ABSTRACT

LAWRENCE III, CHARLIE. Response of a Six-Year-Old Naturally Regenerated Upland Hardwood Stand to Release and Fertilization Treatments in the North Carolina Piedmont. (Under the direction of Daniel J. Robison).

Clear-cutting is a commonly prescribed harvest and regeneration technique for hardwood stands in the southeastern U.S. This often results in a naturally regenerating stand that receives little or no silvicultural intervention in the early stages of development. The current study is a continuation of an experiment installed on 2-year-old mixed pine-hardwood stand on the North Carolina State University Hill Demonstration Forest in the Piedmont region (Durham County) of North Carolina. Six years after fertilization at year one, and the imposition of release treatments at year three within the same stand, the influence of these treatments on individual stem growth, stand-wide growth, and species composition was evaluated. Dominant species were loblolly pine (*Pinus taeda)* red maple (*Acer rubrum*), hickory (*Carya spp)*, sweetgum (*Liquidambar styraciflua*), and tulip poplar (*Liriodendron tulipifera*). Fertilizer treatments were broadcast applied and consisted of an untreated control (*Control*), nitrogen (*N*) only treatments, nitrogen and phosphorus (*N+P*) treatments, and nitrogen, phosphorus and potassium (*N+P+K*) treatments (respectively at 200 kg N per ha, 50 kg P per ha and 100 kg K per ha). Five trees each of loblolly pine, tulip poplar and northern red oak (*Quercus rubra*) were selected in release and non-release conditions. Release treatments consisted of the removal of all above ground vegetation within a 1.8 m radius of selected trees with a brush saw.

On a total stand basis, the fertilizer treatment effects were significant for mean ground-line diameter (GLD), diameter at breast height (DBH), height, and volume index of all species, hardwoods, and seed origin stems. Although fertilizer treatment effects were not

significant for sprout origin stems, the data suggests that fertilization provided some benefit. Hickory GLD, DBH, and volume index means were significantly smaller than under Control conditions, than when treated with N+P+K fertilizer. A significant fertilizer affect was observed for sweetgum height, where it was significantly larger under the N and N+P treatments. No significant fertilizer treatment effect was found for red maple, tulip poplar, or the other size attributes for sweetgum. However the data suggest that fertilization provided some positive growth benefits for these species as well.

Fertilizer treatment effects significantly impacted overall stem density, and the representation of stems in height classes. There were significantly more stems found in the Control treatment compared to the fertilizer treatments after 6 years of growth, for stems less than 3 m tall. For stems 3 m and taller, the number of stems found in fertilizer treatment plots increased substantially compared to the Control, indicating a shift in vertical structure due to fertilization. This indicates that fertilization increased the rate of self-thinning and can be useful in the manipulation of stem density and relative tree size. The 16 largest trees in each plot, regardless of species, increased in DBH in response to N+P and N+P+K treatments, and had larger mean height with N, N+P, and N+P+K treatments, over the Control. The 10 largest trees per plot of loblolly pine, hickory, red maple, and sweetgum also demonstrated a positive growth response to fertilizer treatments. Hickory mean GLD and DBH were smaller in N, N+P, and N+P+K treatments compared to the Control, and may be at a competitive disadvantage under these treatments on this site. Fertilizer treatment effects were not significant for the largest tulip poplar stems, but the results suggested a strong trend with increased size in fertilizer treatments compared to the Control.

Loblolly pine and tulip poplar responded positively to release treatments with significant increases in diameter size and diameter growth under each fertilizer treatment. Although the fertilizer effect, and release by fertilizer interaction, were not statistically significant, the data suggests that size increases with fertilization under released conditions for these species. The oaks demonstrated minimal to no response to release treatments, under any of the fertilizer treatments.

Response of a Six-Year-Old Naturally Regenerated Upland Hardwood Stand to Release and Fertilization Treatments in the North Carolina Piedmont

by
Charlie Lawrence III

A thesis submitted to the Graduate Faculty of
North Carolina State University
in partial fulfillment of the
requirements for the degree of
Master of Science

Forestry

Raleigh, North Carolina

2011

APPROVED BY:

Daniel J. Robison- Chair Committee Chair	Glenn Catts
Stacy Nelson	Sarah Warren

BIOGRAPHY

Charlie Lawrence III was born in Tampa Florida on February 15, 1985 to Charlie and Sheryl Lawrence. After a couple of years stateside, he moved across the Atlantic Ocean to Upper Heyford Air Force base in England. He lived there for six years before moving to Spandhalem Air Force base in Germany, where his passion for conservation bloomed. It was here that his father explained the importance of recycling and enforced his lessons with forest bike rides and M.R.E's. One day, Charlie saw a commercial depicting the deforestation of Brazil's rainforest exclaimed, "I want to save the trees". His father said, "son you will," and from that moment on he knew what he wanted to do.

In 1996, Charlie, his brother "Fatboy," and his Dad left Germany and moved to Goldsboro, North Carolina. He attended Greenwood Middle School and graduated from Eastern Wayne High School in 2003. He went on to Fayetteville State University and graduated in 2007 with a Bachelor of Science in biology. In the fall of 2008, he began his Master of Science in forestry at North Carolina State University. Charlie plans to pursue a career with the United States Forest Service or other federal entity focused on the preservation of our natural resources.

ACKNOWLEDGMENTS

I want to recognize my advisor, Dr. Daniel Robison, for assigning me to this project and the patience he has exhibited throughout this process. I would like to thank Dr. Stacy Nelson and Mr. Thomas Easley for providing a support system from a different perspective and establishing connections for employment opportunities. I would like to thank Ms. Alison Al'Baati for providing support and the internship opportunities that enabled me to attend graduate school. I would like to thank Mr. Slocumb for providing comical relief when issues with arcgis pushed me to the edge of my sanity. Dr. Sarah Warren, thank you for providing a small portion of your library to me so that forestry wasn't so foreign and sitting on my committee. Lastly, I would like to thank to Dr. Glenn Catts for answering any question I had and making sure that I knew how much of a "hoop loser" I was. And, I thank Fikrit Isik for his expert assistance with statistical analysis.

I am truly grateful for the assistance Ben Jackson provided in the field. He braved the intense heat, bitter cold, and jungle of briars while working on his own education at the same time. I am also very appreciative of Hayley Stevenson, Teisha Weymore, Sam "summer" Meeks, and Emrys Treasure for their help with data collection and serving as new menu items for the ticks to sample.Finally, I would like to thank my pop, Pete Smith, Morika Williams, Mychal Smith, and Fatboy Lawrence for their unwavering support. They have all provided an opinion at some point that kept me grounded and able to trudge on. I am truly blessed to have such wonderful people in my life.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

INTRODUCTION

Introduction and Context of Study

Approximately 306 million hectares of land are occupied by forests in the United States. From a global standpoint this represents 6% of the world's forests, 8% of its total volume, and 27% of the world's wood destined for value added products (Guldin and Kaiser 2004). The southeastern U.S. contains nearly one-third or 87 million hectares of U.S. forests that range as far north and south as Virginia and Florida with Texas being the most western limit. Ninety-three percent of these forests are classified as commercially viable timberlands (Conner and Hartsell 2002), with conifers and hardwoods representing approximately 33 and 67 % of the species composition in the SE timberlands, respectively.

Southern forests generate 18% of the world's pulpwood for paper and paper related products, and 7% of its industrial roundwood. In 2006, the region yielded 8.6 billion cubic feet of wood (www.seesouthernforests.org). In order to meet a growing demand for timber products and halt future forest loss, sustainable forestry practices that maximize growth and preserve site integrity are paramount. Given that 60% of all forestland in the Southeast is owned by non-industrial private forest landowners (www.seesouthernforests.org), the private landowner will be a focal point and critically important to timber production and forest conservation, especially due to the dwindling contribution of timber from national forests (Howard 2003). This will also complicate decisions between effective management of natural mixed species stands versus the conversion to pine (*Pinus* spp.) plantations. (Frederick, FOR 507 manual, 2009). Even though landowners often prefer natural regeneration because it is viewed as less expensive and less complex to accomplish (Siry 2002), the potential for poor management practices increases, often leading to less productive forests. This is of particular concern in the southeastern U.S. as private landowners in this region supply nearly 60% of the country's timber products (Prestemon and Abt 2002). As a result of poor management, harvests would produce less in monetary returns and would incite owners to search for more lucrative methods such as conversion to planted pine or other land uses. An increase in pine plantations would increase overall timber production due to the developed technology and intense management prescribed for their success (Albaugh et al. 2004; Fox et al. 2004). However, a substantial portion of timber related goods and ecological benefits would be lost or jeopardized do to the inability of pine to provide some products that require hardwood timber, and the ecological attributes of these systems.

In the southeastern U.S., less than optimal management practices and rates of removal that exceed growth are projected to cause a decline in hardwood inventory around 2025 (Prestemon and Abt 2002). In order to overcome this projected decline, issues of poor growing stock and poor site productivity must be rectified. First, the landowner must be made aware that certain partial cuts or diameter limit cutting reduce the productivity of future rotations and increase low value species representation (Fajvan et al. 1998; Frederick, FOR 507 manual, 2009). Second, the nutritional status of a site must be determined in order to compensate for past land use history. From the mid 1600's to early 1900's, more than 130 million hectares of forestland were converted to agricultural use (MacCleery 1992). Over time, site fertility was severely diminished or altered due to poor land management practices that removed available N and encouraged topsoil erosion (Richter et al. 2000). For the Piedmont and Appalachian Mountain regions of the SE, the slope of the land further exacerbated topsoil losses. Inevitably, the land lost its ability to produce viable agricultural crops and was left to the processes of natural old field succession. As a result, forests of the SE generally reside on lands that are inherently low in available soil nutrients and are characterized by poor productivity (Albaugh et al. 2004; Richter et al. 2000).

As issues of stocking and site productivity are addressed and rectified, the development of desirable species in the stand becomes the focus. Although several operational techniques exist that can accomplish this objective, crop tree release is preferred for individual stem development and usually prescribed after canopy closure (Trimble 1973). This type of release provides the greatest amount of growth resources to a target stem through the removal of competition in a given vicinity of the crop tree. Crop tree release is commonly prescribed in mixed species stands where it can improve the growth of crop trees and stand composition through the removal of the least desirable individuals [quality and species considerations] (Smith 1986; Miller et al. 2007). As the crop trees mature and are eventually harvested, the seed from these more competitive individuals has been added to the site thereby increasing the likelihood of desirable regeneration (Karlsson 2006). It can be applied in plantations as well, encouraging greater growth and has the potential to shorten rotation periods (Pitt et al. 2000, 2004). In either setting, release can work synergistically with site ameliorations to generate substantial gains in growth.

Studies have shown that release can provide growth benefits in mature and young stands for at least five years after the initial treatment (Ward 2002; Bevilacqua 2005; Schuler 2006). Additionally, studies report that the allocation of growth varies by species and that the height response to release may depend on the site. Pines and hardwood species generally respond to the abundance of available growth resources provided by release with expanded crown and greater diameter growth (Shepard 1981; Thomson and Barclay 1984; Barclay and

Brix 1984; Graney 1987). However, the response of pines and hardwoods to the combination of release and fertilization has had mixed results (Johnson et al. 1998; Karlsson 2006). While studies have demonstrated mixed results regarding height response, the consensus is that release can provide larger trees in a shorter period of time.

Crop tree release doesn't come without challenges however. The success and effectiveness of the release treatment is directly influenced by operational costs, feasibility, site, species, and management objective. A complication with any one of these variables could prohibit or negate the potential benefit of applying release. Furthermore, the pros and cons of performing a release with chemical or mechanical operations impacts the decision and adds complexity. For example, release accomplished with a brush saw in hardwoods can be more cost effective than some herbicide applications, but because of resprouting the treated stem may not have access to the full advantage of increased resources. Instead, a stem based application of herbicide can provide greater resource availability and subsequent growth response to release (Wendell and Lamson 1987). Although another complication is that herbicide treatments can pass through connected root systems and damage desirable residual trees inadvertently (Kochenderfer 2001). While this is true for mixed species stands, it is of particular importance in plantations. In any case, knowledge of the potential response of the stand to release will enable the most appropriate application to minimize adverse effects and maximize productivity.

A relatively limited amount of research addresses nutrient amendments in very young naturally regenerated mixed species stands. Since fertilizer studies report significant boosts to site productivity when such intervention follows canopy closure and crown differentiation, interventions prior to canopy closure might also boost productivity (Robison et al. 2004

Berenguer 2006; Schuler and Robison 2006). Work covering crop tree release is generally limited to stands at least 10 years old (Trimble 1973; 1974; Erdmann et al. 1981; Boyette and Brenneman 1978 as described in Lamson and Smith 1983). Some authors have shown that release attempts prior to canopy closure don't necessarily provide the added gains that are expected to follow the removal of competition (Beck 1977; Hilt and Dale 1982 as described in Lamson and Smith 1983; Trimble 1973; Smith 1979). They attribute this lack of response to the absence of a discernable crown class from which the most competitive stems can be selected. There are investigations in the SE into the application of fertilization and competition removal during the early stages of naturally regenerated mixed hardwood stands to improve site and stand productivity. The current study is one of them.

LITERATURE REVIEW

Early Stand Development

Unless management has a direct role in seedling establishment, the environment exerts all influence on the development of forest stand composition. The occurrence of large scale disturbances such as fire, wind or ice can remove significant portions of existing cover. The resulting open space is the site of new development with smaller gaps favoring uneven-aged and shade-tolerant development and larger openings resulting in more even-aged structure and shade-intolerant plants. The stages of succession that follow establishment influence the mature composition of the stand. As vegetation begins to occupy the site, competitive interactions initiate the stand's development and the initial occupancy can consist of diverse vegetation taking advantage of copious amounts of resources. This phase is transient (Oliver and Larson 1996; Smith 1997) however, due to stems quickly focusing on maximizing leaf area causing intensified competition for light, water, growing space and nutrients. Individuals most adept at capturing these resources achieve early dominance and survive (Miller 1995).

Consequently, the most adept species and individuals comprise the dominant and codominant structure of the stand and their developing crowns begin to shape the understory. The developing canopy intercepts a substantial amount of light, minimizing reception by the understory thereby reducing the growth of competition. This stage of succession known as canopy closure raises mortality rates in understory stems unable to compete due to the increased use of available resources by larger stems (Peet and Christensen 1987). Although shade-tolerant species persist, they have less of a competitive advantage. The work of Dillaway et al. (2007), however, revealed that some oaks (Quercus spp.) rely on the canopy's diffusion of light to stimulate carbohydrate production and that this enables the species to take advantage of disturbances in the canopy and increase competitiveness, despite being otherwise in a relatively non-competitive position in the canopy. The first wave of vegetation and their competitive interactions influence stand structure and the location of on-site nutrient pools. According to Miller (1995), fine root biomass and leaf production serve as nutrient sinks and sources to developing trees and are strongly correlated. Early successional vegetation can either contribute by retaining nutrients post harvest (Bormann and Likens 1979) or creating competitive stresses that retard growth of desirable species (Donoso and Nyland 2006). For example, Wilson and Shure (1993) showed that *Robinia* responded to nutrient enrichment with increased biomass as a result of the competitive effects of *Erechtutes* and *Phytolacca* on *Rubus*, two growing seasons after a clearcut in the Appalachian Mountains.

The transition of a young stand to maturity involves reductions in the amount of stems per area of land over time (Smith 1986). The interactions between site and stand characteristics determine the rate of "self-thinning," and it is possible to stimulate this transition within the first year or two of regeneration (Romagosa and Robison 2003). Peet and Christensen (1985) described three scenarios that model the process of self-thinning in a young forest stand. Each example used a different variable to describe the rate of stem reduction, but growth and available nutrients remained as constants in each scenario. The time density scenario based the process of stem reduction on the interaction between time and site quality. Generally, a site of higher quality supplied more growth resources therefore accelerating stand development. Larger stems achieve dominance faster, initiating the differentiation of crown classes earlier in stand development (Smith 1986). Conversely, sites of poor quality have constraints on growth resources and the rate of self-thinning is therefore slowed. The rate of self-thinning is also driven by stand composition. For example, a more pronounced rate of thinning is observed for single species stands than mixed species stands. This is attributable to the uniform demand and depletion of specific resources to support uniform growth patterns. Additionally, shade tolerance influences the rate of reduction. Although mixed stands do self thin, the process is lengthened due to shade tolerant species' ability to survive through canopy closure. As a result, mortality is less pronounced. The third scenario in Peet and Christensen (1985) described the relationship between resource demands of larger stems and the competitive effect on neighboring trees. As trees became larger, growing space and resource utilization increasingly placed the smaller stems at disadvantage. Over time, stems unable to compete were overtopped and eventually succumbed to agents of mortality.

In order to increase the productivity of naturally regenerated SE hardwood and mixed hardwood-pine forests, manipulation of stem densities early in stand development may be critical along with considerations of other site attributes. This is true of the varying densities found in the Piedmont region of the SE where several authors have reported stem densities for naturally regenerated mixed species stands ranging widely:

- Romagosa and Robison (2003) observed stem densities of 32,500 and 33,750 per ha at ages one and two respectively,
- Berenguer (2006) observed stem densities of between 35,000 and 51,000 per ha at age three,
- Schuler and Robison (2001) observed stem densities of 163,000 per ha at ages three and four,
- Steinbeck and Kuers (1996) observed stem densities of 20,700 to 23,000 per ha age four,
- Steinbeck and Kuers (1996) observed stem densities of 19,300 to 25,200 per ha at age seven,
- Zahner and Myers (1982) observed stem densities of 6,425 to 20,000 per ha at age 10, and
- in the current study at age six, stem densities of about 5,000 per ha were recorded.

The options for manipulating mixed species stands towards a desired species composition may decrease with age and self-thinning, and therefore heighten the potential importance of early intervention.

Foresters use different silvicultural techniques to mimic self-thinning to control stand density and species composition in developing stands. Furthermore, these techniques, whether they be mechanical, chemical, or through fertilization; have been shown to increase stand volume and basal area in very young stands (Schuler and Robison 2003). Haywood (2005) reported that thinning, fertilization, and thinning by fertilization interactions significantly increased inside and outside bark volumes as early as 3 years after application in a 7-year-old loblolly pine (*Pinus taeda*) plantation. In another study, Farmer et al. (1970) found basal area growth of older upland mixed pine-hardwood stands increased significantly after nitrogen and phosphorous supplementation. Fertilization, however, appears to provide the most rapid response in young naturally regenerated hardwoods (Newton 2003; Schuler 2005). The use of fertilizer enhances site quality by mitigating nutrient deficiencies, resulting in improved growth and faster stem density reduction, "the time-density effect" (Schuler and Robison 2003; Romagosa and Robison 2003; Berenguer 2006). Experiments and reports on the impact of silvicultural treatments on young hardwood stands prior to the onset of canopy closure are quite limited in the literature (Kellison 1971; Romogosa and Robison 2002; Newton et al. 2002; Robison et al. 2004).

Regeneration Methods—Clearcut

Clearcutting is a common management practice used for the regeneration of natural even-aged forests and plantations. In hardwood regeneration, it simulates the impact of a large scale natural disturbance in a forest ecosystem. As a result, vegetation regenerates at a more even rate due to the uniform abundance of growth resources. Succession following this type of harvest practice can positively or negatively influence the commercial composition of the mature stand, making the management of this early developmental phase paramount (Toit et al. 2010). For planted pine, young stands managed with fertilization, genetically improved seedlings, and site preparation can have dramatically improved growth.

Clearcuts for natural regeneration are generally prescribed in forested stands because of the ready effectiveness of natural hardwood regeneration from the seed bank and pre-existing and latent regeneration stump and root sprouts. Furthermore, clearcutting can produce a mixture of desirable timber species (Boyce 1977), especially shade-intolerant ones, while maintaining cost effectiveness and minimal site and stand damage sometimes associated with other harvesting techniques. Conversely, the absence of management in early establishment phases increases the likelihood of undesirable or exotic species dominating the stand (Kota et al. 2007). As a result, the rate of growth and the development of desirable species could be adversely affected. Although natural regeneration is the primary form of hardwood establishment in the southern U.S., the growth of public opposition and arguments about nutrient removal, are causing concern about the broadcast application of clearcuts (Bliss 2000).

Fertilization of Natural Forest Stands

The nutrient cycle within a forest stand is variable and complicates the assessment of growth limiting nutrients. This fact is further complicated by the high variability encountered in soil properties and microsite characteristics. Therefore, experimental designs that accurately capture treatment responses are crucial to the determination of the most effective site ameliorations (Stape et al. 2006). Studies have shown that clearcutting has some effect on the availability of nutrients to regenerating vegetation. Moreover, the vegetation associated with each phase of succession influences nutrient availability (Marks and Bormann 1972; Marks 1974; Boring et al., 1981; Boring and Swank 1984, as described in

Wilson and Shure 1993). This is significant since nitrogen, followed by phosphorous, is most limited in temperate forests (Fisher 1984; Powers et al. 1990), and that this is particularly characteristic of soils in the SE (Colbert and Allen 1991). The forests in this area largely exist on abandoned agricultural lands that are deficient in essential nutrients (Richter et al. 2000; Devine et al. 2000). In order to overcome these nutrient deficits and imbalances, varying combinations of elemental fertilizers can be applied and these applications can be critical to enhancing processes such as: photosynthesis and amino acid production, cell division and development of meristimatic tissues, and carbohydrate synthesis and sugar transport (May 1985; Uchida 2000).

A substantial amount of literature supports the ameliorative effects of nutrient addition to forest stands. In a study by Fahey et al. (1998) they demonstrated that species that normally do not persist past canopy closure, could survive well into stand development when nutrient limitations were corrected. Other studies have shown that nutrient supplementation may help restore losses that result from site disturbance inflicted by harvesting operations (Hansen and Baker 1979 as described in Johnson and Todd 1998; Leichty and Shelton 2002). Schilling et al. (1999) observed significant reductions in microbial biomass carbon and nitrogen after clear and partial cuts. Others, such as Johnson et al. (1985), found that residual slash supplied a short term flux of nutrients on cut areas. However, in the same study, higher soil moisture and temperature possibly accelerated decomposition and mineralization, resulting in leaching and denitrification, resulting in a reduction in available nutrients. Despite this, the authors concluded that nutrient levels returned to near pre-cut levels after a short time and were consistent with other studies.

The absorption rates for different fertilizer nutrients vary according to application frequency, inherent site characteristics, and the form that the nutrients are delivered (Auchmoody and Philip 1973; Auchmoody 1982; Neary et al. 1984). Johnson and Todd (1988) observed that quarterly and annual applications of N at a rate 100 kg/ha over three years failed to generate a growth response in a short rotation woody crop plantation of tulip poplar (*Liriodendron tuliperifera*) seedlings established on a clearcut in the Tennessee Valley. Furthermore, factors such as leaf area, fine root biomass, microbial activity of the rhizosphere, and the presence of other soil nutrients affects the rate at which applied nutrients are made available for exchange in the soil and translocated by the tree (Scott et al. 2004; Phillips and Fahey 2007). Lee and Jose (2006) demonstrated that species mediated feedback mechanisms such as litter fall and nutrient uptake affect N mineralization. Phelan and Allen (2008) showed that P deficiencies reduced extractability of mineralizable N in a non-fertilized treatment in a loblolly pine plantation study. Sword et al. (1998) observed increased foliar K when N and P were added to loblolly pine plantations on low fertility soils that had been treated with herbicides. Will et al. (2006) showed that fine root uptake of N and P increased dramatically in the presence of competition, while foliage uptake was greater in fertilized and competition free plots of 13-year-old loblolly pine.

Response of Individual Species to Fertilization

Studies have shown that nutrient uptake and use vary by species (Johnson and Todd 1988; Nelson et al. 1995; Dunn et al. 1999; Jacobs et al. 2005), and that moisture levels can significantly affect uptake and use as stems mature (Albaugh et al. 2004). Although the earliest records of forest fertilization studies go back to late 1800’s (Brinkley et al. 1995), formal studies did not begin until the early 1930’s with Wyman (1936) (see Auchmoody

1982). Since then, considerably more effort and research has been expended on intensively managed pine plantation development than that of natural stands. Will et al. (2002) reported that annual fertilization of loblolly pine through age 12 increased standing volume from 163 m^3/ha in non fertilized plots to 370 m^3/ha in fertilized plots on a lower Coastal Plain site. Pines on a Piedmont site in the same study experienced a standing volume increase from 138 m^3/ha to 236 m^3/ha at age 11 due to competition control. Carlson et al. (2009) observed that nine-year-old *Pinus taeda* crown length was affected by fertilization with the highest treatment significantly increasing in length compared to the lowest treatment (6.42 m vs. 6.05 m), respectively. Additionally, fertilization significantly increased the mean dbh of the intermediate and highest fertilizer treatments (14.2 and 14.5 cm, respectively) compared to the lowest (13.6 cm). Finally, the mean diameter growth of trees in the 131 trees per ha was 15.32 cm compared to 12.95 cm in a stand of 294 trees per ha at age nine.

Fertilizer effects on natural stand productivity have not been well documented for stands younger than age 10. This is probably due to the fact that this is generally the age of canopy closure in most naturally regenerated stands, and the age at which most studies begin. In general, hardwoods demonstrate a higher nutrient demand than conifers and therefore respond vigorously to additional nutrients. Studies have shown that positive growth responses are elicited when nitrogen and phosphorous are applied alone or in combination (Acuhmoody and Smith 1977; Berenguer 2006; Schuler and Robison 2006; Phelan and Allen 2008). However, the synergisitic effect of N+P fertilization is dependent upon the exchangeable rates of soil nutrients and the species. Dunn et al. (1999) found that two year cumulative diameter growth increased substantially with the combination of N+P. However, the data also suggested that the sweetgum (*Liquidambar styraciflua*) responded more strongly to the applications of N and the oak species (Quercus spp.) to P, versus N+P. Furthermore, potassium is receiving more attention for its role in growth responses (Tripler et al. 2006). Fertilization has also been observed to increase seedling diameter, height, basal area and stand volume growth. As stated earlier, these responses depend on uptake efficiency and growth allocation, which vary by species.

Providing additional nutrients prior to planting has had mixed results. Von Althen (1976) did not observe improved survival or growth of several hardwood species in response to additions of N, P, K prior to planting in Ontario, Canada. Conversely, Jacobs et al. (2005) reported a positive growth increase in height and root collar diameter in response to the application of controlled release fertilization at planting in southern Indiana. The 60 g/seedling rate increased height and root collar diameter growth 52 and 33 %, respectively, relative to control at year 1. In the second year, height and root collar diameter growth were further stimulated 17 and 21 %, respectively, relative to the control. In their study (Jacobs et al. 2005), the responses of white ash (*Fraxinus Americana*), tulip poplar, and black walnut (*Juglans nigra*) to the treatments were similar. While several studies have shown little to no growth response in hardwoods following the application of potassium alone, or with nitrogen and phosphorus (Auchmoody 1982; Burns and Honkala 1991), interest in potassium's contribution to hardwood growth has increased. Moreover, multiple studies such as (Lea et al. 1980; Erdmann et al. 1988; Mika & Moore 1990, 1991; Vroblesky et al. 1992; Shaw et al. 1998; Yates et al. 2002; Covelo & Gallardo 2002 found in Tripler et al. 2006), have demonstrated that potassium has a significant impact on overall tree growth and tissues. Others, such as Coleman (2003) reported minimal benefits resulting from additional potassium. The comprehension of nutrient interactions and the impact of these interactions on the amelioration of nutrient deficiencies in forest stands require more study.

Stand Wide Competition Control

The use of nutrient supplementation to accelerate the process of natural thinning in very young stands is continuing to be explored. Additionally, research into the effects of the removal of competition is intensifying. Generally, competition in the understory subsides after canopy closure. The site’s quality influences the desirability of the dominant and species and how fast this process can occur. In order to enhance site quality, an understanding of how additional nutrients impact crop tree growth and the growth of competition is critically important. Impediments to the improvement of site quality and growth can be mitigated by several silvicultural techniques that mimic natural processes. One technique commonly utilized is thinning, where species diversity and improved growth of desired species are controlled through reductions of stem density at varying levels. Successful thinning regimes replicate natural self-thinning at a much faster rate and make more growth resources available to the larger stems of the stand, subsequently enhancing growth, while decreasing stand density (Smith 1986, Haywood 2005, Rentch et al. 2009, Frederick FOR 507 manual, 2009) and capturing mortality. The resulting increase in leaf area equates to more photosynthetic area which in turn stimulates stem diameter, basal area, volume, and height growth, especially as canopy-level stand density decreases.

The type of thinning and stage of stand development when it is applied is critical to the final composition of the stand. In some circumstances, a precommercial thinning can be applied before canopy closure if undesirable stems pose a significant threat to future crop tree development. However, in practice, thinning is generally performed at and after canopy closure and performed at different levels within the canopy to accomplish a specific objective. Low-thins are conducted to advance the growth of desirable stems in the midcanopy to a more dominant position. Intermediate thinning provides some monetary return and raises the likelihood of a higher yield at final harvest. Finally, crown-thins are performed to provide more resources to stems of the dominant and codominant crown class (Frederick FOR 507 manual, 2009). After the initial thinning, subsequent thins are light so that training trees remain, diameter growth is maximized, and that stocking is high enough to increase the final yield. Although work exists on these applications in naturally regenerated stands, it is still underdeveloped compared to that of pine, especially in very young stands.

Response of Individual Species to Release and Fertilization

Crop tree release is usually considered a concentrated thinning operation centered on the development of selected individuals in the stand. More resources are made available to selected stems, thus providing the key difference between this practice and thinning (Perkey et al. 1994). In a study conducted by Kockenderfer et al. (2001), three different stem injected herbicides provided 100% crop tree release of black cherry (*Prunus serotina*) and tulip poplar from American beech (*Fagus grandifolia*) and other assorted hardwoods. Cain and Barnett (2002) performed five years of release treatments and saw natural and planted pines gain 150 and 200 %, respectively, in volume growth by age 12. Despite a limited amount of literature addressing crop tree release before age 10 (Lamson and Smith 1978), several studies have shown crop tree release to produce positive growth responses in coniferous plantations and naturally regenerated stands age 10 and higher (Stoeckler and Arbogast 1947; Church 1955; Conover and Ralston 1959 as described in Lamson and Smith 1983; Sondemann 1986; Lamson and Smith 1989; Ward 2006).

Bevilacqua et al. (2005) determined that within three years after release, 68-year-old white pine (*Pinus strobus*) in three dominance classes responded with significant increases in diameter, basal area, and volume increment compared to the control. In another study (Ward 2002), 74- to 94-year-old released northern red oak (*Quercus rubra*) stems were projected to gain 2.5 cm of diameter growth for the next eleven years relative to control stems. Finally, Karlsson (2006) reported a 300% increase in released 170-year-old scots pine (*Pinus sylvestris*) diameter growth on a site in Sweden.

Trimble (1973, 1974) measured the release growth response of favorable species found on excellent and fair sites in West Virginia. He observed a significant increase in dominant and codominant 8- to 12-year-old red maple (*Acer rubrum)* diameter growth in the second study and little to no response from the tulip poplar in the earlier study.

Wendel and Lamson (1986) showed that 8- to 12-year-old artificially and naturally regenerated Appalachian hardwood stands responded positively to release five years after treatment. Diameter growth for released black cherry, red oak , and sugar maple (*Acer saccharum)* was 1.0, 0.8 and 1.8 cm greater than non-released stems, respectively. The crown class of released trees remained the same over the five years. The lack of a height response in this study was consistent with other findings.

Ward (1995) demonstrated that a precommercial release applied in seven stands aged 7- to 22-years-old of scarlet (*Quercus coccinea*) and red oak, black birch (*Betula lenta*), and red maple significantly enhanced diameter growth. In Ward's study, release greater than 75% resulted in nearly double the diameter growth relative to non-release trees. The diameter growth of each species' released trees increased over the four year treatment relative to non-release. Red oak, scarlet oak, black birch, and red maple gained 1.2, 0.9, 0.7, and 0.5 cm diameter over the non-release trees, respectively. In addition, diameter growth within each species crown class was positively correlated with the intensity of release. Although four year height growth of dominant released trees was greater than suppressed trees (1.8 vs. 0.5 m, respectively), the height growth response varied between species and crown class. Overall, codominant trees experienced the greatest diameter growth response to complete release, with an 80% increase compared to the dominants' 47% increase.

Johnson et al. (1997) recorded a growth response to release treatments between two 10-year-old tulip poplar dominated mixed species stands in southwest Virginia, seven years after treatment. Absolute diameter growth to the release treatment was 47.4% over the seven year period. The authors observed that released trees experienced suppressed height growth during the first 5 years of the study. By the end of the seventh growing season however, released trees outgrew non-released trees height (4.7 to 4.5 m, respectively). The response of the crown to release was also significant with an absolute growth responses of crown diameter of 269% and crown volume at 311%. This resulted in 53% of the live crown being maintained compared to 46% of the non-released trees. In the tropics, Guariguata (1999) demonstrated that the diameter growth of four species found in 4.5-year-old dense secondary forest in northeastern Costa Rica improved in the two years following liberation thinning.

Schuler (2006) observed a growth response to crown release for selected stems of pole sized northern red oak and black cherry in West Virginia. Northern red oak nearly doubled the amount of clear stem development compared to untreated trees after 10 years, and 70% of trees in the intermediate crown class progressed to codominate status. One year post treatment, treated black cherry and northern red oak crowns were three and four times greater than untreated crowns (317.9 vs. 97.2 m^2, and 383 vs. 80 m^2, respectively). After ten years, treated black cherry and northern red oak crowns averaged 509.1 vs. 320.3 m^2, and 536.4 m^2 vs. 207.6 m^2, respectively, compared to untreated trees. Although release improved black cherry diameter growth relative to untreated stems, a larger improvement was seen for red oak (22.1 treated vs. 17.0 cm untreated). Schuler's study demonstrated that crown release improved crown stature of northern red oak and improved crown and diameter growth of both species.

Pitt et al. (2000) performed six operational release treatments on 2- to 4-year-old jack pine (*Pinus banksiana*) plantations in Ontario, Canada. The growth responses varied between the treatments after five growing seasons. Similar to Johnson et al. (1997), diameter growth was more responsive to release than tree height. Plots receiving aerial spray (glyphosate herbicide) and annual vegetation removal gained the greatest diameter growth, followed by moderate growth in mist-blower (glyphosate herbicide), brush saw, and basal bark plots (tricoplyr herbicide), and the slowest in control. The authors did observe differences of 14 cm between heights of aerial spray and annual removal plots, and 48 cm between control and basal bark plots. Pitt et al. (2004) conducted a similar study with 2- and 3-year-old planted black spruce (*Picea mariana*) in Ontario, Canada. Diameter growth for the stands ten growing seasons post treatment, averaged 8 cm in plots receiving annual removal. This represented a 140 and 54 % gain over untreated trees for the 2- and 3-year-old sites, respectively. Trees treated with a directed foliar application of glyphosate herbicide averaged 6.2 and 6.5 cm diameter, and were 87 and 25 % larger than untreated trees at 2- and 3-years-old, respectively. On the 2-year-old site, annual removal, directed foliar (glyphosate) and brush-saw treated trees were 3.8, 3.6 and 3.2 m tall; demonstrating gains of 55, 46 and 31 % in height growth, respectively, over untreated trees. The authors observed a less pronounced yet similar response in the 3 year old plantation. Annual removal and direct foliar treatments (glyphosate) provided 476 and 112 % gains in volume growth compared to the control for 2- and 3-year-olds, respectively.

Crop tree release operations are generally influenced by factors such as--

- position of crop trees in the canopy,
- method of release and application intensity, and
- time and frequency of the operation.

Release operations can be achieved with herbicides and mechanical operations; however the most appropriate method is dependent upon management objectives, cost, species, and site (Pitt et al. 2000, 2004). In a study by Wendell and Lamson (1987), injection with glyphosphate was $0.61 cents per crop tree. Although Miller (1984) showed that the cost of chain felling was cheaper. Wendell and Lamson (1987) demonstrated that glyphosphate was more effective at controlling the resprouting, than was chain felled release. Furthermore, damage to residual trees in the stand was minimized by use of herbicide to this kind of operation. Therefore, stems remained released for a longer period with herbicides compared to chain saw. Kochenderfer (2001) found that release costs associated with stem injection were $48.55/ha, while low volume bark band herbicide treatments were $634.15/ha. The author's reported higher average release cost per tree compared to those found in other studies and attributed this to the older and larger diameter stems used in the study. While these costs do not reflect current conditions, they can provide a perspective on how treatment costs influence management decisions. Although release removes competitive stress at the crown level, the potential for below ground and understory constraints persist.

Operational Feasibility

As our population continues to grow, the challenge to keep pace and provide forest products and services will become formidable. This necessity will be complicated by increasingly stringent land use policies. Therefore, the exploration of ways to maximize growth while simultaneously minimizing costs and maintaining sustainability, are of critical importance. Research concerned with the application of silvicultural manipulations in young naturally regenerated systems must increase, so that young stands can contribute quality timber in shorter periods of time and provide a desirable composition for later rotations. In the work of Sendak and Leak (2008), the costs and rates of return of three release operations determined in a previous study by McCauley and Marquis (1972), were reevaluated at stand ages 56 and 69. Their financial analysis assumed the same market conditions as the previous study, but they found that the rates of return were substantially overestimated. However, the authors did determine that light release in 25-year-old northern hardwood stands provided 3.5% return and was the least expensive of the three operations. Furthermore, the selection of 81 crop trees per hectare was more than enough to provide a profitable harvest while minimizing initial treatment costs. The authors concluded that this long-term financial prospective would make release operations more attractive to the small landowner. However, this rate of return under current conditions is marginal at best. Siry et al. (2004) also looked at these questions of financial return, and suggested that real potential exists for silvicultural interventions in young natural hardwoods to be profitable.

Unfortunately, there is a limited amount of current literature regarding the cost of release operations and the impacts of these treatments before stands are ten-years-old. Research into early hardwood crop tree release must intensify if managers are to help landowners take full advantage of the potential benefits resulting from early-age silvicultural manipulations in naturally regenerated stands.

STUDY OBJECTIVES

The objectives of this study were to examine the response of a six-year-old naturally regenerated mixed species upland stand in North Carolina's Piedmont region following N, N+P, and N+P+K fertilization at year one, and the imposition of release treatments within the same stand at year three, on the following variables:

- species composition and stand density;
- total stand and individual species growth;
- growth of largest stems;
- growth of three merchantable species under release and non-release conditions; and
- potential feasibility of these treatments by the private landowner.

METHODS

Site Description

This study (2008-2009) is a continuation of a project installed in 2004 on the North Carolina State University Hill Demonstration Forest in Durham County, North Carolina. This area in the Piedmont region has a 194 day growing season from April through October (www.ces.ncsu.edu/depts/hort/hil/hil-709.html), mean annual temperature of 15°C (www.nc-climate.ncsu.edu/cronos/normals.php), and even distribution of an average annual precipitation of 108 cm throughout the year (www.nc-climate.ncsu.edu).

The study area is 3.63 ha with 6 to 10% slopes at a northeasterly aspect. Georgeville silt loam (clayey, kaolinitic, thermic, typic hapludults) is the predominant soil mapping unit (Kirby 1976). A loblolly pine site index of 23 m at age 50 years is achieved on these soils (unpublished local site data, pers. comm. J. Cox, NC State Forest Manager, 2007), which are characterized with low fertility and organic matter content. Prior to this study, the site supported 33-year-old planted loblolly pine (2 x 3 m spacing) that had been prescribed burned in March 1997 and January 2001. A thinning performed in 2000 reduced the basal area to about 17 m^2 per ha. Heavy damage from a severe ice storm required a salvage clearcut to this stand early in 2003. Surrounded by undamaged mixed planted pine and natural hardwoods, the 2003 clearcut was left to naturally regenerate to a mixed hardwood and loblolly pine stand. No treatments were imposed prior to 2004.

Experimental Design

The initial study was installed in 2004 and data collected through October 2005, and published by Berenguer (2006). The current study assumed those plots, data and experimental conditions, with additional treatments superimposed on the original in winter 2005-2006. Data collection unique to the current study occurred between fall 2008 and spring 2009, ending as the trees (stand) began their seventh growing season.

In 2004 four blocks (replications) of four plots each, in a randomized block design, each plot measuring 20.3 x 40.6 m were established along slope contours (Figure 1). To these plots fertilizer treatments were imposed as: 1) untreated control (Control), 2) application of nitrogen fertilizer (N fert), 3) application of nitrogen and phosphorus (N+P fert), and 4) application of nitrogen, phosphorus and potassium fertilizer (N+P+K fert). Fertilizer treatments were hand broadcast applied (two opposing directions, half the amount of fertilizer each time) in early May 2004 as the stand was beginning its second growing season. Nitrogen was applied at a rate of 200 kg N per ha ammonium nitrate (34-0-0) to all treated plots, phosphorus applied at a rate of 50 kg per ha triple super phosphate (0-46-0) to all N+P fert and N+P+K fert plots, and potassium at a rate of 100 kg per ha muriate of potash (0-0-60) to all N+P+K fert plots.

In winter 2005-2006, each of the 16 plots were divided in half (resulting in plots 20.3 x 20.3 m) and five trees each of loblolly pine (LP), tulip poplar (TP), and northern red oak (RO) were selected in each half plot (Figure 1). Selected trees were those that were dominant/codominant in canopy position, and separated by at least 3.6 m from any other selected tree or 1.8 m from plot borders. One-half of each of the divided plots, randomly assigned, did not receive further treatments; only the identification of the 15 trees (5 of each species) as described above. The other half of each plot, in which 15 trees (5 of each species) were also identified, was then subjected to “release” treatments surrounding each of the 15 trees. No additional fertilizer treatments were assigned to either half of the plots. Release treatments around each of the 15 trees were imposed by cutting at ground level with a power brush saw, all vegetation in a 1.8 m radius around the identified trees.

Measurement Plots

In spring 2004, before fertilizer treatment effects began, a single transect was delineated in each plot measuring 2 x 30 m, and located in the center of each plot and 2.65 m from plot boundaries (Figure 1). In October 2005, after two growing seasons of fertilizer effects, two transects were delineated in each plot measuring 2 x 30 m located equidistant from plot boundaries and each other (Figure 1). After the plots were divided, and trees released on half, in the non-released half of each plot, in Fall 2008, 5 years after fertilizer treatment effects began, two transects were delineated in each plot measuring 2 x 15 m, located equidistant from each other, and 2.65 m from plot boundaries (Figure 2).

In each of these transects, data was collected on every stem greater than 60 cm tall, as follows: 1) species, 2) stem origin -- seed or sprout determined by visual estimation (recognizing the difficulty of discriminating between seedling, seedling sprout and root sucker regeneration), 3) total height (±1cm), 4) groundline diameter (GLD) (±1mm) in 2005 and 2008, and 4) diameter at breast height (DBH) (±1mm) in 2008 for stems having surpassed that height. For all individually identified trees of LP, TP, and RO, in the released area of each original plot (15 trees) and in the non-released plot halves (15 trees), total stem height (±1cm) and DBH (±1mm) were recorded in winter 2005/2006 and again in winter 2008/2009. In winter 2008/2009 the trees were 6-years-old, 5 years following fertilizer treatments, and 3 years after release treatments. The formula V_i=DBH^2 x Height was used to calculate a volume index (V_i) for all trees. This formula is a generalized approach for estimating volume for non-merchantable stems of species with differing taper characteristics at very young ages.

Inventory data were categorized into the following components: deciduous hardwoods or loblolly pine, stem origin, and by individual species. The 16 largest trees regardless of species per combined inventory plot were used to assess the overall dominant tree response to the treatments in non-released conditions. The response of the five most prevalent species to the non-released treatments was assessed with the 10 largest trees (all taller than species mean height) per combined inventory transects. Failure of a species to provide 10 stems above mean height resulted in using the next available tallest stems greater than 80 cm. The five most prevalent species were hickory (*Carya* spp.), loblolly pine, red maple, sweetgum, and tulip poplar. Stem data were also segregated into five categories according to height: 70-200 cm, 201-331 cm, 332-462 cm, 463-593 cm and >594 cm.

Statistical Analysis

Data from the two transects per plot from the winter 2008/2009 inventory were combined to represent a single sample plot. The analyses included block effects and treatment main effects. The GLM procedure of SAS/STAT software (SAS Institute Inc. 2011) was used for analysis of data for individual species. Treatment responses for mean DBH, height and volume index were assessed using this procedure. The following linear model was used to obtain F tests for each species.

$y_{ij} = \mu + \beta 1D + B_i + F_j + e_{ij}$

where y_{ij} is the observation of j-th treatment in the i-th block, μ is the intercept, Bi is the i-th block effect (i=1,..4), Fj is the j-th fertilization effect (j=1,...,4), e_{ij} is the error with the expectations ~NID (0, σ^2_e). Treatment means were compared using multiple range tests. Tukey's adjusted multiple range test was used with an alpha of 0.10 to separate treatment differences when ANOVA results indicated significant treatment effects at P-values ≤0.15.

An ANOVA was also performed to analyze treatment differences for the trees under release treatments. The analyses included block effects, treatment main effects, and interactive effects (block x treatment, release x treatment). A Proc Mixed model (SAS Institute Inc. 2011) was used for analysis due to the unbalanced data on the per species level. Treatment responses for mean DBH growth, DBH, height growth, height, volume index and volume index growth were assessed using this procedure. A multiple comparisons analysis via Tukey's procedure with an alpha of 0.10 was used to separate treatment differences when ANOVA results indicated significant treatment effects at P-values ≤0.15.

Significance testing in the ANOVA at the probability level of 0.15 was used as this level is more relevant given the amount of environmental variation found in a study and site like this. Variation in the current study includes significant slope and microsite changes, mixed species with composition influenced by site conditions within the study, and the variety of stem origins from seed to seedling of unknown ages, to seedlings, stem sprouts and stump root sprouts. Quinn and Keough (2002) discuss the need for rationale selection of significance levels and hence the selection of $P \leq 0.15$ in the current study, as used in other related studies (Berenguer 2006; Schuler and Robison 2010). For all of the scenarios in the current study (Tables 1-10) the actual calculated P-values are reported so that the reader can assess values directly. Tree size measurements prior to 2008-2009 were tested as covariates in the analyses and when covariate values had $P \geq 0.10$, the analysis was run again without the covariate included.

RESULTS

Total Stand - Stem Density and Species Composition

At the stand level, mean stem density in Control plots was 86% greater than that of N plots. Stem densities in N+P and N+P+K plots were not significantly different from any other plots (Table 1). Stems were categorized as deciduous hardwood of sprout or seed origin, and loblolly pine. The percent representation of stems for each of these groupings was not statistically different for any fertilizer treatment. However, the data suggests that most stems were of seed origin. Stems were further categorized by the five most common species: loblolly pine, hickory, red maple, sweetgum and tulip poplar. The percent representation of hickory stems in Control plots was significantly and 58% greater than in N+P+K plots. Tulip poplar exhibited a significant treatment response at P=0.06, however Tukey's HSD could not separate the treatment means (Table 1).

Total Stand - Groundline Diameter (GLD)

The treatment effect of fertilizer on GLD for all species combined and for hardwoods was statistically significant at P=0.09. However, at P=0.10, mean separation procedure with Tukey's HSD did not reveal differences for either category. Although the treatment effect of fertilizer on the GLD of sprout origin stems was not statistically significant, the data suggests that fertilization increases size. The treatment response of fertilizer on seed origin stem GLD was marginally significant at P=0.14, but the mean separations procedure with Tukey's HSD could not separate treatment means (Table 2). Individual species response varied by treatment (Table 2). Compared to the Control (3.8 cm), hickory mean GLD in N+P plots (3.1 cm) was not significantly different. Hickory mean GLD was significantly and 52% greater in the Control plots than in the N+P+K treatment plots (3.8 vs. 2.5 cm), and significantly and 40% greater in the N plots than in N+P+K plots (3.5 vs. 2.5 cm). Control, N and N+P plot GLD for hickory were statistically the same. Red maple, tulip poplar, sweetgum and loblolly pine GLD did not differ among treatments.

Total Stand - Diameter at Breast Height (DBH)

Mean DBH for all species combined was significantly and 41 and 35 % greater in N and N+P treatments than Control plots (2.4 vs. 1.7 cm) and (2.3 vs. 1.7 cm), respectively (Table 2). The mean DBH for all hardwood stems in N and N+P treatments were significantly and 35 and 41 % greater than in Control plots (2.3 vs. 1.7 cm) and (2.4 vs. 1.7 cm), respectively. Although the treatment effect of fertilizer on the DBH of sprout origin stems was not statistically significant, the data does suggest that fertilization can increase size. The treatment response of fertilizer on seed origin stem DBH was statistically significant at P=0.08, but mean separations procedure with Tukey's HSD could not separate treatment means. Again, the data suggests that fertilization can increase size. Hickory DBH in N+P+K plots was significantly and 57% smaller than in Control plots. No significant treatment differences for DBH were observed for loblolly pine, red maple, sweetgum or tulip poplar (Table 2).

Total Stand – Height

The mean heights for all stems in N+P and N+P+K plots were significantly and 28 and 30 % taller than in Control plots (377.7 vs. 294.9 cm) and (382.2 cm vs. 294.9 cm), respectively (Table 2). The height of stems in N treated plots was greater than in Control plots, but was not statistically different from any fertilizer treatment (Table 2). Deciduous hardwoods experienced a 28 and 29 % size increase in N+P and N+P+K plots and were significantly taller than in the Control plots (378.7 vs. 295.4 cm) and (382.2 vs. 295.4 cm), respectively. Although the treatment effect of fertilizer on the height of sprout origin stems was not statistically significant, the data suggests that fertilization can improve size. The height of seed origin stems in N+P and N+P+K treatment plots were significantly and 28 and 30 % taller than stems in Control plots (376.1 vs. 294.0 cm) and (383.3 cm vs. 294.0 cm), respectively. The treatment effect of fertilizer on the height of loblolly pine stems was not statistically significant however the data suggests that fertilization can improve size. Sweetgum heights in N and N+P plots were significantly and 39 and 30 % taller (422.3 vs. 303.4 cm) and (395.5 cm vs. 303.4 cm), respectively; than in Control plots. Sweetgum mean height in the N+P+K treatment was not significantly different from the other treatments. The mean height responses for hickory, red maple, and tulip poplar were statistically the same and not significantly different among treatment (Table 2).

Total Stand - Volume Index

For all stems in the N+P+K plots, the mean volume index was significantly and 133% greater than in Control plots (4141.2 vs. 1771.8 cm^3); while volume index in the Control, N and N+P plots were statistically the same (Table 2). Volume index for hardwood stems was significantly and 132% greater in N+P+K plots than in Control plots (4141.2 vs. 1779.0 cm^3) (Table 2). Hardwood mean volume index in the Control, N and N+P plots were statistically the same but the data suggests that these treatments can substantially increase volume index relative to the Control. Volume index for sprout origin stems was not statistically different for any treatment, but the data does suggest that fertilizer treatments can increase volume index with respect to the Control. Seed origin volume index in the N+P+K plots was significantly and 141% greater than in the Control plots (4172.9 vs. 1732.9 cm^3). Hickory mean volume index in N plots was significantly and 258 and 338 % greater than in N+P and N+P+K plots (3057.3 vs. 853.4 cm^3) and (3057.3 vs. 697.8 cm^3) respectively; while Control plots were statistically the same as N, N+P, and N+P+K plots. Each set of loblolly pine, red maple, sweet gum, and tulip poplar values were statistically the same for each treatment and not significant, but the data suggests that volume index can benefit from fertilizer treatments (Table 2).

Total Stand - Stems by Height Class

Stems were segregated into five categories based on height. Fertilizer treatment had a significant treatment effect on the number of stems in each height class (Table 3). Approximately 16% of the stems in the Control plots were in the 70-200 cm height class and this was significantly and 54, 207, and 110 % greater than the percentage of similar stems in the N, N+P, and N+P+K plots (16.6 vs.10.8 %, 16.6 vs.5.4 %, and 16.6 vs. 7.9 %), respectively. Approximately 11% of the stems in N plots in 70-200 cm height class were significantly and 100 and 37 % greater than the percentage of stems in N+P and N+P+K plots (16.6 vs.5.4 %) and (16.6 vs. 7.9 %). Fifty percent of the stems in the 201-331 cm height class were in Control plots and were significantly and 62, 45, and 43 % more than the percentage of stems in N, N+P, and N+P+K plots (50.6 vs.31.3 %, 50.6 vs. 35 %, and 50.6 vs. 35.4 %), respectively. Also in the 201-331 cm height class, the percentage of stems in N+P and N+P+K plots were significantly and 12 and 13 % greater than those in N plots (35 vs. 31.3 % and 35.4 vs. 31.3 %), respectively.

In the 332-462 cm height class, approximately 31% of stems were in N plots and significantly and 12 and 0.3 % greater than the percentage of similar stems in Control and N+P+K plots (30.6 vs. 26.8 %) and (30.6 vs. 29.9 %), respectively; while the percentage of stems in that height class in N+P plots was significantly and 5% greater than the percentage of those stems in N plots (31.6 vs. 30.6 %). In the 463-593 cm height class, 20.6, 22.7, and 18.3 % of stems were in N, N+ P and N+ P + K plots and were significantly and 275, 313, and 233 % greater than the percentage of similar stems in the Control (20.6 vs. 5.5 %, 22.7 vs. 5.5 %, and 18.3 vs. 5.5 %), respectively. Twenty-two-point-seven (22.7) percent of stems in N+P plots in the 463-593 cm height class were significantly and 10% greater than the percentage of similar stems in N plots (22.7 vs. 20.6 %), while N plots yielded a significantly and 13% greater percentage of stems than in N+P+K plots (20.6 vs. 18.3 %)

For stems greater than 594 cm, the percentage of stems in N, N+P, and N+P+K plots were significantly and 1360, 960, and 1620 % greater than the percentage of similar stems found in Control plots (7.3 vs. 0.5 %, 5.3 vs. 0.5 %, and 8.6 vs. 0.5 %), respectively.

Dominant Trees

The 16 largest trees per plot, by treatment, regardless of species, gained greater diameter size in N+P and N+P+K plots, than in Control plots (Table 4). Diameter size in N+P and N+P+K plots were significantly and 18 and 23 % greater than in Control plots (4.5 vs. 3.8 cm, and 4.7 vs. 3.8 cm), respectively, while N plots were statistically the same as Control, N+P and N+P+K plots (Table 4). The mean height of 16 largest stems in N+P+K plots were significantly and 15, 6 and 7 % greater than in Control, N and N+P plots (595.5 vs. 516.6 cm, 595.5 vs. 563.4 cm, and 595.5 vs. 566.8 cm), respectively. Also, the mean height of stems in N and N+P plots were significantly and 9 and 7 % greater than in Control plots (563.4 vs. 516.6 cm, and 566.8 vs. 516.6 cm), respectively. Volume index of the 16 largest trees in N, N+P and N+P+K plots was significantly and 52, 64 and 90 % greater than in Control plots (12281.7 vs. 8057.7 cm^3, 13215.7 vs. 8057.7 cm^3, and 15294.5 vs. 8057.7 cm^3), respectively. The fertilizer treatments did not significantly affect GLD (P= 0.33) for the 16 largest trees (Table 4).

The mean GLD for the ten largest loblolly pine stems in N+P+K plots was significantly and 20, 33 and 31 % greater than in Control, N and N+P plots (7.2 cm vs. 6.0 cm, 7.2 cm vs. 5.4 cm, and 7.2 cm vs. 5.5 cm), respectively. Loblolly pine mean DBH in N+P plots was significantly and 29% greater than in N plots (4.5 cm vs. 3.5 cm) respectively;

while pine DBH in the Control, N and N+P+K plots were statistically the same. The mean height in N+P+K plots was significantly and 13, 22 and 18 % greater than in Control, N and N+P plots (486.1 cm vs. 431.4 cm, 486.1 cm vs. 397.9 cm, and 486.1 cm vs. 411.4 cm), respectively; while the Control, N and N+P plots were statistically the same. Loblolly pine volume index in N+P plots was significantly and 83% greater than in N plots (11263.9 cm^3 vs. 6166.9 cm^3), respectively; while the Control, N and N+P+K plots were statistically the same. The mean GLD for the ten largest hickory stems in the N, N+P and N+P+K plots was significantly and 32, 55 and 67% smaller than in Control plots (4.5 cm vs. 3.4 cm, 4.5 cm vs. 2.9 cm, and 4.5 cm vs. 2.7 cm), respectively. The DBH of hickory stems in the N, N+P and N+P+K plots were significantly and 33, 60 and 60 % smaller than in Control plots (2.4 cm vs. 1.8 cm, 2.4 cm vs. 1.5 cm, and 2.4 cm vs. 1.5 cm), respectively. Accordingly, the mean volume index of the largest hickories in N, N+P and N+P+K plots were significantly and 121, 294 and 289 % smaller than in Control plots (3038.6 cm^3 vs. 1375.6 cm^3, 3038.6 cm^3 vs. 770.9 cm^3, and 3038.6 cm^3 vs. 782.1 cm^3), respectively (Table 4). The mean GLD of red maple stems in the N, N+P and N+P+K plots were significantly and 112, 112 and 94 % greater than in the Control plots (3.4 cm vs. 1.6 cm,3.4 cm vs. 1.6 cm, and 3.1 cm vs. 1.6 cm), respectively; while the N, N+P and N+P+K plots were statistically the same (Table 4). Red maple DBH in N, N+P and N+P+K plots was significantly and 120, 130 and 100 % greater than in Control plots (2.3 cm vs. 1.0 cm, 2.2 cm vs. 1.0 cm, and 2.0 cm vs. 1.0 cm, respectively), while the N, N+P and N+P+K plots were statistically the same. Similarly, the volume index of red maple in N, N+P and N+P+K plots were significantly and 95, 82 and 68 % greater than in Control plots 2967.4 vs. 31 cm^3, 2676.0 vs. 31 cm^3, and 2147.4 vs. 31 cm^3), respectively; while the N, N+P and N+P+K plots were statistically the same. For sweetgum, the mean stem heights of N, N+P and N+P+K plots were significantly and 231, 262 and 234 % greater than in Control plots (485.6 vs. 146.8 cm), (530.9 vs. 146.8 cm) and (490.3 vs. 146.8 cm), respectively. The treatment effect of fertilizer on any growth variable for the ten largest tulip poplars was not significant (Table 4).

Release Treatments by Species - DBH

Loblolly pine mean DBH under release conditions was significantly different from non-release conditions for each fertilizer treatment (Table 5). Mean DBH of stems in release Control plots was significantly and 34% greater than stems in non-release Control plots (6.7 cm vs. 5.0 cm). The mean pine DBH of stems in N release plots was significantly and 58 % greater than stems in non-release N plots (7.4 cm vs. 4.7 cm). For N+P release plots the mean DBH of pine was significantly and 36% larger than in N+P non-release plots (6.0 vs. 4.4 cm). In N+P+K treated plots the mean pine DBH of release plots was significantly and 48% larger than in non-release plots (6.7 vs. 4.5 cm). The mean DBH of tulip poplar stems in the Control release plots was significantly and 16% larger than the mean of Control non-release plots stems (6.5 vs. 5.6 cm). The mean tulip poplar DBH in N release plots was significantly and 28% greater than in non-release plots (7.0 cm vs. 5.5 cm). Tulip poplar diameter means in the N+P treatment under release and non-release conditions were statistically the same. In the N+P+K treatment, the mean tulip poplar DBH in release plots was significantly and 36% larger than that of the non-release plots (7.3 cm vs. 5.4 cm) (Table 6). The mean red oak DBH in Control release plots was significantly and 19% greater than in Control non-release plots (3.6 cm vs. 3.1 cm). No statistically significant differences existed between the release and non-release means for any fertilizer treatment (Table 7).

Release Treatments by Species - Height

The mean height of loblolly pine stems under release conditions in N+P and N+P+K plots were significantly and 12 and 15 % greater than in non-release N+P and N+P+K plots (495.1 cm vs. 442.0 cm, and 525.2 cm vs. 457.6 cm), respectively, while means from the other treatments were statistically the same (Table 5). The mean height of tulip poplar stems in N, N+P, and N+P+K release plots were significantly and 8.9, 14, and 9 % greater than in non-release N, N+P, and N+P+K plots (708. 0 cm vs. 650.3 cm, 655.0 cm vs. 573.3 cm, and 716.6 cm vs. 659.7 cm), respectively, while the means for release and non-release conditions in the Control treatment were not statistically different from each other (Table 6). No statistically significant differences existed between release and non-release means per treatment for northern red oak (Table 7).

Release Treatments by Specie - Volume Index

Loblolly pine mean volume index under release conditions was significantly different from non-release conditions for each fertilizer treatment (Table 5). Mean pine volume index of stems in release Control plots was significantly and 64% greater than stems in non-release Control plots (26586.0 cm^3 vs. 16183.0 cm^3). The mean pine volume index of stems in N release plots was significantly and 146 % greater than stems in non-release N plots (30037.0 cm^3 vs. 12196.0 cm^3). For N+P release plots the mean volume index of pine was significantly and 61% larger than in N+P non-release plots (20956.0 cm^3 vs. 12985.0 cm^3). In N+P+K treated plots the mean pine volume index in release plots was significantly and 176% larger than in non-release plots (27061.0 cm^3 vs. 9823.8 cm^3) (Table 5). For tulip poplar, volume index means in N and N+P+K release plots were significantly and 83 and 95 % greater than in N and N+P+K non-release plots (46989.0 cm^3 vs. 25663.0 cm^3, and 48336.0 cm^3 vs.

24750.0 cm^3), respectively; while the other treatment means were statistically the same (Table 6.) Release and non-release means per treatment were statistically the same for northern red oak (Table 7).

Release Treatments by Species - DBH Growth

Three years after release treatments, loblolly pine diameter growth means in release conditions were greater and significantly different from non-release means for N, N+P, and N+P+K treatments. The mean pine DBH growth in N release plots was 59% greater than in non-release plots (5.9 cm vs. 3.7 cm). Pines in N+P release treated plots grew 49% more than pines in non-release plots (4.7 cm vs. 3.2 cm). Pines in N+P+K release plots gained 59% more growth than in non-release plots (5.7 cm vs. 3.6 cm). Release and non-release means in the Control treatment were statistically the same for pine DBH growth (Table 8).

The mean DBH growth in N release plots was 54% greater than in N non-release plots for TP (4.6 cm vs. 3.0 cm), and in N+P plots trees in release plots were 58% greater than in non-release plots (4.6 cm vs. 2.9 cm) (Table 9). TP stems in N+P+K release plots had 61% more growth than TP stems in non-release plots (5.3 cm vs. 3.3 cm). Release and non-release means in the Control treatment were statistically the same for tulip poplar DBH growth (Table 9).

Northern red oak mean DBH growth in Control release plots was significantly and 45% greater than in Control non-release plots (2.2 cm vs. 1.5 cm). Oaks in N release plots grew 31% more than in N non-release plots (2.6 cm vs. 2.0 cm), while comparisons of release condition means for the remaining treatments were not statistically significant (Table 10).

Release Treatments by Species - Height Growth

For loblolly pine, the Control, N+P and N+P+K treatments yielded statistically significant differences between release and non-release tree height means. The mean pine height growth in Control release plots was 13% greater than in Control non-release plots (336.0 cm vs. 297.5 cm) (Table 8). Pine stems in N+P released plots grew 20% faster in height than stems in non-released plots (303.4 cm vs. 253.2 cm) and stems in N+P+K released plots gained 19% more growth than stems in non-release plots (335.2 cm vs. 280.8 cm). There were no statistically significant differences among the release means of each treatment or the non-release means of each treatment (Table 8).

For tulip poplar, the N and N+P+K treatments were the only treatments that yielded differences in height between release and non-release conditions that were significantly different (Table 9). TP stems in N released plots acquired 32% more height growth than stems in non-released plots (263.4 cm vs. 199.5 cm), and stems in N+P+K released plots gained 29% more growth than stems in non-release plots (282.7 cm vs. 219.2 cm).

For northern red oak, the mean height growth in N+P non-release plots was significantly and 28% greater than that in release plots (236.0 cm vs. 170.5 cm), while the remaining treatments did not have statistically significant differences in height growth between release and non-release conditions for RO (Table 10).

Release Treatments by Species - Volume Index Growth

Loblolly pine volume index growth means in release conditions were greater and significantly different from non-release means for every treatment except the N+P treatment. LP mean volume index growth in Control release plots was 113% more than in non-release plots (27160.0 cm^3 vs.12760.0 cm^3). Pines in N release plots grew 92% more than in non-release plots (25573.0 cm^3 vs. 13285.0 cm^3). In N+P+K plots, pine stems in release conditions experienced 132% more volume growth than in non-release conditions (29889.0 cm^3 vs. 12908.0 cm^3) (Table 8).

Tulip poplar volume index growth significantly increased by 108% in N release plots compared to N non-release plots (41825.0 cm^3 vs. 20054.0 cm^3). Tulip poplar in N+P and N+P+K release plots gained 86 and 94 % more volume index than in N+P and N+P+K non-release plots (40230.0 cm^3 vs. 21587.0 cm^3, and 53802.0 cm^3 vs. 27760.0 cm^3), respectively. The mean comparisons for volume index growth in release and non-release conditions in the Control treatment were the same statistically (Table 9) and RO volume index growth means in release conditions were statistically the same as non-release means for every treatment (Table 10).

DISCUSSION

Nutritional amendments that ameliorate site deficiencies can accelerate the growth and development of forest stands, however the needs of specific species can differ, and therefore the most effective treatment for one species may not produce the same kind of response in another. Control of competition can further advance the growth of released (typically merchantable) species within the stand, sometimes especially when combined with fertilizer treatments. However, the effectiveness of this silvicultural combination depends on species composition, tree density and site characteristics. The results of this study support these ideas, as reported in the literature (for example, Schuler 2005; Schuler and Robison 2006; Berenguer 2006;), and suggest that fertilizer amendments and competition control are silvicultural techniques that have the potential to accelerate the development and growth of both the stand and merchantable crop species in young mixed-species naturally regenerated stands in the Piedmont.

The total density of stems in the Control treatment was nearly double that of the fertilized treatments after 6 years. Also, the variability associated with stem density means in each fertilized plot was small in comparison to the Control (Table 1). This suggests that fertilizer treatments exerted a significant impact on stem density by promoting self-thinning and stand uniformity. Schuler (2006) and Berenguer (2006) also noted a similar fertilizer effect for this particular forest. In the current study, the greatest rate of mortality occurred in smaller stems, those between 2 and 3 m tall (Table 4). This is further evidence that fertilizer treatments accelerated the shift of vertical structure within the stand by eliminating smaller stems and increasing resources for the larger stems (e.g., Spurr and Barnes 1980).

While the means were not statistically different, hardwood representation increased in response to fertilization with respect to the Control. An inverse relationship observed between hardwood density and loblolly pine density suggests that hardwoods became more competitive as the site's fertility increased. Berenguer (2006) observed a similar response on the same site. This apparent fertilizer effect can serve as a valuable silvicultural manipulation to encourage the development of a stand, on sites like the one in the current study, so that certain species, in this case hardwoods, comprising a more substantial portion of the canopy as the stand develops, than it otherwise would have. This assumes that hardwoods would be preferred over pines. If the converse were true, than fertilization alone would be problematic. If hardwoods were preferred, or at least certain hardwood species, then if they could be specifically encouraged the value of such silvicultural interventions would be greater still. There is however concern that improvement in site quality, even while promoting hardwood growth, could preferentially encourage the growth of lower value faster growing species such as sweetgum, for example, at the expense of more valuable oaks (Morrisey et al. 2008). Thus stand-wide responses to nutrient amendments need to be examined thoroughly.

Approximately 9.8, 14.1 and 14.7 % of the overall stand density on this site was represented by sweetgum, tulip poplar and red maple after 6 growing seasons, on average across all treatments. How these species became prominent is a reflection of stand and site history, such as thinning, fire, previous stand seed source and fertilization regimes. For example, the work of Van Lear and Waldrop (1989) and Shearin et al. (1972) demonstrated that tulip poplar's highly viable and abundant seedlings respond with vigorous germination after disturbance by fire. On the site of the current study, prescribed burns were administered in 1997 and 2001 prior to the salvage clearcut in 2003, and this disturbance history, coupled with the fertilization treatments later imposed may have had a significant bearing on the prevalence of this species on this site.

Red maple responds with vigorous seed production and seedling growth in the presence of fertilizer, responds to large scale disturbances with increased seed germination success (Burns and Honkala 1991), and with adequate soil moisture red maple seedlings can take advantage of additional nutrients and gain a competitive edge (Pham et al. 1978). The density and distribution of red maple in the current study was very likely influenced by stand history and the application of fertilizer. Finally, sweetgum regeneration usually results from the release of suppressed buds on roots as a result of some type of site disturbance (Burns and Honkala 1991), as is the case with the history of the current stand.

Fertilization positively impacted cumulative mean DBH, height and volume index, on a total stand basis. Treatment effects on GLD were significant at P=.09, however the Tukey's HSD procedure could not separate the means (Table 2). Treatment with N and N+P significantly increased DBH by 41 and 35 % over diameter size in the Control. The N+P+K treatment mean was statistically the same as the Control although it was greater than the Control. The addition of phosphorous and potassium significantly increased height about 29% more than the Control stems. Stems may have had a minutely positive response to the addition of K considering the mean responses of N+P+K treated plots, in comparison to N+P alone (Table 2). Lastly, nitrogen alone provided a substantial boost but was statistically the same as the Control and the other treatments. The volume index mean in N+P+K plots was significantly greater than the Control and reflected the diameter and height used in its calculation. This is of some interest due to the literature reporting a lack of response to additional K on these kinds of sites (Phares 1971, Lamson1978, Auchmoody 1982, Berenguer 2006 Burns and Honkala 1991). These results indicate that fertilizer amendments, applied at sufficient rates, containing N, P and K can enhance the overall growth of the stand. Similar conclusions were made by Berenguer (2006) on this same stand at age three.

The process of accelerated self-thinning was evident by the influence of fertilizer treatments on the representation of stems in different height classes (Table 3). Stems between 2 and 3.3 meters tall were common in control plots, but were significantly less common in each fertilized plot, by about 33%. Furthermore, about 31% more of stems 3.3 to 4.6 m were found in fertilized plots compared to about 27% in the Control plots. For stems 4.6 to 6 m tall, about 21% percent were found in fertilized compared to about 6% in the Control plots. And for stems taller than 6 m in the fertilizer plots they represented about 7% of all stems, while in Control plots they were less than 1% of stems. The fertilizer effect was highly significant for each height class. The data show that the percentage of taller stems increased in fertilized relative to Control plots. These findings demonstrate that stand development can be accelerated through nutrient supplementation, and corroborate the findings of Berenguer (2006) and Schuler and Robison (2006).

The response of deciduous hardwoods to fertilization closely resembled the response observed for all species on this study site with respect to size attributes (Table 2). The diameter response of all species and hardwoods in N and N+P treated plots were significantly greater than in Control plots, by 41 and 21 %, respectively. The diameter means in N+P+K plots were statistically the same as the other treatments. Similarly, N+P and N+P+K treated plots increased the mean height for all species over Control plots to the same degree as observed for the mean height of just hardwoods. Volume index means for fertilized plots were substantially greater than in Control plots. Treatment effects on GLD were significant at P=.09, however the Tukey's HSD procedure could not separate the means. Despite the disturbance history of the site, the positive response for stems of all species and hardwoods to fertilizer treatments suggests that the soil's capacity for nutrient exchange experienced minimal degradation (Carter et al. 2006).

The GLD, DBH, height and volume index for tulip poplar and red maple was increased by fertilizer treatments. Despite treatment means failing to be significantly different from each other, the data suggests that fertilization enhanced growth (Table 2). Tulip poplar GLD and DBH in N treated plots demonstrated a substantially positive size increase despite the treatments being the same statistically. Sweetgum GLD, DBH and volume index increased with fertilizer treatments but they behaved similar to red maple and tulip poplar statistically. However, the height increase in N and N+P treated plots was significantly and 35% greater than Control plots. Although the addition of P and K appeared to increase the size, the application of nitrogen alone resulted in nearly double the percent increase of N+P and N+P+K combined. A similar response was observed in the work of Nelson et al. (1995), and the positive response suggested that these young stems were nitrogen deficient (Scott et al. 2004). The hickory mean GLD and DBH in Control plots was larger than in fertilized plots, and was significantly greater than N+P+K treated stems for both attributes. The relatively low density of this species across treatments may be the result of its inability to compete for resources being utilized more effectively by stems of other species (Table 1). This could possibly explain why the size of hickory in fertilizer treatments was suppressed, while in Control plots it increased (Table 2).

Stem origin was based on visual determination in the field. Stems were classified as seedling, seedling sprout or root sucker origin and stump sprout. The most accurate determination was attempted given the obscurities present in the field, but the data reveal trends that are not explained (Tables 1 and 2).

Mean GLD, DBH and volume index for loblolly pine responded to fertilizer treatments in a similar fashion to that of red maple and tulip poplar. Fertilizer treatments produced considerable gains in size, but treatment means were statistically the same. The height of stems in N+P+K treated plots increased 30% over the Control, although the means were not significantly different.

Fertilizer amendments had a positive impact on the DBH, height and volume index of the 16 largest trees per plot, regardless of species. Fertilization with N had a positive effect on diameter size but was statistically the same as the other treatments, while N+P and

N+P+K were significantly greater than the Control. It is possible that the addition of P, and perhaps K, better alleviated limiting nutrient factors than N alone, and thus contributed to this positive growth response (Table 4), as has been commonly found in pine planted on similar sites (need reference). Similarly, mean height of the largest stems regardless of species in the three fertilizer treatments were significantly greater than the Control, and height in N and N+P plots were significantly different from N+P+K plots. It is possible that the tulip poplar and pine stems that responded to additional K (Tables 2 and 3), both of which had representation in the 16 largest stems, were responsible for this difference among the fertilizer treatments.

Fertilizer treatments significantly affected size attributes specifically for loblolly pine, hickory and red maple (Table 4). For loblolly pine, the mean GLD and height in N+P+K plots was significantly greater than the other treatments (Table 4). Fertilizer treatments also had a significant effect on red maple. While the fertilizer treatment means were statistically similar to each other, each was significantly greater than the Control. It has been reported that red maple responds vigorously to fertilization (Pham et al. 1978) and the data in the current study supports this. The ten largest hickory stems did not appear to respond positively to fertilizer treatments (Table 4). Hickory GLD and DBH size in fertilized plots was significantly less than in the Control. The diminished size observed for fertilized plots further demonstrated its inability to compete as resources increased the size of other species (Table 4). With the exception of hickory, the increases associated with fertilizer addition indicate that larger trees can be grown at a faster rate than without nutrientre additions.

The effect of release was highly significant for the total diameter size and growth of loblolly pine and tulip poplar. The data demonstrated that release resulted in loblolly pine size increases ranging from 34 to 58 %, and growth increases ranging from 49 to 59 %, when release conditions were compared for each fertilizer treatment. Similarly, tulip poplar benefited from release with gains in DBH and DBH growth ranging from 16 to 36 %, and 58 to 61 %, across the fertilizer treatments. Lamson and Smith (1983) saw a 59% increase in the three year diameter growth of 10-year-old released tulip poplar crop trees. In the current study, greater tulip poplar growth was captured at age 6 suggesting that early release can drastically raise response potential. It is unknown how long this diameter response will persist, but Della-Bianca (1975) found that the response lasted about six years in an eleven-year-old mixed-species hardwood stand.

Overall, northern red oak demonstrated a marginal response to release on a per treatment basis when mean DBH and diameter growth was considered. The mean total diameter of release stems in the Control was 16% larger than in the non-release plots. In the N and N+P treatments, the release DBH means were greater but not significantly different from those in the non-release plots. A similar condition was found for RO diameter growth, but Control and N release plots had 47 and 30 % more growth than in the non-release treatments. These percentage differences are less than half of the five year average diameter response observed by Lamson and Smith (1978) for 9-year-old codominant oaks, but the means at age 6 in the current study are 1.0 to 1.7 cm greater than the 9-year-old means they reported, suggesting that an even greater response is possible as the stand matures.

Neither fertilization or the release by fertilization interaction were statistically significant for loblolly pine (Table 5), but the data suggests some influence of fertilization on total diameter response, with N supplemented stems achieving 7.4 cm in diameter three seasons after release treatments, versus 7.4 cm DBH in the Control plots. Cain and Barnett

(2002) found that the combination of release and herbaceous control during the first five years of a twelve year study resulted in natural pine mean DBH of 13.2 cm, as compared to 8.6 cm without these treatments. The magnitude of response in the current study, after three years of growth in release conditions, suggests that these young stems may be utilizing the additional nutrients and that merchantable size has the potential to be achieved earlier in the rotation with continued herbaceous control. In the current study, tulip poplar mean diameter in the N and N+P+K treatments were the largest of the treatment means for total size and growth, although fertilization was not statistically significant. Johnson et al. (1998) found that 10-year-old tulip poplar stems in their study did not respond to favorable growing conditions or exhibit a fertilizer response after seven years. However, the data in the current study suggests that young released stems could have experienced some benefit from the additional nutrients, and a significant response could occur. Stems in the N+P+K treatment obtained the greatest size and had the most growth after three growing seasons. The addition of potassium in the N+P+K plots may have promoted growth through mechanisms related to K-mediated water uptake (May 1985; Uchida 2000) or preserved leaf functionality during periods of frost (Burns and Honkala 1991).

Statistically, release had a significant influence on growth/size, but the students t-test per fertilizer treatment showed that means in release and non-release conditions were not significantly different for northern red oak. Furthermore, the N+P+K treatment appeared to negatively impact size (Table 7). It is possible that the added potassium caused a reduction in the availability of magnesium or other nutrients and this adversely impacted growth (Lea et al. 1980; Sun & Payn 1999 see Tripler et al. 2006), or the addition of K enhanced the growth and competition from other plants, such as *Rubus* sp. The Control treatment contained the only statistically significantly comparison between the release means for RO. The lack of response in the remaining fertilizer treatments could be the result of not enough time elapsing in the release treatment, or improved competitiveness of non-release stems as a result of fertilization, or insufficient N, P and/or K to alleviate a nutritional deficiency for this species. The oaks had the least amount of diameter growth of the three species included in the release study. This relative lack of response was similar to the findings of Lamson and Smith (1978) and Wendell and Lamson (1987).

The ANOVA for both pine and tulip poplar total height indicated that the release effect was highly significant for these species. However, there was a marginal percentage difference observed between the release and non-release condition means per treatment for both species. Robison et al. (2004) performed a similar study with similar species and concluded that the relaxation in above ground competition for sunlight may have reduced the rate of height growth necessary to maintain canopy dominance. Johnson et al. (1997) observed a reduction in released tulip poplar height for the first five years and then a reversal in the seventh year of their study, following thinning, when height growth began to accelerate. It is possible in the current study that a greater difference in height would have been observed between the release and non-release conditions, by fertilizer treatment, if below-ground competition had also been controlled. Pine and tulip poplar both exhibited the greatest mean size difference between release and non-release conditions in the N+P and N+P+K treatments. It is possible that competition from the ten largest stems in the non release plots of these treatments suppressed non release stems and contributed to the large disparity between the means (Table 4).

The ten largest trees of the five most prevalent species demonstrated positive size gains in the N+P and N+P+K and probably resulted in the suppression of non-release stems. Although the release effect on northern red oak height was significant, none of the Students t-test comparisons for each treatment were significantly (Table 7). Mercker et al. (2007) attributed the lack of response in RO to the fixed rate of growth that red oaks use and in that study they concluded that more than five years would be needed to record a response. It is possible that the three seasons of growth recorded for the current study were not long enough to observe a response.

The fertilization effect was not significant for pine and tulip poplar height growth, however growth means in the N+P+K release condition gained the greatest amount with respect to the non-release plots (Table 8 and 9). Other authors have reported that many hardwoods do not respond when potassium is combined with nitrogen or phopsorous on particular soils (Auchmoody 1982; Burns and Honkala 1991), but the data suggests that young tulip poplars in the current study may have benefited from K. Potassium may have eased restrictions to cambial activity and improved osmoregulation crucial to wood formation, as Wind et al. (2003) concluded given that K is essential to these processes because it has a key role in the maintenance of turgor pressure associated with the elongation of plant tissues.

The data also suggests that northern red oak height growth was negatively affected by release. Trimble (1973, 1974) reported a similar response in stands before age ten. Other authors, such as Lamson and Smith (1989) and Miller et al. (2007), have reported similar observations in stands 10 years or older and attribute the lack of clear stem development to the lateral expansion of the crown and root systems into the new unoccupied growing space.

Conversely, Miller (2000) reported that crown release did not increase the height of 16-year-old stems or cause crown class regression after ten years. Therefore, the application of release at this early age could create a competitive disadvantage for these RO stems later in the stand's development, or be better suited for the enhancement of older/larger stems. site quality must also be critical to the magnitude of response.

Northern red oak in non-released conditions appeared to respond positively to the N+P treatment, despite the fertilizer effect being non significant (Table 10). It also appeared to be more effective at utilizing the resources than non-release tulip poplar stems in the N+P fertilizer treatment. Dillaway et al. (2007) proposed that oaks use diffuse light coming through the canopy to create starch reserves that initiate a growth response when a break in the canopy occurs. Competition from stems in the N+P treatments (Table 4) could have caused some mortality that may have provided the canopy breaks needed for the oaks to become more competitive.

The total volume index and volume index growth of pines and tulip poplars were significantly impacted by release. The data suggest that stems of both species benefited from the addition of nutrients despite the effect of fertilizer being non significant. However, each species had variability among the treatments with respect to the difference between means in release and non-release conditions (Tables 5 and 6), making it difficult to assess which treatment had the potential to provide the greatest benefit. Tables 8 and 9, however, suggest that N+P+K could be the most effective treatment when growth of these species is considered, due to the amount of apparent growth gained by release by both species. Consequently, this consistency in the data could suggest which treatment is more effective in the long term. These implications are not founded on statistically significant differences in the current study, but rather by assessing the trends in growth response from the treatments.

According to Avery and Burkhart (1984) standing timber volume estimates are commonly used to estimate stand value because they represent the total growth on the ground and more merchantable volume translates into a greater return on the investment. In today's timber market, the private landowner will be relied upon to contribute more timber in the wake of increased demand (Beach et al. 2005). If active management in young naturally regenerated stands could be reliably demonstrated to result in higher returns at final harvest, then landowner production might increase.

Many NIPF lands are owned by older individuals that don't see forest productivity extending beyond their lifetime, and this results in poor practices that diminish future productivity (Hicks et al. 2004). Some landowners manage their lands intensively for non-timber goods. This also can reduce the production of timber (Newmann and Wear 1993), but intensive silviculture to promote growth is not necessarily incompatible with other forest goals. There should be an opportunity for some landowners to accomplish both. There is a general lack of experience and information regarding the process and cost of silvicultural treatments before age 10 in natural stands, and the subsequent effect on productivity up to the final harvest. Conversely, an abundance of information exists for pine plantation silviculture (Straka et al. 1999; Zhang and Flick 2001; Fox et al. 2007; Phelan and Allen 2008; Carlson et al. 2009), and this has probably had some bearing on the increased conversion of natural hardwood to pine plantations, and replacement of planted pines with more planted pine after harvest. If trends continue with regard to the current low-intensity silviculture practiced in naturally regenerated mixed-hardwood-pine stands, then hardwood inventory may decline by

2025 (Prestemon and Abt 2002). In order to mitigate the loss of hardwood inventory/productivity, the dissemination of technology, such as silvicultural means to enhance growth and improve species composition, and market information, will be a key to improving timber production (Boyd 1984).

The results of the current study indicate that after five growing seasons fertilization is continuing to influence stand composition and growth on this site. Fertilization has also improved the competitive status of hardwoods on this site while improving the growth of pine, thus providing some insight into the potential productivity of properly managed mixed hardwood stands. Therefore the productivity, composition, and growth of a stand can be enhanced with fertilization by initiating the process of self-thinning as early as possible, resulting in larger more desirable stems in shorter rotation lengths. The results also demonstrate that release substantially increased pine and poplar diameter growth but exerted a marginal impact on height growth. The oaks however demonstrated little to no response to release treatments and may require the application of this treatment after canopy closure.

CONCLUSIONS

The objectives of this study were to examine the response of a six year old naturally regenerated mixed species upland stand in North Carolina’s Piedmont region following N, N+P, and N+P+K fertilization at year one and the imposition of release treatments within the same stand at year three. The responses measured were species composition and stand density, total stand and individual species growth, growth of largest stems, and growth of three merchantable species under release and non-release conditions.

The results indicate that five growing seasons after fertilizer treatments there was increased hardwood representation and a reduction in loblolly pine density. Seed origin stem density increased regardless of treatment and sprout origin density decreased. Hickory density decreased with fertilizer treatments and was significantly lower in the N+P+K treatment. Red maple and sweetgum density improved with fertilizer treatments despite the treatment effect being non significant. This suggests that the stand's composition and stem origin are influenced by the addition of fertilizer at an early age. These findings suggest the potential effectiveness of these silvicultural manipulations in mixed young even-aged hardwood-pine stands.

On a total stand basis, the fertilizer treatment effect was significant for mean GLD, DBH, height, and volume index of all species, hardwoods, and seed origin stems, and these attributes increased in fertilized plots. Although the treatment effect was not significant for sprout origin stems, the data suggests that fertilization provided some benefit. Hickory GLD, DBH, and volume index means decreased with fertilizer treatments and were significantly lower in the presence of N+P+K fertilizer. A significant fertilizer effect was observed for sweetgum height and it was significantly increased in the N and N+P treatments. No significant fertilizer treatment effect existed for red maple, tulip poplar, or the remaining the attributes of sweetgum; although the data suggests that fertilization has provided some growth benefits.

The fertilizer treatment effect significantly impacted the distribution of stems in each height class. There were significantly more stems found in the Control treatment compared to the fertilizer treatments when stems were less than 3 m tall. For stems 3 m and taller, the number of stems found in fertilizer treatments increased considerably compared to the

Control indicating a shift in vertical structure. Thus fertilization increased the rate of self-thinning and can be useful for the manipulation of stem density.

Loblolly pine and tulip poplar responded positively to release treatments with significant increases in diameter size and diameter growth compared to non-released stems in each fertilizer treatment. Although the fertilizer effect and release by fertilizer interactions were not statistically significant, the data suggests that size increases with fertilization. The height and height growth of pines and poplars also responded positively to release. However, the percentage difference between means for released and non-released trees for each fertilizer treatment demonstrated that release had less of an effect on height, than on diameter. This indicates that the removal of competition for sunlight enables release stems to divert more energy and resources to diameter growth.

The pine and poplar volume index and volume index growth responded like each species' diameter and diameter growth. The oaks were the least responsive of the three species to release treatments.

RECOMMENDATIONS

This study demonstrates that the early application of silvicultural treatments has the potential to improve growth on an individual stem and stand-wide basis. Further investigation into the following issues would be meaningful as these findings are considered as guides for operational silviculture:

- the replication of the study to include different rates and combinations of fertilizer elements;
- application of treatments at different stand ages;

- modeling the economic aspects of these kinds of silvicultural treatments under different conditions;
- expansion of the study to be formally replicated to encompass all of the Piedmont, Coastal Plain and Mountain regions;
- the optimal linkage of young stand treatments with more traditional older stand crop tree releases; and
- stand response to these treatments with regard to carbon sequestration, wildlife, biodiversity, invasive species, site water yield and erosion potential, recreational or aesthetic values.

LITERATURE CITED

Auchmoody, L., Clay, H., 1977. Response of Yellow-Poplar and Red Oak to Fertilization in West Virginia1. Soil Sci. Soc. Am. J. 41(4): 803-807.

Auchmoody, L.R. 1982. Fertilization of young Allegheny hardwoods. Ph.D. Thesis. Department of Forestry, North Carolina State University, Raleigh, NC. 75 p.

Auchmoody, L.R. and Philip, S.M. 1973. Forest fertilization in the eastern United States: hardwoods. In: Forest Fertilization Symposium Proceedings. Gen. Tech. Rep. NE-3. Upper Darby, PA: USDA Forest Service, Northeastern Forest Experiment Station: pp. 211-222.

Albaugh, T.J., Allen, H.L., Dougherty, P.M., Johnsen, K.H., 2004. Long term growth responses of loblolly pine to optimal nutrient and water resource availability. For. Ecol. Manage. 192(1): 3-19.

Barclay, H., Brix, H. 1984. Effects of urea and ammonium nitrate fertilizer on growth of a young thinned and unthinned Douglas-fir stand. Canadian Journal of Forest Research 14(6): 952-955.

Beach, R.H., Pattanayak, S.K., Yang, J.C., Murray, B.C., Abt, R.C. 2005. Econometric studies of non-industrial private forest management: a review and synthesis. Forest Policy and Economics 7(3): 261-281.

Bevilacqua, E., Puttock, D., Blake, T.J., Burgess, D. 2005. Long-term differential stem growth responses in mature eastern white pine following release from competition. Canadian Journal of Forest Research 35(3): 511-520.

Beck, D.E. 1977. Growth and development of thinned versus unthinned yellow-poplar sprout clumps. USDA. For. Serv. Res. Pap. SE 173, 11p.

Berenguer, B.J. 2006. Fertilization impacts on growth and species composition in a very young naturally regenerated Piedmont upland hardwood stand in North Carolina. M.S. Thesis. Department of Forestry, North Carolina State University, Raleigh, NC. 83 p.

Berenguer, B.J., Schuler, J.L., Robison, D.J., Gocke, M.H., Treasure, E. 2009. Response of a rising 2-year-old natural Piedmont upland stand to fertilization. New Forests 37(2): 155-174.

Berenguer, B., Gocke, M., Schuler, J., Treasure, E., Robison, D. 2010. Accelerating development with fertilization in a young natural Piedmont mixed hardwood pine stand. In: Stanturf, John A., ed. 2010. Proceedings of the 14th biennial southern silvicultural research conference. Gen. Tech. Rep. SRS–121. Asheville, NC:USDA Forest Service, Southern Research Station. pp. 471-472.

Bliss, J.C., 2000. Public perceptions of clearcutting. J. For. 98(12): 4-9.

Bormann, F.H., Likens, G.E. 1979. Pattern and Process in a Forested Ecosystem. Springer-Verlag, New York, New York, USA.

Boyd, R. 1984. Government Support of Nonindustrial Production: The Case of Private Forests. Southern Economic Journal 51(1): 89-107.

Boyce, S.G. 1977. Management of Eastern Hardwood forests for multiple benefits DYNAST-MB). Research Paper SE-168. USDA Forest Service, Southeastern Forest Experiment Station. 116 p.

Brinkley, D., Carter, R. and Allen, H.L. 1995. Nitrogen fertilization practices in forestry. In: Bacon, P.E., ed. Nitrogen Fertilization in the Environment. New York: Marcel Dekker, Inc.: pp. 421-441.

Burns, R.M. and Honkala, B.H.,eds. 1991. Silvics of North America. 2: Hardwoods. Agric. Handbook 654. Washington DC: USDA Forest Service.

Cain, M.D., Barnett, J. 2002. Effects of early release on natural versus container loblolly pines 12 years after field establishment. South. J. Appl. For. 26(4): 173-180.

Carlson, C.A., Fox, T.R., Creighton, J., Dougherty, P.M., Johnson, J.R. 2009. Nine-Year Growth Responses to Planting Density Manipulation and Repeated Early Fertilization in a Loblolly Pine Stand in the Virginia Piedmont. South. J. Appl. For. 33(3): 109-114.

Carter, E.A., Rummer, R.B., Stokes, B.J. 2006. Evaluation of site impacts associated with three silvicultural prescriptions in an upland hardwood stand in northern Alabama, USA. Biomass Bioenergy 30(12): 1025-1034.

Carter, G., Miller, J., Davis, D., Patterson, R. 1984. Effect of vegetative competition on the moisture and nutrient status of loblolly pine. Canadian Journal of Forest Research 14(1): 1-9.

Christensen, N.L. 1977. Changes in structure, pattern and diversity associated with climax forest maturation in Piedmont, North Carolina. Am. Midl. Nat. 97(1): 176-188.

Christensen, N.L., MacAller, T. 1985. Soil mineral nitrogen transformations during succession in the Piedmont of North Carolina. Soil Biol. Biochem. 17(5): 675-681.

Clark III, A., Borders, B.E., Daniels, R.F. 2004. Impact of vegetation control and annual fertilization on properties of loblolly pine wood at age 12. For. Prod. J. 54, 90-96.

Colbert, S.R. and Allen, H.L. 1991. Potential productivity of loblolly pine plantations inthe Southeastern United States. Gen. Tech. Rep. SE.US Dep. Agric. For. Serv. Southeast. For. Exp. Stn. Asheville, N.C. May 1991(68): pp. 146-147.

Coleman, M.D., Chang, S.X., and Robison, D.J. 2003. DRIS analysis identifies a common potassium imbalance in sweetgum plantations. Communications in Soil Science and Plant Analysis 34(13): 1919-1941.

Connor, R.C. and Hartsell, A.J. 2002. Forest area and conditions. In: Wear, D.N. and Greis, J.G., eds. Southern Forest Resource Assessment. USDA Forest Service Gen. Tech. Rep. SRS-53:pp. 299-325.

Cramer, J., Fahey, T.J., Battles, J.J. 2000. Patterns of leaf mass, area and nitrogen in young northern hardwood forests Am. Midl. Nat. 144(2): 253-264.

Dillaway, D.N., Stringer, J.W., Rieske, L.K. 2007. Light availability influences root carbohydrates, and potentially vigor, in white oak advance regeneration. For. Ecol. Manage. 250(3): 227-233.

Donoso, P.J., Nyland, R.D. 2006. Interference to hardwood regeneration in Northeastern North America: the effects of raspberries (Rubus spp.) following clearcutting and shelterwood methods. Northern Journal of Applied Forestry 23, 288.

Devine, W.D., Houston, A.E., Tyler, D.D. 2000. Growth of three hardwood species through 18 years on a former agricultural bottomland. South. J. Appl. For. 24(3): 159-165.

Dubois, M.R., McNabb, K., Straka, T.J., Watson, W. 1999. Costs and cost trends for forestry practices in the South. Forest Landowner 58, 3-8.

Dunn, M.A., Farrish, K.W., Adams, J.C. 1999. Fertilization response in a natural bottomland hardwood stand in north-central Louisiana. For. Ecol. Manage. 114, 261-264.

Erdmann, G.G., Peterson Jr, R.M., Godman, R.M. 1981. Cleaning yellow birch seedling stands to increase survival, growth, and crown development. Canadian journal of forest research 11(1): 62-68.

Fahey, T.J., Battles, J.J., Wilson, G.F., 1998. Responses of early successional northern hardwood forests to changes in nutrient availability. Ecol. Monogr. 68, 183-212.

Fajvan, M.A., Grushecky, S.T., Hassler, C.C. 1998. The effects of harvesting practices on West Virginia's wood supply. J. For. 96(5): 33-39.

Farmer, R., Bengtson, G., Curlin, J. 1970. Response of pine and mixed hardwood stands in the Tennessee Valley to nitrogen and phosphorus fertilization. For. Sci. 16(2): 130-136.

Fisher, R.F. Predicting tree and stand response to cultural practices, 1984. In: Forest Soils and Treatment Impacts, Proceedings of the Sixth North American Forest Soils Conference. Department of Forestry, Wildlife and Fisheries, University of Tennessee, Knoxville, TN. , 53–65.

Fox, T.R., Jokela, E.J., Allen, H.L. 2007. The development of pine plantation silviculture in the southern United States. J. For. 105(7): 337-347.

Frederick, D. 2009. Hardwood Silviculture FOR 507 manual

Graney, D., Ten-year growth of red and white oak crop trees following thinning and fertilization in the Boston Mountains of Arkansas, 1987. In: Proceedings of the Fourth Biennial Southern Silvicultural Research Conference. pp. 445-450.

Groninger, J.W., Long, M.A. 2008. Oak ecosystem management considerations for central hardwoods stands arising from silvicultural clearcutting. Northern Journal of Applied Forestry 25(4): 173-179.

Guariguata, M. 1999. Early response of selected tree species to liberation thinning in a young secondary forest in Northeastern Costa Rica. For. Ecol. Manage. 124(2): 255-261.

Guldin, R.W., Kaiser, H.F. 2004. National report on sustainable forests-2003. FS-766.Washington, DC: USDA For. Serv. 139 p.

Harrington, C.A., Devine, W.D. 2006. A practical guide to oak release. PNW-GTR-666. USDA For. Serv., Pacific Northwest Research Station, Olympia, WA.

Haywood, J.D. 1995. Prescribed burning and hexazinone herbicide as release treatments in a sapling hardwood-loblolly pine stand. New Forests 10(1): 39-53.

Haywood, J.D. 2005. Influence of precommercial thinning and fertilization on total stem volume and lower stem form of loblolly pine. South. J. Appl. For. 29(4): 215-220.

Haywood, J.D., Burton, J.D. 1989. Phosphorus fertilizer, soils, and site preparation influence loblolly pine productivity. New Forests 3(4): 275-287.

Hicks Jr, R.R., Kennard, D.K., Rauscher, H.M., Schmoldt, D.L., Flebbe, P.A. 2001. Silviculture and management strategies applicable to southern upland hardwoods. In: Proceedings. Southern Conference, 8 pp.

Jacobs, D.F., Salifu, K.F., Seifert, J.R. 2005. Growth and nutritional response of hardwood seedlings to controlled-release fertilization at outplanting. For. Ecol. Manage. 214(3): 28-39.

Johnson, J.E., Smith, D.W., Burger, J.A. 1985. Effects on the forest floor of whole-tree harvesting in an Appalachian oak forest. Am. Midl. Nat. 114(1): 51-61.

Johnson, J.E., Bollig, J.J., Rathfon, R.A. 1997. Growth response of young yellow-poplar to release and fertilization. South. J. Appl. For. 21(4): 175-179.

Johnson, J.E., Bollig, J.J., Rathfon, R.A. 1998. Above-ground biomass and nutrient distribution of released and fertilized yellow-poplar trees. For. Ecol. Manage.105(3): 231-240.

Johnson D.W and D.E Todd, Harvesting effects on long-term changes in nutrient pools of mixed oak forest. Soil Sci. Soc. Am. J., 62 (1998), pp. 1725–1735.

Kellison, R.C. 1971. Hardwood management philosophies and practices. In: Proc. 1st Symposium on Southeastern Hardwoods, USDA Forest Service, Southeast Area, State and Private Forests, Atlanta, GA :pp. 8-16.

Karlsson, C. 2006. Fertilization and release cutting increase seed production and stem diameter growth in Pinus sylvestris seed trees. Scand. J. For. Res. 21(4): 317.

Kochenderfer, J.D., Zedaker, S., Johnson, J., Smith, D., Miller, G. 2001. Herbicide hardwood crop tree release in central West Virginia. Northern Journal of Applied Forestry 18(2): 46-54.

Kota, N.L., Landenberger, R.E., McGraw, J.B. 2007. Germination and early growth of Ailanthus and tulip poplar in three levels of forest disturbance. Biol. Invasions 9(2): 197-211.

Lamson, N.I., Smith, H.C. 1978. Response to crop-tree release: sugar maple, red oak, black cherry, and yellow-poplar saplings in a 9-year-old stand. USDA. For. Serv. Res. Pap. NE-394. 8 p.

Lamson, N.I., Smith, H.C. 1989. Crop-Tree Release Increases Growth of 12-Year-Old Yellow-Poplar and Black Cherry. USDA. For. Serv. Res. Pap. NE-62. 7 p.

Lee, K.H., Jose, S. 2006. Nitrogen mineralization in short-rotation tree plantations along a soil nitrogen gradient. Canadian Journal of Forest Research 36(5): 1236-1242.

Liechty, H.O., Shelton, M.G., Luckow, K.R., Turton, D.J. 2002. Impacts of shortleaf pine-hardwood forest management on soils in the Ouachita Highlands: A review. South. J. Appl. For. 26(1): 43-51.

MacClerry, D.W. 1992. American Forests: A History of Resilience and Recovery. USDA For. Serv., FS-590

Man, C.D., Comeau, P.G., Pitt, D.G. 2008. Competitive effects of woody and herbaceous vegetation in a young boreal mixedwood stand. Canadian Journal of Forest Research 38(7): 1817-1828.

May, J.T. 1985. Nutrients and fertilization. In: Lantz CW (ed) Southern pine nursery handbook, chap 12. USDA, For. Serv, Southern Region, pp 1–27

Miller, G.W. 1984. Releasing young hardwood crop trees-use of a chain saw costs less than herbicides. USDA. For. Serv. Res. Pap. NE-550. 5 p.

Miller, G.W. 2000. Effect of crown growing space on the development of young hardwood crop trees. Northern Journal of Applied Forestry 17(1): 25-35.

Miller, G.W., Stringer, J.W., Mercker, D.C. 2007. Technical Guide to Crop Tree Release in Hardwood Forests. University of Tennessee Cooperative Extension Publication SREF-FM-011.

Miller, H.G. 1995. The influence of stand development on nutrient demand, growth and allocation. Plant Soil 168(1): 225-232.

Neary, D.G., Morris, L.A. and Swindel, B.F. 1984. Site preparation and nutrient management in pine forests. In: Stone, E.L., ed. Forest soils & treatment impacts :proceedings of the sixth North American Forest Soils Conference held at the University of Tennessee, Knoxville in June 1983 Knoxville, Tenn.: Dept. of Forestry, Wildlife and Fisheries, University of Tennessee: pp. 121-143.

Nelson, L., Shelton, M., Switzer, G. 1995. Aboveground net primary productivity and nutrient content of fertilized plantation sweetgum. Soil Sci. Soc. Am. J. 59(3): 925-932.

Newman, D.H., Wear, D.N. 1993. Production Economics of Private Forestry: A Comparison of Industrial and Nonindustrial Forest Owners. Am. J. Agric. Econ.75(3): 674-684.

Newton, L.P., Robison, D.J., Hansen, G., Allen, H.L. 2002. Fertilization and thinning in a 7-year-old natural hardwood stand in eastern North Carolina. P. 193–195 in Proc. of 11th Biennial southern silviculture research conference, Outcalt, K.W. (ed.). USDA For. Serv. Gen. Tech. Rep. SRS-48.

Newton, L.E. 2003 Thinning and fertilizing young coastal plain hardwoods. M.S. Thesis. Department of Forestry, North Carolina State University, Raleigh, NC. 80 p.

Oliver, C.D. and Larson, B.C. 1996. Forest Stand Dynamics. New York: John Wiley & Sons, Inc. 520 p.

Pham, C. H., Howard G. Halverson, and Gordon M. Heisler. 1978. Red maple (Acer rubrum L.) growth and foliar nutrient responses to soil fertility level and water regime. USDA For. Serv. Res. Paper NE-412.

Peet, R.K., Christensen, N.L. 1987. Competition and Tree Death. Bioscience 37(8): 586-595.

Perkey, A.W., H.C. Smith and Wilkins, B.L. 1994. Crop tree management in eastern hardwoods. USDA For. Serv. Publ. NA-TP-19-93. 108 p.

Phelan, J., Allen, H.L. 2008. Have repeated applications of nitrogen and phosphorus to a loblolly pine plantation changed stand productivity and soil nutrient supply? Canadian Journal of Forest Research 38(3): 637-644.

Phillips, R.P., Fahey, T.J. 2007. Fertilization effects on fineroot biomass, rhizosphere microbes and respiratory fluxes in hardwood forest soils. New Phytol. 176(3): 655-664.

Pitt, D.G., Wagner, R.G., Towill, W.D. 2004. Ten years of vegetation succession following ground-applied release treatments in young black spruce plantations. Northern Journal of Applied Forestry 21(3): 123-134.

Pitt, D., Morneault, A., Bunce, P., Bell, F. 2000. Five years of vegetation succession following vegetation management treatments in a jack pine ecosystem. Northern Journal of Applied Forestry 17(3): 100-109.

Prestemon, J.P., Abt, R.C. 2002. Southern Forest Resource Assessment highlights: The Southern Timber Market to 2040. J. For. 100(7): 16-22.

Powers, R.F., Alba, D.H., Miller, R.E., Tarks, A.E., Wells, C.G., Avers, P.E., Cline, R.G., Fitzgerald, R.O. and Loftus, Jr, N.S. 1990. Sustaining site productivity in North American Forests: problems and prospects. In: Gessel, S.P., Lacate, D.S.,Weetman, G.F. and Powers, R.F., eds. Sustained Productivity of Forest Soils. Proc. 7th North American Soils Conference, University of British Colombia, Faculty of Forestry Publication, Vancouver, BC: pp. 49-79.

Raulund-Rasmussen, K., Stupak, I., Clarke, N., Callesen, I., Helmisaari, H.-S., Karltun, E., and Varnagiryte-Kasbaskiene, I. 2008. Effects of very intensive forest biomass harvesting on short and long-term site productivity. In Sustainable use of forest biomass for energy – a synthesis with focus on the Nordic and Baltic Region. Edited by D. Röser, A. Asikainen, K. Raulund-Rasmussen, and I. Stupak. Managing Forest Ecosystems, 12: 29-78.

Rentch, J.S., Miller, G.W., Gottschalk, K.W. 2009. Crown Class Dynamics of Oaks, Yellow-Poplar, and Red Maple after Commercial Thinning in Appalachian Hardwoods: 20-Year Results. Northern Journal of Applied Forestry 26(4): 156-163.

Richter, D.D., Markewitz, D., Heine, P.R., Jin, V., Raikes, J., Tian, K., Wells, C.G., 2000. Legacies of agriculture and forest regrowth in the nitrogen of old-field soils. For. Ecol. Manage. 138(3): 233-248.

Robinson, D.J., Schuler, J.L., Jervis, L., Cox, J.L., and Birks, P.J. 2004. Individual tree release and enrichment planting in young natural upland hardwoods. In Proceedings of the 12th Biennial Southern Silvicultural Research Conference. U.S. For. Serv. Gen. Tech. Rep. SRS-71. pp. 283–286.

Romagosa, M.A., Robison, D.J., 2003. Biological constraints on the growth of hardwood regeneration in upland Piedmont forests. For. Ecol. Manage. 175(3): 545-561.

Schilling, E.B., Lockaby, B.G. and Rummer, R. 1999. Belowground nutrient dynamics following three harvest intensities on the Pearl River Floodplain, Mississippi. Soil Sci. Soc. Am. J. 63(6): 1856-1868.

Schuler, J.L. 2005. Stand dynamics and ecological constraints on growth in young naturally regenerated hardwood stands. Ph.D. Thesis. Department of Forestry, North Carolina State University, Raleigh, NC. 149p.

Schuler, J.L., Robison, D.J, 2006. Stand development and growth responses of 1-and 3-year-old natural upland hardwoods to silvicultural treatments. For. Ecol. Manage. 232(3): 124-134.

Schuler, J.L., Robison, D.J., 2008. The effects of intensive management on the leaf characteristics and growth phenology of young yellow-poplar stems. For. Ecol. Manage. 255(4): 787-796.

Sendak, P.E., Leak, W.B., United States. Forest Service. Northern Research Station, 2008. Early Crop-Tree Release and Species Cleaning in Young Northern Hardwoods: A Financial Analysis. USDA. For. Serv. Res. Pap. RS-NRS-6

Shepard, R.K., 1981. Early results from thinned, fertilized red spruce (*Picea rubens* Sarg.) stands near Rangeley. Univ. of Maine School of For. Resources Misc. Rep. 254. Orono, ME, 7 pp.

Smith, H.C., Lamson, N.I. 1983. Precommercial Crop-Tree Release Increases Diameter Growth of Appalachian Hardwood Saplings. USDA For. Serv. Res. Pap. NE-534.

Smith ,D.M., 1986. The Practice of Silviculture. New York: John Wiley & Sons Inc, 37-256 p.

Smith, W.B., Miles, P.D., Vissage, J.S., Pugh, S.A. 2004. Forest resources of the United States, 2002. Gen. Tech. Rep. NC-241. St. Paul, MN: USDA Forest Service, North Central Research Station. pp. 137

Sonderman, D.L. 1987. Stem-Quality Changes on Young, Mixed, Upland Hardwoods After Crop-Tree Release. USDA For. Serv. Res. Pap. NE-597.

Spurr and Barnes, 1980 S.H. Spurr and B.V. Barnes, Forest Ecology John Wiley, New York, NY (1980), 687 p.

Stanturf, J.A., Auchmoody, L., Walters, R.S., 1997. Regeneration responses of oak-dominated stands to thinning and clearcutting in northwestern Pennsylvania. In: Pallardy, Stephen G.; Cecich, Robert A.; Garrett, H. Gene; Johnson, Paul S., eds.
Proceedings of the 11th Central Hardwood Forest Conference; Gen. Tech. Rep. NC-188. St. Paul, MN: USDA Forest Service, North Central Research Station. pp. 321-330.

Stape, J.L., Binkley, D., Jacob, W.S., Takahashi, E.N. 2006. A twin-plot approach to determine nutrient limitation and potential productivity in Eucalyptus plantations at landscape scales in Brazil. For. Ecol. Manage. 223(3): 358-362.

Steinbeck, K., Kuers, K., 1996. Development of pine-hardwood mixtures following clearcutting on two upland sites in the Georgia Piedmont: 10 year results. South. J. Appl. For. 20(4): 203-208.

Swank, W.T., Vose, J.M. 1988. Effects of cutting practices on microenvironment in relation to hardwood regeneration. p. 71-88. In: Smith, H.C., A.W. Perkey, and W.E. Kidd (eds.). Proceedings of workshop, guidelines for regenerating Appalachian hardwood stands. SAF Publ. 88-03. West Virginia University Books, Morgantown.

Sword, M.A., Tiarks, A.E., Haywood, J.D., 1998. Establishment treatments affect the relationships among nutrition, productivity and competing vegetation of loblolly pine saplings on a Gulf Coastal Plain site. For. Ecol. Manage. 105(1): 175-188.

Thomson, A., Barclay, H., 1984. Effects of thinning and urea fertilization on the distribution of area increment along the boles of Douglas-fir at Shawnigan Lake, British Columbia. Canadian Journal of Forest Research 14(6): 879-884.

Toit, B., Smith, C.W., Little, K.M., Boreham, G., Pallett, R.N., 2010. Intensive, site-specific silviculture: manipulating resource availability at establishment for improved stand productivity. A review of South African research. For. Ecol. Manage. 259(9): 1836-1845.

Trimble Jr, G.R. 1971. Early crop tree release in even-aged stands of Appalachian hardwoods. USDA. For. Serv. Res. Pap. NE-203.

Trimble Jr, G.R., 1973. Response to crop-tree release by 7-year-old stems of yellow-poplar and black cherry. USDA. For. Serv. Res. Pap. NE-253. 10 p.

Trimble Jr, G.R., 1974. Response to crop-tree release by 7-year-old stems of red maple stump sprouts and northern red oak advance reproduction. USDA. For. Serv. Res. Pap. NE-303. 6 p.

Tripler, C.E., Kaushal, S.S., Likens, G.E., Todd Walter, M., 2006. Patterns in potassium dynamics in forest ecosystems. Ecol. Lett. 9(4): 451-466.

Uchida, R., 2000. Essential nutrients for plant growth: Nutrient functions and deficiency symptoms. Plant nutrient management in Hawaii's soils. College of Tropical Agriculture and Human Resources, University of Hawaii at Manoa. pp. 31–55.

Von Althen, F.W. 1976 Fertilization at time of planting fails to improve growth of hardwood seedlings. Report: 0-X-249, Great Lakes Forest Research Centre, Canadian Forest Service 249. 13 p.

Voorhis, N.G., 1990. Precommercial crop-tree thinning in a mixed northern hardwood stand. USDA For. Serv. Res. Pap. NE-640. 6 p.

Ward, J.S. 1995. Intensity of precommercial crop-tree release increases diameter and crown growth in upland hardwoods. In: Gottschalk, Kurt W.; Fosbroke, Sandra L.C., eds. Proceedings, 10th central hardwood conference; 1995 March 5-8; Morgantown, WV. Gen. Tech. Rep. NE-197. Northeastern Forest Experiment Station. pp. 388-398.

Ward, J.S., 2002. Crop tree release increases growth of mature red oak sawtimber. Northern Journal of Applied Forestry 19(4): 149-154.

Ward, J.S., 2007. Crop-Tree Release Increases Growth of Black Birch (Betula lenta L.) in Southern New England. Northern Journal of Applied Forestry 24(2): 117-122.

Ward, J.S., 2008. Intensity of precommercial crop tree release increases diameter growth and survival of upland oaks. Canadian Journal of Forest Research 39(1): 118-130.

Wear, D.N., Carter, D.R., Prestemon, J. 2007. United States. Forest Service. The US South's Timber Sector in 2005: A Prospective Analysis of Recent Change. US Dept. of Agriculture, Forest Service, Southern Research Station

Wear, D.N., Greis, J.G., 2002. Southern forest resource assessment: summary of findings. J. For. 100(7): 6-14.

Wendel, G., Lamson, N.I., 1987. Effects of Herbicide Release on the Growth of 8-to 12-Year-Old Hardwood Crop Trees. USDA. For. Serv. Res. Pap. NE-598. 4 p.

Will, R.E., Munger, G.T., Zhang, Y., Borders, B.E., 2002. Effects of annual fertilization and complete competition control on current annual increment, foliar development, and growth efficiency of different aged Pinus taeda stands. Canadian Journal of Forest Research 32(10): 1728-1740.

Will, R.E., Markewitz, D., Hendrick, R.L., Meason, D.F., Crocker, T.R., Borders, B.E., 2006. Nitrogen and phosphorus dynamics for 13-year-old loblolly pine stands receiving complete competition control and annual N fertilizer. For. Ecol. Manage. 227(2): 155-168.

Wilson, A.D., Shure, D.J., 1993. Plant Competition and Nutrient Limitation during Early Succession in the Southern Appalachian Mountains. Am. Midl. Nat. 129(1): 1-9.

Wind, C., Arend, M., Fromm, J., 2004. Potassium-dependent cambial growth in poplar. Plant Biol 6(1): 30-37.

Zahner, R., Myers, R.K., 1984. Productivity of young Piedmont oak stands of sprout origin. South. J. Appl. For. 8(2): 102-108.

Zhang, D., Flick, W.A., 2001. Sticks, Carrots, and Reforestation Investment. Land Econ. 77(3): 443-456.

Table 1. Mean (±SD, n=4) stand density and percent representation of six-year-old stems by type, origin and species for all stems ≥70 cm in height (cm), measured January 2009, six growing seasons after fertilizer treatments on a 1-year old upland NC Piedmont naturally regenerated even-aged mixed species stand.

Attributes	Control	N Fert	N+P Fert	N+P+K Fert	ANOVA
Total stems (1000s)/ha	26 ± 15.8 a	14.8 ± 4.6 b	20 ± 4.8 ab	22.8 ± 10.7 ab	F=4.15 ; Ptrt=0.05 *
% Representation					
Hardwood	52.4±10.5	76.6 ± 10.5	70.8 ± 10.5	71.2 ± 10.5	F=1.01 ; Ptrt=0.43
Sprout Origin	14.9 ±3.5	37.9 ± 12.6	18.2 ± 10.0	10.4 ± 8.2	F=1.15 ; Ptrt =0.40
Seed Origin	85.1 ±8.3	80.2 ± 8.3	84.3 ± 8.3	89.6 ± 8.3	F=0.21 ; Ptrt =0.88
Loblolly pine	47.6 ± 12.6	24.6 ± 16.3	30.2± 16.3	31.8± 16.3	F=0.46 ; Ptrt =0.72
Hickory	9.3 ± 0.9 a	6.6 ± 0.9 ab	6.6 ± 0.9 ab	5.9 ± 0.9 b	F=3.19 ; Ptrt =0.08 *
Red Maple	8.4 ± 5.7	21.2 ± 4.9	14.3 ± 5.7	15.0 ± 4.9	F=1.01 ; Ptrt=0.44 *
Sweetgum	1.3± 5.9	7.9 ±4.9	16.0 ± 5.9	13.8 ± 4.9	F=1.43 ; Ptrt T=0.31
Tulip poplar	7.3 ± 3.0	7.8 ± 2.5	21.1± 3.8	20.3 ± 3.2	F=5.75 ; Ptrt =0.06 *

Table 1. Continued.

Notes: Fertilizer treatments described in text. Means within a row followed by different letters were significantly different by ANOVA at P≤.15 and distinguished by Tukey's HSD at P≤.10. * associated with values in ANOVA indicate that means generated under the same conditions for that attribute in the 2006 study; were used as the Covariate in the analysis and were statistically significant at P≤.10. When the covariate was not significant at P≤.10, it was excluded from the analysis and the ANOVA was run again.

Table 2. Mean (±SD, n=4) tree size for six-year-old stems ≥70 cm in height (cm), measured January 2009, six growing seasons after fertilizer treatments on a 1-year old upland NC Piedmont naturally regenerated even-aged mixed species stand.

	--Fertilizer Treatments---				
Attributes	Control	N Fert	N+P Fert	N+P+K Fert	ANOVA
All species					
GLD (cm)	3.2 ± 0.2	3.9 ± 0.2	3.9 ± 0.2	3.8 ± 0.2	F=2.96 ; Ptrt=0.09
DBH (cm)	1.7 ± 0.1 b	2.4 ± 0.1 a	2.3±0.1 a	2.3 ± 0.1 ab	F=4.03 ; Ptrt=0.05
Height (cm)	294.9 ± 21.5 b	373.1 ± 21.5 ab	377.7 ± 21.5 a	382.2 ± 21.5 a	F=3.73 ; Ptrt=0.05
Volume Index(d^2h)	1771.8 ± 623.8 b	3724.7 ± 623.8 ab	3928 ± 623.8 ab	4141.2 ± 623.8 a	F=3.07 ; Ptrt=0.08
Hardwoods					
GLD (cm)	3.2 ± 0.2	3.9 ± 0.2	3.9± 0.2	3.8 ± 0.2	F=2.97 ; Ptrt=0.09
DBH (cm)	1.7 ± 0.1 b	2.3 ± 0.1 a	2.4 ± 0.1 a	2.3 ± 0.1 ab	F=3.96 ; Ptrt=0.05
Height (cm)	295.4 ± 21.8 b	373.1 ± 21.8 ab	378.7 ± 21.8 a	382.2 ± 21.8 a	F=3.61 ; Ptrt=0.06
Volume Index (d^2h)	1779.0 ± 626.7 b	3724.7± 626.7 ab	3945.5± 626.7 ab	4141.2 ± 626.7 a	F=3.04 ; Ptrt=0.08
Sprout origin stems					
GLD (cm)	3.1 ± 0.4	3.4 ± 0.4	3.7± 0.3	3.4 ± 0.3	F=0.94 ; Ptrt=0.48
DBH (cm)	1.7 ± 0.2	1.9 ± 0.2	2.2± 0.3	2.0 ± 0.2	F=0.64 ; Ptrt=0.62
Height (cm)	296.7 ± 30.9	323.5 ± 47.7	365.0 ± 37.8	346.5 ± 30.9	F=0.78 ; Ptrt=0.54
Volume Index (d^2h)	1748.8 ± 610.5	2395.1 ± 943.5	3353.8 ± 747.7	2595.0 ± 610.5	F=0.95 ; Ptrt=0.47
Seed origin stems					
GLD (cm)	3.2 ± 0.2	3.7 ± 0.2	3.9 ± 0.2	3.8 ± 0.2	F=2.35 ; Ptrt=0.14
DBH (cm)	1.7 ± 0.2 a	2.2 ± 0.2 ab	2.3 ± 0.2 a	2.3 ± 0.2 ab	F=3.20 ; Ptrt=0.08

Table 2. Continued.

	----------------Fertilizer Treatments----------------				
Attributes	Control	N Fert	N+P Fert	N+P+K Fert	ANOVA
Height (cm)	294.0 ± 19.8 b	358.2 ± 19.8 ab	376.1 ± 19.8 a	383.3 ± 19.8 a	F=4.21 ; Ptrt=0.04
Volume Index (d^2h)	1732.9 ± 638.3 b	3072.5 ± 638.3 ab	3850.9 ± 638.3 ab	4172.9 ± 638.3 a	F=2.90 ; Ptrt=0.09
Loblolly pine					
GLD (cm)	3.1 ± 0.3	3.7 ± 0.3	3.8 ±0.3	3.6 ± 0.3	F=1.11 ; Ptrt=0.42
DBH (cm)	1.7 ± 0.2	2.1 ± 0.3	2.3 ±0.3	2.1 ± 0.3	F=1.35 ; Ptrt=0.34
Height (cm)	289.8 ± 16.4	329.9± 21.2	340.5 ± 21.2	357.5 ± 21.2	F=2.30 ; Ptrt=0.18
Volume Index (d^2h)	1787.1 ±637.5	2346.6 ± 822.9	3451.6 ±822.9	2872.3 ± 822.9	F=0.94 ; Ptrt=0.47
Hickory					
GLD (cm)	3.8 ± 0.2 a	3.5 ± 0.2 a	3.1 ± 0.2 ab	2.5 ± 0.2 b	F=5.01 ; Ptrt=0.02
DBH (cm)	2.2 ± 0.2 a	2.0 ± 0.2 ab	1.9 ± 0.5 ab	1.4 ± 0.2 b	F=3.82 ; Ptrt=0.05
Height (cm)	329.4 ± 22.9	337.5 ± 22.9	355.6 ± 22.9	292.8 ± 22.9	F=0.49 ; Ptrt=0.69
Volume Index (d^2h)	1919.0 ±519.1 ab	3057.3 ± 519.1 a	853.4 ± 519.1 b	697.8 ± 519.1 b	F=4.44 ; Ptrt=0.03
Red Maple					
GLD (cm)	2.3 ± 0.4	3.5 ± 0.4	3.3 ± 0.5	2.8 ± 0.4	F=1.49 ; Ptrt=0.29
DBH (cm)	1.1 ± 0.3	2.1 ± 0.3	2.0 ± 0.3	1.7 ± 0.3	F=2.20 ; Ptrt=0.17
Height (cm)	260.1 ± 32.9	352.6 ± 32.9	371.0 ± 39.6	334.0 ± 32.9	F=2.01 ; Ptrt=0.19
Volume Index (d^2h)	536.6 ± 667.4	2626.8 ± 667.4	2411.5 ± 814.2	1484.4± 677.4	F=1.90 ; Ptrt=0.20
Sweetgum					

Table 2. Continued.

	--------------------------------------Fertilizer Treatments	---			
Attributes	Control	N Fert	N+P Fert	N+P+K Fert	ANOVA
GLD (cm)	2.9 ± 0.4	4.0 ± 0.4	3.6 ± 0.4	3.5 ± 0.4	F=1.35 ; Ptrt=0.33
DBH (cm)	1.4 ± 0.3	2.3 ±0.3	2.1 ± 0.3	2.0 ± 0.2	F=2.25 ; Ptrt=0.17
Height (cm)	303.4 ± 24.9 b	422.3 ± 20.4 a	395.5 ± 24.9 a	366.9 ± 20.4 ab	F=5.03 ; Ptrt=0.04
Volume Index (d^2h)	1179.9 ± 269.8	3140.7 ± 1230.7	3334.6 ± 2144.4	3230.9 ± 2436.7	F=0.94 ; Ptrt=0.47
Tulip poplar					
GLD (cm)	3.4 ±1.2	5.1 ± 0.9	3.1 ± 1.1	4.4 ± 1.2	F=0.84 ; Ptrt=0.52
DBH (cm)	1.8 ± 0.8	3.2 ± 0.6	1.8 ± 0.9	2.6 ± 0.8	F=0.86 ; Ptrt=0.51
Height (cm)	316.2 ± 77.0	428.7 ± 62.6	348.1 ± 75.7	429.1 ± 77.0	F=0.67 ; Ptrt=0.60
Volume Index (d^2h)	3912.3 ±4435.1	9036.7 ± 3605.8	1407.8 ± 4359.2	7482.1 ± 4435.1	F=0.73 ; Ptrt=0.56

Notes: Fertilizer treatments described in text. Means within a row followed by different letters were significantly different by ANOVA at P≤.15 and distinguished by Tukey’s HSD at P≤.10. * associated with values in ANOVA indicate that means generated under the same conditions for that attribute in the 2006 study; were used as the Covariate in the analysis and were statistically significant at P≤.10. When the covariate was not significant at P≤.10, it was excluded from the analysis and the ANOVA was run again.

Table 3. Mean percent (±SD, n=4) distribution of all species and seed origin trees six-year–old stems ≥70 cm in height (cm), measured January 2009, six growing seasons after fertilizer treatments on a 1-year old upland NC Piedmont naturally regenerated even-aged mixed species stand.

	--------Fertilizer Treatments--------				
Height (cm) Class	Control	N Fert	N+P Fert	N+P+K Fert	ANOVA
70-200 cm	16.6 ± 2.7 a	10.8 ± 4 c	5.4 ± 1.1 b	7.9 ± 2.4 b	F=32.11 ; Trt=0.01
201-331 cm	50.6 ± 2.6 a	31.3 ± 6.5 c	35.0 ± 3.6 b	35.4 ± 3.6 b	F=57.72 ; Trt=0.01
332-462 cm	26.8 ± 2.1 a	30.0 ± 1.6 b	31.6 ± 2.6 a	29.9 ± 2.0 a	F=7.01 ; Trt=0.01
463-593 cm	5.5 ± 4.1 b	20.6 ± 5.1 d	22.7 ± 4.6 c	18.3 ± 3.0 ac	F=14.79 ; Trt=0.01
>594 cm	0.5 ± 0.2 b	7.3 ± 3.1 a	5.3 ± 3.5 a	8.6 ± 5.2 a	F=4.83 ; Trt=0.02

Notes: Fertilizer treatments described in text. Means within a row followed by different letters were significantly different by ANOVA at P≤.15 and distinguished by Tukey's HSD at P≤.10.

Table 4. Mean (±SD, n=4) size measurements for the 16 largest non sprout origin trees per plot (regardless of species), or the 10 largest non sprout origin trees per plot for common timber species, all stems ≥70 cm in height (cm), measured January 2009, six growing seasons after fertilizer treatments on a 1-year old upland NC Piedmont naturally regenerated even-aged mixed species stand.

	--Fertilizer Treatments	--	--	--	
Species / Attributes	Control	N Fert	N+P Fert	N+P+K Fert	ANOVA
From 16 Largest Trees					
GLD (cm)	6.8 ± 0.2	6.6 ± 0.2	7.1 ± 0.2	6.6 ± 0.2	F=1.16 ; Ptrt=0.33 *
DBH (cm)	3.8 ± 0.2 b	4.3 ± 0.2 ab	4.5 ± 0.2 a	4.7 ± 0.2 a	F=4.74 ; Ptrt=0.03
Height (cm)	516.6 ± 8.7 b	563.4 ± 7.7 a	556.8 ± 7.8 a	595.4 ± 7.7 c	F=14.5 ; Ptrt=0.01 *
Volume Index (d^2h)	8057.7 ± 1058.2 b	12281.7 ± 1058.2 a	13215.7 ± 1058.2 a	15294.5 ± 1058.2 a	F=8.27 ; Ptrt=0.01
From 10 Largest Trees					
Loblolly pine					
GLD (cm)	6.0 ± 0.2 b	5.4 ± 0.3 b	5.5 ± 0.3 b	7.2 ± 0.3 a	F=9.92 ; Ptrt=0.01 *
DBH (cm)	4.1 ± 0.2 ab	3.5 ± 0.3 b	4.5 ± 0.3 a	3.8 ± 0.3 ab	F=3.10 ; Ptrt=0.02
Height (cm)	431.4 ± 10.8 b	397.9 ± 14.2 b	411.4 ± 14.9 b	486.1 ± 14.4 a	F=8.44 ; Ptrt= 0.01 *
Volume Index (d^2h)	8766.5 ± 2799.0 ab	6166.9 ± 1531.3 b	11263.9 ± 1442.1 a	9913.3 ± 1508.6 ab	F=2.56; Ptrt=0.05
Hickory					
GLD (cm)	4.5 ± 0.2 a	3.4 ± 0.3 b	2.9 ± 0.3 b	2.7 ± 0.3 b	F=10.12 ; Ptrt=0.01 *
DBH (cm)	2.4 ± 0.2 a	1.8 ± 0.2 b	1.5 ± 0.2 b	1.5 ± 0.2 b	F=7.26 ; Ptrt=0.02
Height (cm)	356.1 ± 16.7	317.8 ± 19.7	312.4 ± 21.5	298.9 ± 23.3	F=1.39 ; Ptrt=0.29
Volume Index (d^2h)	3038.6 ± 439.6 a	1375.6 ± 517.9 b	770.9 ± 567.3 b	782.1 ± 613.3 b	F=5.16 ; Ptrt=0.02
Red Maple					
GLD (cm)	1.6 ± 0.3 b	3.4 ± 0.2 a	3.4 ± 0.3 a	3.1 ± 0.3 a	F=14.21 ; Ptrt=0.01 *

Table 4. Continued.

	---------------------------------------Fertilizer Treatments---				
Attributes	Control	N Fert	N+P Fert	N+P+K Fert	ANOVA
DBH (cm)	1.0 ± 0.4 b	2.2 ± 0.4 a	2.3 ± 0.4 a	2.0 ± 0.4 a	F=3.72 ; Ptrt=0.06
Height (cm)	253.8 ± 17.4 b	407.3 ± 15.5 a	416.8 ± 17.3 a	381.3 ± 15.6 a	F=23.10 ; Ptrt=0.01
Volume Index (d^2h)	31.0 ± 552.3 b	2967.4 ± 494.1 a	2676.0 ± 550.8 a	2147.4 ± 498.6 a	F=7.07 ; Ptrt=0.02
Sweetgum					
GLD (cm)	1.9 ± 0.6	5.2 ± 0.6	5.8 ± 0.6	5.3 ± 0.5	F=12.89 ; Ptrt=0.01 *
DBH (cm)	1.2 ± 0.6	2.9 ± 0.6	3.6 ± 0.7	3.2 ± 0.6	F=2.93 ; Ptrt=0.10
Height (cm)	146.8 ± 35.3 b	485.6 ± 30.4 a	530.9 ± 33.9 a	490.3 ± 25.2 a	F=25.56 ; Ptrt=0.01 *
Volume Index (d^2h)	686.8 ± 2394.8	7198.1 ± 2328.5	9262.5 ± 2552.1	8579.7 ± 2127.2	F=7.54 ; Ptrt=0.02
Tulip poplar					
GLD (cm)	5.0 ± 0.6	5.6 ± 0.5	6.1 ± 0.5	4.8 ± 0.4	F=1.60 ; Ptrt=0.19
DBH (cm)	3.4 ± 1.2	3.6 ± 1.2	4.0 ± 1.2	3.6 ± 1.2	F=0.28 ; Ptrt=0.84
Height (cm)	433.1 ± 38.8	503.1 ± 34.9	479.3 ± 32.8	463.4 ± 24.4	F=0.61 ; Ptrt=0.61
Volume Index (d^2h)	9082.8 ± 2720.4	4.4 1083.7± 2205.8	12598.0 ± 2302.4	13523.0 ± 1709.6	F=0.37 ; Ptrt=0.78

Notes: Fertilizer treatments described in text. Means within a row followed by different letters were significantly different by ANOVA at $P \leq .15$ and distinguished by Tukey's HSD at $P \leq .10$.* associated with values in ANOVA indicate that means generated under the same conditions for that attribute in the 2006 study; were used as the Covariate in the analysis and were statistically significant at $P \leq .10$. When the covariate was not significant at $P \leq .10$, it was excluded from the analysis and the ANOVA was run again.

Table 5. Mean (±SD, n = 4) dbh (cm), height (cm) and volume index (d^2h) of loblolly pine stems three growing seasons after Release and Non Release conditions and six growing seasons after fertilizer treatments on a 1-year old upland NC Piedmont naturally regenerated even aged mixed species stand.

Fertilizer Treatments	Attributes	Release	Non Release	t value	P value
Control	DBH (cm)	6.7 ± 3.6	5.0 ± 3.5	t =4.13	p = 0.0001
	Height (cm)	522.4± 26.4	489.4 ± 26.2	t =1.53	p =0.1281
	Volume Index (d^2h)	26586 ± 2692.8	16183 ± 2655.7	t =3.29	p =0.0013
N Fert	DBH (cm)	7.4 ± 3.6	4.7 ± 4.1	t =5.85	p =0.0001
	Height (cm)	525.7 ± 26.6	510.0 ± 29.1	t =0.65	p =0.5190
	Volume Index (d^2h)	30037 ± 2724.5	12196 ± 3123.7	t =5.04	p =0.0001
N+P Fert	DBH (cm)	6.0 ± 3.6	4.4 ± 4.7	t =3.08	p =0.0026
	Height (cm)	495.1 ± 26.5	442.0 ± 31.6	t =1.95	p =0.0535
	Volume Index (d^2h)	20956 ± 2708.1	12985 ± 3600.8	t =2.02	p =0.0454
N+P+K Fert	DBH (cm)	6.7 ± 3.5	4.5 ± 3.8	t =5.14	p =0.0001
	Height (cm)	525.2 ± 26.1	457.6 ± 27.3	t =3.00	p =0.0034
	Volume Index (d^2h)	27061 ± 2656.9	9823.8 ± 2837.6	t = 5.32	p =0.0001

Table 5. Continued.

Note: Fertilizer treatments described in text. For each pair of attribute values; for Release and Non-Release conditions; under each fertilizer condition; the t-test and associated p value indicate statistical difference between the Release and Non-Release conditions; by attribute and fertilizer treatment at $P \leq .10$. * associated with values in ANOVA indicate that means generated under the same conditions for that attribute in the 2006 study; were used as the Covariate in the analysis and were statistically significant at $P \leq .10$. When the covariate was not significant at $P \leq .10$, it was excluded from the analysis and the ANOVA was run again.

ANOVA dbh	Release F=81.32 ; P=0.0001 ; Fertilization F=1.23 ; P=0.3535 ; Fert*Release F=1.24 ; P=0.3003 *
ANOVA height	Release F=12.40 ; P=0.0006 ; Fertilization F=0.70 ; P=0.5759 ; Fert*Release F=0.94 ; P=0.4220 *
ANOVA volume index	Release F=59.21 ; P=0.0001 ; Fertilization F=0.83 ; P=0.5107 ; Fert*Release F=1.91 ; P=0.1321 *

Table 6. Mean (±SD, n = 4) dbh (cm), height (cm) and Volume Index (d^2h) of tulip poplar stems three growing seasons after Release and Non Release conditions and six growing seasons after fertilizer treatments on a 1-year old upland NC Piedmont naturally regenerated even aged mixed species stand.

Fertilizer Treatments	Attributes	Release	Non Release	t value	P value
Control	DBH (cm)	6.5 ± 4.1	5.6 ± 4.0	t =1.98	p = 0.0504
	Height (cm)	649.9 ± 25.0	638.1 ± 24.0	t =0.35	p =0.7269
	Volume Index (d^2h)	38122.0 ± 4715.2	28744.0 ± 4609.2	t =1.59	p =0.1135
N Fert	DBH (cm)	7.0 ± 4.1	5.5 ± 4.2	t =3.28	p =0.0014
	Height (cm)	708.0 ± 24.4	650.3 ± 24.5	t =1.68	p =0.0960
	Volume Index (d^2h)	46989.0 ± 4675.8	25663.0 ±4806.5	t =3.50	p =0.0007
N+P Fert	DBH (cm)	6.2 ± 4.3	5.4 ± 4.2	t =1.60	p =0.0960
	Height (cm)	655.0 ± 26.4	573.0 ± 25.2	t =2.25	p =0.0262
	Volume Index (d^2h)	35513.0 ±4975.8	25473.0 ± 4839.3	t =1.57	p =0.1198
N+P+K Fert	DBH (cm)	7.3 ± 4.1	5.4 ±4.3	t =4.17	p =0.0001
	Height (cm)	716.6 ± 24.1	659.7 ± 26.1	t =1.62	p =0.1079
	Volume Index (d^2h)	48336.0± 4627.6	24750.0 ± 4989.7	t = 3.85	p =0.0002

Table 6. Continued.

Note: Fertilizer treatments described in text. For each pair of attribute values, for Release and Non-Release conditions, under each fertilizer condition, the t-test and associated p value indicate statistical difference between the Release and Non-Release conditions, by attribute and fertilizer treatment at $P \leq .10$.. * associated with values in ANOVA indicate that means generated under the same conditions for that attribute in the 2006 study; were used as the Covariate in the analysis and were statistically significant at $P \leq .10$. When the covariate was not significant at $P \leq .10$, it was excluded from the analysis and the ANOVA was run again.

ANOVA dbh	Release F=29.98 ; P=0.0001 ; Fertilization F=1.00 ; P=0.4356 ; Fert*Release F=1.37 ; P=0.2544 *
ANOVA height	Release F=8.88 ; P=0.0035 ; Fertilization F=3.68 ; P=0.0559 ; Fert*Release F=0.70 ; P=0.5551 *
ANOVA volume index	Release F=27.49 ; P=0.0001 ; Fertilization F=0.82 ; P=0.5137 ; Fert*Release F=1.48 ; P=0.2249 *

Table 7. Mean (±SD, n = 4) dbh (cm), height (cm) and Volume Index (d^2h) of northern red oak stems three growing seasons after Release and Non Release conditions and six growing seasons after fertilizer treatments on a 1-year old upland NC Piedmont naturally regenerated even aged mixed species stand.

Fertilizer Treatments	Attributes	Release	Non Release	t value	P value
Control	DBH (cm)	3.6 ± 2.6	3.1 ± 2.8	t =1.70	p = 0.0921
	Height (cm)	403.9 ± 31.5	412.0 ± 32.3	t =0.27	p =0.7878
	Volume Index (d^2h)	7701.9 ± 1330.1	5015.0 ± 1394.9	t =1.53	p =0.1280
N Fert	DBH (cm)	4.0 ± 2.5	3.3 ± 2.6	t =2.28	p =0.0241
	Height (cm)	427.3 ± 30.8	428.3 ± 31.6	t =0.03	p =0.9720
	Volume Index (d^2h)	8110.5 ± 1270.7	6166.5 ± 1330.2	t =1.17	p =0.2442
N+P Fert	DBH (cm)	3.9 ± 2.7	3.9 ± 2.5	t =0.03	p =0.9786
	Height (cm)	424.4 ± 31.7	410.2 ± 30.7	t =0.50	p =0.6178
	Volume Index (d^2h)	8743.4 ±1340.8	8276.3 ± 1270.4	t =0.28	p =0.7799
N+P+K Fert	DBH (cm)	3.4 ± 2.8	3.3 ± 2.8	t =0.18	p =0.8591
	Height (cm)	393.2 ± 32.4	415.3 ± 32.5	t =-0.71	p =0.4816
	Volume Index (d^2h)	7265.2 ± 1396.3	8365.0 ± 1403.8	t = -0.61	p =0.5453

Table 7. Continued.

Note: Fertilizer treatments described in text. For each pair of attribute values, for Release and Non-Release conditions, under each fertilizer condition, the t-test and associated p value indicate statistical difference between the Release and Non-Release conditions, by attribute and fertilizer treatment at P≤.10. * associated with values in ANOVA indicate that means generated under the same conditions for that attribute in the 2006 study; were used as the Covariate in the analysis and were statistically significant at P≤.10. When the covariate was not significant at P≤.10, it was excluded from the analysis and the ANOVA was run again.

ANOVA dbh	Release F=4.27 ; P=0.0409 ; Fertilization F=1.37 ; P=0.3123 ; Fert*Release F=1.22 ; P=0.3053 *
ANOVA height	Release F=0.08 ; P=0.7754 ; Fertilization F=0.14 ; P=0.9327 ; Fert*Release F=0.26 ; P=0.8567*
ANOVA volume index	Release F=1.36 ; P=0.2482 ; Fertilization F=0.87 ; P=0.4909 ; Fert*Release F=0.89 ; P=0.4467 *

Table 8. Cumulative growth (±SD, n = 4) of dbh (cm), height (cm) and Volume Index (d^2h) of loblolly pine stems during three seasons of growth under Release and Non Release conditions ages 4-6; (2006-2008) on an upland NC Piedmont naturally regenerated mixed species stand fertilized between growing seasons 1-2.

Fertilizer Treatments	Attributes	Release	Non Release	t value	P value
Control	DBH (cm)	5.7 ± 4.5	3.7 ± 4.4	t =4.27	p = 0.0001
	Height (cm)	336.0 ± 27.8	297.5 ± 27.5	t =1.75	p =0.0825
	Volume Index (d^2h)	27160 ± 4468.5	12760 ± 4408.4	t =3.27	p =0.0014
N Fert	DBH (cm)	5.9 ± 4.5	3.7 ± 5.1	t =4.18	p =0.0001
	Height (cm)	330.1 ± 27.9	322.8 ± 30.6	t =0.29	p =0.7709
	Volume Index (d^2h)	25573 ± 4487.6	13285± 5068.1	t =2.48	p =0.0145
N+P Fert	DBH (cm)	4.7 ± 4.5	3.2 ± 5.7	t =2.63	p =0.0097
	Height (cm)	303.4 ± 27.9	253.2 ± 33.1	t =1.79	p =0.0754
	Volume Index (d^2h)	18136 ± 4487.6	10654 ± 5663.8	t =1.35	p =0.1808
N+P+K Fert	DBH (cm)	5.7 ± 4.4	3.6 ± 4.6	t =4.44	p =0.0001
	Height (cm)	335.2 ± 27.5	280 ± 28.4	t =-2.39	p =0.0183
	Volume Index (d^2h)	29889 ± 4408.8	12908 ± 4623.6	t =3.74	p =0.0003

Table 8. Continued.

Note: Fertilizer treatments described in text. For each pair of attribute values, for Release and Non-Release conditions, under each fertilizer condition, the t-test and associated p value indicate statistical difference between the Release and Non-Release conditions, by attribute and fertilizer treatment at P≤.10. * associated with values in ANOVA indicate that means generated under the same conditions for that attribute in the 2006 study; were used as the Covariate in the analysis and were statistically significant at P≤.10. When the covariate was not significant at P≤.10, it was excluded from the analysis and the ANOVA was run again.

ANOVA dbh	Release F=57.76 ; P=0.0001 ; Fertilization F=1.00 ; P=0.4346 ; Fert*Release F=0.27; P=0.8479 *
ANOVA height	Release F=9.42 ; P=0.0027 ; Fertilization F=0.60; P=0. 6322 ; Fert*Release F=0.74; P=0. 5277*
ANOVA volume index	Release F=27.44 ; P=0.0001 ; Fertilization F=0.55; P=0.6636 ; Fert*Release F=0.62; P=0.6040 *

Table 9. Mean (±SD, n = 4) dbh (cm), height (cm) and Volume Index (d^2h) of tulip poplar stems during three seasons of growth under Release and Non-Release conditions ages 4-6; (2006-2008) on an upland NC Piedmont naturally regenerated mixed species stand fertilized between growing seasons 1-2.

Fertilizer Treatments	Attributes	Release	Non Release	t value	P value
Control	DBH (cm)	3.7 ± 5.4	2.9 ± 5.3	t =1.40	p = 0.1638
	Height (cm)	199 ± 29.8	190.3 ± 29.3	t =0.30	p =0.7652
	Volume Index (d^2h)	26635 ± 9899.5	16784 ± 9770.8	t =1.12	p =0.2654
N Fert	DBH (cm)	4.6 ± 5.4	3.0 ± 5.5	t =2.95	p =0.0039
	Height (cm)	263.4 ± 29.7	199.5 ± 29.8	t =2.16	p =0.0328
	Volume Index (d^2h)	41825 ± 9881.8	20054 ± 10063	t =2.39	p =0.0185
N+P Fert	DBH (cm)	4.6 ± 5.7	2.9 ± 5.7	t =2.85	p =0.0052
	Height (cm)	220.9 ± 30.9	184.5 ± 31.7	t =1.11	p =0.2696
	Volume Index (d^2h)	40230 ± 10193	21587 ± 10420	t =1.88	p =0.0622
N+P+K Fert	DBH (cm)	5.3 ± 5.4	3.3 ± 5.6	t =3.66	p =0.0004
	Height (cm)	282.7 ± 29.4	219.5 ± 27.1	t =-2.10	p =0.0380
	Volume Index (d^2h)	53802 ± 9793.9	27760 ± 10288	t =2.85	p =0.0052

Table 9. Continued.

Note: Fertilizer treatments described in text. For each pair of attribute values, for Release and Non-Release conditions, under each fertilizer condition, the t-test and associated p value indicate statistical difference between the Release and Non-Release conditions, by attribute and fertilizer treatment at P≤.10. * associated with values in ANOVA indicate that means generated under the same conditions for that attribute in the 2006 study; were used as the Covariate in the analysis and were statistically significant at P≤.10. When the covariate was not significant at P≤.10, it was excluded from the analysis and the ANOVA was run again.

ANOVA dbh	Release F=29.89 ; P=0.0001 ; Fertilization F=2.29 ; P=0.1475 ; Fert*Release F=1.01; P=0.3902 *
ANOVA height	Release F=8.03 ; P=0.0055 ; Fertilization F=1.45; P=0. 2931 ; Fert*Release F=0.80; P=0. 4984*
ANOVA volume index	Release F=17.07 ; P=0.0001 ; Fertilization F=1.52; P=0.2738 ; Fert*Release F=0.59; P=0.6231 *

Table 10. Mean (±SD, *n* = 4) dbh (cm), height (cm) and Volume Index (d^2h) of northern red oak stems after three seasons of growth under Release and Non Release conditions Release and Non-Release conditions ages 4-6; (2006-2008) on an upland NC Piedmont naturally regenerated mixed species stand fertilized between growing seasons 1-2.

Fertilizer Treatments	Attributes	Release	Non Release	t value	P value
Control	DBH (cm)	2.2 ± 3.2	1.5 ± 3.4	t =1.78	p = 0.0779
	Height (cm)	151.2 ± 20.3	173.5 ± 21.5	t =-0.99	p =0.3251
	Volume Index (d^2h)	6547.6 ± 2349.7	4687.1 ± 2429.5	t =0.70	p =0.4863
N Fert	DBH (cm)	2.6 ± 3.4	2.0 ± 3.3	t =1.64	p =0.1039
	Height (cm)	173.1 ± 19.6	194.5 ± 20.7	t =1.00	p =0.3197
	Volume Index (d^2h)	6985.5 ±2271.5.8	6278.2 ± 2400.1	t =0.28	p =0.7802
N+P Fert	DBH (cm)	2.9 ± 3.2	2.5 ± 3.5	t =0.97	p =0.3327
	Height (cm)	170.5 ± 20.6	236.0 ± 22.1	t =2.75	p =0.0007
	Volume Index (d^2h)	11115.1 ± 2389.1	8334.8 ± 2551.6	t =-0.99	p =0.3227
N+P+K Fert	DBH (cm)	1.8 ± 3.3	1.7 ± 3.3	t =0.22	p =0.8277
	Height (cm)	139.2 ± 21.0	160.8 ± 21.1	t =-0.94	p =0.3511
	Volume Index (d^2h)	5826.2 ± 2431.4	6251.6 ± 2445.1	t =-0.16	p =0.8759

Table 10. Continued.

Note: Fertilizer treatments described in text. For each pair of attribute values, for Release and Non-Release conditions, under each fertilizer condition, the t-test and associated p value indicate statistical difference between the Release and Non-Release conditions, by attribute and fertilizer treatment at P≤.10. * associated with values in ANOVA indicate that means generated under the same conditions for that attribute in the 2006 study; were used as the Covariate in the analysis and were statistically significant at P≤.10. When the covariate was not significant at P≤.10, it was excluded from the analysis and the ANOVA was run again.

ANOVA dbh	Release F=5.17 ; P=0.0248 ; Fertilization F=3.81 ; P=0. 0517 ; Fert*Release F= 0.48; P=0.6996 *
ANOVA height	Release F=8.28; P=0.0048 ; Fertilization F=1.78 ; P=0.2205 ; Fert*Release F=0.87 ; P=0.4589
ANOVA volume index	Release F=0.84; P=0. 3610 ; Fertilization F=1.07 ; P=0.4095 ; Fert*Release F=0.26 ; P=0.8543 *

Figure 1. Map and layout of study site: Hill Forest, Durham County, North Carolina.

Legend

(open rectangle)	2 x 30 m Transect, June 2004, before treatment effects
(hatched rectangle)	2 x 30 m Transect, October 2005, two seasons after treatments

N
Inventory Transect
04
05
Fertilizer Treatment
Control
N
NP
NPK
0 4.5 9 18 27 36
Meters
Created by: Charlie Lawrence III
Data: Dr. Glenn Catts
Date: 12/25/2010

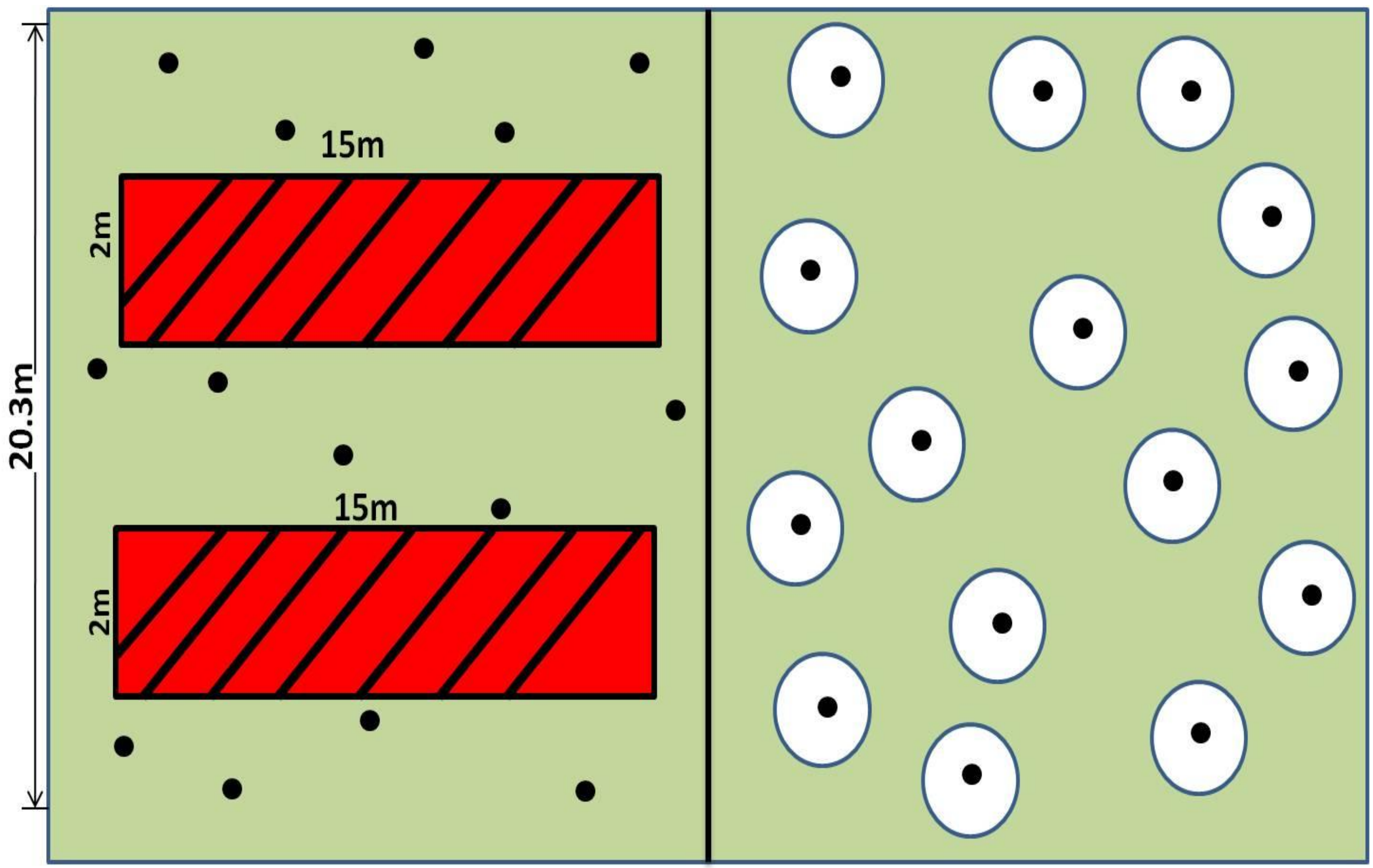
Figure 2. Detailed view of fertilization and release treatments in a study plot.

Legend

2 x 15 m Transect. Fall 2008. five seasons after treatments

Individual trees, 5 each of LP, TP, RO (15 per plot), identified in the “non release” side of each original plot

Individual trees, 5 each of LP, TP, RO (15 per plot), identified with all woody vegetation removed in a 1.8 m radius around each tree, in the “released “ side of each original plot


20.3m
15m
2m
15m
2m