimate percent ground cover, total plant height, and lower above ground "mat" coverage height. Sample points were located systematically at approximately 55 feet at diagonal directions from treatment unit corner markers. These metrics were used to describe the competitive environment around the marked seedlings.

Natural Regeneration Survey

Density measurements for each individual treatment unit were also conducted following the two-year seedling re-measurements. One-hundredth acre circular plots (11' 8" radius) were established within each unit using a random grid projection using GIS software. The GPS coordinates were generated for each point while downloaded into a handheld GPS unit. All woody tree species within the plot were tallied by species and regeneration origin. These origins included stump sprouts and natural seedlings. Size class categories were established as small seedlings (under three feet in height), large seedlings (three to six feet in height), and saplings (all stems over six feet in height). Plot centers were permanently established with rebar painted with white coloring and flagged with florescent flagging to facilitate future re-measurement as needed.

Weather Data

Weather data for precipitation and Palmer drought severity index (PDSI) were acquired from the National Oceanic and Atmospheric Administration (NOAA) website. The web addresses for precipitation data (https://w2.weather.gov/climate/index.php?wfo=ohx) and PDSI (https://www7.ncdc.noaa.gov/CDO/CDODivisionalSelect.jsp) allowed access to archived previous monthly weather history by the weather station in Nashville,TN (for precipitation) or regional (for PDSI).

Analysis

The experimental design is a randomized complete block (RCBD) with sampling (single treatment factor) and split-plots. Fixed variables include the six treatments and the three blocks. Random variables include the seedlings samples. The statistical model used to compare individual treatments using all seedlings is: $y_{ij} = \mu + B_i + T_j + B*T_{ij}$

The statistical model used to compare individual species combinations by treatments is:

$y_{ijk} = \mu + B_i + T_j + B*T_{ij} + F_k + F*T_{jk} + B*F*T_{ijk}$

Statistical analyses were performed for analysis of variance (ANOVA) using mixed models (PROC MIX) (SAS Institute Inc., Cary, NC version 9.4). Data tests indicated satisfactory normality and equal variances. No transformations were utilized in the analyses. Tukeys' significant difference test was incorporated to separate the least squares means. The significance level was set at alpha = 0.05.

A complete randomized block design with sampling was performed to evaluate the effectiveness in accelerating combined (all species groups) seedling diameter growth between the herbicide treatments, to analyze the effectiveness in accelerating combined seedling height growth between the herbicide treatments, and to analyze the comparison of individual species groups (white oak, red oak, and yellow-poplar) to enhance seedling ground line diameter growth between the herbicide treatments. The third analysis included a sampling with split plot design. A mixed model analysis of variance utilizing the Glimmex procedure (SAS Institute Inc., Cary, NC version 9.4) in the Statistical Analysis Software (SAS) package was used for all three analyses.

5. **RESULTS**

Pre-harvest Inventory Data

Pre-harvest densities for merchantable stems (greater than five inches in diameter at breast height) was diverse for all three blocks. Block A had an oak component totaling approximately 41% of the estimated density (Figure 12). Hickory, sweetgum (*Liquidambar styraciflua*), and yellow-poplar were the next largest contributors to the species composition forming approximately 23%, 13%, and 8% of the population, respectively. Ash (*Fraxinus* sp.), sugar maple, sourwood, sassafras, black cherry, elm, red maple, boxelder (*Acer negundo*), dogwood, eastern redbud (*Cercis canadensis*), hackberry (*Celtis occidentalis*), and tree of heaven (*Ailanthus altissima*) formed the remainder of the population each at less than four percent of the overall composition.

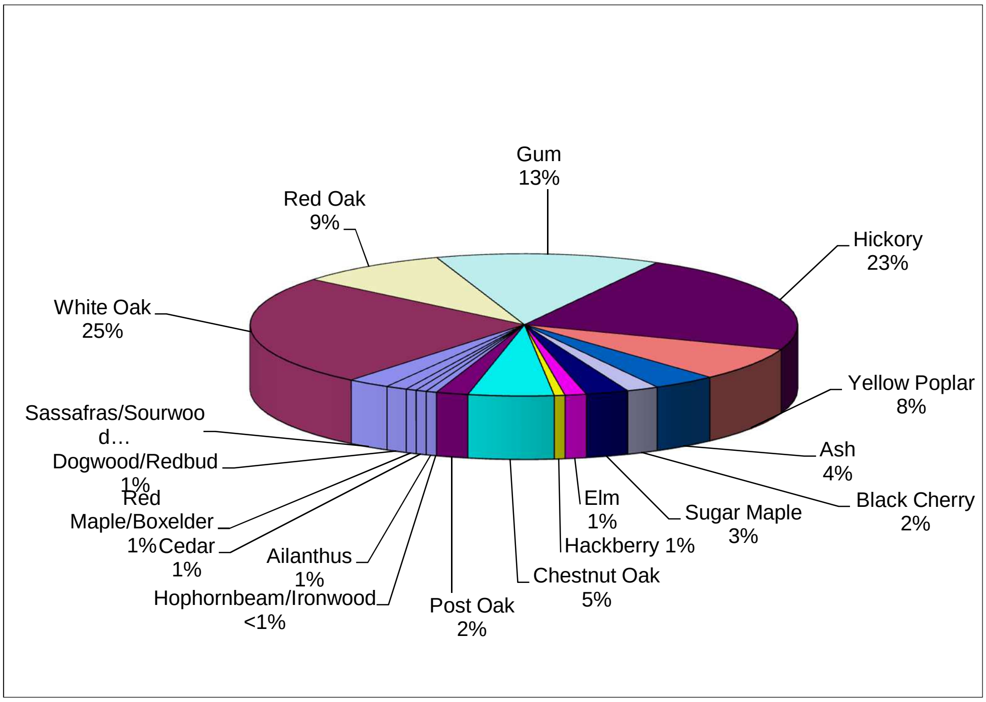

Figure 12. Merchantable stem (>4.5 inches dbh) species composition within block A on the hardwood response study in west-central Tennessee.

The majority of the inventoried stems were pulpwood sized materials (less than 12 inches dbh). A diameter distribution table (Figure 13) illustrates the sample data values for each diameter class by tree count. The diameter distribution represents a J-shaped curve which is commonly associated with an uneven-aged stand. The average diameter for the sample was approximately 9.4 inches. The estimated trees per acre (TPA) was calculated to be 106 trees. Stand stocking was determined to 55 ft.^{2} of basal area per acre. Sawtimber volume was computed to be approximately 1,730 board feet per acre.

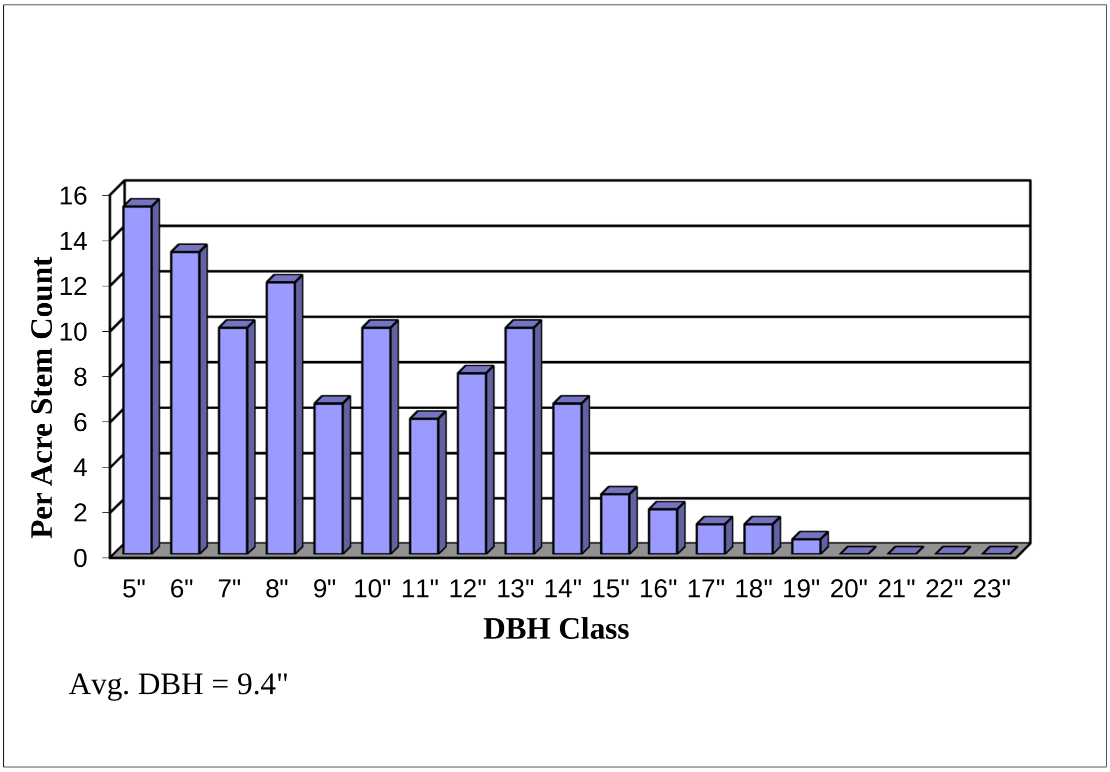

Figure 13. Diameter distribution table for block A on the hardwood response study in west-central Tennessee.

Understory reproduction (for all size classes combined) sample data revealed diversity in species composition (Table 3). Yellow-poplar was the largest contributor of the estimated population at 35.5% (estimated 874 stems per acre). Combined oak species only accounted for 4.3% (109 stems per acre) of the entire sample. Ash species were the second largest portion of the composistion at 13.8% (339 stems per acre). All other nineteen recorded species accounted for less than 4.2% (Table 3).

Table 3. Reproduction composition (block A), by species and percentages of the sampled population, on the hardwood response study in west-central Tennessee.

Species	Stem Count (Per Acre)	Percentage
Hophornbeam	104	4.2
Yellow-poplar	874	35.5
White oak	48	1.9
Red oak	48	1.9
Sugar maple	48	1.9
Ash	339	13.8
Beech	22	0.9
Sourwood	4	0.2
Sassafras	26	1.1
Elm	22	0.9
Cedar	17	0.7
Ailanthus	61	2.5
Dogwood	65	2.7
Devil's walking stick	13	0.5
Redbud	65	2.7
Ironwood	22	0.9
Persimmon	26	1.1
Hickory	65	2.7
Black cherry	117	4.8
Blackgum	191	7.8
Sumac	39	1.6
Miscellaneous	226	9.2
Hackberry	4	0.2
Chestnut Oak	13	0.5
Totals	2461	100

Size classes of reproduction was skewed towards large seedlings and saplings (Table 4). Seedlings that were either greater than 3 foot in height or less than one inch diameter accounted for 36.2% of the inventoried stems. These seedlings had a count of approximately 891 stems per acre. Larger saplings (1" – 3" in diameter) followed as the next largest component of the reproduction with 34.4% (843 stems per acre) of the sampled stems. Interestingly, there were no small seedlings less than one foot in height that were observed on the 23 plots.

Table 4. Pre-harvest reproduction within block A by species and size class

Species	Regeneration Size Class						Total
	>1' ht.	1' - 3' ht.	>3' ht. OR <01.0" diameter	1.0" - 2.99" diameter	3.0" - 5.99" diameter	6.0' and above	Count
Hophornbeam	0	22	65	17	0	0	104
Yellow-poplar	0	39	374	404	43	13	874
White oak	0	13	13	4	4	13	48
Red oak	0	30	13	0	0	4	48
Sugar maple	0	9	13	22	0	4	48
Ash	0	126	104	83	22	4	339
Beech	0	0	9	13	0	0	22
Sourwood	0	0	0	0	0	4	4
Sassafras	0	4	13	9	0	0	26
Elm	0	0	0	13	4	4	22
Cedar	0	13	4	0	0	0	17
Ailanthus	0	9	52	0	0	0	61
Dogwood	0	17	17	17	13	0	65
Devil	0	0	4	9	0	0	13
Redbud	0	0	13	22	22	9	65
Ironwood	0	4	9	9	0	0	22
Persimmon	0	17	9	0	0	0	26
Hickory	0	26	9	9	9	13	65
Black cherry	0	17	39	39	22	0	117
Blackgum	0	26	65	48	22	30	191
Sumac	0	0	4	35	0	0	39
Miscellaneous	0	74	61	91	0	0	226
Hackberry	0	0	0	0	0	4	4
Chestnut Oak	0	9	0	0	0	4	13
Totals	**0**	**457**	**891**	**843**	**161**	**109**	**2461**
Percent (%)	**0**	**18.6**	**36.2**	**34.3**	**6.5**	**4.4**	

Block B had almost half of the species composition consisting of shade tolerant hickory species and sugar maple (Figure 14). The oak component was marginal forming only slightly greater than 15% percent of the overall composition. The remainder of the stand consisted of elm, sourwood, sassafras, yellow-poplar, gum, ironwood (*Carpinus caroliniana*), eastern hophornbeam, ash, American beech, dogwood, black walnut (*Juglans nigra*), eastern red cedar (*Juniperus virginiana*), and common persimmon (*Diospyros virginiana*).

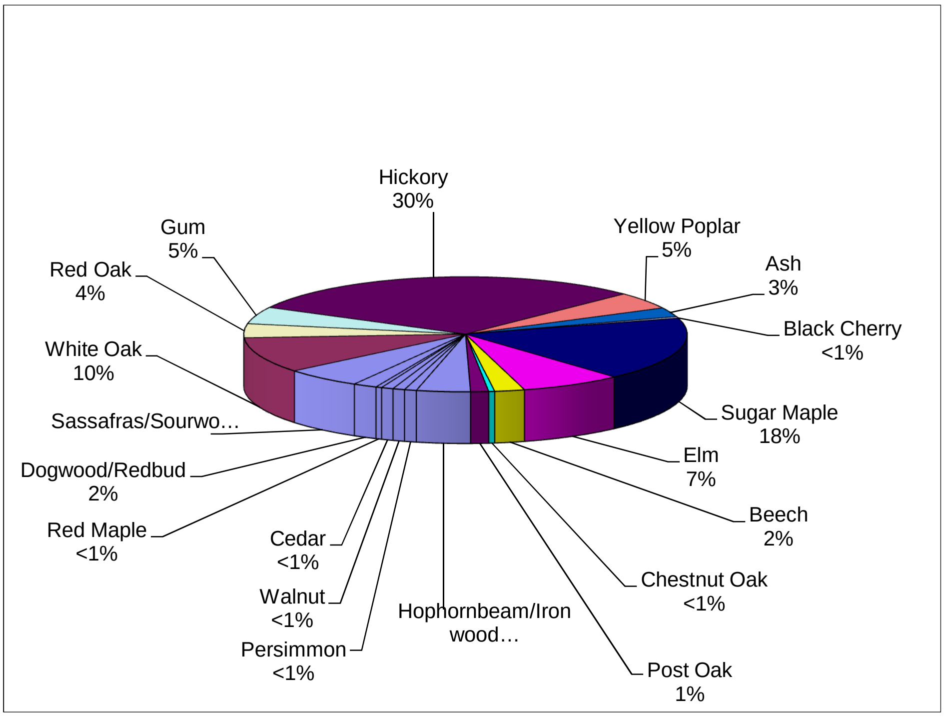

Figure 14. Merchantable stem (>4.5 inches dbh) species composition within block B on the hardwood response study in west-central Tennessee.

Block B had a similar diameter distribution as block A (Figures 13 and 15). Pulpwood sized materials (less than 12 inches DBH) formed the majority of sampled stems (Figure 15). The diameter distribution was J-shaped representing an uneven-aged stand. The average diameter for the sample was approximately 9.0 inches. The estimated trees per acre was calculated to be 153 trees. Stand stocking was determined to 73 $ft.^2$ of basal area per acre. Sawtimber volume was computed to be approximately 2,164 board feet per acre

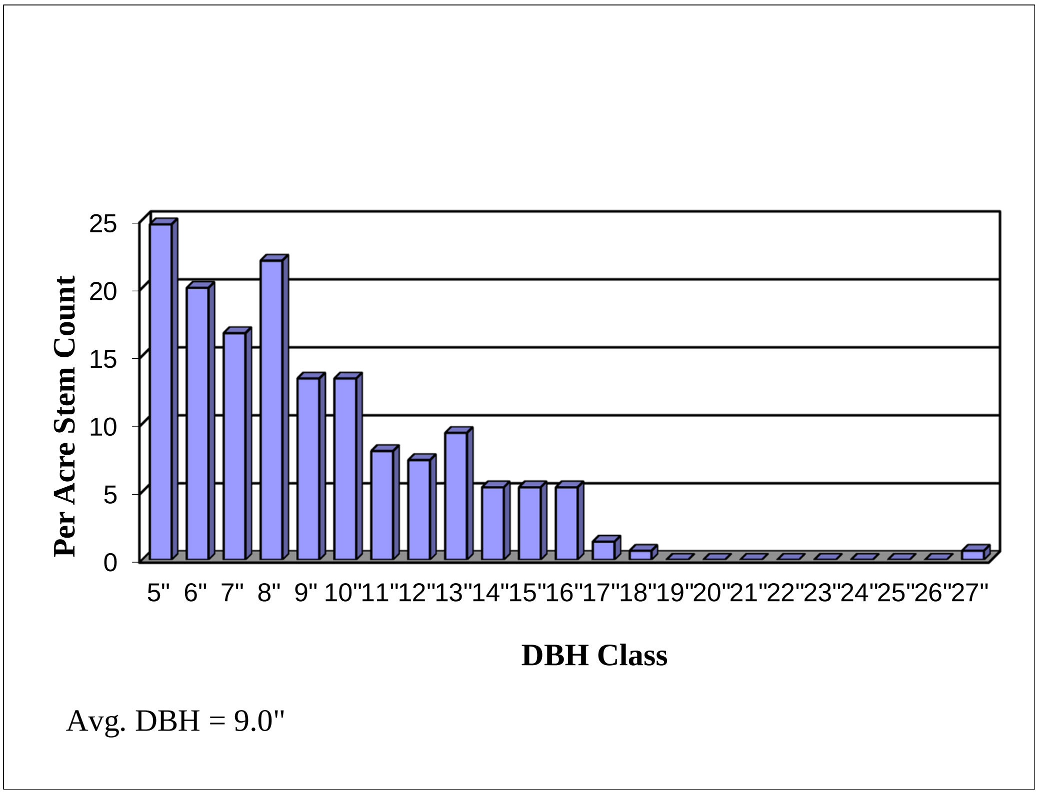

Figure 15. Diameter distribution table for block B on the hardwood response study in west-central Tennessee.

Similar to the reproduction status of block A, understory reproduction sample data in block B also displayed a vast array of species diversity (Tables 3 and 5). Eastern hophornbeam was the largest contributor and comprised greater than one-third of the estimated population at 34.1% (estimated 613 stems per acre) (Table 5). Other sizeable contributors included ash at 12.8% (230 stems per acre), sugar maple at 8.5% (152 stems per acre), sassafras at 7.3% (130 stems per acre), flowering dogwood with 5.3% (96 stems per acre) and hickory comprising 4.8% (87 trees per acre). Combined oak species only accounted for 6.2% (114 stems per acre) of the entire sample. Devil's walking stick, American beech, and blackgum all had respective percentage values of 3.9%. Ironwood was slightly less than this at 3.6%. All remaining species were under 1.5% for contribution to the overall species composition.

Table 5. Reproduction composition by species and percentages for Block B on the hardwood response study in west-central Tennessee.

Species	Stem Count (Per Acre)	Percentage
Hophornbeam	613	34.1
Yellow-poplar	9	0.5
White oak	57	3.1
Red oak	57	3.1
Sugar maple	152	8.5
Ash	230	12.8
Beech	70	3.9
Sourwood	13	0.7
Sassafras	130	7.3
Elm	26	1.5
Walnut	4	0.2
Boxelder	9	0.5
Dogwood	96	5.3
Devil's walking stick	70	3.9
Redbud	30	1.7
Red Maple	0	0.0
Persimmon	4	0.2
Hickory	87	4.8
Black cherry	4	0.2
Blackgum	70	3.9
Ironwood	65	3.6
Miscellaneous	0	0
Totals	1796	100

Size classes of reproduction was primarily moderate sized seedlings to saplings for block B (Table 6). Seedlings that were either greater than three foot in height or less than one inch diameter accounted for slightly greater than thirty-four percent (34.4%) of the inventoried stems. These seedlings had a count of approximately 617 stems per acre. Moderate advanced seedlings one foot to three feet in height were the next largest component of the reproduction with 28.3% (509 stems per acre) of the sampled stems. Saplings between one inch to three inches in diameter were estimated to form slightly greater than one-quarter (25.4% or 457 stems per acre) of the regeneration. All other regeneration size classes were less than 5.6% of observed data.

Table 6. Pre-harvest reproduction within block B by species and size class on the hardwood response study in west-central Tennessee

	Regeneration Size Class					
Species	>1' ht.	1' - 3' ht.	>3' ht. OR <1.0" diameter	1.0" - 2.99" diameter	3.0" - 5.99" diameter	6.0' and above
Hophornbeam	0	91	309	187	22	4
Yellow-poplar	0	0	4	4	0	0
White oak	0	52	4	0	0	0
Red oak	0	30	13	4	0	9
Sugar maple	0	30	26	61	22	13
Ash	0	152	57	17	4	0
Beech	0	4	26	26	9	4
Sourwood	0	0	0	4	4	4
Sassafras	0	13	48	65	0	4
Elm	0	4	0	0	17	4
Walnut	0	0	0	0	0	4
Boxelder	0	4	4	0	0	0
Dogwood	0	65	22	4	4	0
Devil's walking stick	0	22	30	17	0	0
Redbud	0	0	13	17	0	0
Red Maple	0	0	0	0	0	0
Persimmon	0	4	0	0	0	0
Hickory	0	30	4	9	4	39
Black cherry	0	0	0	4	0	0
Blackgum	0	4	13	30	9	13
Ironwood	17	0	43	4	0	0
Totals	17	509	617	457	96	100
Percent (%)	1.0	28.3	34.4	25.4	5.3	5.6

*height denotes seedling height from ground to terminal bud

Slightly greater than half of the pre-harvest inventory for block C was comprised of shade tolerant species (Figure 16). Hickory species was the largest contributor at 29%. The oak component totaled approximately 21% of the sample data. Blackgum/sweetgum, sugar maple, ash, and elm were the next largest contributors to the species composition forming 9%, 10%, 7%, and 6% of the population, respectively. Black cherry, yellow-poplar, sourwood, sassafras, red maple, eastern hophornbeam, American hornbeam, and American beech formed the remainder of the population each at less than 4% of the overall composition.

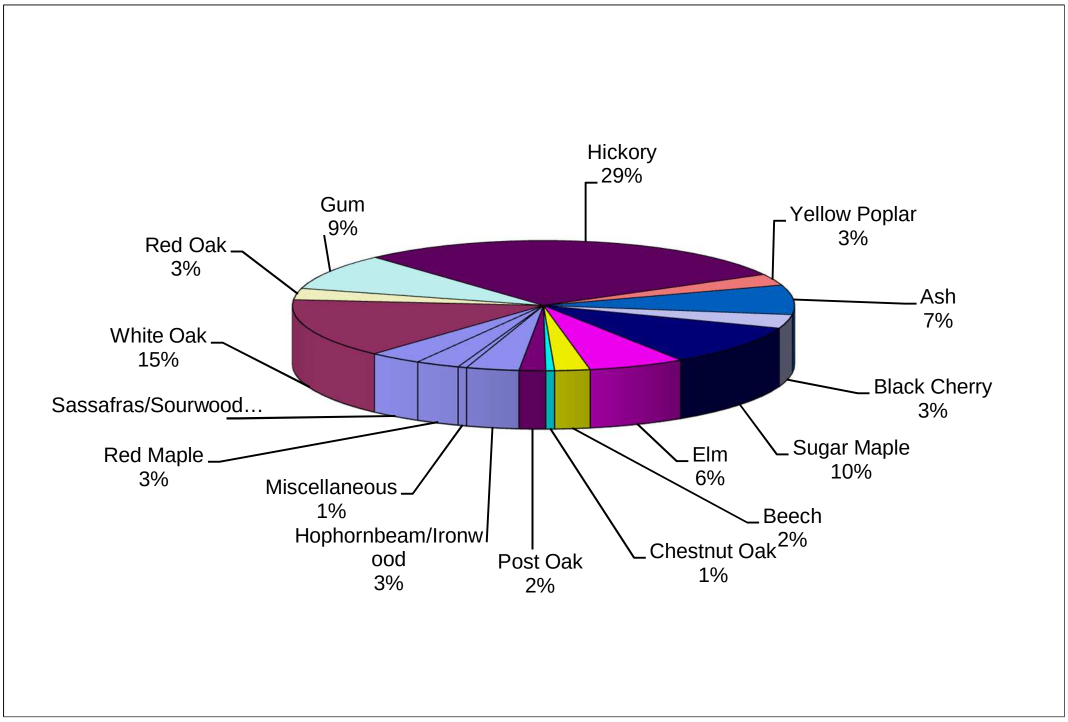

Figure 16. Merchantable stem (>4.5 inches dbh) species composition within block C on the hardwood response study in west-central Tennessee.

The majority (74%) of the inventoried stems were pulpwood sized materials (less than 12 inches dbh) (Figure 17). Similar to the previous blocks, the diameter distribution represents a J-shaped curve. The average diameter for the sample was approximately 9.25 inches. The estimated trees per acre was calculated to be 118 trees. Stand stocking was determined to 56 $ft.^2$ of basal area per acre. Sawtimber volume was computed to be approximately 1,523 board feet per acre.

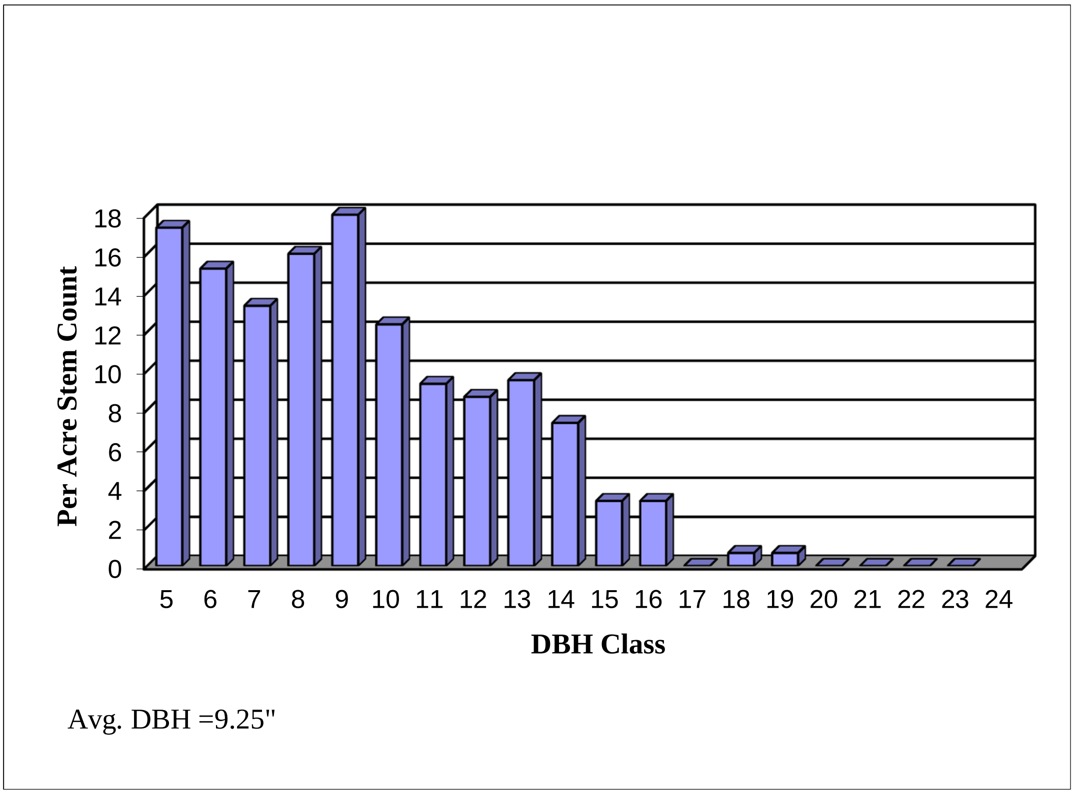

Figure 17. Diameter distribution table for block C on the hardwood response study in west-central Tennessee.

The understory reproduction in Block C has a greater number of stems (3,857 stems per acre) with a variety of tree species (Table 7). Eastern hophornbeam was the largest contributor and comprised almost exactly one-third of the estimated population at 33.4% (estimated 1,287 stems per acre). Other sizeable contributors included ash at 13% (500 stems per acre), yellow-poplar at 11.5% (443 stems per acre), miscellaneous species at 12.5% (483 stems per acre), sassafras with 6.9% (265 stems per acre) and white oak comprising 4.3% (165 trees per acre). Combined oak species only accounted for 5.7% (217 stems per acre) of the entire sample. All other tree species accounted for 2.8% as individual species contributors.

Table 7. Reproduction composition (pre-harvest) by species and percentages for Block C on the hardwood response study in west-central Tennessee.

Species	Stem Count (Per Acre)	Percentage
Hophornbeam	1287	33.4
Yellow-poplar	443	11.5
White oak	165	4.3
Red oak	52	1.4
Sugar maple	43	1.1
Ash	500	13.0
Beech	30	0.8
Sourwood	0	0.0
Sassafras	265	6.9
Elm	96	2.5
Cedar	4	0.1
Sumac	4	0.1
Dogwood	100	2.6
Ironwood	61	1.6
Redbud	109	2.8
Red Maple	0	0.0
Persimmon	0	0.0
Hickory	74	1.9
Black cherry	13	0.3
Blackgum	48	1.2
Devil’s walking stick	78	2.0
Miscellaneous	483	12.5
Total	3857	100.0

Similar to previous blocks, size classes of reproduction were primarily moderate seedlings to saplings (Table 8). Seedlings that were either greater than three foot in height or less than one inch diameter accounted for slightly less than half (49%) of the inventoried stems. The estimated total for seedlings in this size class was approximately 1,891 stems per acre. Moderate sized sapling greater than one inch but less than three inches were the next largest component of the reproduction with 26.9% (1,039 stems per acre) of the sampled stems. Seedlings between one foot to three feet in height were estimated to form a significant component (16.1% or 626 stems per acre) of the regeneration. Saplings greater than three inches but less than six inches in ground line diameter formed 5.4% (209 stems per acre) of inventoried stems. Pulpwood sized stems greater than six inches in diameter on comprised 2.4% of observed data.

Table 8. Pre-harvest reproduction within block C by species and size class on the hardwood response study in west-central Tennessee

Species	Regeneration Size Class >1' height	1' - 3' height	>3' height OR <1.0" diameter	1.0" - 2.99" diameter	3.0" - 5.99" diameter	6.0' and above
Hophornbeam	0	87	726	387	78	9
Yellow-poplar	0	9	178	222	22	13
White oak	0	126	13	0	0	26
Red oak	0	17	30	0	0	4
Sugar maple	0	4	13	9	13	4
Ash	0	165	317	17	0	0
Beech	0	0	13	13	4	0
Sourwood	0	0	0	0	0	0
Sassafras	0	30	109	126	0	0
Elm	0	0	9	39	39	9
Cedar	0	4	0	0	0	0
Sumac	0	0	0	4	0	0
Dogwood	0	4	61	22	13	0
Ironwood	0	4	35	22	0	0
Redbud	0	0	30	61	17	0
Red Maple	0	0	0	0	0	0
Persimmon	0	0	0	0	0	0
Hickory	0	17	26	13	0	17
Black cherry	0	0	4	9	0	0
Blackgum	0	0	0	22	17	9
Devil's walking stick	0	35	30	13	0	0
Miscellaneous	0	122	296	61	4	0
Totals	0	626	1891	1039	209	91
Percent (%)	0	16	49	27	5	2

*height denotes seedling height from ground to terminal bud

Seedling Summary Data for Herbicide Treatments

Initial seedling diameters were measured in the fall of 2014 with a sample size of 2,625 observations. Seedling diameter measurements collected in the winter of 2017 had a smaller sample size of 1,560 observations. Each individual treatment unit had some variation in the species composition of measured seedlings (Table 9 and 10).

Table 9. Individual seedling counts, by species class, for each individual treatment unit across all blocks on the hardwood response study in west-central Tennessee

Block #	Treatment	YP	ROAK	WHO	Total
A	Banded	45	38	25	108
B	Banded	29	40	34	103
C	Banded	32	8	14	54
A	Radial	12	39	31	82
B	Radial	24	40	21	85
C	Radial	12	28	40	80
A	SFM 75	41	32	13	86
B	SFM 75	68	32	27	127
C	SFM 75	7	16	35	58
A	Control	28	35	33	96
B	Control	32	39	36	107
C	Control	10	22	49	81
A	Banded/SFM 75	12	63	20	95
B	Banded/SFM 75	67	21	5	93
C	Banded/SFM 75	8	24	43	75
A	Radial/SFM 75	13	33	14	60
B	Radial/SFM 75	52	32	12	96
C	Radial/SFM 75	9	13	42	64
			Total Count =		1550

The three combined banded treatment units contained a total of 265 measured seedlings. One-hundred and six of these seedlings were yellow-poplars, 75 were red oak species, and 84 were white oak species. The banded plus sulfometuron methyl treatments contained 263 sample seedlings. The seedling composition included counts of 87 for yellow-poplar, 104 for red oak, and 72 for white oak. Untreated control units were represented by 294 tree seedlings. The species breakdown included 70 yellow-poplars, 92 red oaks, and 132 white oaks. The sulfometuron methyl only treatment units contained 271 measured seedlings. One hundred and sixteen of these seedlings were yellow-poplar. Red oak and white oak counts were 80 and 75, respectively. Two hundred and forty-seven quantified seedlings were accounted for in the radial units. Species arrangement included 48 yellow-poplar seedlings, 94 red oak seedlings, and 105 white oak seedlings. Two hundred and twenty measured seedlings exist on the radial plus sulfometuron methyl treatment units. Seventy-four yellow-poplar, 72 red oak, and 74 white oak are combined for the Radial/SFM75 treatment (Table 10).

Table 10. Total counts for species grouping by treatment (summary for 2017) on the hardwood response study in west-central Tennessee

Treatment	Species grouping			Treatment Totals
	yellow-poplar	red oak	white oak	
Banded	106	86	73	265
Banded/SFM 75	87	108	68	263
Control	70	96	118	284
Control/SFM 75	116	80	75	271
Radial	48	107	92	247
Radial/SFM 75	74	78	68	220
Totals	501	555	494	1,550

**counts for individual treatments are totals for all three blocks combined*

Statistical Results of Ground Line Diameter Change Among Treatments

Data for the change in ground line diameter was normal according to the Shapiro-Wilk test (W-value = 0.9313; P-value <0.0001). The analysis did not suggest any severe outliers or influential points existed in the data and that equal variance existed in the data set. The least squares means were separated using Tukey's significant difference test. Results indicate there were not significant differences between the three blocks (P=0.1998). A significant difference did exist however between treatments by block (P=0.0389) (Table 11).

Table 11. Covariance parameter estimates for combined oak/yellow-poplar seedling diameter change

Covariate Parameter	Estimate	Std. Error	Z value	P-value	95% Confidence Intervals	
Block	0.002825	0.003354	0.84	0.1998	.000659	0.4136
Treatment*Block	0.002560	0.001452	1.76	0.0389	.001076	0.01195
Residual	0.05169	0.00186	27.79	<.0001	.04823	0.05554

The test of fixed effects indicates that a significant difference (Pr > F = 0.0037) existed among the treatments when all seedlings were combined for the analysis (Table 12).

Table 12. Type III tests of fixed effects for diameter change among treatments for all seedlings combined

Effect	Num DF	Den DF	F-Value	Pr > F
Treatment	5	1556	3.51	0.0037

Post ANOVA analysis using the Tukey mean separation found a difference among the treatments for the change in diameter growth. The sulfometuron methyl only differed from the control and radial treatments. All other treatments were similar. The greatest mean value (0.3749 inches) was for the sulfometuron treatment (Table 13).

Table 13. Tukey mean separation results among combined oak/yellow-poplar seedling diameter growth

Treatment	Observations	Mean (inches)	Std. Error	Letter Group
Banded	265	0.3480	0.01446	AB
Banded + SFM 75	263	0.3231	0.01454	AB
Control	294	0.3114	0.01373	B
Control + SFM 75	271	0.3749	0.01430	A
Radial	248	0.3037	0.01494	B
Radial + SFM 75	222	0.3504	0.01580	AB

Statistical Results of Height Change Among Treatments

A randomized complete block design with sampling was incorporated for this analysis. Data for the change in height was normal according to the Shapiro-Wilk test (W-value = 0.9405; P-value <0.0001) and equal variance was satisfactory. The statistical software did not suggest that any severe outliers or influential points existed in the data set. The least squares means were separated using Tukey's significant difference test. Analysis results indicate there were not significant differences between the three blocks (P=0.1701) (Table 14). A significant difference did not exist between treatments by block (P=0.0550).

Table 14. Covariance parameter estimates for combined oak/yellow-poplar seedling height change

Covariate Parameter	Estimate	Std. Error	Z value	P-value	95% Confidence Intervals	
Block	36.1153	37.8608	0.95	0.1701	9.3986	1951.78
Treatment*Block	7.8136	4.8880	1.60	0.0550	3.0683	45.7162
Residual	231.78	8.3408	27.79	<.0001	216.28	249.03

A type III test of fixed effects was conducted for the change in height for all seedlings combined. The test indicated a difference (Pr > F <0.0001) existed among the treatments when all seedlings were combined for the analysis (Table 15).

Table 15. Type III tests of fixed effects for height change among treatments for all seedlings combined

Effect	Num DF	Den DF	F-Value	Pr > F
Treatment	5	1556	14.19	<0.0001

Post ANOVA analysis using the Tukey mean separation found a significant difference between the sulfumeturon methyl only treatment and the radial treatment compared to all other treatments in regards to the change in diameter growth. These treatments also differed from one another. The sulfometuron methyl only had the greatest mean with 28.9446 inches. The radial release treatments has the least mean value of 17.2641 inches (Table 16).

Table 16. Tukey mean separation results among combined oak/yellow-poplar seedling height growth

Treatment	Observations	Mean (inches)	Std. Error	Letter Group
Banded	265	24.3953	0.99410	B
Banded + SFM 75	263	21.9399	0.9998	B
Control	294	23.744	0.9438	B
Control + SFM 75	271	28.9446	0.9831	A
Radial	248	17.2641	1.0276	C
Radial + SFM 75	222	22.8266	1.0862	B

Statistical Results of Ground Diameter Change: White Oak Species as Related to Red Oak Species and Yellow-Poplar

Data for the change in ground line diameter was normal according to the Shapiro-Wilk test (W-value = 0.9327; P-value <0.0001). Equal variance was less than a five-fold difference indicating acceptability. The statistical software did not suggest any severe outliers or influential points existed in the data set. The least squares means were separated using Tukey's significant difference test. Analysis results indicate there were not significant differences between the three blocks (P=0.2055) (Table 17). A significant difference did not exist between treatments by block (P=0.0659). There was also no difference between treatments (p=0.9297). A difference does exist between species groups (p<0.001).

Table 17. Covariance parameter estimates for species groups seedling ground line diameter change

Covariate Parameter	Estimate	Std. Error	Z value	P-value	95% Confidence Intervals	
Block	.0014	.0017	0.82	0.2055	.0003	.2579
Treatment*Block	.0012	.0008	1.51	0.0659	.0005	.0084
Residual	.0472	.0017	27.66	<.0001	.0441	.0508

An analysis of variance indicated that there was a significant difference (p = 0.02988) between diameter growth of individual seedlings but not between species by treatments (p = 0.10249) or individual treatments (p = 0.07823). Post ANOVA analysis using the Tukey mean separation had no significant difference between any of the treatments in regards to the change in diameter growth with species grouping. The individual ground line diameter growth did vary between the three groups however. Yellow-poplar seedlings had appreciably larger means compared to both red and white oak groups on all treatments. Yellow-poplar mean ground line diameter for all treatments combined was the largest (0.4389 inches) and differed from both oak groups. All three species groups differed from one another with the red oak and white oak mean diameters being 0.3100 and 0.2576 inches, respectively (Table 18). Tests for normality were acceptable and equal variance did not exceed a five-fold difference in standard deviation values.

Table 18. Tukey mean separation results between species groups for seedling ground line diameter

Species Group	Observations	Mean (inches)	Std. Error	Letter Group
White Oak	542	0.2576	0.02519	C
Red Oak	517	0.3100	0.02519	B
Yellow-poplar	501	0.4389	0.02555	A

The Tukey mean separation test indicated that some difference existed for yellow-poplar in all of the individual treatments though the findings were not significant at the $\alpha = 0.05$ level (Table 19). For each case, the mean diameter change was equal to or greater than 0.4070 inches. The highest white oak group diameter growth was only 0.2909 inches. The red oak group was marginally better with a maximum diameter change of 0.3211 inches.

Table 19. Tukey mean separation results among combined treatments for seedling diameter growth

Treatment	Species	Observations	Mean (inches)	Std. Error	Letter Group
Banded	Red Oak	75	0.3075	0.0396	CDE
Banded	White Oak	84	0.2645	0.0383	CDE
Banded	Yellow-poplar	106	0.4618	0.0364	A
Banded + SFM 75	Red Oak	104	0.2906	0.0370	CDE
Banded + SFM 75	White Oak	72	0.2322	0.0403	CDE
Banded + SFM 75	Yellow-poplar	87	0.4312	0.0401	A
Control	Red Oak	92	0.3211	0.0374	CD
Control	White Oak	132	0.2527	0.0352	EF
Control	Yellow-poplar	70	0.4070	0.0397	AB
Control + SFM 75	Red Oak	80	0.3144	0.0385	BCDE
Control + SFM 75	White Oak	75	0.2718	0.0391	CDE
Control + SFM 75	Yellow-poplar	116	0.4574	0.0369	A
Radial	Red Oak	94	0.3077	0.0372	CE
Radial	White Oak	105	0.2334	0.0366	DF
Radial	Yellow-poplar	48	0.4486	0.0434	A
Radial + SFM 75	Red Oak	72	0.3189	0.0397	BCDE
Radial + SFM 75	White Oak	74	0.2909	0.0400	CDE
Radial + SFM 75	Yellow-poplar	74	0.4275	0.0404	A

Statistical Results of Height Change for Oak Species Against Yellow-Poplar

Data for the change in height change over the two full growing seasons were normal according to the Shapiro-Wilk test (W-value = 0.9469; P-value <0.0001). Equal variance was potentially an issue with a two-fold difference in standard deviation. This is within tolerance limits however as concerns should only be addressed if a five-fold difference is evident. The statistical software did not suggest any severe outliers or influential points existed in the data set. The least squares means were separated using Tukey's significant difference test. Analysis results indicate there were not significant differences between the three blocks (P=0.1691) (Table 20). A significant difference did not exist between treatments by block (P=0.1186). A difference was found between both the treatments (p=0.0399) and species groups (p<0.0001).

Table 20. Covariance parameter estimates for species groups seedling height change

Covariate Parameter	Estimate	Std. Error	Z value	P-value	95% Confidence Intervals	
Block	20.1648	21.0512	0.96	0.1691	5.2668	1058.57
Treatment*Block	2.7006	2.2848	1.18	0.1186	0.8421	43.7539
Residual	200.14	7.2335	27.67	<.0001	186.69	215.11

Statistical analysis suggested that there was a significant difference between the treatments based on the change in height growth when using the individual species groups (p =0.0399). There was also a disparity between the height growth for the species groups (p < 0.0001). Post ANOVA analysis using the Tukey mean separation found a statistical difference between the treatments when using species group data for the change in height. The test also indicated that individual height growth did vary between the three groups. Yellow-poplar mean ground line diameter was the largest (31.59 inches) (Table 21) and differed from both oak groups. The red oak and white oak groups did not differ from one another. The groups' mean diameters were 18.12 and 19.07 inches, respectively. Tests for normality were acceptable and equal variance did not exceed a five-fold difference in standard deviation values.

Table 21. Tukey mean separation results amongst species groups for seedling height change

Species Group	Observations	Mean (inches)	Std. Error	Letter Group
White Oak	542	19.070	2.6997	B
Red Oak	517	18.182	2.6996	B
Yellow-poplar	501	31.585	2.7134	A

The Tukey mean separation test indicated that some difference existed for yellow-poplar in all of the individual treatments. For each case, the mean diameter change was equal to or greater than 27.7 inches. The highest oak group height growth was only 21.58 inches for the sulfometuron methyl only treatment (Table 22).

Table 22. Tukey mean separation results amongst combined treatments for seedling height growth

Treatment	Species	Observations	Mean (inches)	Std. Error	Letter Group
Banded	Red Oak	75	20.0562	3.2421	D
Banded	White Oak	84	17.6618	3.1798	DE
Banded	Yellow-poplar	106	32.1280	3.0873	ABC
Banded + SFM 75	Red Oak	104	16.9839	3.1156	DE
Banded + SFM 75	White Oak	72	16.9539	3.2763	DE
Banded + SFM 75	Yellow-poplar	87	31.2443	3.2565	ABC
Control	Red Oak	92	21.0624	3.1344	D
Control	White Oak	132	19.9161	3.0287	D
Control	Yellow-poplar	70	33.7130	3.2528	AB
Control + SFM 75	Red Oak	80	21.3403	3.1915	D
Control + SFM 75	White Oak	75	21.5894	3.2226	D
Control + SFM 75	Yellow-poplar	116	36.1491	3.1046	A
Radial	Red Oak	94	16.4435	3.1258	DE
Radial	White Oak	105	12.7909	3.0939	E
Radial	Yellow-poplar	48	28.4910	3.4455	BC
Radial + SFM 75	Red Oak	72	18.5342	3.2506	D
Radial + SFM 75	White Oak	74	20.1784	3.2613	D
Radial + SFM 75	Yellow-poplar	74	27.7837	3.2819	C

New Germinant Versus Sprout Reproduction Absolute Growth for Combined Species

Statistical analyses found that all but one comparisons between reproduction class (new germinant or sprout) versus absolute diameter or absolute height growth were significant at the alpha = 0.05 level. The test for the new germinant reproduction paired with the absolute diameter growth was not significant (P = 0.2244). The pairwise test for sprout reproduction with absolute diameter change was significant (P = 0.0268) (Table 23).

Table 23. Type III tests of fixed effects for absolute diameter change among treatments for all sprout reproduction combined

Effect	Num DF	Den DF	Chi-Square	F-Value	Pr > F
Treatment	5	1045	12.72	2.54	0.0268

The sulfometuron methyl only treatment produced the highest mean estimate (0.3693 inches) for absolute diameter growth for the combined sprout reproduction. The radial release application resulted in the lowest estimate of 0.2896 inches which is below the control estimate (Table 24).

Table 24. Least square means estimates for absolute change in diameter for sprout reproduction among treatments

Treatment	Estimate	Std. Error	T - value	P - value
Banded	0.3339	0.03136	10.65	0.0002
Banded + SFM 75	0.3003	0.03091	9.71	0.0004
Control	0.316	0.02943	10.74	0.0007
SFM 75	0.3693	0.03012	12.26	0.0003
Radial	0.2896	0.02988	9.69	0.0008
Radial + SFM 75	0.3375	0.0306	11.03	0.0003

The sulfometuron treatment was significantly different from both the control and radial applications for sprout reproduction and absolute diameter growth. The sulfometuron treatment also had the greatest level of separation from the control treatment (Table 25) depicts these findings.

Table 25. Tukey-Kramer least squares means comparison estimates for absolute change in diameter for sprout reproduction among individual treatment comparisons

Treatments Compared	Estimate	Std. Error	T - value	Pr > |t|	Adjusted P-value
Banded + SFM75 / SFM75	-0.06901	0.02633	-2.62	0.0089	0.0931
Control / SFM75	-0.05325	0.02445	-2.18	0.0297	0.2491
SFM75 / Radial	0.07969	0.02497	3.19	0.0015	0.0183

The type III test indicated a difference (P = 0.0245) also existed between treatments for new germinant reproduction in regards to absolute height change (Table 26).

Table 26. Type III tests of fixed effects for absolute height change among treatments for all new germinant reproduction combined

Effect	Num DF	Den DF	Chi-Square	F-Value	Pr > F
Treatment	5	502	13.02	2.6	0.0245

The sulfometuron methyl only treatments had the largest response in absolute height growth for new germinant reproduction. The mean estimate for sprout height growth over the three growing seasons was 29.035 inches. This was approximately seven inches greater than the control germinant reproduction. In a similar fashion as absolute diameter growth, the radial treatment had the least growth increase with an estimate of only 21.4344 inches. This value was also lower than the control estimate (Table 27).

Table 27. Least square means estimates for absolute change in height for sprout reproduction among treatments

Treatment	Estimate	Std. Error	T - value	P - value
Banded	24.6094	5.0621	4.86	0.0312
Banded + SFM 75	23.7461	5.0919	4.66	0.0325
Control	22.4371	5.1245	4.38	0.0354
SFM 75	29.035	5.1241	5.67	0.0201
Radial	21.4344	5.2351	4.09	0.035
Radial + SFM 75	24.0605	5.2608	4.57	0.026

Five pairwise comparisons out of 15 were significant. The sulfometuron treatment differed from both the control and radial treatments. These treatments also had the largest separation between estimate values (Table 28).

Table 28. Tukey-Kramer least squares means comparison estimates for absolute change in height for sprout reproduction between individual treatment comparisons

Treatments Compared	Estimate	Std. Error	T - value	Pr > |t|	Adjusted P-value
Banded / SFM75	-4.4256	2.0714	-2.14	0.0331	0.2702
Banded + SFM75 / SFM75	-5.289	2.1207	-2.49	0.0130	0.1278
Control / SFM75	-6.5979	2.2133	-2.98	0.0030	0.0355
SFM75 / Radial	7.6006	2.4726	3.07	0.0022	0.0269
SFM75 / Radial + SFM75	4.9745	2.5187	1.98	0.0488	0.3582

The type III test that compared sprout reproduction to absolute height change also found differences between treatments (P = <0.0001) (Table 29).

Table 29. Type III tests of fixed effects for absolute height change among treatments for all sprout reproduction combined

Effect	Num DF	Den DF	Chi-Square	F-Value	Pr > F
Treatment	5	1044	56.97	11.39	<0.0001

The same pattern as found for other reproduction to growth comparisons was also observed in the test comparing absolute height change with sprout reproduction. The sulfometuron methyl treatment has the largest increase in height growth with an estimate of 26.91 inches. The sprouts in the radial treatments had the poorest height change response with an estimate of 15.59 inches (Table 30).

Table 30. Least square means estimates for absolute change in height for sprout reproduction among treatments

Treatment	Estimate	Std. Error	T - value	P - value
Banded	22.5347	3.1151	7.23	0.0075
Banded + SFM 75	19.6778	3.0966	6.35	0.0112
Control	23.6151	3.0363	7.78	0.0086
SFM 75	26.9101	3.0642	8.78	0.0057
Radial	15.5904	3.0543	5.1	0.022
Radial + SFM 75	20.7444	3.0834	6.73	0.0102

Ten out of 15 treatment comparison were significant according to the Tukey-Kramer post-ANOVA test of least squares means. An average difference of 11.32 inches existed between the radial and sulfometuron treatments. Treatment comparisons are presented in Table 31.

Table 31. Tukey-Kramer least squares means comparison estimates for absolute change in height for sprout reproduction among individual treatment comparisons

Treatments Compared	Estimate	Std. Error	T - value	Pr > |t|	Adjusted P-value
Banded / SFM75	-4.3754	1.7092	-2.56	0.0106	0.1083
Banded / Radial	6.9443	1.6979	4.09	<.0001	0.0007
Banded + SFM75 / Control	-3.9372	1.6318	-2.41	0.016	0.1527
Banded + SFM75 / SFM75	-7.2322	1.6929	-4.27	<.0001	0.0003
Banded + SFM75 / Radial	4.0875	1.6652	2.45	0.0143	0.1389
Control / SFM75	-3.295	1.5718	-2.10	0.0363	0.2899
Control / Radial	8.0247	1.5511	5.17	<.0001	<.0001
SFM75 / Radial	11.3197	1.6052	7.05	<.0001	<.0001
SFM75 / Radial + SFM75	6.1657	1.6538	3.73	0.0002	0.0028
Radial / Radial + SFM75	-5.154	1.6415	-0.14	0.0017	0.0214

New Germinant Versus Sprout Reproduction (by Species) Absolute Diameter Growth Response to Treatments

Only yellow-poplar new germinant reproduction absolute change in diameter was significant (P = 0.0161) among all the species by reproduction size comparisons (Table 32). Red oak new germinant and sprout reproduction, white oak new germinant and sprout reproduction, and yellow-poplar sprout reproduction were all insignificant with P-levels of 0.1984, 0.9517, 0.3792, 0.1252, and 0.2434 respectively.

Table 32. Type III tests of fixed effects for absolute diameter change among treatments for yellow-poplar new germinant reproduction

Effect	Num DF	Den DF	Chi-Square	F-Value	Pr > F
Treatment	5	310	14.16	2.83	0.0161

Yellow-poplar germinants had the greatest mean estimate for absolute diameter growth within the banded treatments (0.4542 inches) followed by sulfometuron only application (0.4203 inches). All herbicide applications were higher than the control estimate (0.3268 inches) however (Table 33).

Table 33. Least square means estimates for absolute change in diameter for yellow-poplar new germinant reproduction among treatments

Treatment	Estimate	Std. Error	T - value	P - value
Banded	0.4542	0.0694	6.54	0.0155
Banded + SFM 75	0.385	0.0706	5.45	0.0198
Control	0.3268	0.0714	4.58	0.0269
SFM 75	0.4203	0.0703	5.98	0.0167
Radial	0.4148	0.0746	5.56	0.0108
Radial + SFM 75	0.3936	0.0749	5.26	0.0122

Four of the 15 treatment pairwise comparisons were significant at the 95% level (Table 34). The greatest difference in estimate values (0.1274 inches) occurred between the banded and control treatment. The sulfometuron treatment paired with the control was the second greatest difference.

Table 34. Tukey-Kramer least squares means comparison estimates for absolute change in diameter for yellow-poplar new germinant reproduction among individual treatment comparisons

Treatments Compared	Estimate	Std. Error	T - value	Pr > |t|	Adjusted P-value
Banded / Banded + SFM75	0.06917	0.03345	2.07	0.0395	0.307
Banded / Control	0.1274	0.03539	3.6	0.0004	0.005
Control / SFM75	-0.09347	0.03599	-2.6	0.0098	0.101
Control / Radial	-0.08798	0.04428	-1.99	0.0478	0.3521

New Germinant Versus Sprout Reproduction (by Species) Absolute Height Growth Response to Treatments

Red oak new germinant and yellow-poplar new germinant reproduction were not significant (P-values of 0.9685 and 0.2425, respectively) in regards to absolute change in height among treatments. Red oak sprout reproduction was almost or moderately significant (P = 0.0551). White oak new germinant reproduction was found to be different for absolute height change among treatments with a P-value of 0.0152 (Table 35).

Table 35. Type III tests of fixed effects for absolute height change among treatments for white oak new germinant reproduction

Effect	Num DF	Den DF	Chi-Square	F-Value	Pr > F
Treatment	5	80.6	15.07	3.01	0.0152

The most intensive herbicide treatments yielded the greatest mean absolute height estimates for white oak germinants. The radial with the sulfometuron application had an estimate of 22.76 inches. The next highest means were the banded with the sulfometuron treatment (18.52 inches) followed by the sulfometuron treatment (18.47 inches). Both glyphosate only applications were lower than the control estimate (Table 36).

Table 36. Least square means estimates for absolute change in height for white oak new germinant reproduction among treatments

Treatment	Estimate	Std. Error	T - value	P - value
Banded	12.2889	3.5911	3.42	0.0395
Banded + SFM 75	18.5166	4.0705	4.55	0.0061
Control	13.2852	3.5828	3.71	0.0325
SFM 75	18.4657	4.1376	4.46	0.0056
Radial	12.3481	3.759	3.28	0.0337
Radial + SFM 75	22.7603	3.9997	5.69	0.0029

Three of the 15 treatment comparisons showed a difference in the least square means post-ANOVA test. The most intensive treatments had the greatest separation from the control and glyphosate only applications. The estimates ranged from approximately 9.5 – 10.5 inches for the three comparisons (Table 37).

Table 37. Tukey-Kramer least squares means comparison estimates for absolute change in height for white oak new germinant reproduction between individual treatment comparisons

Treatments Compared	Estimate	Std. Error	T - value	Pr > |t|	Adjusted P-value
Banded / Radial + SFM 75	-10.472	3.3149	-3.16	0.0022	0.0262
Control / Radial + SFM 75	-9.4751	3.2535	-2.91	0.0046	0.0509
Radial / Radial + SFM75	-10.412	3.4564	-3.01	0.0035	0.0391

The absolute change in height for white oak sprout reproduction was also strongly different among treatments. A low P-value of <0.0001 was estimated from the type III two-way pairwise test (Table 38).

Table 38. Type III tests of fixed effects for absolute height change among treatments for white oak sprout reproduction

Effect	Num DF	Den DF	Chi-Square	F-Value	Pr > F
Treatment	5	346	27.43	5.49	<.0001

Similar to data presented for the absolute diameter change for sprout reproduction, the sulfometuron methyl treatment had the optimal performance with an estimate of 21.05 inches of height growth. Likewise, the radial application was dramatically lower with only 12.84 inches of absolute height change. Contrary to results for white oak germinants, the more intensive treatments were lower, for white oak sprouts, than the control estimate (Table 39).

Table 39. Least square means estimates for absolute change in height for white oak sprout reproduction among treatments

Treatment	Estimate	Std. Error	T - value	P - value
Banded	20.5589	2.9019	7.08	0.0019
Banded + SFM 75	16.0717	2.794	5.75	0.0065
Control	19.9888	2.5972	7.7	0.0069
SFM 75	21.0504	2.7628	7.62	0.003
Radial	12.841	2.657	4.83	0.0181
Radial + SFM 75	19.5755	2.8922	6.77	0.0023

Six out of the 15 treatment comparisons were significantly dissimilar from one another. The most pronounced range between mean height change estimates was found between the sulfometuron and radial treatments. Table 40 contains all significant comparisons between individual treatments.

Table 40. Tukey-Kramer least squares means comparison estimates for absolute change in height for white oak sprout reproduction between individual treatment comparisons

Treatments Compared	Estimate	Std. Error	T - value	Pr > |t|	Adjusted P-value
Banded / Radial	7.7179	2.19	3.52	0.0005	0.0064
Banded + SFM75 / Control	-3.9171	1.9031	-2.06	0.0403	0.3119
Banded + SFM75 / SFM 75	-4.9787	2.1239	-2.34	0.0196	0.1794
Control / Radial	7.1478	1.7205	4.15	<.0001	0.0006
SFM75 / Radial	8.2094	1.9804	4.15	<.0001	0.0006
Radial / Radial + SFM75	-6.7245	2.1251	-3.17	0.0017	0.0205

The absolute height change for yellow-poplar sprouts was also different among treatments. The pairwise test indicated that a P-value of 0.0031 existed (Table 41).

Table 41. Type III tests of fixed effects for absolute height change among treatments for yellow-poplar sprout reproduction

Effect	Num DF	Den DF	Chi-Square	F-Value	Pr > F
Treatment	5	178	18.64	3.73	0.0031

All herbicide treatment mean estimates were lower than the control mean estimate of 44.04 inches. The radial with the sulfometuron treatment and the radial only treatment had the lowest estimates with 24.75 inches and 24.84 inches, respectively. This is a substantial difference of almost 20 inches (Table 42).

Table 42. Least square means estimates for absolute change in height for yellow-poplar sprout reproduction among treatments

Treatment	Estimate	Std. Error	T - value	P - value
Banded	32.4182	5.6518	5.74	0.0015
Banded + SFM 75	34.8579	6.4344	5.42	0.0004
Control	44.0357	6.2495	7.05	<.0001
SFM 75	39.1072	5.1483	7.6	0.0021
Radial	24.8441	6.4684	3.84	0.0035
Radial + SFM 75	24.7472	5.3228	4.65	0.0084

The post-ANOVA least squares means test indicated that 4 of the 15 treatments were statistically dissimilar. The greatest contrast appears to be between the control and both radial treatments. Table 43 depicts the post-ANOVA summary.

Table 43. Tukey-Kramer least squares means comparison estimates for absolute change in height for yellow-poplar sprout reproduction between individual treatment comparisons

Treatments Compared	Estimate	Std. Error	T - value	Pr > |t|	Adjusted P-value
Control / Radial	19.1916	6.9248	2.77	0.0062	0.0669
Control / Radial + SFM75	19.2884	5.8933	3.27	0.0013	0.0159
SFM75 / Radial	14.2631	5.8844	2.42	0.0164	0.1537
SFM75 / Radial + SFM75	14.36	4.4318	3.24	0.0014	0.0176

Relative Growth Change for All Analysis

Relative changes in growth for diameter and height were also analyzed using similar statistical methodology. Comparisons for both diameter change and height change were made between treatments, reproduction size classes, individual species groupings, and size class by species groupings. The relative change in growth had similar findings to each respective absolute growth comparison. The findings are presented in the Appendix section.

Competitive Vegetation Analysis for Ground Covers

Ocular estimation was used to discern the percentage of ground cover by various plant competitors (Table 44). These plants primarily included broomsedge bluestem, Nepalese browntop, *Rubus* species, leaf litter beneath conglomerations of sapling sized stems, and herbaceous vegetation with limited bare ground exposure. There was a tremendous response by grass species over the two growing seasons following treatment implementation. Fifteen out of the 18 treatments units were estimated to be covered by 50% or more by warm-season grass species. Ten of these units had a ground coverage percentage, by grass, of 70% or more. Blackberry (Rubus species) were also fairly common on site but typically covered less ground area compared to the grasses. Isolated pockets of larger saplings (½ inch – 4 inches ground diameter) were present infrequently across each block. Limited grass or herbaceous vegetation existed beneath denser accumulations of woody stems due to heavier shading. All treatments that received the post-emergent application of sulfometuron methyl herbicide had a minimum assessment of 50% grass cover. The data do not suggest any convincing difference between the three blocks and the responded plant community.

Table 44. Ocular estimates of vegetative ground cover percentages by individual treatment units on the hardwood response study in west-central Tennessee

Block	Treatment	Vegetative Cover Type				
		Broomsedge	Microstegium	Rubus sp.	Leaf litter/ Saplings	Herbaceous/ sparse grass
A	Control	***	40%	60%	***	***
B	Control	95%	***	5%	***	***
C	Control	80%	***	5%	***	15%
A	Control + SFM 75	40%	10%	50%	***	***
B	Control + SFM 75	60%	***	25%	***	15%
C	Control + SFM 75	95%	***	***	***	5%
A	Radial	10%	40%	30%	20%	***
B	Radial	15%	***	85%	***	***
C	Radial	90%	***	10%	***	***
A	Radial + SFM 75	60%	***	***	20%	20%
B	Radial + SFM 75	50%	***	5%	45%	***
C	Radial + SFM 75	85%	***	15%	***	***
A	Banded	10%	75%	15%	***	***
B	Banded	15%	***	70%	15%	***
C	Banded	85%	***	15%	***	***
A	Banded + SFM 75	95%	***	5%	***	***
B	Banded + SFM 75	95%	***	5%	***	***
C	Banded + SFM 75	70%	***	***	***	30%

Competitive Vegetation Analysis for Tree Reproduction Density Measurements

Data accumulated for the six individual (1/100- acre) plots were summarized to per acre values for each of the three replicated blocks on the study area (Table 45). Block A has two prominent species that comprise over half of the estimated tree population. Blackgum and yellow-poplar are estimated to for approximately 29% apiece of the estimated species composition. Ash (9%) and hickory (8%) were also significant competitors with oak (4%) species for available growing space. These numbers followed a similar pattern as presented for pre-harvest regeneration (Figure 12) with the exception to blackgum, which had a significant increase in abundance.

Table 45. Reproduction composition by species and percentages within block A (two growing season after treatments) on the hardwood response study in west-central Tennessee

Species	Stem Count (Per Acre)	Percentage
Hophornbeam	33	1.3
Yellow-poplar	750	28.7
White oak	50	1.9
Red oak	50	1.9
Sugar maple	17	0.6
Ash	233	8.9
Elm	83	3.2
Blackgum	767	29.3
Ailanthus	167	6.4
Buckthorn	33	1.3
Persimmon	33	1.3
Hickory	217	8.3
Black cherry	33	1.3
Red maple	33	1.3
Sumac	67	2.5
Paulownia	17	0.6
Loblolly pine	17	0.6
Hackberry	17	0.6
Totals	2617	100

The majority (68% or 1,783 stems per acre) of the reproduction on block A occupied the larger seedling and small sapling size classes (Table 46). Yellow-poplar formed the greater abundance (217 stems per acre) of large saplings within the block. Ash, sugar maple, tree of heaven, and Carolina buckthorn also had larger sized reproduction on site but at a lesser quantity. Small seedlings less than one foot in height were limited within the area consisting of only approximately 4% of the sampled population.

Table 46. Reproduction after two complete growing seasons within block A, by species and size class, on the hardwood response study in west-central Tennessee

	Regeneration Size Class					
Species	>1' ht.	1' – 3' ht.	>3' ht. OR <01.0" diameter	1.0" – 2.99" diameter	3.0" – 5.99" diameter	6.0' and above
Hophornbeam	0	17	0	17	0	0
Yellow-poplar	0	150	117	267	217	0
White oak	0	50	0	0	0	0
Red oak	0	33	17	0	0	0
Sugar maple	0	0	0	0	17	0
Ash	0	50	150	0	33	0
Elm	33	33	17	0	0	0
Blackgum	33	333	400	0	0	0
Ailanthus	0	0	33	117	17	0
Buckthorn	0	0	0	0	33	0
Persimmon	0	0	33	0	0	0
Hickory	33	133	50	0	0	0
Black cherry	0	0	33	0	0	0
Red maple	0	17	17	0	0	0
Sumac	0	17	50	0	0	0
Paulownia	0	0	17	0	0	0
Loblolly pine	0	17	0	0	0	0
Hackberry	0	0	0	17	0	0
Totals	100	850	933	417	317	0
Percent (%)	3.8	32.5	35.7	15.9	12.1	0.0

Block B findings have yellow-poplar dominating the species composition at 40% or 1,683 stems per acre (Table 47). Shade tolerant species including hickory and eastern hophornbeam also form a sizeable percentage of the sampled population at 17% apiece. Red and white oak species form approximately 5% of the sample. Species diversity was lower than block A and the same as block C however overall stem count estimation was the highest at 4,167 stems per acre.

Table 47. Reproduction composition by species and percentages within block B (two growing seasons after treatments) on the hardwood study in west-central Tennessee

Species	Stem Count (Per Acre)	Percentage
Hophornbeam	700	16.8
Yellow-poplar	1683	40.4
White oak	50	1.2
Red oak	167	4.0
Ash	267	6.4
Persimmon	100	2.4
Hickory	700	16.8
Red maple	50	1.2
Sumac	450	10.8
Totals	4,167	100

Size class distribution within block B is also dominated by larger seedlings and small saplings (Table 48). Approximately 91% of the projected reproduction falls within these categories. Minimal small seedlings were present on the block after two complete growing seasons have elapsed. A small proportion of the sample (7%) were larger hickory and yellow-poplar saplings.

Table 48. Reproduction after two complete growing seasons within block B, by species and size class, on the hardwood response study in west-central Tennessee

	Regeneration Size Class					
Species	>1' ht.	1' – 3' ht.	>3' ht. OR <01.0" diameter	1.0" – 2.99" diameter	3.0" – 5.99" Diameter	6.0' and above
Hophornbeam	33	267	400	0	0	0
Yellow-poplar	0	983	567	133	0	0
White oak	33	17	0	0	0	0
Red oak	0	83	83	0	0	0
Ash	0	217	50	0	0	0
Persimmon	0	33	67	0	0	0
Hickory	0	300	250	150	0	0
Red maple	0	50	0	0	0	0
Sumac	0	367	83	0	0	0
Totals	67	2,317	1,500	283	0	0
Percent (%)	1.6	55.6	36.0	6.8	0.0	0.0

*ht denotes seedling height from ground to terminal bud
*Diam. Denotes stem diameter at ground line

Block C deviated from the other two blocks in overall reproduction abundance. A meaningfully lower quantity (567 stems per acre) (Table 49) of reproduction was observed within the area. Fewer stems is likely attributed to the location of the loading deck utilized for timber extraction and also the use of heavy equipment to clear logging slash from some of the area. Species composition was more diversified within this block. Yellow-poplar again had the highest tally (133 stems per acre or 23.5%) in the sample data but with lower margin of difference compared to all other species. Other significant contributors included black cherry (17.6%), red oak (14.7%), common persimmon (11.8%), ash (8.8%), and eastern hophornbeam (8.8%) (Table 49) depicts the summation of plot data.

Table 49. Reproduction composition by species and percentages within block C (two growing seasons after treatments) on the hardwood response study in west-central Tennessee

Species	Stem Count (Per Acre)	Percentage
Hophornbeam	50	8.8
Yellow-poplar	133	23.5
White oak	17	2.9
Red oak	83	14.7
Ash	50	8.8
Persimmon	67	11.8
Elm	33	5.9
Redbud	33	5.9
Black cherry	100	17.6
Totals	567	100.0

In accordance with the previous two blocks, block C had the preponderance (72%) of reproduction occupying the larger seedling and small sapling size classes (Table 50). A greater amount of small seedlings were noted within block C as compared to the aforementioned blocks however. The removal of debris, along with advanced regeneration present during the harvest activity, may have removed stems that likely would have yielded some occurrence of larger sized reproduction. New germinates following the disturbance is a plausible reasoning for the higher count of small seedlings.

Table 50. Reproduction after two complete growing seasons within block C, by species and size class, for the hardwood response study in west-central Tennessee

Species	Regeneration Size Class					
	>1' ht.	1' – 3' ht.	>3' ht. OR <01.0" diameter	1.0" – 2.99" diameter	3.0" – 5.99" diameter	6.0' and above
Hophornbeam	0	17	33	0	0	0
Yellow-poplar	0	133	0	0	0	0
White oak	17	0	0	0	0	0
Red oak	0	83	0	0	0	0
Ash	0	50	0	0	0	0
Persimmon	0	17	50	0	0	0
Elm	0	33	0	0	0	0
Redbud	0	33	0	0	0	0
Black cherry	83	17	0	0	0	0
Totals	100	383	83	0	0	0
Percent (%)	17.6	67.6	14.7	0.0	0.0	0.0

*ht denotes seedling height from ground to terminal bud
*Diam. Denotes stem diameter at ground line

Precipitation Records

Monthly precipitation data was collected from the National Oceanic and Atmospheric Administration webpage (http://w2.weather.gov/climate) for the middle Tennessee region. Herbicide treatments were conducted during the growing season of 2014. For that year through the year of 2017, there were 13 months out of 24 (April – September for each year) in which actual measured rainfall fell below average. The droughty months are highlighted in Table 51 below. Yellow months are negative values up to 1.7 inches below the ten year average. Red months are deviations of greater than 1.7 inches below the average.

Table 51. Monthly Total Precipitation for Nashville Area, TN

	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	
2007	3.32	1.84	2.26	2.75	3.30	2.37	1.47	1.38	1.99	4.95	6.20	3.83	35.66
2008	4.76	2.53	5.56	7.20	5.54	2.21	4.32	1.67	0.88	5.03	1.75	6.72	48.17
2009	4.59	2.85	2.92	4.13	8.45	4.53	6.03	2.14	11.08	6.49	0.67	3.99	57.87
2010	4.13	2.77	3.52	3.48	16.43	4.96	5.86	6.99	1.17	2.49	5.41	1.87	59.08
2011	2.31	5.54	4.59	7.51	4.38	5.04	3.46	1.78	6.20	0.93	6.15	4.25	52.14
2012	5.13	2.81	3.11	2.86	4.01	0.26	8.38	3.70	5.64	3.83	1.38	4.71	45.82
2013	7.14	2.58	4.32	7.63	2.77	4.48	6.60	1.99	4.52	2.34	2.53	7.98	54.88
2014	2.61	5.09	4.36	7.29	2.47	5.73	2.38	5.47	0.21	8.43	3.34	3.21	50.59
2015	2.22	4.60	4.29	6.33	3.56	3.38	7.07	2.99	2.28	4.32	4.84	4.92	50.80
2016	2.17	4.46	4.33	1.12	2.37	4.45	6.28	6.44	1.87	0.43	1.87	6.94	42.73
2017	3.34	1.56	4.02	7.40	3.94	4.03	4.23	8.32	3.58	3.48	4.46	4.56	52.92
2018	1.63	M	M	M	M	M	M	M	M	M	M	M	M
Mean	3.61	3.33	3.93	5.25	5.20	3.77	5.10	3.90	3.58	3.88	3.51	4.82	50.06
Max	7.14 2013	5.54 2011	5.56 2008	7.63 2013	16.43 2010	5.73 2014	8.38 2012	8.32 2017	11.08 2009	8.43 2014	6.20 2007	7.98 2013	59.08 2010
Min	1.63 2018	1.56 2017	2.26 2007	1.12 2016	2.37 2016	0.26 2012	1.47 2007	1.38 2007	0.21 2014	0.43 2016	0.67 2009	1.87 2010	35.66 2007

**Records span a 10-year period; mean average is derived from this period*

Palmer Drought Severity Index (PDSI) Comparison

The PDSI remained in the near normal over most of the growing seasons of 2014, 2015, and 2016. One slight drought period is presented for late winter and spring of 2016. The PDSI ranking values do not match the actual precipitation values. There were multiple months for each of the three years that had rainfall well below the mean rainfall average. The PDSI values are positive for all of the 2014 and 2015 time periods however. Figure 18 depicts the PDSI values for the middle Tennessee region.

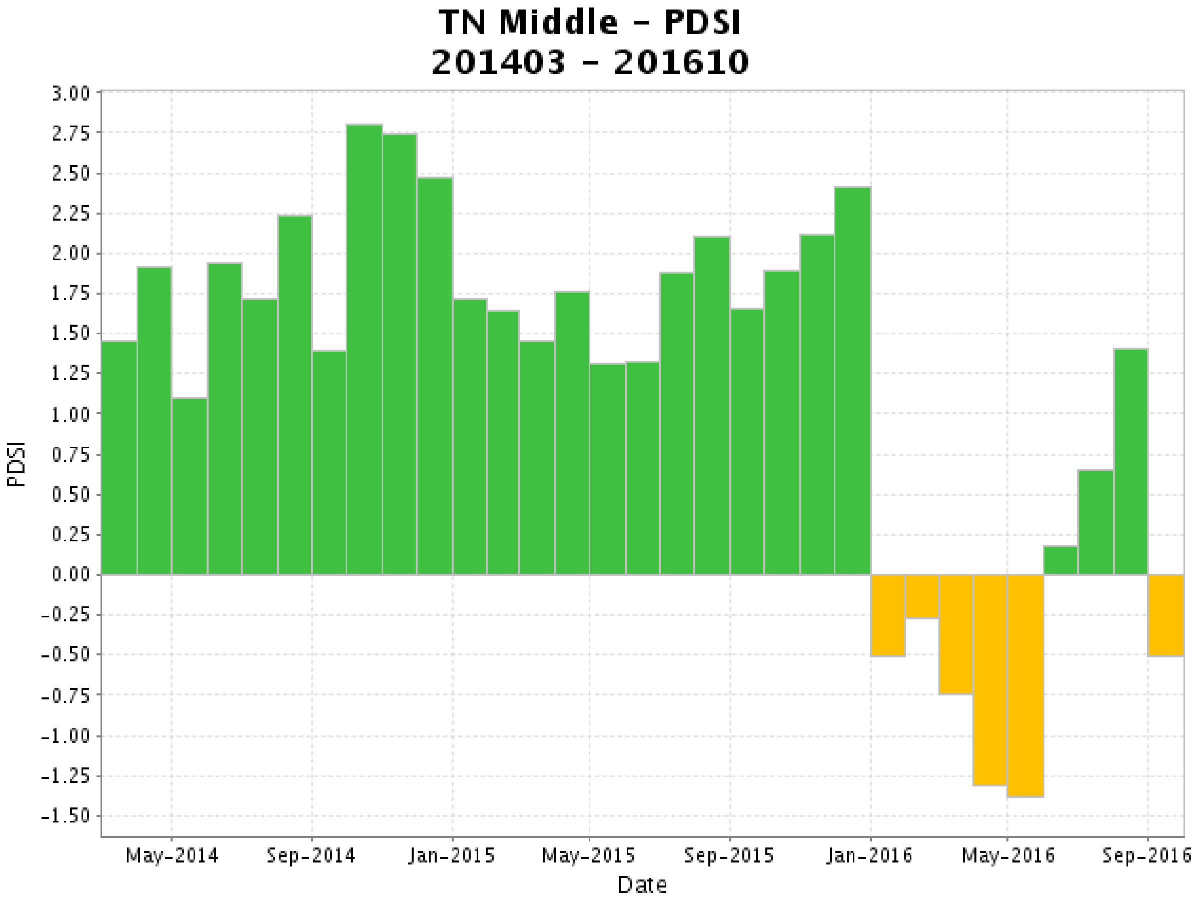

Figure 18. Palmer Drought Severity Index (PDSI) values for the middle Tennessee region for the period of March 2014 – October 2016

6. DISCUSSION

Potential Impact of Season of Harvest

Pre-harvest reproduction data indicated a high proportion of shade tolerant species were prevalent in all three replicated blocks prior to timber harvesting. Block A was slightly dissimilar from blocks B and C in that half of the pre-harvest advance reproduction consisted of yellow-poplar. Overall for all blocks combined, it was expected that the shade-tolerant, advance reproduction would dominate the site following harvesting disturbance. A significant component of the future reproduction was expected from coppice sprouting as block B had the lowest amount (1,270 stems) of reproduction greater than three feet in height. Post-harvest regeneration data indicated however that the majority of the regeneration was comprised of stems greater than three feet in height. Most of this reproduction are also shade intolerant species (Block A – 1,083 seedlings, Block B – 2,167 seedlings, and Block C – 283 seedlings). These shade intolerant species included oaks, yellow-poplar, and ash species. Oak species were in the minority of these population estimates with 100, 217, and 100 per respective block. Following treatment applications, a reduction in the abundance of the shade tolerant species was observed after two growing seasons.

Of the measured sample seedlings, approximately 52% were classified as root sprout reproduction. Most of these sprouts derived from smaller diameter stems which may have been severed during the harvest activity but the root stock remained intact. The smaller sized reproduction probably had a greater probability of remaining in place due to avoidance of hanging or being moved by harvesting equipment, unlike the larger sized shade tolerant reproduction. As indicated within the pre-harvest data, over 72% of reproduction were in size classes over three feet in height for each individual block. The larger stems conceivably were unable to maintain their respective root stock in place due to being gripped and ripped from the ground by the equipment or felled stems during skidding. This may be the cause for the reduction of most of the larger pre-harvest reproduction including shade tolerant species.

Reproduction favored shade intolerant species after two complete growing seasons. The majority of this reproduction was greater than three feet in height which may be attributed to the more rapid growth rates. Adequate time has probably elapsed and given the enhanced light environment created by disturbance, shade tolerant reproduction could have grown faster while oak reproduction may have become suppressed. In similar forested conditions, Heilegmann and

Ward (1993), Heilegmann and others (1985), and Nyland and others (1993) found that shade tolerant reproduction became abundant and reached larger diameters of up to 3 – 3.5 inches, fifteen to twenty years after a diameter-limit harvest. The stand in the study was estimated to have been cut between 20 – 25 years prior. Thus, sapling growth had adequate time to establish. This size class of reproduction would conceivably be most likely to be removed from the ground by logging equipment.

During the early (first herbicide treatments implemented) applications of sulfometuron methyl, a substantial amount of bare ground was observed over portions of each research block. These open areas principally included areas around loading decks and skidding trails. Higher traffic activity by heavy equipment was apparent along the upper slope and ridge positions but decreased with descent down the slope. The use of heavy equipment, including a feller-buncher and ground skidder, during the late winter and early spring may have facilitated enhanced removal of potential stump sprouts as compared to what might have transpired from harvesting in the seasonal dry periods of summer or fall. Soil moisture is typically highest during the winter and spring in the southeast. Some studies (Aust and others 1995, Greacen and Sands 1980) suggest that site degradation resulting from soil disturbance can be greater in moist soil conditions. The increased soil moisture could potentially have lead to loosening of the silt loam soil around root stock. This Bodine soil type is classified as a cohesionless soil which more readily breaks apart and has increased porosity compared to other soil types. These soil conditions may have facilitated easier extraction of the root system for sapling and large seedling sized stems during felling and dragging of downed trees across the area. Schweitzer and Dey (2011) found that the majority of oak seedlings remained undisturbed by unrestricted harvesting equipment. However, results from the study also indicate that there was a reduction in larger saplings (greater than 1.5 inches) and small poletimber sized stems when incorporating other species into the analysis. These findings support the theory that larger sized reproduction has an increased probability of being removed during timber harvest. The study site had abundant sapling sized stems in the understory and midstory canopy. Thus, a greater component of individual stems may have been "ripped" from the ground during skidding or by the blade of the operating feller-buncher. Removal of the root stock would directly reduce the prevalence of stump/root sprouting.

There was a noticeable discrepancy between the blocks in the abundance of reproduction within each block. Most obvious was the nominal abundance of total seedlings present in block C (567 stems per acre) as compared to blocks A (2,617 stems per acre) and B (4,167 stems per acre). Block C was harvested in late spring whereas the other blocks were harvested in March and April. A relationship may exist between having abundant reproduction to harvesting when trees are still in the dormant period versus harvesting in an active growth period. Roth and Hepting (1947), and Keyser and Zarnoch (2013) observed that season of harvest did not impact hardwood stump sprouting potential. Severance of smaller stems after leaf flush, in the middle of the growing season, may lead to individual stem mortality due to lacking resources from the already depleted carbohydrate reserves in the root system (Buell 1940, Kays and Canham 1991, Babeux and Mauffette 1994, Belz 2003). Block C was harvested in May (early growing season prior to cessation of above ground growth) which may not have killed the reproduction stems but could diminish growth involving both stem elongation and foliar flush. Some smaller advance reproduction with lesser root stock may have been unable to respond from this disturbance and could have contributed to increased mortality or at a minimum, experienced an overall reduction in seedling abundance. Babeux and Mauffette (1994) observed a 53% mortaility rate in red maple stump sprouts following stem severance in May.

Natural Reproduction After Disturbance

Despite the lack in abundant oak reproduction indicated by pre-harvest regeneration inventory data (Tables 3-8), all ¾ - acre treatment units contained at least 75 oak seedlings to serve as samples for later data collection and analysis. On a per acre basis, this equaled approximately 100 oak seedlings per acre. The presence of these oak seedlings suggested that even high-graded stands may contain a limited amount, but less that of shade tolerant species, of oak or other shade intolerant reproduction due to canopy gap creation (Canham 1989). This disturbance increases sunlight penetration to the understory. Within gap openings, shade intolerant and intermediate species can establish and respond favorably in growth (Delucca and others 2009, Cowden and others 2014, Keasberry and others 2016). Such forested stands may contain a less than desirable abundance of oak reproduction before disturbance. Following a clearcut potentially more oak seedlings have the ability to emerge. With increased active forest management such as weeding or crop tree release over time, these seedlings may possibly maintain competitiveness and recruit into more dominant canopy positions in the future stand. Early forms of active forest management will be necessary for these oak seedlings to establish competitive crown positions. This is especially essential with the presence of yellow-poplar reproduction. High intensity disturbances that dramatically increase sunlight penetration to the forest floor may result in a conversion of stands to yellow-poplar (McGee and Hooper 1975, Beck and Hooper 1986, Groninger and Long 2008, Loftis 1990). In addition, the presence of other less desirable species including eastern hophornbeam, blackgum, and hickory species will also reduce the probability of successful oak establishment in the future stand as indicated by Johnson et al (1989) and Ward and Heilegmann (1990). Some control applications after the clearcut disturbance are needed to reduce these competitor species will increase the probability of oak seedlings establishing dominance at crown closure. Oak may likely lose dominance in heavily disturbed stands without post-clearcutting competition control.

A significant difference existed between individual treatment units that received the same herbicide or combination of herbicides. Thus, dissimilar groupings included sulfometuron methyl only treatments, glyphosate only treatments, both combined sulfometuron methyl and glyphosate (banded or radial combinations), and control treatments. The difference is attributed to the variation in species composition amongst each replicated treatment unit on the three blocks (Tables 9 and 10). The difficulty in finding seedlings with the excessive grass competition created disparities in available samples. For some replications, yellow-poplar may have dominated the samples within a particular unit whereas the same treatment on different units had a greater percentage of oak. The growth rate differences were evident between the yellow-poplar and oak groups. This growth rate variation amongst species lead to a more significant growth increase in units with more yellow-poplar.

Impact from Grass Competition

The minimal difference in growth response between herbicide treatments can likely be explained in part by non-woody plant competition. Notable competition on the site was primarily accredited to the dense establishment of warm-season grasses following the treatments. These grasses can impact tree seedling growth in a variety of ways. Seedling survival can be decreased by reduced moisture taken up by grass. The reduced moisture may enhance drought stress. The shallow root systems of grass may diminish available resources for uptake by tree roots which include both water and nutrients. The grass roots can also restrict root expansion of the desired crop seedlings. A reduction in bare ground cover by grass and straw could alter microclimate around seedlings by creating thermal inhibition during both heat and cold temperature extremes. All these detrimental factors caused by grass can contribute to reduced seedling growth. The loss of previously dominant forb vegetation due to herbicide use contributed to the grass establishment on the research site.

One deleterious result of the herbicide applications is that it created areas devoid of woody competitors, and herbaceous competitors quickly invaded. Growing space conditions were altered that enabled broomsedge bluestem (*Andropogon virginicus*) and Nepalese browntop (*Microstegium vimenium*) to dominate most of the site. Each treatment unit that received any herbicide application resulted in a higher percentage of ground coverage by grasses compared to the control units. Rice and others (1997) had similar results where a grass dominated cover established following herbicide applications to control invasive forbs. Ezell and Nelson (2001) and Groninger and others (2004) also observed that broomsedge coverage increased on a planted oak study site that received treatments using sulfometuron methyl. Minogue and others (2012) stated that sulfometuron methyl is weak on controlling perennial grasses including broomsedge.

Glyphosate treatments also appeared to assist in grass establishment. The locations that received the directed foliar spray applications had grass encompass higher percentages of ground coverage in the respective units. Ristau and others (2011) also observed an increase in graminoid cover for areas that received herbicide applications using both glyphosate and sulfometuron methyl in a shelterwood harvested area. Horsley (1994) also noted an increase in grass from the seed bank within a shelterwood harvest treated with glyphosate. On this study, the grass emergence was especially noticeable within banded spray units. On block C, the glyphosate only treatment had a robust grass response isolated along sprayed strips. The untreated strips within this block were primarily occupied by blackberry (*Rubus sp.*). The glyphosate sprays enabled the grass to establish due to the control of herbaceous forbs. The forbs likely suppressed the grass but once removed, the grass became free to grow. Broomsedge has been shown to respond even after herbicide (glyphosate) treatments that attempted to control the species (Butler and others 2002). The researchers also reported that spring herbicide applications did not affect broomsedge density in areas with old-standing top growth. Thus, treatments conducted on this study site would not likely have reduced any pre-existing grass population.

The dense establishment of grass in young forestland can be problematic. Kozlowski (2002) suggests that dense fields of tall grass my strongly impact crop tree survival. Various perennial grasses can have unfavorable influences on tree seedling establishment and they may be considered as the most widely recognized competitors of tree seedlings (Davies 1987, Otsamo and others 1997, Mitchell and others 1999. Grass roots have been documented to have high levels of moisture uptake (Gordon and others 1989, Coll and others 2004), resulting in substantially lower available soil moisture for seedling utilization. Reductions in soil moisture are directly correlated with reduced seedling growth. Gordon and others (1989) reported that fibrous grass roots had a greater competitive effect compared to annuals with tap roots. The Gordon study indicated higher soil water extraction, decreased blue oak (*Quercus douglasii*) seedling emergence, reduced root/shoot relative growth rates, and shorter length of growing season perpetuates denser abundance of grass (*Bromus sp*.).

Pockets of area occupied by higher densities of grass root create sections of nutrient and water depletion. The diminution of resources directly leads to condensed seedling root growth (Collet and others 2006). Tree seedling growth may also have been impacted due to decreased root stock as similar to Harmer and Robertson (2003) and Collet and others (2006). Ball and others (2002) also observed that root growth for Eucalyptus seedlings was primarily confined to lateral exploration in early spring with minimal penetration to greater depths beginning in late spring. In this study, the oak and yellow-poplar seedlings may have had reduced lateral expansion of root systems due to the established presence of grass roots similar to the observances of Ball and others (2002), Harmer and Robertson (2003), and Collet and others (2006). Thus, seedling growth may have been directly influenced by the dense establishment of grasses on the study site.

Nitrogen fertilization has been observed to improve tree growth (Harris 1966), however, Coll and others (2004) reported that approximately 97% of the available nitrogen added to seedlings and grass planted in containers was utilized by the grass and not tree seedlings. Thus the potential addition of fertilizer as a management option, in presence of existing grasses, would likely only be utilized by the grass competition.

Oak is known to be drought tolerant, has long taproots, has the ability to photosynthesize and conduct water through the xylem under high water stress, flexible in maintaining high root:shoot ratios through recurrent shoot dieback, and has physiological plasticity that facilitates adjustment to water stress (Kriebel and others1988, Matsuda and others 1989, Abrams 1990, Kubiske and Abrams 1992, Bragg and others 1993, Pallardy and Rhoads 1993, Parker and Dey 2008). New germinants and smaller reproduction have shallow root systems, however, and are likely more prone to environmental stressors including drought and root zone competition. Thus, both grass and small tree reproduction have root systems existing in the same soil horizons. The grass root system serves as a physical barrier that reduces both tree seedling growth and available resource uptake. Thus, grasses are highly competitive for the first initial years after disturbance (Miller and others 2003) but, if the seedling survives, the root stock increasingly reaches deeper soil horizons and escapes grass root competition. Thus, tree reproduction size is an important determinant of establishment success due to differences in competitive capability, predation risk, and disturbance tolerance between small and large seedlings (Armstrong and Westoby 1993; Harms and Dalling 1997; Lahoreau and others 2006; Seiwa 2000).

The detrimental competition caused from grasses and ferns (Horsley 1981 1993, Hanson and Dixon 1987, McCormick and Bowersox 1997) to tree seedlings has been documented for both above ground and below ground. Shallow, lateral roots of trees compete with grass roots for substances which likely affect tree growth. Harmer and Robertson (2003) noted a reduced development of the lateral root system by decreased numbers of root tips on for multiple hardwood species due to grass competition. Collet and others (2006) also observed oak seedling root system size was reduced by competition from grass. Coll and others (2004) witnessed significant reductions in both diameter and height growth of beech (*Fagus sylvatica*) when grown in the presence of grass. Grass root expansion can also impact root zone placement by trees as grass roots typically create zones of nutrient and water depletion (Gordon and others 1989, Coll and others 2004). Tree roots respond to this by favoring resource rich areas that have not been colonized by grass root systems (Maina and others 2002). Fine roots (less than 2 millimeters in diameter) serve as the water and nutrient absorbing components of trees and the prevalence of fine roots typically decline as soil nutrient availability increases (Barnes and others 1998). Thus, reduced root space that is occupied by grass root systems could impede absorption of available resources needed for growth by seedlings.

For many of the research units in this study, coverage of over 80% grass left minimal space for tree roots to successfully expand and thrive. The reduced available area likely resulted in reduced size of root stock, thus reducing the capacity for maximizing growth. Richardson

(1953) used a root observation chamber to observe the impact of root zone competition between *Acer pseudoplatanus* (sycamore maple) with *Lolium perenne* (English ryegrass). Richardson's (1953) key results were: 1. The presence of *L. perenne* depressed root growth rate, shortened the length of active growth, reduced root hair density, and restricted rooting depth/lateral spread of tree roots.; 2. Nitrogen deficiency reduced the size and growth of tree roots, but promoted elongation of the grass roots.; 3. Grass root active growth began approximately three weeks earlier in spring and had a more rapid spread compared to the tree roots.; and 4. The absorptive surface of the grass roots was greater than the tree roots in the same volume of soil. Because there was extensive grass coverage in this study, the conclusion is, as Richardson had reported (1953), that the grass roots exhibited more absorption surface in the same volume of soil as the tree roots, and the trees were under greater stress.

Grasses have been shown to seriously interfere with tree growth. Whitcomb and Roberts (1973) observed that *Acer saccharinum* (silver maple) roots were eliminated from the upper centimeter of undisturbed soil following seeding of *Poa pratensis* L (Kentucky bluegrass). Grass has been reported to reduce diameter and height growth (Harris 1966), who also documented a decrease in girth and height growth for Southern magnolia (*Magnolia grandiflora*) and (*Zelkova serrata*) cultivars when tall fescue (*Festuca arundinacea*) turf was established.

The heavy abundance of grasses, such as was present on this research site, may also reduce tree seedling growth by means of thermal inhibition during both high and low temperature extremes. Rosenberg and others (1983) and Oke (1987) surmised that grassy ground cover alters soil and air temperatures compared to bare soil conditions. This alteration may lead to plant stress, particularly in the summer season, due to changes in transpiration rates directly attributed to temperature stresses which affect seedling function (Barnes and others 1998, Zahner 1956). Balisky and Burton (1995) suggest that heat conduction through grass is poor which directly reduces diurnal fluctuation for soil temperatures in temperate climates. During winter, this may have prolonged the duration of extreme cold temperatures beneath the grass layer subjecting seedlings to frost damage. This longer period under grass cover slows diurnal fluctuation with the passing of seasons (winter to spring and summer to fall) compared to bare soil. In a study by Oke and Hannell (1966) where straw mulch was placed atop of a soil surface, the change in diurnal fluctuation was found to slow with time (season) compared to that of bare soil. They reported that the straw impeded the loss of stored summer heat during autumn and also retarded heat penetration into the soil in the spring (Oke and Hannell 1966, Lambers and others 1998). The occurrence of grass may have shortened the overall length of the growing season on this research site due to the abundance of grasses which could have reduced seedling growth. Temperature differences between bare versus covered ground surfaces have been observed to affect the timing and growth rate of plants in agricultural areas (Rosenberg and others 1983; Oke 1987).

Such effects may also be possible for tree seedlings following clearcutting. Within weeks, vegetation began re-establishing on the research site but over half of the area would be considered as bare ground. The use of herbicide added extra duration of bare soil conditions for approximately three weeks (glyphosate) up to two months (sulfometuron). Tree seedlings within grass cover are exposed to greater temperature extremes (minimum and maximum) than seedlings with bare soil conditions (Oke 1987), as grass cover can expose seedlings to scalding temperatures during periods of high insolation and low wind speed during the summer. Waggoner and others (1960) compared surface temperatures of bare soil with soil covered with hay (60 millimeters thick) and found they were 38°C and 50°C, respectively. This difference in temperature was attributed to poor heat conduction through the hay with minimal transmission of heat into the soil, and the hay restricted the water vapor movement from the soil to the air which limited latent heat loss by approximately 50%. Air temperature above the hay cover was up to 10° C hotter than measurements taken above the bare soil surface up to a height of 20 centimeters. Thus, seedlings are exposed to greater heat and drought stress when grass cover is present. Initially, the study site had bare soil conditions, both following disturbance and herbicide applications but grass responded rapidly. The ground coverage by grass, particularly in areas treated with both sulfometuron and glyphosate, could have caused temperature stresses to the measured seedlings as it did for all of the aforementioned studies.

Lower temperatures during the colder seasons can also be problematic for seedlings within grass or hay groundcover. Long-wave thermal radiation from an exposed soil surface is the most important mechanism for nocturnal cooling. The presence of mulch or straw atop soil would then serve as the active cooling surface (from the surface to the top of the ground cover) or the site where maximum frost occurs (Oke 1987). The ground cover then forms a thermal insulation zone and restricts the flow of heat from the soil to the air. Thus, temperatures directly above the grass and the grass surface are lower than the bare soil surface (Leuning 1988). Ball and others (1997) observed that relative to bare soil, grassy ground cover reduced minimum air temperature by an average of 2° C and leaf temperatures above grass being another 1° - 3° C lower than air temperature. These lower minimum temperatures can result in more frequent and more severe frosts than seedlings within bare soil (Ball and others 1997, Lambers and others 1998). A grass or straw covering provides negative impacts by insulating the soil from heating and cooling. Grass ground cover can potentially subject tree seedlings to slower recovery of photosynthetic activity, delayed bud break, greater damage to elongating stems and developing leaves from frost damage, and reduced stem elongation growth. Given the continuous vertical presence of broomsedge over the winter period versus herbaceous forbs which die and decompose on the ground surface, grass can directly influence cold weather problems related to tree seedling growth. Areas containing forbs, such as the control units, had conditions which are similar to bare ground thus such negative consequences were not as severe or even a factor for seedling growth.

Findings suggest that grass cover can alter soil and water temperatures during both high and low temperature extremes. Significant changes in the thermal environment can yield negative responses in plant growth and photosynthesis. The reduction in these two physiological processes may lead to a reduction in seedling competitive ability and probability of survival (Ball and others 1997). Ball and others (2002) observed greater seedling biomass and root biomass for Eucalyptus seedlings grown in bare soil compared to seedlings grown in both grass and hay ground cover. The bare ground seedlings also begin root growth earlier in late winter and had a greater rate of root growth in the spring. Shoot biomass for the seedlings also begin to expand in early spring for those growing in bare soil versus late summer for seedlings within both live grass and straw treatments. Seedlings having grass and straw ground cover began growth (bud break) approximately three weeks later than bare soil seedlings. Bare soil eucalyptus seedling shoot biomass was four to five times greater than seedlings within grass and straw. Collet and others (2006) also observed increased root stock for sessile oak (Quercus petraea) in bare soil containers compared to containers which also contained grass competition. Coll and others (2004) reported that following two growing seasons, beech seedlings in the presence of grass showed significant reductions in diameter and height growth, annual shoot elongation, and stem, root and leaf biomass, but an increase in root to shoot biomass ratio. The grass emergence in this study likely reduced my sampled seedling biomass due to reduced competitive ability and duration of active growth similar to the reported works of Ball and others (1997), Collet and others (2006), and Coll and others (2004).

Ball and others (2002) also observed that soil moisture was significantly lower under the growing grass compared to that of the straw treatment when precipitation was relatively abundant and grass was actively growing. Soil moisture beneath the straw approached field capacity (24%) during the early spring. Soil moisture reduction was attributed to transpiration by the living grass. Interestingly, tree seedling growth was poor for both treatments compared to the bare ground seedlings. Based on these various research findings, grass cover appears to negatively affects the microclimate surrounding tree seedlings due to thermal inhibition (Lambers and others 1998, Ball and others 1997, Oke 1987).

Typically, grass is able to begin establishment earlier in late winter whereas tree seedlings begin growth in early spring. The presence of grass ground cover may further inhibit tree seedling development by enhancing the potential for frost damage and extending the initiation of root growth/expansion (Ball and others 1997, Ball and others 2002). Thus, tree seedlings may fail to capture all potentially available resources present during the spring season due to microclimatic conditions being altered by grasses. In summer, soil temperatures rise to favor tree growth, however the well-established grass likely has depleted moisture and nutrients from the upper soil horizons leaving minimal resources for tree seedlings (Ball and others 2002). The enhanced frost damage, resulting from decreased temperature created by the grass layer, in autumn may also reduce the length of the growing season.

The high establishment rate of grasses suggest that the reduction of forbs through herbicide applications essentially released grasses from suppression. The vigorous emergence of warm season grasses, primarily broomsedge and Nepalese browntop likely hindered growth of the existing seedlings due to root zone competition. This is of primary importance with oak as root stock development is a primary growth strategy with oak. The dense, fibrous root systems of the grasses likely caused excessively high competition for space in the same soil horizon as new tree seedlings. Available soil moisture was likely intercepted by the fibrous grass roots that limited the growth potential for tree seedlings. The ability for a given tree to expand its root system is also impacted by the abundance of grass roots. The result of this competition by grass was a reduction in above ground height growth with growth instead allocated more towards root biomass (Harmer and Robertson (2003), Collet and others (2006). These authors also suggested that total root length and the number of root tips decrease with increasing competition. The sample seedlings in this study likely experienced reductions in growth due to the same findings of Harmer and Robertson (2003) and Collet and others (2006).

Treatments that received higher intensity herbicide applications using both sulfometuron methyl and glyphosate had a higher percentage of coverage by grasses based on ocular estimates. A secondary treatment during the growing season of 2015 to attempt to control the emerging grass may have proved beneficial to enhance seedling growth. Self (2011) reported that planted oak seedlings that received two years of vegetation control using Sulfometuron yielded greater seedling stem and root biomass compared to a single application and an untreated control. The continuance of bare ground condition in this study from a subsequent application would likely produce similar results to Self (2011). Additional treatments using bromacil, diuron, tebuthuron, buthidazole (Griffen and others 1988) and glyphosate (Butler and others 2002) may provide sufficient control of broomsedge. Use of these pesticides may injure the crop tree seedlings however. The timing of the herbicide application could have altered the early successional vegetation response. Applying the herbicides after a full growing season may yield a contradictory plant type response similar to prescribed fire or disking among different seasons (Harper 2007). The probability is greater, however, that grass would re-emerge from seed stock even with a change in application timing as sulfometuron applied at the low application rate of 2 ounces per acre will not control most grasses. Later applications may have been more difficult to perform as seedlings would likely be hidden by herbaceous vegetation. Given these uncertainties and management challenges, the pre-emergent or early spring seedling release application is likely the most acceptable option. Eventually, the released oak and yellow-poplar will develop and create shaded environments that diminish the presence of the grasses. The addition of lime may prove to further benefits by altering the Ph level which would likely reduce broomsedge presence and enhance nutrient uptake the crop trees. Long and others (2011) found that a one-time application of dolomitic lime increased the growth rate of sugar maple but decreased black cherry growth. Oak species may also be improved but further investigation is warranted.

Negative impacts to seedling growth should be mitigated through some form of chemical release to control grass competition. McCormick and Bowersox (1997) demonstrated that height growth was significantly less for planted northern red oak and yellow-poplar in areas dominated by poverty grass compared to seedlings in areas that received grass control. Yellow-poplar was

1.6 times greater in height in the grass free areas whereas northern red oak was 1.2 times taller four years after treatment (McCormick and Bowersox 1997). Sims and Mueller-Dombois (1968) studied competition from grasses including *Andropogon gerardi* on coniferous tree species and found the grasses inhibited tree growth via shading and root competition.

Precipitation Effects on the Study Site

Results indicate that initially there was a measureable response among the herbicide treatments and the untreated control after two growing seasons. This result may be attributed to below average precipitation during the growing season following herbicide application. Seven of the twelve months (April – September) had below average rainfall for the 2015 and 2016 growing seasons according to NOAA (https://www.weather.gov/) data. Of particular interest is the period during April and May of the 2016 growing season. Monthly rainfall for these months was 4.05 inches and 3.16 inches below the average (dating back to the year 2000). During this time, trees in the Highland Rim region are usually optimizing growth. The reduction in moisture available for uptake by trees probably affected tree seedling growth. If these spring months had a normal or above average rainfall, seedling growth response may likely have been different amongst treatments.

Spring Droughty Conditions

Early findings suggest that there is no statistically significant difference in either diameter or height growth between herbicide treatments. The lack of differentiation was probably caused by a deficit from the mean average precipitation during the early spring (in particular May) season for years 2014, 2015, and 2016. April, 2016 also experienced strong droughty conditions well below the mean (Table 94). Tree growth is most prolific during the spring season but a lack of moisture will diminish growth potential (Robbins 1921). During the initial growing season of 2014, rainfall for September dropped to 0.2 inches for the entire month. Extreme dry soil conditions may have impacted the photosynthetic capacity and physiology of the seedlings creating growth loss. Should rainfall amounts been normal for one or both of these times during the active growing season, seedling diameter or height response may have been greater.

Palmer Drought Severity Index (PDSI) Comparison with Actual Precipitation

The PDSI values for the middle Tennessee region did not match very well with the actual precipitation values. Fekedulegn and others (2003) found that yellow-poplar growth strongly followed both precipitation and PDSI values, and that the species ring growth was dependent on precipitation rates particularly on xeric sites. The use of PDSI may not be representative of actual conditions when given on a regional scale as there existed an obvious discrepancy between the ranking value and the actual precipitation amounts. PDSI does take into account multiple variables other than just precipitation. A deficit was given for only the 2016 growing season using PDSI. The 2014 and 2015 seasons were average or moist seasons. Thus, PDSI would suggest no extreme weather irregularities exist overall. This is in contract to precipitation amounts recorded in Nashville over the three seasons. Perhaps there existed a large variation over the entire middle Tennessee region that did not represent recorded precipitation at the measurement station in Nashville. The use of PDSI may not be as reliable as actual recorded rainfall measurements taken on site. Attempts should be made to use a rain gauge at the research site for future research requiring precipitation data.

Transference of Glyphosate to Non-Target Plants

The radial spray treatments using glyphosate experienced minimal increases in both seedling diameter and height growth in multiple statistical analyses. Statistical analyses indicated that radial applications yielded the lowest mean absolute diameter growth among all treatments for combined seedlings (Table 13). The radial treatment also yielded the lowest absolute rate of height growth (Table 16) for all treatments as well. The same trend was observed for each species group (red oak, white oak, and yellow-poplar), as depicted in Table 22 in that the radial spray application had the lowest absolute change in height growth for all treatments. The radial treatment also showed the lowest or next to lowest means estimates for relative change in height for white oak sprout, yellow-poplar sprout, and yellow-poplar germinant reproduction. The radial treatment effect did not appear to be as detrimental for relative diameter growth when individual species group reproduction was analyzed by germinant or sprout classes however.

These treatments had glyphosate applied within inches of the crop tree seedlings. The seedling foliage was protected during application, but it may be possible that the active ingredient or a by-product could have been absorbed to some extent below ground. Glyphosate eventually reaches the soil through either direct contact or by release from dead plant matter (Neumann and others 2006). After reaching the soil, the chemical may be absorbed onto soil particles, experience degradation by soil microorganisms, or leach through pores or root canals into deeper soil horizons. Tesfamariam and others (2009) proposed that there may be some possibility of toxicity to non-target plants due to rhizosphere transfer of glyphosate. Neumann and others (2006) observed the exudation of glyphosate from treated plant roots into the adjacent soil. Kremer and others (2005) reported that exudation of glyphosate can restrict growth of adjacent plants and seedlings. Negative effects to non-target plants may include heightened sensitivity to plant diseases connected with low magnesium and iron availability in soil, increased nematode infections, inhibition of root growth, and reduced nitrogen fixation (King and others 2001). Glyphosate has been witnessed to alter nitrogen metabolism by directly affecting mycorrihizae or indirectly by causing an effect on plant physiology (Zobiole and others 2010). Glyphosate applications can reduce nodulation due to reductions of symbiotic bacteria in glyphosate resistant soybeans (Zobiole and others 2012, Zobiole and others 2010) . This factor leads to a loss of energy and fixed nitrogen that could inhibit plant growth and production.

Glyphosate is stored within plant metabolic sites including root and shoot meristems after translocation within the plant. Enhanced growth rate areas including nodules, root tips, and shoot apices are important sinks for glyphosate storage. A small transference of herbicide may occur at these below ground locations. A metabolite of glyphosate named amino-methylphosphonic acid (AMPA) forms from glyphosate after degradation by microorganisms. AMPA is a recognized phototoxin that has been suggested to cause glyphosate-induced injuries in glyphosate resistant plants (Reddy and other 2004). The authors also observed that AMPA affected chlorophyll biosynthesis and caused plant growth reduction. AMPA has also been observed to reduce the amino acids glycine, serine, and glutamate in treated mouseear cress (*Arabidopsis thaliana*) plants (Serra and others (2013). Thus a possibility exists on the study site in treatment units receiving glyphosate applications that measured seedlings may have had AMPA transferred through the rhizosphere. The uptake of some limited amount of AMPA could have stunted growth without causing mortality to the affected seedlings.

Though most of these research findings are associated with genetically modified soybeans and other plants, similar effects could have occurred within the oak and yellow-poplar seedlings within the radial treatments. The statistical data in this study does support the likelihood that glyphosate applied around crop seedlings may inhibit growth. This may especially be true of the radial treatments as higher amounts of herbicide were applied all around the favored seedlings. The banded spray treatments also used glyphosate, however not all of the sample seedlings were located on the edge of the untreated bands. Thus, the herbicide may not have transferred into the crop seedling due to the buffer distance between the root stock and any movement of the herbicide directly down the soil profile. The sampled seedlings that were on the edge of the treated strip would be potentially exposed to only half (one side) the area compared to the entire area around radial sprays. Thus, the lack of or reduced amount of exposure may have had no or a lesser effect on the sample seedlings.

Diameter and Height Response Among Species

Growth rates of yellow-poplar was significantly different from that of both the red oak and white oak groups. The rapid growth of yellow-poplar compared to other hardwood species following the clearcut disturbance were expected (McGee and Hooper 1975, Beck and Hooper 1986, Heilegmannn and others 1985, Hilt 1985). Early successional competitor species such as yellow-poplar and pine species focus energy on stem elongation or above ground growth. Alternatively, oak species implement more conservative growth strategies by allocating more growth to root stock than stem elongation above ground (Crow 1988, Dickson 1991). Oak species focus carbohydrate allocation towards root development as opposed to above ground stem elongation during the early years of development. The use of chemical treatments creates conditions to counteract the lesser rate of above ground growth exhibited by oak. The removal of competing vegetation around the oaks enables oak seedlings more time to become established without being overtopped by adjacent seedlings or saplings.

Carlisle and others (2002) showed that white oak height growth was unaffected by both radial and complete broadcast sprays compared to a control where alternatively ash and black walnut did have significant growth increases. For this study, a difference in both diameter and height growth emerged between treatments when species grouping were statistically analyzed. The sulfometuron methyl only treatment promoted overall height growth when used in combination in all of the treatments that included glyphosate. Height growth differences were found between the sulfometuron methyl treatments and all other treatments. Yellow-poplar, in particular, appeared to respond the best to sulfometuron treatments. This response is likely explained by the prolonged bare soil conditions created by the residual soil activity of sulfometuron methyl, and no negative impact by the active ingredient within the plant unlike glyphosate. Although bare soil conditions only existed for two months during the initial growing season, this duration was of sufficient length to allow for a height growth response. Yellow-poplar capitalized on this open growing space more readily than the oaks. The average of all combined seedlings (without grouping) for the two growing seasons as well as species group comparisons did have a significant difference among the treatments. The sulfometuron methyl only treatment yielded the best results for absolute diameter (Table 13) and height growth (Table 16 and Table 22) for each treatment comparison. Post emergent applications using this herbicide at a rate of two ounces per acre promoted seedling development in the analyses for combined species. Given the benefits of creating bare ground using this herbicide and seedling response implementing chemical treatments to hardwood seedlings is advisable.

Other Potential Management Options for Degraded Stands

Findings from this study suggested that more intensive herbicide applications which use multiple herbicides may impede or not have a significant response for seedling growth. A reduction of competing tree species is necessary however to enable oak to occupy at least 50 – 100 stems per acre at crown closure. Radial sprays applied directly around individual seedlings appeared to reduce growth of natural reproduction. The loss of productivity is likely accredited to the increased abundance of detrimental microorganisms or potentially to incidental drift or contact with a protective apparatus. This application yields increasing growing space by deadening surrounding competitors but at the cost of reduced diameter and height growth by favoring grass competition. An alternative solution to controlling tree competitors would be a pre-harvest chemical midstory control applied as a stem injection treatment to deaden all less desirable reproduction occupying canopy space in both the midstory and understory. The application would further enhance stump regeneration/coppice control. Some stump sprout reproduction was still alive though apparently stunted based on casual observation within treatment units. Thus, foliar sprays of stump sprouts may prove ineffective in providing an acceptable level of control for this highly competitive regeneration source.

Another alternative management action may be direct foliar sprays to individual less desirable reproduction as opposed to sprays around the preferred seedlings. This treatment could potentially reduce incidental contact with the preferred seedlings thus eliminating any potential growth loss attributed to herbicide. Alternative herbicides with residual soil activity, such as Imazapyr, could be substituted which may further improve rates of control. Uptake of the active ingredient by the desired crop trees may not be a factor given the proximity of the target stem. For target stems within the drift zone (within approximately five feet), stumps or seedlings could be chemically treated by injection or cut stump applications. These silvicultural activities could be considered as forms of an early weeding thinning. The effect from treatments should still provide the needed additional growing space required by oak seedlings to occupy a dominant or codominant position in the overstory at crown closure.

Herbicide Applications Enable Oaks to Remain Competitive with Yellow-poplar

The early herbicide applications provided a level of competition control which will enable a greater growth rate for the natural oak reproduction compared to untreated controls. Chemical treatments applied in the initial year have improved early seedling survival and height growth. Robinson and others (2003) also found that use of herbicides including Garlon, Accord plus Oust XP assisted oak competitive status with yellow-poplar. Chemical applications may not only improve early growth but may also enhance the probability of oak stems to successfully establish more dominant positions at crown closure by creating extra available growing space. The importance of controlling adjacent non-oak tree species will likely prove to be a necessity in oak establishment. Woody competitors within a given stand hinder oak development by overtopping adjacent oak stems; ultimately rendering them to occupy suppressed crown positions. Some of the research treatments were able to successfully control adjacent non-oak stems. Future seedling measurements are expected to test the theory that early applications will be needed to promote oak development.

Findings in this study indicate the initial change in diameter between the red oak, white oak group, and yellow-poplar were significantly different. This is relevant since yellow-poplar is one of the primary competitors with oak for available growing space. The herbicide treatments may have improved the oak growth rate to a point in which oaks may maintain higher competitive status reducing the chance of mortality or delaying the time until the oak stem is overtopped. Future seedling measurements may reveal that the early chemical applications enable oak species to form a higher proportion of the dominant crown positions. If this prediction is confirmed, early chemical applications may be a crucial component to oak regeneration methodology.

7. CONCLUSION

The use of diameter limit harvesting or high-grading methodology is vigorously used across Tennessee upland hardwood stands. Such inappropriate management leads to stands that commonly regenerate with shade tolerant species. This response is attributed to a higher prevalence of shade and loss of desirable parent seed stock. These conditions occurred on the study site for this project prior to any management disturbance. Larger sized reproduction greater than three feet in height comprised approximately 80% of the pre-harvest population sample. Forest stands will typically regenerate after a disturbance from these larger seedlings and saplings. Findings from this study suggest that implementation of clearcutting can yield a significant abundance of more desirable seedling growing stock, though early sampling indicated minimal advanced regeneration in place, within degraded stands. The implementation of timber harvesting during the late winter/early spring facilitated the removal of larger sized shade tolerant reproduction from the site. Moist soil conditions may have created loosened soil conditions that enabled complete root extraction of residual stems or seedlings by heavy equipment during active logging periods.

The removal of larger reproduction improves the possibility that newly germinated seedlings or small advance reproduction can establish dominance in the future developing stand. Larger seedlings and saplings will sprout from root stock and out-complete new seedlings. The removal of these larger reproduction stems, however, means that new seedlings will occupy most of the available growing space on the site with exception to stump sprouts derived from merchantable poletimber sized stems. Given the site contains an adequate stocking of oak and yellow-poplar seedlings and more advanced regeneration sources have been removed, the future stand has an increased probability of being comprised of more favorable and economically attractive species.

Research has demonstrated that oak species will typically be outcompeted in natural environments by other faster growing tree species without some form of applied management to enable oaks to reach competitive size. Herbicide applications to control undesirable or competing vegetation have been shown to improve early survival and growth of artificially planted hardwood seedlings. Both sulfometuron methyl and glyphosate are commonly used to control competing vegetation around seedlings. This deadening of adjacent vegetation has multiple benefits including increased microclimate conditions for favorable soil temperatures and moisture/nutrient availability. Photosynthetic activity can also be enhanced by promoting sun exposure to seedling foliage.

Within the first few years post-disturbance, some early form of management such as silvicultural weeding or early crop tree release should be conducted. These management practices should incorporate common forestry herbicides, applied within a naturally regenerated clearcut, to potentially improve the probability that oak will form dominant positions at crown closure. Nix (2004) reported that ten years following an early chemical competition control treatment, applied within a four year oak clearcut, had nearly 400 oaks per acre remaining in at least codominant canopy positions. This finding was nearly three times more numerous compared to those in control. Reducing reproduction density should create the available growing space needed for crown expansion and prevent overtopping or suppression of desired oak stems. This may involve direct foliar spray treatments of individual competing trees and unwanted herbaceous weeds and grasses. Chemical control of plant competition should promote growth by creating bare soil conditions around the crop tree seedlings. Bare soil conditions extends overall duration of the growing season by more rapidly increasing soil temperature which directly can add extra weeks of active growth for various plants (Rosenberg and others 1983; Oke 1987). Bare ground also minimizes seedling damage attributed to both extreme cold and heat including frost damage and loss of soil moisture (Ball and others 1997, Oke 1987, Lambers and others 1998).

The change in diameter and height growth was statistically different among some of the herbicide treatments and the untreated control when all seedlings were compiled for analysis. For individual species groups (red oak, white oak, and yellow-poplar) of seedlings for each treatment, differences were present between species. Yellow-poplar had greater growth for both diameter and height compared to the oak groups. White oak had inferior amounts of growth compared to those of the red oaks. Results indicated that height growth using sulfometuron methyl only yielded the greatest response of all the herbicide treatments but was not significantly different than the untreated control.

There are various potential explanations for the lack of differentiation between treatments. The first may be attributed to the low precipitation levels of the early spring period for 2014, 2015, and 2016. At the end of the 2014 growing season (September), rainfall was extremely low. This lack of soil moisture during these periods may have caused high levels of stress which may have altered physiological processes in the young seedlings reducing diameter and height growth.

The unexpected response within the area was the copious establishment of warm-season grasses including primarily broomsedge bluestem. Control of competing plants was effective for the initial growing season following chemical applications in 2014. The grasses emerged the following growing season when all other herbaceous plants had been controlled. These grasses share the same active growing season and were able to overtop the vast majority of the sample oak and yellow-poplar seedlings. The great abundance of warm-season grasses could have reduced the available soil moisture for seedlings as the root systems of both plants inhabit the same soil horizons. The grass root systems likely altered the tree seedling root stock as tree roots are not as effective in absorbing moisture as the fibrous root system of grasses. The presence of grass also alters the soil surface microclimate creating shorter growing seasons, enhances frost damage potential and soil moisture loss, and may create semi-shaded conditions that reduce the photosynthetic ability of oak and yellow-poplar seedlings.

The use of glyphosate may have had some impact on seedling growth and development within the study. The active ingredient of glyphosate is utilized by various micro-organisms with the soil community. Certain types of bacteria and fungi can utilize the extra available micronutrients. As such communities are able to expand their range within the soil horizons and likely impact interactions with tree root systems. In some instances, this result may positively affect tree growth by promoting symbiotic mycorrihizal fungi. Potentially detrimental organisms are promoted that are pathogens causing tree disease which could reduce tree growth. The breakdown of glyphosate creates a metabolite named amino-methylphosphonic acid (AMPA) which is a known phototoxin in plants. Plants can uptake AMPA in the rhizosphere after it is released from dead plant material. The compound can affect chlorophyll biosynthesis, reduce the amount of amino acids, and ultimately reduce plant growth.

The lack of early growth response between treatments was expected prior to study implementation. The hypothesis still being tested is that even though growth responses were significant at these early growth stages, they may become even more pronounced as the stand reaches crown closure evident and and may become more relevant with additional growth. The early management activity is suspected to create the additional growing space likely required for the oak species to still occupy more dominant crown positions at crown closure (Beck 1970, Hannah 1987). Without the initial year weeding or release treatments, other tree species would have developed at a more rapid rate of growth in close proximity of the preferred crop tree seedlings. Ultimately, as with previous findings (Loftis 1988, Beck and Hooper 1986, Johnson and others 1985) the majority of oak stems would likely have become suppressed by non-oak species and succumb to natural mortality. The sulfometuron methyl treatment may have increased early survival but may not ultimately improve the percentage of oak stems in more dominant crown positions at the onset of the stem exclusion stage; where the glyphosate treatments may have a beneficial impact by reducing woody competitor stems. Future measurements will reveal whether the hypothesis holds true and is validated statistically.

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APPENDIX

Relative Ground Line Diameter Change Among Treatments

The type III test found that the treatments differed (P <0.0001) when the analysis was performed using all seedlings combined. Table A1 portrays the statistical test summary.

Table A1. Type III tests of fixed effects for relative diameter change among treatments for all seedlings combined

Effect	Num DF	Den DF	Chi-Square	F-Value	Pr > F
Treatment	5	1554	38.39	7.68	<.0001

The sulfometuron methyl treatment had the greatest performance with an estimate of 2.0717 of relative diameter growth (Table A2). The radial application had the lowest estimated relative growth at only 1.4819.

Table A2. Least square means estimates for relative diameter change for among treatments for all seedlings combined

Treatment	Estimate	Std. Error	T - value	P - value
Banded	1.9836	0.258	7.69	0.0091
Banded + SFM 75	1.5772	0.258	6.11	0.0157
Control	1.727	0.2564	6.74	0.0134
SFM 75	2.0717	0.2577	8.04	0.0084
Radial	1.4819	0.2588	5.73	0.0177
Radial + SFM 75	1.5573	0.2607	5.97	0.0148

Post ANOVA analysis using the Tukey least squares means comparison found a significant difference for ten of the fifteen treatment comparisons. The sulfumeturon methyl only treatment and the radial treatment had the greatest separation compared to all other significant treatment comparisons in regards to the relative change in diameter growth (Table A3).

Table A3. Tukey-Kramer least squares means comparison estimates for relative change in diameter for all seedlings combined between individual treatment comparisons

Treatments Compared	Estimate	Std. Error	T - value	Pr > |t|	Adjusted P-value
Banded / Banded + SFM75	0.4064	0.1226	3.31	0.0009	0.012
Banded / Control	0.2566	0.1194	2.15	0.0317	0.2623
Banded / Radial	0.5017	0.1245	4.03	<.0001	0.0008
Banded / Radial + SFM 75	0.4263	0.1282	3.32	0.0009	0.0117
Banded + SFM 75 / SFM 75	-0.4945	0.1221	-4.05	<.0001	0.0008
Control / SFM 75	-0.3447	0.1187	-2.9	0.0037	0.0432
Control / Radial	0.2451	0.1212	2.02	0.0432	0.3296
SFM75 / Radial	0.5898	0.1239	4.76	<.0001	<.0001
SFM75 / Radial + SFM 75	0.5144	0.1273	4.04	<.0001	0.0008
Radial / Radial + SFM 75	-0.0754	0.13	-0.58	0.5621	0.9924

Relative Height Change Among Treatments

The relative height change for combined seedlings among treatments strongly differed. The pairwise test indicated that a P-value of <0.0001 existed. Table A4 presents the statistical test summary.

Table A4. Type III tests of fixed effects for relative height change among treatments for all seedlings combined

Effect	Num DF	Den DF	Chi-Square	F-Value	Pr > F
Treatment	5	1554	65.66	13.13	<.0001

Similar to data presented for the relative diameter change, the sulfometuron methyl treatment had the optimal performance with an estimate of height growth equal to 4.6273 (Table A5). Likewise, the radial application was dramatically lower with an estimate of only 2.2343. The radial estimate was also less than the control estimate.

Table A5. Least square means estimates for relative height change for among treatments for all seedlings combined

Treatment	Estimate	Std. Error	T - value	P - value
Banded	3.281	0.5018	6.54	0.0091
Banded + SFM 75	3.1098	0.5018	6.20	0.0104
Control	3.0526	0.4968	6.14	0.0119
SFM 75	4.6273	0.5009	9.24	0.0037
Radial	2.2343	0.5042	4.43	0.0239
Radial + SFM 75	3.2676	0.5101	6.41	0.0079

Nine out of the fifteen treatment comparisons were significantly dissimilar from one another (Table A6). The most pronounced range (2.393) between mean height change estimates was found between the sulfometuron and radial treatments. The significant comparisons are presented below.

Table A6. Tukey-Kramer least squares means comparison estimates for relative change in height for all seedlings combined between individual treatment comparisons

Treatments Compared	Estimate	Std. Error	T - value	Pr > |t|	Adjusted P-value
Banded / SFM75	-1.3463	0.2982	-4.52	<.0001	<.0001
Banded / Radial	1.0467	0.3053	3.43	0.0006	0.0082
Banded + SFM 75 / SFM 75	-1.5175	0.2993	-5.07	<.0001	<.0001
Banded + SFM 75 / Radial	0.8755	0.3053	2.87	0.0042	0.0481
Control / SFM 75	-1.5747	0.2909	-5.41	<.0001	<.0001
Control / Radial	0.8183	0.2971	2.75	0.0059	0.0656
SFM75 / Radial	2.393	0.3038	7.88	<.0001	<.0001
SFM75 / Radial + SFM 75	1.3597	0.3122	4.35	<.0001	0.0002
Radial / Radial + SFM 75	-1.0333	0.3187	-3.24	0.0012	0.0153

Relative Diameter Change by Reproduction Size

Only yellow-poplar new germinant reproduction absolute change in diameter was significant (P = 0.0161) among all the species by reproduction size comparisons (Table A7). Red oak new germinant and sprout reproduction, white oak new germinant and sprout reproduction, and yellow-poplar sprout reproduction were all insignificant with P-levels of 0.1984, 0.9517, 0.3792, 0.1252, and 0.2434 respectively.

Table A7. Type III tests of fixed effects for relative diameter change among treatments for new germinant reproduction

Effect	Num DF	Den DF	Chi-Square	F-Value	Pr > F
Treatment	5	502	13.59	2.72	0.0195

The sulfometuron methyl treatment had the best relative diameter change for new germinant reproduction with an estimate of 2.9406 (Table A8). The most intensive herbicide treatments that utilized both glyphosate and sulfometuron had the lowest mean estimates. Only the banded and sulfometuron only applications were higher than the control estimate (2.292).

Table A8. Least square means estimates for relative diameter change for among treatments for new germinant reproduction

Treatment	Estimate	Std. Error	T - value	P - value
Banded	2.5336	0.3850	6.58	0.0110
Banded + SFM 75	2.2571	0.3902	5.78	0.0132
Control	2.2920	0.3960	5.79	0.0112
SFM 75	2.9406	0.3959	7.43	0.0057
Radial	2.2828	0.4152	5.50	0.0077
Radial + SFM 75	2.0155	0.4195	4.80	0.0108

The post-ANOVA least squares means test indicated that four of the fifteen treatments were statistically dissimilar (Table A9). The greatest contrast appears to be between the most intensive treatments when paired with the sulfometuron only treatment. The post-ANOVA summary is presented below.

Table A9. Tukey-Kramer least squares means comparison estimates for relative change in diameter for new germinant reproduction between individual treatment comparisons

Treatments Compared	Estimat e	Std. Error	T - value	Pr > |t|	Adjusted P-value
Banded + SFM 75 / SFM 75	-0.6835	0.247	-2.77	0.005 9	0.0644
Control / SFM 75	-0.6486	0.2578	-2.52	0.012 2	0.1213
SFM75 / Radial	0.6578	0.2879	2.28	0.022 7	0.2021
SFM75 / Radial + SFM 75	0.9251	0.2933	3.15	0.001 7	0.0210

The absolute diameter change for the combined sprout reproduction was also highly different among treatments. The pairwise test indicated that a P-value of <0.0001 existed. Table A10 presents the statistical test summary.

Table A10. Type III tests of fixed effects for relative diameter change among treatments for sprout reproduction

Effect	Num DF	Den DF	Chi-Square	F-Value	Pr > F
Treatment	5	1045	29.49	5.90	<.0001

The sulfometuron treatment yielded the greatest estimate (1.6841) for relative diameter growth (Table A11). The control estimate (1.494) was greater than all other treatments except for the banded and the sulfometuron only applications.

Table A11. Least square means estimates for relative diameter change for among treatments for sprout reproduction

Treatment	Estimate	Std. Error	T - value	P - value
Banded	1.5388	0.1929	7.98	0.0038
Banded + SFM 75	1.1344	0.1914	5.93	0.0099
Control	1.4940	0.1864	8.01	0.0061
SFM 75	1.6841	0.1887	8.92	0.0038
Radial	1.2220	0.1879	6.50	0.0095
Radial + SFM 75	1.3990	0.1903	7.35	0.0058

Post ANOVA analysis using the Tukey-Kramer least squares means found a significant difference between eight of the fifteen treatment comparisons (Table A12). The sulfumeturon methyl only treatment and the banded plus sulfometuron treatment had the largest range (0.5497) between diameter growth estimates for sprout reproduction. The pairwise treatment comparisons that were significant are illustrated below.

Table A12. Tukey-Kramer least squares means comparison estimates for relative change in diameter for sprout reproduction among individual treatment comparisons

Treatments Compared	Estimat e	Std. Error	T - value	Pr > |t|	Adjusted P-value
Banded / Banded + SFM75	0.4044	0.1267	3.19	0.0015	0.018
Banded / Radial	0.3168	0.1211	2.62	0.009	0.0942
Banded + SFM 75 / Control	-0.3596	0.1164	-3.09	0.0021	0.0250
Banded + SFM 75 / SFM 75	-0.5497	0.1207	-4.55	<.0001	<.0001
Banded + SFM 75 / Radial + SFM 75	-0.2646	0.1229	-2.15	0.0315	0.2610
Control / Radial	0.272	0.1106	2.46	0.0141	0.1376
SFM75 / Radial	0.4621	0.1145	4.04	<.0001	0.0008
SFM75 / Radial + SFM 75	0.2851	0.118	2.42	0.0158	0.1512

Relative Height Change by Reproduction Size

The relative change in diameter growth for sprout reproduction was also strongly different among treatments (Table A13). A low P-value of <0.0001 was estimated from the type III two-way pairwise test.

Table A13. Type III tests of fixed effects for relative height change among treatments for sprout reproduction

Effect	Num DF	Den DF	Chi-Square	F-Value	Pr > F
Treatment	5	503	45.29	9.06	<.0001

The relative diameter change for sprout reproduction had the greatest estimate (2.9192) for the sulfometuron methyl only treatment (Table A14). The radial treatment had the poorest response in relative diameter change with an estimate of 1.5933.

Table A14. Least square means estimates for relative height change among treatments for sprout reproduction

Treatment	Estimate	Std. Error	T - value	P - value
Banded	2.0135	0.349	5.77	0.0083
Banded + SFM 75	1.8854	0.346	5.45	0.0108
Control	2.1756	0.3359	6.48	0.0093
SFM 75	2.9192	0.3406	8.57	0.0036
Radial	1.5933	0.3389	4.70	0.0197
Radial + SFM 75	2.4716	0.3438	7.19	0.0052

Eight of the fifteen treatment comparisons showed a difference in the least square means post-ANOVA test. The largest separation of relative diameter growth was between the sulfometuron treatment and the radial treatment (Table A15).

Table A15. Tukey-Kramer least squares means comparison estimates for relative change in height for sprout reproduction among individual treatment comparisons

Treatments Compared	Estimate	Std. Error	T - value	Pr > |t|	Adjusted P-value
Banded / SFM75	-0.9057	0.2328	-3.89	0.0001	0.0015
Banded + SFM 75 / SFM 75	-1.0338	0.2305	-4.48	<.0001	0.0001
Banded + SFM 75 / Radial + SFM 75	-0.5862	0.2347	-2.50	0.0126	0.1256
Control / SFM 75	-0.7435	0.2141	-3.47	0.0005	0.0071
Control / Radial	0.5824	0.2113	2.76	0.0059	0.0655
SFM75 / Radial	1.3259	0.2186	6.06	<.0001	<.0001
SFM75 / Radial + SFM 75	0.4476	0.2253	1.99	0.0472	0.3504
Radial / Radial + SFM 75	-0.8783	0.2236	-3.93	<.0001	0.0013

The relative change in height for new germinant reproduction was also highly significant among treatments (Table A16). A low P-value of <0.0001 was estimated from the type III two-way pairwise test.

Table A16. Type III tests of fixed effects for relative height change among treatments for new germinant reproduction

Effect	Num DF	Den DF	Chi-Square	F-Value	Pr > F
Treatment	5	1045	44.04	8.81	<.0001

The sulfometuron methyl only treatments had the largest response (8.3351) in relative height growth for new germinant reproduction (Table A17). The radial treatment had the lowest estimate for relative diameter growth at 4.2896. All glyphosate applications, other than the radial plus the sulfometuron methyl treatment were lower estimates than the control.

Table A17. Least square means estimates for relative height change for among treatments for new germinant reproduction

Treatment	Estimate	Std. Error	T - value	P - value
Banded	4.9281	0.5654	8.72	0.0002
Banded + SFM 75	4.948	0.5877	8.42	<.0001
Control	5.1636	0.6136	8.41	<.0001
SFM 75	8.3351	0.6129	13.6	<.0001
Radial	4.2896	0.6928	6.19	<.0001
Radial + SFM 75	5.7758	0.7093	8.14	<.0001

Five out of the fifteen treatment comparisons were significantly dissimilar from one another (Table A18). The most pronounced range between mean height change estimates was found between the sulfometuron and radial treatments. Multiple significant comparisons between individual treatments are presented below.

Table A18. Tukey-Kramer least squares means comparison estimates for relative change in height for new germinant reproduction between individual treatment comparisons

Treatments Compared	Estimate	Std. Error	T - value	Pr > |t|	Adjusted P-value
Banded / SFM75	-3.407	0.6211	-5.49	<.0001	<.0001
Banded + SFM 75 / SFM 75	-3.3871	0.6361	-5.33	<.0001	<.0001
Control / SFM 75	-3.1715	0.6638	-4.78	<.0001	<.0001
SFM75 / Radial	4.0455	0.7409	5.46	<.0001	<.0001
SFM75 / Radial + SFM 75	2.5593	0.7543	3.39	0.0007	0.0097

Relative Change in Growth by Species Groups

Relative diameter change for all combined red oak stems was marginally insignificant (P = 0.0940). Relative diameter change for white oak was found to be different. The type III test estimated a P-value of 0.0048 (Table A19).

Table A19. Type III tests of fixed effects for relative diameter change among treatments for all white oak stems

Effect	Num DF	Den DF	Chi-Square	F-Value	Pr > F
Treatment	5	434	17.13	3.43	0.0048

The sulfometuron treatment estimate (1.5101) was the only treatment greater than the control estimate (1.5027) (Table A20). The more intensive treatments and the radial treatment appear to have the lesser estimates. All significant comparisons between individual treatments are below.

Table A20. Least square means estimates for relative diameter change among treatments for all white oak stems

Treatment	Estimate	Std. Error	T - value	P - value
Banded	1.4803	0.2485	5.96	0.0047
Banded + SFM 75	0.8967	0.2480	3.62	0.0251
Control	1.5027	0.2303	6.52	0.0090
SFM 75	1.5101	0.2464	6.13	0.0048
Radial	1.2267	0.2360	5.20	0.0130
Radial + SFM 75	1.4523	0.2549	5.70	0.0041

The post-ANOVA least squares means test indicated that four of the fifteen treatments were statistically dissimilar. The greatest contrast appears to be between the sulfometuron only treatment and the banded with the sulfometuron. Table A21 depicts the post-ANOVA summary.

Table A21. Tukey-Kramer least squares means comparison estimates for relative change in diameter for all white oak stems between individual treatment comparisons

Treatments Compared	Estimate	Std. Error	T - value	Pr > |t|	Adjusted P-value
Banded / Banded + SFM75	0.5836	0.1993	2.93	0.0036	0.0415
Banded + SFM 75 / Control	-0.6061	0.1703	-3.56	0.0004	0.0055
Banded + SFM 75 / SFM 75	-0.6134	0.1914	-3.20	0.0015	0.0181
Banded + SFM 75 / Radial + SFM 75	-0.5556	0.1979	-2.81	0.0052	0.0582

The relative diameter change for yellow-poplar reproduction was also strongly different among treatments (Table A22). A low P-value of <0.0001 was estimated from the type III two-way pairwise test. illustrates the test summary.

Table A22. Type III tests of fixed effects for relative diameter change among treatments for all yellow-poplar stems

Effect	Num DF	Den DF	Chi-Square	F-Value	Pr > F
Treatment	5	494	31.25	6.25	<.0001

Yellow-poplar relative diameter growth had the greatest mean estimate (3.0021) for the sulfometuron only treatment (Table A23). The two treatments that used both herbicides had the lowest estimates. These two treatments were also lower than the control estimate (2.3717).

Table A23. Least square means estimates for relative diameter change for among treatments for all yellow-poplar stems

Treatment	Estimate	Std. Error	T - value	P - value
Banded	2.9054	0.4924	5.90	0.0192
Banded + SFM 75	2.3924	0.5028	4.76	0.0259
Control	2.3717	0.5067	4.68	0.0251
SFM 75	3.0021	0.4934	6.08	0.0176
Radial	2.4499	0.5230	4.68	0.0191
Radial + SFM 75	1.7716	0.5068	3.50	0.0494

Nine of the fifteen treatment comparisons were significant according to the Tukey least squares means test (Table A24). The largest separation occurred between the sulfometuron treatment and the radial plus sulfometuron comparison (1.2305). Treatments using singly applied herbicides or control were distinguished from the combination herbicide treatments.

Table A24. Tukey-Kramer least squares means comparison estimates for relative change in diameter for all yellow-poplar stems between individual treatment comparisons

Treatments Compared	Estimate	Std. Error	T - value	Pr > |t|	Adjusted P-value
Banded / Banded + SFM75	0.513	0.2492	2.06	0.0401	0.3110
Banded / Control	0.5337	0.2547	2.10	0.0367	0.2914
Banded / Radial + SFM 75	1.1338	0.2569	4.41	<.0001	0.0002
Banded + SFM 75 / SFM 75	-0.6097	0.2349	-2.60	0.0097	0.1002
Banded / Radial + SFM 75	0.6208	0.2591	2.40	0.0170	0.1596
Control / SFM 75	-0.6304	0.2488	-2.53	0.0116	0.1163
Control / Radial + SFM 75	0.6001	0.2759	2.17	0.0301	0.2514
SFM75 / Radial + SFM 75	1.2305	0.2453	5.02	<.0001	<.0001
Radial / Radial + SFM 75	0.6783	0.3054	2.22	0.0268	0.2298

Relative diameter change was not different (P = 0.2121) among treatments for red oak stems. The relative change in diameter for white oak was significant (P = 0.0161) among all the treatments. Table A25 illustrates the test summary for white oak.

Table A25. Type III tests of fixed effects for relative height change among treatments for all white oak stems

Effect	Num DF	Den DF	Chi-Square	F-Value	Pr > F
Treatment	5	433	24.13	4.83	0.0003

The radial with the sulfometuron methyl treatment yielded the greatest mean relative height estimate (2.7123) for white oak stems (Table A26). The sulfometuron only application had the next largest estimate of 2.4431. The lowest mean estimate (1.5514) was associated with the radial treatment.

Table A26. Least square means estimates for relative height change among treatments for all white oak stems

Treatment	Estimate	Std. Error	T - value	P - value
Banded	1.7944	0.2822	6.36	0.0002
Banded + SFM 75	1.6549	0.2806	5.90	0.0005
Control	2.1126	0.2414	8.75	0.0007
SFM 75	2.4431	0.2774	8.81	<.0001
Radial	1.5514	0.2544	6.10	0.0014
Radial + SFM 75	2.7123	0.2954	9.18	<.0001

Eight of the fifteen treatment comparisons showed a difference in the least square means post-ANOVA test. The largest separation occurred between the radial with the radial plus sulfometuron treatment. Applications with higher amounts of glyphosate tended to separate from both the control and sulfometuron treatments (Table A27).

Table A27. Tukey-Kramer least squares means comparison estimates for relative change in height for all white oak stems between individual treatment comparisons

Treatments Compared	Estimate	Std. Error	T - value	Pr > |t|	Adjusted P-value
Banded / SFM75	-0.6487	0.3053	-2.12	0.0342	0.2763
Banded / Radial + SFM 75	-0.9178	0.3242	-2.83	0.0049	0.0545
Banded + SFM 75 / SFM 75	-0.7883	0.2996	-2.63	0.0088	0.0920
Banded + SFM 75 / Radial + SFM 75	-1.0574	0.3104	-3.41	0.0007	0.0093
Control / Radial	0.5612	0.2417	2.32	0.0207	0.1875
Control / Radial + SFM 75	-0.5997	0.2825	-2.12	0.0344	0.2775
SFM 75 / Radial	0.8917	0.2783	3.2	0.0015	0.0181
Radial / Radial + SFM 75	-1.1609	0.2933	-3.96	<.0001	0.0012

The relative change in height for yellow-poplar reproduction was also highly different among treatments. A low P-value of <0.0001 was estimated from the type III two-way pairwise test. Table A28 illustrates the test summary.

Table A28. Type III tests of fixed effects for relative height change among treatments for all yellow-poplar stems

Effect	Num DF	Den DF	Chi-Square	F-Value	Pr > F
Treatment	5	494	36.56	7.31	<.0001

The sulfometuron methyl only treatments had the largest response in relative height growth for yellow-poplar reproduction (Table A29). The radial treatment yielded the lowest estimate at 4.8276. All treatments other than the sulfometuron only treatment were lesser estimates compared to the control estimate.

Table A29. Least square means estimates for relative height change among treatments for all yellow-poplar stems

Treatment	Estimate	Std. Error	T - value	P - value
Banded	5.5882	0.8466	6.6	0.0083
Banded + SFM 75	5.807	0.8847	6.56	0.005
Control	5.9773	0.8997	6.64	0.0038
SFM 75	8.1304	0.8496	9.57	0.0029
Radial	4.8276	0.9586	5.04	0.0048
Radial + SFM 75	5.1854	0.8997	5.76	0.0061

Five of the fifteen treatment comparisons showed a difference in the least square means post-ANOVA test (Table A30). The greatest separation in estimates was found between the sulfometuron and radial applications. presents the least squares means test results.

Table A30. Tukey-Kramer least squares means comparison estimates for relative change in height for all yellow-poplar stems between individual treatment comparisons

Treatments Compared	Estimate	Std. Error	T - value	Pr > |t|	Adjusted P-value
Banded / SFM75	-2.5423	0.5795	-4.39	<.0001	0.0002
Banded + SFM 75 / SFM 75	-2.3234	0.5993	-3.88	0.0001	0.0017
Control / SFM 75	-2.1531	0.6349	-3.39	0.0008	0.0097
SFM75 / Radial	3.3028	0.7237	4.56	<.0001	<.0001
SFM75 / Radial + SFM 75	2.9450	0.6260	4.70	<.0001	<.0001

New Germinant Versus Sprout Reproduction (by Species) Relative Diameter Growth Response to Treatments

An analysis of variance indicated that four of the six analyses did have a significance between treatments. The two species by size groups that were not significant included white oak germinants (Pr>ChiSq = 0.2100) and red oak sprout (P = 0.1208) reproduction. Post ANOVA testing of least squares means is not provided for these insignificant groups. White oak new germinant, yellow-poplar new germinant, white oak sprout, and yellow-poplar sprout reproduction all had a difference in relative diameter growth among treatments.

Red oak new germinant reproduction relative diameter growth did vary significantly (Pr > ChiSq = 0.0191) among treatments (Table A31). All treatments had inferior relative diameter growth compared to the control (mean estimate of 2.2032). The radial application returned the next highest mean estimate at 2.1497. All treatments were significant at the 95% level.

Table A31. Least squares means estimates for relative change in diameter for new germinant red oak reproduction among treatments

Treatment	Estimate	Std. Error	T - value	P - value
Banded	1.1254	0.3141	3.58	0.0101
Banded + SFM 75	1.4630	0.3057	4.79	0.0026
Control	2.2032	0.3334	6.61	<.0001
SFM 75	1.1651	0.3514	3.32	0.0066
Radial	2.1497	0.3883	5.54	<.0001
Radial + SFM 75	1.7160	0.3880	4.42	0.0004

The least squares mean separation test revealed a difference between five out of the fifteen individual treatment comparisons. Table A32 illustrates the significant treatment comparisons. The greatest relative diameter change estimate was -1.0777 between the banded and control treatments.

Table A32. Tukey-Kramer least squares means comparison estimates for relative change in diameter for new germinant red oak reproduction between individual treatment comparisons

Treatments Compared	Estimate	Std. Error	T - value	Pr > |t|	Adjusted P-value
Banded / Control	-1.0777	0.3739	-2.88	0.0050	0.0548
Banded / Radial	-1.0243	0.4283	-2.39	0.0190	0.1713
Banded + SFM 75 / Control	-0.7402	0.3717	-1.99	0.0497	0.3562
Control / SFM 75	1.0381	0.4099	2.53	0.0132	0.1267
SFM 75 / Radial	-0.9846	0.4531	-2.17	0.0327	0.2617

Yellow-poplar new germinant relative diameter growth was different between treatments (P = 0.0020) (Table A33). The sulfometuron methyl only application yielded the highest estimate (3.5055) for all treatments. The comparison of all treatments for new germinant yellow-poplar reproduction is depicted below.

Table A33. Least squares means estimates for relative change in diameter for new germinant yellow-poplar reproduction among treatments

Treatment	Estimate	Std. Error	T - value	P - value
Banded	3.2543	0.396	8.22	0.0043
Banded + SFM 75	2.6463	0.4136	6.4	0.0053
Control	2.4159	0.4266	5.66	0.0053
SFM 75	3.5055	0.4087	8.58	0.0024
Radial	2.6361	0.4741	5.56	0.0015
Radial + SFM 75	2.2188	0.4778	4.64	0.0035

The post ANOVA differences of least squares means test exposed differences for six individual treatment comparisons (Table A34). The estimate for the sulfometuron only with the radial with sulfometuron treatments was the highest among treatment comparisons. This estimate was 1.2867. The lowest estimate (-1.0896) was for the control with sulfometuron only comparison.

Table A34. Tukey-Kramer least squares means comparison estimates for relative change in diameter for new germinant yellow-poplar reproduction between individual treatment comparisons

Treatments Compared	Estimate	Std. Error	T - value	Pr > |t|	Adjusted P-value
Banded / Control	0.8384	0.3390	2.47	0.0139	0.1353
Banded / Radial + SFM75	1.0354	0.3984	2.60	0.0098	0.1005
Banded + SFM75 / SFM75	-0.8592	0.3227	-2.66	0.0082	0.0858
Control / SFM75	-1.0896	0.3450	-3.16	0.0017	0.0214
SFM75 / Radial	0.8694	0.4079	2.13	0.0338	0.2739
SFM75 / Radial + SFM75	1.2867	0.4061	3.17	0.0017	0.0207

White oak sprout reproduction relative diameter change was also significant among treatments (P = 0.0006). The banded treatment had the maximal estimate with 1.5866. The minimum estimate was 0.7411 for the banded with the sulfometuron treatment. Table A35 illustrates relative diameter change values and statistics for the treatments.

Table A35. Least squares means estimates for relative change in diameter for white oak sprout reproduction among treatments

Treatment	Estimate	Std. Error	T - value	P - value
Banded	1.5866	0.2634	6.02	0.0025
Banded + SFM 75	0.7411	0.253	2.93	0.0446
Control	1.347	0.234	5.76	0.012
SFM 75	1.4476	0.25	5.79	0.0056
Radial	1.0617	0.2398	4.43	0.0195
Radial + SFM 75	1.271	0.2624	4.85	0.0062

The post-ANOVA differences of least square means test revealed that six of the fifteen treatment comparisons were distinctive (Table A36). The banded treatment and the banded with sulfometuron treatment has the largest separation with an estimate of 0.8454. Four of the comparisons were highly different. Each of these comparisons included the sulfometuron only treatment.

Table A36. Tukey-Kramer least squares means comparison estimates for relative change in diameter for white oak sprout reproduction between individual treatment comparisons

Treatments Compared	Estimate	Std. Error	T - value	Pr > |t|	Adjusted P-value
Banded / Banded + SFM75	0.8454	0.2204	3.84	0.0001	0.0021
Banded - Radial	0.5249	0.2043	2.57	0.0106	0.1078
Banded + SFM 75 - Control	-0.6059	0.1776	-3.41	0.0007	0.0093
Banded + SFM75 / SFM75	-0.7065	0.1982	-3.57	0.0004	0.0055
Banded / Radial + SFM75	-0.531	0.2088	-2.54	0.0114	0.114
SFM75 / Radial	0.386	0.1848	2.09	0.0374	0.2955

Yellow-poplar sprout reproduction relative diameter change also varied (P = 0.0071) between treatments (Table A37). Seedlings within the control treatment performed better than all other treatments. The radial release with the sulfometuron treatments showed the largest reduction in growth (1.3749). The treatments and there statistical values are depicted below.

Table A37. Least squares means estimates for relative change in diameter for yellow-poplar sprout reproduction among treatments

Treatment	Estimate	Std. Error	T - value	P - value
Banded	2.1306	0.4425	4.81	0.0161
Banded + SFM 75	1.8098	0.4716	3.84	0.019
Control	2.2575	0.4642	4.86	0.0099
SFM 75	2.1761	0.4267	5.1	0.0197
Radial	2.173	0.4721	4.6	0.0101
Radial + SFM 75	1.3749	0.4325	3.18	0.0554

The post ANOVA differences of least squares means test exposed differences for four individual treatment comparisons. The estimate for the optimal (control) treatment paired against the minimal (radial with sulfometuron) treatment had the greatest difference in estimate (0.8825) for all significant comparisions. Table A38 illustrates the significant treatment comparisons.

Table A38. Tukey-Kramer least squares means comparison estimates for relative change in diameter for yellow-poplar sprout reproduction between individual treatment comparisons

Treatments Compared	Estimate	Std. Error	T - value	Pr > |t|	Adjusted P-value
Banded / SFM75	0.7557	0.2841	2.66	0.0085	0.0888
Control / Radial + SFM75	0.8825	0.3088	2.86	0.0048	0.0532
SFM75 / Radial + SFM75	0.8011	0.2313	3.46	0.0007	0.0086
Radial / Radial + SFM75	0.7981	0.3157	2.53	0.0123	0.1215

New Germinant Versus Sprout Reproduction (by Species) Relative Height Growth Response to Treatments

An analysis of variance indicated that there half of the six analyses did not show any significance between treatments (Table A39). This included red oak sprout (Pr > ChiSq = 0.2093), red oak new germinant (P = 0.8530), white oak new germinant (P = 0.115) reproduction. Post ANOVA testing is not provided for these insignificant groups. White oak sprout reproduction did vary significantly (P = 0.0001) among treatments. The sulfometuron methyl with radial spray yielded the highest mean estimate (2.3539 inches) for relative change. The minimal estimated mean was 1.423 for the sulfumeturon and banded spray treatment. All treatments were significant at the 95% level.

Table A39. Least squares means estimates for relative change in height for white oak sprout reproduction among treatments

Treatment	Estimate	Std. Error	T - value	P - value
Banded	1.8244	0.3073	5.94	0.0005
Banded + SFM 75	1.423	0.2889	4.92	0.0031
Control	2.0396	0.2552	7.99	0.0022
SFM 75	2.2305	0.2839	7.86	0.0004
Radial	1.3137	0.2657	4.94	0.0072
Radial + SFM 75	2.3539	0.3055	7.7	0.0001

A post-ANOVA analysis of the white oak sprout reproduction indicated that six treatment comparisons out of the total fifteen were significantly different from one another (Table A40). The largest positive separation was for the sulfometuron and radial treatments followed by the control and radial treatments (mean estimates of 0.9168 and 0.7259, respectively). The significant treatment comparisons are presented in Table A40.

Table A40. Tukey-Kramer least squares means comparison estimates for relative change in height for white oak sprout reproduction between individual treatment comparisons

Treatments Compared	Estimate	Std. Error	T - value	Pr > |t|	Adjusted P-value
Banded + SFM75 / Control	-0.6167	0.2517	-2.45	0.0148	0.1424
Banded + SFM75 / SFM75	-0.8075	0.2807	-2.88	0.0043	0.0485
Banded + SFM75 / Radial + SFM75	-0.931	0.2963	-3.14	0.0018	0.0223
Control / Radial	0.7259	0.2278	3.19	0.0016	0.0194
SFM75 / Radial	0.9168	0.2617	3.50	0.0005	0.0069
Radial / Radial + SFM75	-1.0402	0.2812	-3.70	0.0003	0.0034

Yellow-poplar sprout reproduction also differed (P = 0.0009) among treatments for relative height change. The sulfometuron methyl only application yielded the highest mean estimate (4.7867) for relative change. The minimal estimated mean was 2.8775 for the sulfumeturon and banded spray treatment. Individual treatments were statistically different (Table A41).

Table A41. Least squares means estimates for relative change in height for yellow-poplar sprout reproduction among treatments

Treatment	Estimate	Std. Error	T - value	P - value
Banded	3.5531	0.9489	3.74	0.0366
Banded + SFM 75	3.8983	0.9985	3.90	0.0230
Control	3.7175	0.9857	3.77	0.0277
SFM 75	4.7867	0.9226	5.19	0.0211
Radial	3.2292	0.9991	3.23	0.0390
Radial + SFM 75	2.8775	0.9323	3.09	0.0640

Post ANOVA analysis using the Tukey mean separation found an apparent difference between three out of the fifteen treatment combinations for the relative change in height growth (Table A42). The greatest contrast was between the sulfometuron methyl only and sulfometuron and radial spray treatment. The mean estimate was 1.9093.

Table A43. Tukey-Kramer least squares means comparison estimates for relative change in height for yellow-poplar sprout reproduction between individual treatment comparisons

Treatments Compared	Estimate	Std. Error	T - value	Pr > |t|	Adjusted P-value
Banded / SFM75	-1.2336	0.5169	-2.39	0.0181	0.1666
Control / Radial	1.5576	0.5843	2.67	0.0084	0.087
SFM75 / Radial + SFM75	1.9093	0.4397	4.34	<.0001	0.0003

The relative change in height for yellow-poplar new germinants was also significant (P < 0.0001). The sulfometuron only treatment again generated the largest mean estimate (10.2732 inches) for the six treatments. A value of 6.0248, for the radial treatment, was the lowest mean estimate. All treatments were strongly different (Table A43).

Table A44. Least squares means estimates for relative change in height for new germinant yellow-poplar reproduction among treatments

Treatment	Estimate	Std. Error	T - value	P - value
Banded	6.7140	0.5466	12.28	<.0001
Banded + SFM 75	6.6934	0.5888	11.37	<.0001
Control	7.0293	0.6613	10.63	<.0001
SFM 75	10.2732	0.5862	17.52	<.0001
Radial	6.0248	0.8280	7.28	<.0001
Radial + SFM 75	8.2555	0.8257	10	<.0001

The post-ANOVA differences of least square means test revealed that six of the fifteen treatment comparisons were distinctive. The sulfometuron only and the radial treatment has the largest separation with an estimate of 4.2484. Four of the comparisons were highly different. Each of these comparisons included the sulfometuron only treatment (Table A44).

Table A44. Tukey-Kramer least squares means comparison estimates for relative change in height for new germinant yellow-poplar reproduction between individual treatment comparisons

Treatments Compared	Estimate	Std. Error	T - value	Pr > |t|	Adjusted P-value
Banded / SFM75	-3.5593	0.7528	-4.73	<.0001	<.0001
Banded + SFM75 / SFM75	-3.5798	0.7675	-4.66	<.0001	<.0001
Control / SFM75	-3.2439	0.8308	-3.9	0.0001	0.0016
SFM75 / Radial	4.2484	0.9733	4.37	<.0001	0.0003
SFM75 / Radial + SFM75	2.0177	0.965	2.09	0.0374	0.295
Radial / Radial + SFM75	-2.2307	1.1266	-1.98	0.0486	0.3564

VITA

Stephen Eric Peairs was born in Baton Rouge, LA, and was legally adopted by his parents Jimmy and Sue Nell Peairs. He attended Silliman Institute in Clinton, LA from kindergarten until graduation from high school. Stephen then enrolled Mississippi State University where he earned his Bachelor of Science degree in Forestry – wildlife management option. During his latter years at State, Stephen worked under Dr. Andrew Ezell on various herbicide studies. Stephen graduated in May of 2001 and in August of 2001 was offered a graduate researcher assistantship by Dr. Ezell to begin work on a Master of Science degree in Forestry. The emphasis of study involved methods to improve natural oak regeneration in bottomland hardwood forests. Stephen graduated with his Master of Science degree in December of 2003 from Mississippi State University. He then began his professional career working with the Tennessee Department of Agriculture – Division of Forestry serving as a Forest Inventory and Analysis Forester (Forester 2) from October 2004 – October 2005. Stephen was then promoting into a Forester 3 position serving as an Area Forester. He served the State of Tennessee in this capacity until August of 2014. At that point, he accepted a Graduate Research/Teaching Assistantship offered by Dr. Wayne Clatterbuck at the University of Tennessee – Knoxville. Stephen's research focused on upland hardwood natural regeneration and herbicide applications to enhance natural reproduction growth. Stephen will graduate with his Doctor of Philosophy degree in Natural Resources in August of 2018.