

ABSTRACT

BERENGUER, BRYAN JACOB. Fertilization Impacts on Growth and Species Composition in a Very Young Naturally Regenerated Piedmont Upland Hardwood Stand in North Carolina. (Under the direction of Daniel J. Robison.)

Hardwood stands in the southern U.S. are often regenerated naturally following clearcutting, with little or no silvicultural intervention in the early stages of stand development. Fertilizer was applied to a very young naturally regenerating stand in order to evaluate the effectiveness of nutrient addition as a silvicultural tool in recently clearcut stands and to better understand the ecological relationships between site fertility and stand development. The study was installed on a rising 2-year-old naturally regenerated mixed pine-hardwood stand in the Hill Demonstration Forest in the Piedmont region (Durham County) of North Carolina. Dominant species were red maple (*Acer rubrum*), sweetgum (*Liquidambar styraciflua*), white oak group (*Quercus alba*, *Quercus phellos* and *Quercus prinus*), redbud (*Cercis canadensis*), hickory (*Carya spp*), red oak group (*Quercus falcate*, *Quercus rubra* and *Quercus coccinea*), loblolly pine (*Pinus taeda*) 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).

On a whole stand basis, increased growth rates were observed for *N+P* and *N+P+K* plots. Fertilizer treatments did not affect total stand density, but the density of evergreens significantly decreased in *N+P* plots compared to the *Control*. The density of

stems of stump origin also increased in plots receiving $N+P$. Density of sweetgum significantly increased and hickory density decreased with the application of $N+P$.

Dominant hardwood species (with the exception of tulip poplar) responded with an increase in height to only $N+P$ fertilizer treatments. Tulip poplar increased in groundline diameter, height and mean tree volume with the application of $N+P$. Loblolly pine responded to $N+P+K$ fertilizer treatment with an increase in height, diameter and volume over the *Control*. The 16 largest trees increased groundline diameter (*GLD*) 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*). There was no growth response among treatments for the 10 largest trees per species per plot, with the exception of red oak which responded with an increase in height in $N+P$ plots. There were slight differences among treatments in elemental foliar nutrients in dominant red oak, loblolly pine and tulip poplar trees, but none were found to be deficient.

The lack of growth response to N alone suggests the primary nutrient limitations for the site is not N or at least N alone. However, the strong response to $N+P$ in hardwoods and $N+P+K$ in loblolly pine suggests the site is deficient in these elemental combinations. Current and projected growth responses, both on a whole stand level and among individual species, indicate that the use of $N+P$ fertilizer may be an effective silvicultural instrument to increase growth and accelerate stand development in very young naturally regenerated stands, and thereby shorten rotation time.

**Fertilization Impacts on Growth and Species Composition in a Very Young
Naturally Regenerated Piedmont Upland Hardwood Stand in North Carolina**

by
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BIOGRAPHY

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Shortly after finishing his undergraduate degree, he went San Diego, CA to work in the research pharmacology department of Pfizer Pharmaceuticals as an assistant scientist. After coming to the realization that working in a large corporation was not the career path he desired to follow, BJ took a position with Consortium-Thailand in Mae Sot, Thailand. There he taught science and trained science teachers in refugee camps as well as worked on projects establishing demonstration gardens in schools along the border of Thailand and Myanmar.

After 18 months in Thailand, he decided to return to school and pursue a Master of Science degree in Forestry. In between his second and third semesters, he spent over four months working as an agricultural advisor in Cambodia and close to one year as an agroforestry extension agent with the US Peace Corps in The Gambia, West Africa. He will move to Comarapa, Boliva to work with small farmers as an agroforester/natural resource manager for UNAIS in September 2006.

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INTRODUCTION AND LITERATURE REVIEW

Scope

Currently in the United States (U.S.), forests occupy approximately 306 million hectares of land. Globally 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). Production of relatively inexpensive wood-based products and the development of technologies designed to enhance the growth, processing, and use of timber has helped establish the U.S. as a major player in the world's timber market.

Nearly a third of all forested land in the U.S. is located in the Southeastern (SE) region of the country. Extending south from Virginia to Florida, and west to Texas, the SE consists of 87 million hectares of forests, 93% classified as potentially viable commercial timberland (Conner and Hartsell 2002). This region produces more timber than any other single country in the world and is projected to remain the world's dominant producing region for many decades to come. The SE also supplies the U.S. with approximately 60% the country's timber products, the vast majority coming from private landowners (Prestemon and Abt 2002). Conifers account for approximately 33% of the species composition in SE timberlands, while hardwoods account for the remaining 67%.

The population of the U.S. has more than doubled between the years of 1929 to 2000, while the area of forested land has remained relatively stable (Guldin and Kaiser 2004). The resulting nationwide increase in demand for wood requires additional efficiencies in timber production and wood product technologies. Softwood, primarily

conifers, harvests from private lands in the SE are projected to increase by 56% in the next 35 years. This increase in harvest from forestland area will be met by increasing the intensity of forest management to enhance productivity, or through imports. Conifer plantations in the southeast, mostly southern pines, are increasingly managed intensely and the technology to do so has been well developed (Allen 2000). However, management of hardwoods in the SE has been mostly generally passive and neglected by comparison. Hardwood plantations compose a small number of ha in the SE, with as much as 99% of production in natural stands. Most hardwood forests belong to non-industrial private landowners, who often view hardwood silviculture difficult (Siry 2002). Around 2025, hardwood inventory is projected to significantly decline due to harvest and conversion to pine (Prestemon and Abt 2002). Unless hardwood growth rates are enhanced, harvest is projected to exceed growth, resulting in a declining forest stock.

If the SE U.S. is to meet the growing demand for hardwoods, issues of poor growing stock and productivity must be overcome. Many hardwood stands contain poor growing stock of low value species as a result of poorly prescribed continual partial cuttings and high grading (Fajvan et al. 1998). Additionally, the productivity of these forests in many places has been severely constrained by past land use. From the mid 1600's to early 1900's, U.S. forestland declined by more than 130 million hectares with forestland mostly being converted for agricultural use (MacCleery 1992). Poor land management practices rendered most of this land infertile as continued cropping and topsoil erosion removed most of the soil fertility resources. This was especially true for the Piedmont and Appalachian Mountain regions of the SE as the slope of the land encouraged topsoil losses. Eventually, land unable to sufficiently produce agricultural

commodities was abandoned and naturally reclaimed into forest. As a result, many SE forest soils are now inherently low in available nutrients and are currently below potential production capacity (Allen 2000).

Recent attempts to improve the productivity of naturally regenerated hardwood stands in the SE include efforts to increase soil fertility through the application of fertilizer during early stages of natural regeneration. This current study addresses the role of fertilization in the natural regeneration and development of an upland hardwood stand after clearcutting. The study was developed and installed by the Hardwood Research Cooperative at North Carolina State University. Growth response, species composition, stand density and foliar nutrient concentrations were examined 2 years after fertilizer applications.

Early Stand Development

Forest stand regeneration follows major disturbances, such as wind and ice storms, flooding, wild fire, insect and disease outbreaks and/or even aged forest harvesting systems. These disturbances open up growing space and resources once occupied by previously existing vegetation. The size of such disturbances range from small areas, or gaps within the forest to larger, more extensive areas such as an entire portion of an existing stand. Gaps encourage a small area of new growth and can result in the development of uneven aged stand. Larger disturbances promote the growth of thousands of stems originating from seed or advance regeneration to form a more evenly aged stand. This new vegetation competes intensely for light, water and nutrients as the

developing stand segregates into dominant and subdominant components. Regardless of the size of the disturbance, species with a competitive advantage (eg., those with rapid growth) will often be the first to claim the site's resources and, therefore, establish themselves as the dominant vegetation in that stand. In the earliest stages of stand development a site will contain a variety of vegetation including trees, shrubs, herbs, and vines. For a short while, perhaps less than one full growing season, this diverse vegetation is in limited competition with one another as growing space is widely available to all (Oliver and Larson 1996, Smith et al. 1997).

Competition intensifies as the site becomes fully occupied and resources become more limited. This can occur as early as one year after a disturbance. The “brushy stage” of stand development, in which trees and large shrubs occupy the same canopy layer typically restricts light to the forest floor and prevents further invasion from potentially competitive vegetation (Gingrich 1971). As time progresses, the emerging trees form a canopy and reduce the amount of light available to less competitive trees or other vegetation remaining in the understory. Canopy closure results in the death of shade intolerant species and acts to suppress the growth of smaller shade tolerant species. With access to light, the dominant trees also continue to expand their root systems and exclude other individuals by restricting water and nutrient availability. Above and below ground competition continues to influence stand development as a dominant class matures (Oliver and Larson 1996).

As young stands mature the number of stems per hectare decreases over time. This process of “self-thinning” is dependent on specific site and stand characteristics and can be organized into one of three categories; time-density, size-density and density-size

(Peet and Christensen 1987). In the time-density category, also referred to as the “Sukachev effect” (Gause 1934, Harper 1977), the rate of stem density reduction is the result of the interaction between time and site quality. For example, self thinning begins earlier on sites of higher quality. Poorer sites offer more limited resources and are therefore less capable of supporting growth than higher quality sites. Self-thinning rates for forest stands in the time-density category are also dependent on stand composition. In single-species stands the rate of stem reduction is often more pronounced than in mixed stands. The vegetation’s similar growth patterns and nutrient requirements increase the depletion of necessary resources, especially if the species is shade intolerant. Mixed stands will also “self-thin”. However, shade tolerant species in the stand can exist in the forest understory for decades and therefore slow the effect of “natural thinning” (Oliver and Larson 1996, Smith et al. 1997).

The size-density category refers to the relationship between individual tree volume and the resources available for growth. As individual trees become larger, they take up more growing space and compete with adjacent trees for nearby resources. Over time the most competitive trees will overtake their neighbors by capturing a greater share of the site’s resources and/or more efficiently utilizing the available resources. The third category of self-thinning, density-size relations, can be useful in predicting the maximum number of trees that can occupy a site. These predictions are based on the size of existing trees and is commonly referred to as the “ $-3/2$ power law of self-thinning”. Management diagrams based on the density-size category have been widely used to assess stand development and aid in predicting stem mortality (Drew and Flewelling 1979, Smith et al. 1997). Forest managers are able to use these density diagrams to schedule thinning

operations to prevent managed stands from reaching a “zone of imminent competition mortality” (Jack and Long 1996). Currently, most of the existing management diagrams are for older stands, though there are currently studies underway to develop density management tools in very young stands (Schuler and Robison 2003)

Young naturally regenerated hardwoods have been described by Kellison (1988) as “a jungle of undesired and desired species, vines, briars and annuals”. In the Piedmont of the SE, unmanaged natural stand stem densities vary from 32,500 per ha at age one (Romagosa and Robison 2003), 33,750 at age two (Romagosa and Robison 2003), 35,000 to 51,000 at age three (current study), 163,000 at age three and four (Schuler and Robison, 2001), 20,700 to 23,000 age four (Steinbeck and Kuers 1996), 19,400 to 20,700 at age six (Waldrop 1997), 19,300 to 25,200 at age seven (Steinbeck and Kuers 1996) and 6,425 SPH (Zahner and Myers 1982) to 20,000 at age 10 (Steinbeck and Kuers 1996).

Managing stand density throughout the development of the stand is an integral part of silviculture and significantly affects the productivity of a stand (Jack and Long 1996). Stand basal area in young Piedmont hardwood stands can increase basal area with a decrease in stand density and an increase in age. Steinbeck and Kuer (1996) reported basal area growth of 3.45 to 3.7 m² per ha (19,300 to 25,200 stems per ha) at age seven and 6.02 to 6.24 m² per ha (16,400 stems per ha to 20,000 stems per ha) at age 10.

Mechanical and chemical thinning is used by foresters to control stand density and species composition. Thinning alone or in combination with fertilization has been found to increase basal area and volume in young and very young stands, with fertilization providing the most rapid response (Schuler 2005, Newton 2003). This is evidence of the time-density (“Sukachev”) effect, where fertilization enhances site

quality, which promotes growth and competition and intensifies density reduction. Limited information exists concerning silvicultural treatments for very young natural stands and some attempts to control species composition and stocking have generally failed (Kellison 1971).

Regeneration Methods – Clearcuts

Stand disturbance is often initiated by forest managers to harvest mature stands and/or initiate new growth. It is becoming more common for pines to be regenerated artificially by clearcutting in concert with site preparation, fertilization, and planting of improved seedlings (Guldin and Wigley 1998, Preston and Abt 2002). Artificial regeneration of hardwoods is less common and is primarily employed as a tool for the reclamation of drastically disturbed land, to enrich stands with low quality stock, or to control the precise stocking of a stand. Systems such as seed tree cuts, single-tree selection, group selection, shelterwood and clearcut are most commonly used for regeneration in hardwood management (Kelty 1988, Smith et al. 1997). Natural regeneration, especially in the U.S. South, is the primary form of hardwood stand establishment. This may be due to most hardwood forests belonging to non-industrial private forest (NIPF) land owners, who view intensive hardwood silviculture as too complex (Siry 2002). For these landowners, natural regeneration is viewed as an inexpensive and effective management practice (Dutrow 1980, Shropshire 1980) resulting in a desirable mix of species (Boyce 1977).

Clearcutting currently offers the greatest potential for effective natural regeneration of economically viable mixes of southern hardwoods suitable for timber production (Kellison et al. 1988, Clatterbuck and Meadows 1993), as well as a viable method for pines (Cain and Shelton 2001). Natural regeneration is characterized by low establishment costs, reduced soil disturbance, limited use of heavy equipment, decreased labor costs, and reduced risk of damage by insects and disease (Barnett and Baker 1991). Also, the abundance of light created from a clearcut favors shade intolerant and semi-intolerant trees often desired by landowners (Dale et al. 1995).

Clearcut pine stands can be successfully regenerated naturally by utilizing seed already contained in the seed bank as well as introduced from adjacent stands (Cain and Shelton 2001). Hardwood regeneration also relies on the seed bank and new seed, but also from sprouts from previously established stumps and roots and advance regeneration (Kelty 1988, Johnson 1993). Fast growing trees such as sweetgum and tulip poplar can be regenerated from seed or sprouts while slower growing trees, such as oaks, generally require advanced regeneration or stump sprouts to compete (Kays et al. 1988, Meadows and Stanturf 1997). Harrington and Edwards (1996) found that clearcut stands in the Georgia Piedmont favored hardwood and volunteer pine basal area over planted pine basal area. In trials of various reproduction methods, clearcutting was found to produce four times the desired pine stems and twice the desired hardwood stems (Guldin et al. 2004). However, clearcutting can regenerate 25,000 to 100,000 stems per ha, resulting in a mix that includes substantial numbers of undesirable species as well as full stocking and intense competition.

Less desirable timber species such as red maple can dominate a stand with its ability to act as both a primary shade intolerant species and a secondary tolerant species (Abrams 1988). In upland stands, blackberry species (*Rubus spp.*) and grape vine (*Vitis spp.*) can also inhibit growth during the early years of regeneration. Grape vine not only competes for resources, but also effects tree form by attaching to trees and restraining upward growth. Furthermore, vines often girdle the tree, causing breakage and deformity. In one study conducted in the NC Appalachians, grape vine reportedly covered 17% of the study area five years after clearcutting and had damaged a considerable number of regenerating trees (McGee and Hooper 1970). Many past attempts to control species composition and stocking early on through fertilization, particularly of young hardwoods, have generally failed (Kellison 1971).

Fertilization of Natural Forest Stands

Predicting the potential productivity of a site is often a difficult task. Limiting factors can vary within a site by microclimate, slope, aspect and soil type. Foresters often rely on site index values derived by county soil surveys to assess stand productivity. However, soil series and tree growth are often uncorrelated as trees respond to features not included in soil series classification (Khanna and Ulrich 1984). In forest soils, often the soil texture, depth of A horizon and drainage are the most important factors affecting tree growth. (Coil 1952, Gladstone and Gray 1973). Furthermore, forests in the eastern U.S. are often located on old agricultural land, abandoned once fertility was reduced and crop yields declined. Silvicultural treatments designed to raise site quality and

productivity can augment water supply and soil moisture, increase nutrient availability or ameliorate adverse conditions such as low pH or elemental toxicity (Stone 1984). In the eastern U.S., nutrient limitations have been well documented as a major constraint to stand productivity (Allen 2000) and forest fertilization is increasingly recognized as option to raise site quality (Smith et al. 1997).

Nitrogen, followed by phosphorus, are often the limiting elements in temperate forest soils (Fisher 1984, Powers et al. 1990), especially in the southeastern U.S. (Colbert and Allen 1991). Nitrogen is an integral element in the production of leaf area and Rubisco, the key enzyme in photosynthesis. This relationship between N and leaf area has been found to be linear, with the amount of nitrogen absorbed by the plant positively correlated with leaf area production (Ingestad 1982, Cannel 1989). Increased leaf area resulting from N availability not only increases the amount of sunlight intercepted, but also canopy development and the competitive position of trees.

Studies have shown that fertilizer applications can dramatically increase growth and leaf area, with productivity limited by water and temperature constraints. Forest soils can also be degraded by disturbance and nutrient removals associated with timber harvest. The forest floor often experiences a significant decrease in nitrogen, phosphorus and sulfur after harvest (Leichty and Shelton 2004). Microbial biomass carbon and nitrogen also significantly fall after clear and partial cuts (Schilling et al. 1999). Nitrogen removal from pine harvests can range from 52 to 375 kg nitrogen per ha (Neary et al. 1984). Tew et al. (1986) estimated 50 to 300 kg nitrogen, 10 to 30 kg phosphorus, and 100 to 1000kg calcium is removed per ha when pine stem and bark were harvested. In the Piedmont, 257 kg nitrogen, 31 kg phosphorus, 165 kg potassium, 187 kg calcium and 46

kg magnesium per hectare were removed from aboveground biomass following conventional harvest of a loblolly pine (*Pinus taeda*) stand (Wells et al. 1975). Calcium, magnesium and manganese removal was generally found to be higher in the harvest of hardwoods than conifers (Leichty and Shelton 2004). Demchik and Sharpe (2000) also found that stands amended with fertilizer had most of the added nutrients removed with harvest, leaving the following stand to grow at the same low rates as untreated areas. This removal of nutrients not only has a detrimental effect on subsequent stand growth but also can reduce vigor and increase insect and disease problems associated with low soil fertility (Shigo 1973). Fertilization can ameliorate soils nutrient deficiency as well as act as a critical component in the replacement of soil nutrients removed from harvest (Gessel and Atkinson 1984).

Plant absorption of applied nitrogen in the form of urea and ammonium nitrate is around 20 to 30 % and is even higher for applied phosphorus (Neary et al. 1984). Studies have shown that growth responses resulting from applied nitrogen will last for 5 to 10 years (Graney and Pope 1978, Lamson 1978, Beck and Della-Bianca 1981). Phosphorus is also projected to remain in the ecosystem from 20 years (McNeil et al. 1984) to whole rotations (Prichett and Comerford 1982; Allen 2000). Auchmoody (Auchmoody and Philip 1973, Auchmoody 1982) estimated that an application of triple-super-phosphate can provide an elevated supply of P for at least five years before decline and increase yields by 20% and decrease rotation age by 5 years.

Nutrients retention in a stand is thought to be attributed to immobilization by soil microbes, soil adsorption and plant biomass storage including translocation of elements among foliage and roots. For example, sweetgum was observed to translocate 70% of

nitrogen absorbed after the first year after fertilizer application and 50% the following year. The same was true of phosphorus, with 61% of absorbed P retained after the first year and 41% the following year (Nelson et al. 1995). The prolonged persistence of soil P is due to the buffering capacity of the soil from adsorption by aluminum and iron (Havlin et al. 1999, Brady and Weil 1996). Adding fertilizer, and therefore increasing the soil nutrients, has also been found to increase favorable microflora and fauna such as earthworms, mites and myriapods. The more favorable soil environment created by an increase in nutrients may allow for less tree stress and increase the ability to fight off pests and disease (Shigo 1973). Enhanced site nutrition and the associated positive changes in soil biology, when alleviating limiting soil conditions, can improve soil fertility and plant growth.

Response of Individual Species to Fertilization

Forest fertilization studies began in the late 1800's (Brinkley et al. 1995), but formal studies did not begin until the early 1930's with Wyman (1936) (reported in Auchmoody 1982). Since then, much of the reported research has been conducted on pine stands, with recent studies focusing primarily on intensively managed plantations. Pine growth rates generally respond positively to the addition of nitrogen, phosphorus and potassium individually as well as in combination, often with the best growth responses to N+P+K (Auchmoody 1989). A gain of 20 to 30 % growth in loblolly pine over a 6 to 10 year period can be expected with pre-plant fertilizer treatments of N+P (Allen 2000). Furthermore, site index (at 25 years) gains of 2 to 3 m or more have been found with the

addition of pre-plant phosphorus (Gent et al. 1986). Older loblolly pine stands fertilized mid rotation with N and P have also been observed to exhibit a growth gain of 30% lasting for six years or more (Allen 2000).

The effect of fertilizer on productivity in natural stands has not been well documented with a majority of the trials performed on stands 10 years or older. Overall, hardwoods respond to fertilization with nitrogen and phosphorus applied alone or in combination. Hardwoods are generally more nutrient demanding than conifers and therefore have been found to respond vigorously to increased nutrient availability. Fertilized hardwoods have been observed to grow twice as fast as unfertilized trees for up to seven years (Auchmoody 1982). N and P applied individually generally elicit a growth response in most hardwood species and often have a synergistic effect when applied together (Auchmoody 1989). In general, tree species have been found to increase seedling diameter and height growth as well as stand basal area and volume in older trees. Species also differ in natural allocation patterns, with oaks responding strongly in terms of diameter growth, sweetgum and red maple in height and black cherry and tulip poplar responding with both height and diameter growth (Burns and Honkala 1990). However, fertilizer administered to sites before hardwood planting designed to increase seedling growth has given mixed results. Trials in Ontario consisting of N, P and K alone and in various combinations added pre-plant had no effect on seedling growth and survival in newly planted black walnut (*Juglans nigra*), silver maple (*Acer saccharum*), red oak (*Quercus rubra*) and basswood (*Tilia Americana*) (Von Althen 1976). Several studies have shown that hardwoods generally do not exhibit a growth response to the application of potassium either as a sole nutrient or combined with nitrogen and phosphorus (Phares

1971, Auchmoody 1982, Burns and Honkala 1990). However, Coleman et al. (2003) reported that K may be a broadly limiting factor in planted sweetgum.

In a review of hardwood forest fertilization studies from the 1930's until the early 1970's, natural stands in the Northeast demonstrated favorable growth responses to N, P and K and in young and middle aged stands of mixed species. Pin oak (*Quercus palustris* Muenchh.), white ash (*Fraxinus americana* L.), honey locust (*Gleditsia trincanthos* L.), black locust (*Robinia pseudoacacia* L.), northern red oak (*Q. rubra*), and tulip poplar (*Liriodendron tulipifera*) were among the species positively affected by nutrient addition (Auchmoody and Filip 1973). In more recent studies, growth rates of sweetgum treated with nitrogen and phosphorus alone demonstrated an increase in growth of 41 and 27 % respectively and treatments of nitrogen and phosphorus together have been found to increase growth 70% over non-treated stands (Nelson and Switzer 1990).

Individual hardwood species have been reported to respond differently to elemental fertilizer treatments. Wells and Allen (1985) reported that sweetgum plantations responded largely to N and N+P with a growth rate of 150% and 170%, respectively, over unfertilized plots, but did not respond to P. They further reported northern red oak responded positively to N, P and N+P with growth increases of 38%, 9% and 70% respectively. Also white oaks showed no increase in growth to the addition of N, but increased growth rates by 176 % and 192 % with P and N+P together. They indicated that this could be attributed to the increased root growth associated with the addition of P. Wells and Allen (1985) also reported that oak seedlings and advance regeneration had increased survival as well as growth when treated with N+P+K. Nuttall oak (*Q. nuttallii*) fertilized seedlings had significant increases in height growth while

ground-line diameter was unaffected (Taylor et al. 2004). Oak mortality was generally found to be high in sites with low potassium and calcium availability (Demchik and Sharpe 2000) and a lack of response to N or N+P may be due to competition from more vigorous seedlings/sprouts of faster growing species (Grany and Rogerson 1985)

Dunn et al. (1999) recorded a growth response to fertilizer treatments in a 30 to 40 year old bottomland hardwood stand in Louisiana two years after treatment. Stand mean diameter increment increased by 41, 27 and 82 % in plots receiving N, P and N+P over the control, respectively. In the same study, red oak had increased diameter increment by 93% with P addition alone and by 70% with N+P, over the control. White oak responded similarly, with diameter increment increases of 176% with phosphorus and 193% with N+P additions. However, neither red oak nor white oak responded to fertilizer treatments consisting of nitrogen alone. In much older, 80 year old northern red oak, additions of lime and phosphate caused a 100% increase in terminal elongation as well as a 10% increase in basal area over two years. However, in the same study there was no increase in sprouting vigor when the fertilized oaks were harvested two years after treatment (Demchik and Sharpe 2000).

Farmer et al. (1970) performed nitrogen and fertilizer trials on several upland mixed pine and hardwood sites with poor to medium soil fertility throughout Tennessee. All of the sites responded with an increase in growth of 55 to 133 % in both the N and N+P treatments. On average, the authors reported a 50% growth increase for hardwoods and 30 % for pines. Response to fertilizer was more prevalent 2 and 3 years after treatment than the year of treatment. Of the dominant trees in the stands, he reported that tulip poplar exhibited the highest rate of growth, followed by oak. Hickory (*Carya spp.*)

in the stand responded to nitrogen application more than nitrogen and phosphorus combined. In Farmer's study, foliar N concentrations increased in tulip poplar, loblolly pine and white oak with only tulip poplar and loblolly pine having increased foliar phosphorus. Smith and McCay (1979) reported that growth rates both hardwoods and pines varied by stand and individual tree age, with age negatively correlated with fertilizer response.

Broadfoot (1966) observed similar responses in a 20 year old Louisiana sweetgum-oak stand to N+P+K fertilizer applied annually for 5 years. The author observed a 65% increase in annual growth and elevated foliar nitrogen. Pole-sized sweet gum and oak species also demonstrated a 70% increase in diameter growth after two growing seasons at another Louisiana site (Dunn et al. 1999). Mixed oak stands in Pennsylvania demonstrated a 28% increase in mean diameter increase when fertilized with nitrogen (Ward and Bowersox 1970).

Black cherry (*Prunus serotina*) sapling stands in Pennsylvania increased in volume growth three times that of unfertilized saplings and height growth was about 125% higher with N+P and 65% higher with N alone (Auchmoody and Philip 1973). In another study, foliar concentrations of N, P and K as well as leaf weight also increased with added fertilizer (Auchmoody 1982). Growth responses to fertilizer were observed to be sustained for up to four to five years before they returned to that of untreated stands. Germination of dormant black cherry seeds contained in the seed bank were also found to increase with the addition of fertilizer (Auchmoody and Philip 1973).

Research has shown mixed results on tulip poplar response to fertilizer treatments. Several papers have shown dramatic increase in growth rates, such as Auchmoody (1989)

who found tulip poplar and oaks to increase in basal area by 150% and 75% on medium sites when fertilized, respectfully. Tulip poplar increased radial growth for seven to eight years and overall growth by 30%. However, Johnson et al. (1997) found no growth response of 10 year old tulip poplar to the application of N+P+K in the southern Appalachians.

Red maple significantly increased shoot growth in mature and seedling stages with fertilization, while root biomass was significantly reduced (Canham et al. 1996). On the coastal plain of NC, seven-year-old red maple receiving nitrogen treatments were found to grow twice as fast as those in the control and foliar analysis of these trees showed significant N responses as well (Newton 2003).

Relatively little research exists on silvicultural treatments for very young natural stands, and some attempts to control species composition and stocking early on through fertilization, particularly in young hardwoods, have failed (Kellison 1971). However, some studies indicate substantial opportunities to promote young stand development through fertilization and thinning. Researchers in Michigan (Huberty et al. 1998) fertilized a newly abandoned agricultural field yearly with nitrogen for seven years. The area responded vigorously to the treatment with 59 % more biomass in treated areas than in the than control plots, but species composition remained relatively unchanged. The Hardwood Research Cooperative at North Carolina State University has performed fertilizer trials on young and very young hardwood stands. Schuler (2005) conducted a trial in a 1-year-old regenerating clearcut in the NC Piedmont. Fertilization with nitrogen and phosphorus produced a decrease in stem density by greater than 50% over the control plots three seasons after treatment, with stem mortality was mostly restricted to those in

the lower height classes. Individual tree height and volume also increased with N+P treatments by approximately 21% and 50%, respectively, over control plots (Schuler 2005).

With little research done on the benefits of silvicultural treatments in very young naturally regenerated hardwood stands, there is also a lack of analysis to project growth rates and economic incentives of early site manipulation. Growth and yield projections and even-aged stocking guide development for natural hardwood stands has been limited to stands with a minimum mean diameter of 10 to 15 cm (McTague et al. 2006, Rausher et al. 2000, Schuler and Robison 2003, Auchmoody and Philip 1973), usually restricting these models to stands of at least five years old. This lack of reporting on early silvicultural intervention and growth response on very young stands has made it difficult to form growth and yield projections early in stand development.

Siry et al. (2004) suggested that an investment of up to US\$320/ha for early stand intervention in the first year of stand development may be profitable if species composition is improved and growth rates are raised by 33%. Also, as much as US\$122/ha could be spent if growth rates were increased by 17% (assuming an internal rate of return (IRR) hurdle of 7.3) (Siry et al. 2004). However, landowner surveys have indicated that NIPF owners in the South are unlikely to invest in timber production strategies that last 25 years or more unless the expected IRR was 10% or greater (Bullard et al. 2002). Using this 10% hurdle rate, as much as US\$184/ha could be spent on very young stands if growth rates increased 33% (Siry et al 2004). With the cost of fertilization in the U.S. South averaging about US\$137 per ha (Dubois et al 2003), this

projection indicates that manipulating forest nutrition in very young stands may be economically viable if appropriate increases in growth rates can be achieved.

STUDY OBJECTIVES

The objectives of this study were to evaluate the impact of broadcast N, N+P, N+P+K fertilization of a rising two-year-old naturally regenerated mixed species upland Piedmont stand in North Carolina on the following variables:

- species composition and stand density;
- total stand and individual species growth;
- growth of the largest stems; and
- stand growth projections.

METHODS

Site Description

This study was installed on the Hill Demonstration Forest in the Piedmont region (Durham County) of North Carolina. The forest is 972 hectares (ha) owned and managed by the Department of Forestry and Environmental Resources at North Carolina State University. The area has a mean annual temperature of 16°C with a 200 day growing season from April through October and experiences an average annual precipitation of

approximately 108 cm with precipitation evenly distributed throughout the year (www.nndc.noaa.gov, accessed 13, January 2006).

The study area (Hill Demonstration Forest Compartment B, Stand No. 54) is 3.63 ha. The predominant soil mapping unit at this site is a Georgeville silt loam (clayey, kaolinitic, thermic, typic hapludults), with 6 to 10 % slopes at a northeasterly aspect (Kirby 1976). This soil series is characteristically low in fertility and organic matter content. Site index is 22.9 m at 50 years for loblolly pine (*Pinus taeda*). The site was previously composed of a 33 year old loblolly pine stand with a mixed hardwood understory, having been planted to loblolly pine in 1969 at a 2.13 x 3.05 meter spacing. The stand was thinned in 2000 to an estimated basal area of 25 m² per ha and prescribed burned in March 1997 and January 2001. The remaining stand was salvage clearcut in early 2003 following heavy damage from winter ice storms and is currently surrounded by undamaged remnants of mature pine. Following the 2003 clearcut, the site was left to naturally regenerate to a mixed hardwood and loblolly pine stand. No stand treatments were imposed prior to the current study.

Experimental Design

The current study was installed in spring 2004 as a randomized complete block design with four blocks arranged along slope contours (Figure 1). Each block was equally divided into four plots, each receiving a different treatment. Plots were rectangular and measured 40.23 m by 22.12 m (0.08 ha).

Treatments

Treatments consisted of an untreated control (*Control*), an application of nitrogen fertilizer (*N Fert*), an application of nitrogen and phosphorus fertilizer (*N+P Fert*) and an application of nitrogen, phosphorus and potassium fertilizer (*N+P+K Fert*). Fertilizer was applied in early May 2004. Nitrogen was applied to all fertilizer treatment plots as ammonium nitrate (34-0-0) at a rate of 200 kg N per ha. Phosphorus was applied to all *N+P Fert* and *N+P+K Fert* plots as triple super phosphate (0-46-0) at a rate of 50 kg P per ha. Potassium was applied to all *N+P+K Fert* plots as muriate of potash (0-0-60) at a rate of 100 kg K per ha. Fertilizer was applied to treated plots in split applications by hand scattering in each direction (up-down and across the slope) to ensure equal coverage across the plots. At the time of initial treatment, the current stand was beginning its 2nd growing season following clearcutting. Residuals greater than 15 cm diameter at breast height (DBH) scattered throughout the study site were girdled with an axe and undiluted glyphosate herbicide sprayed into the cuts on 5 May 2004.

Tree Species Composition, Density and Size

A chronological pre-treatment inventory of the species composition and tree size was not possible due to time constraints. However, an initial inventory was performed on 21 June 2004 (five weeks after fertilizer was applied) using a single 2 m wide transect through the middle of each plot that extended 15 m in length. This inventory strip began and ended 2.5 m from plot boundaries to eliminate edge effect. Stem height was

measured (± 1 cm) to the point of growth cessation at the end of the 2003 growing season (visually apparent on all stems) to avoid 2004 growth and any treatment effects that might have emerged between early May and June 2004. Only stems greater than 60 cm tall at this point of measurement were recorded.

A second inventory was taken in late October 2005 at the end of the second growing season after treatment (stand age three). Inventory transects consisted of two 2 m wide strips per plot 15 m in length and beginning and ending at least 2.5 m from plot borders evenly spaced in the plot. Species, stem origin (seed or sprout), total height (± 1 cm) and ground-line diameter (*GLD*) (± 1 mm) measured at 1 cm above ground-line were recorded for every tree in the inventory strip over 60 cm tall. Origin (seed versus stump) and number of stems per stump were determined by visual observation. Volume index (volume trees₁ or VT₁) was calculated for all trees with the formula $VT_1 = GLD^2 \times \text{height}$. Total ground-line basal area (TBA_{GL}) was calculated with the formula

$$TBA_{GL} = \frac{\pi}{4000} * \frac{\sum GLD^2}{a}, \text{ where } a = \text{area in ha and } GLD = \text{ground-line diameter in}$$

centimeters. Stem density was calculated by summing the number of stems recorded in transects and expanding the data to estimate stems per ha.

Data was categorized for detailed analysis into the following components: hardwoods or evergreens, stem origin stems and by individual species. Overall dominant tree response to the treatments was assessed with the 16 largest trees regardless of species per combined inventory plot (equivalent to 98 trees per ha at the end of the rotation). The response of the seven most prevalent species or species groups to the treatments was assessed with the 10 largest trees per combined inventory plot. These categories were: red oak group (*Quercus falcate*, *Quercus rubra* and *Quercus coccinea*); white oak group

(*Quercus alba*, *Quercus phellos* and *Quercus montana*); sweetgum (*Liquidambar styraciflua*); tulip poplar (*Liriodendron tulipifera*); hickory (*Carya spp.*); red maple (*Acer rubrum*); and loblolly pine. Ten stems per species (or group) per combined inventory plot were chosen to ensure all species were equally represented and that all individual stems included were above mean height. Stem data were also segregated into five categories according to height: 60-100 cm, 101-200 cm, 201-300 cm, 301-400 cm and >401 cm.

Herbaceous Cover

The quality of herbaceous undergrowth was visually estimated and entered into one of three categories: *High*, *Medium* and *Low* for each major herbaceous species. The two primary understory species were blackberry (*Rubus spp.*) and muscadine grape (*Vitis rotundifolia*). The categories for blackberry quantity were based on approximate height: *High*- blackberry greater than or equal to 2 m tall, *Medium*- blackberry 1.0 to 1.9 m tall and *Low*- blackberry less than 1.0 m tall. Muscadine grape quantity was recorded by visual obscurrence of the ground below the grape when looking down through it: *High*-66-100 % obscurrence, *Medium*- 33-65 % obscurrence and *Low*- 0-32 % obscurrence. Broomsedge (*Andropogon spp.*), viburnum (*Viburnum spp.*) and other herbaceous vegetation were also present, but at low density. Herbaceous cover information was not subjected to statistical analysis.

Foliar Analysis

Foliar samples were collected on 10 May, 2006. Only the three most common species were sampled: tulip poplar, northern red oak (*Quercus rubra*) and loblolly pine. Leaf samples were collected from five trees per species per plot and were pooled. All sampled trees were taller than mean stand height. All loblolly pine was of seed origin and all tulip poplar and northern red oak were of sprout origin. Sampling techniques were performed as recommended by Jones et al. et al (1991) and A&L laboratories (Memphis, Tennessee 2006). Samples were from the sunlit lower third of the crown from tulip poplars and northern red oaks. Samples consisted of 4 cm cuttings starting at the apical bud and including bud, leaves, petioles and 4 cm of stem; all included in the analysis. Loblolly pine was sampled by collecting five fascicles per tree on lateral branches near the top of the trees. Foliar samples were then dried at 65°C and analyzed by A&L laboratories for the elements: nitrogen (N), phosphorus (P), potassium (K), magnesium (Mg), calcium (Ca), and sulfur (S).

Statistical Analysis

A two-way analysis of variance (ANOVA) was performed to determine treatment differences for each of the recorded variables. Data from the two transects per plot from the October 2005 inventory were combined to represent a single sample plot. Plot data was expanded to ha scale where appropriate (e.g. stem density, *GLD* basal area) before performing the ANOVA. The analyses included block effects, treatment main effects, and interactive effects (block x treatment). Due to unbalanced data on a per species level,

a “proc mixed” model (SAS 1999) was used for analysis of data for individual species or groups. Treatment responses for mean diameter, height, volume and foliar nutrients were assessed using this procedure. “Proc GLM” (SAS 1999) was used to analyze all data on a stand basis, namely total volume, *GL* basal area, stems per ha, percent of total stems and height class.

Where the treatment P-value was ≤ 0.15 , a multiple comparisons analysis via Tukey’s procedure with an alpha of 0.10 was used to separate treatment differences. A P-value of 0.15 was used for significance testing in the ANOVA due to the tremendous variation encountered in tree size within plots attributed to the young age of the stand and differences in stem origin and species. A smaller P-value was used during the multiple comparisons analysis to more conservatively evaluate treatment differences. All analyses were performed using SAS (1999). For all ANOVA applications, variance homogeneity was visually evaluated and, where necessary, transformations used to improve it as indicated for specific tests in tables and figures.

Height Growth Predictions

The potential impact of the treatments on stand response over many years was evaluated by applying the June 2004 and October 2005 inventory data for stem height to mixed species (hardwood and pine-hardwood) natural even aged site index (SI) models developed for the southeastern U.S. (McTague et al. 2006). Rotation length was modeled at 60 years, a typical age for most southern hardwood stands at harvest (Siry et al 2004). For the *Control* and the treatment yielding the largest growth response, SI was

determined from the height of the tallest 5 trees per combined transect plots (equivalent to 98 trees per ha). Using the June 2004 inventory data (stand age= one) and the October 2005 inventory data (stand age= three), the projected stand height at age five and continuing every five years through age 60 was calculated using the formula (McTague et

al 2006): $SI = 251 \left[\frac{H}{251} \right]^{\left(\frac{A}{25} \right)^{0.38509}}$, where SI = site index (base age 25); H = predominant

mean height of the 98 tallest trees per ha irrespective of species; and A = total stand age.

This formula was used to predict mean stand height over time under three scenarios, 1) where growth rate projections follow this formula unaltered, using heights recorded in the *Control* plots (Scenario No. 1), 2) where the growth rate increase impact of a treatment between age one and three continue unaltered for 60 years (Scenario No. 2), and 3) where the growth rate increase impact of a treatment at age one to three remained in place until age five, with the growth rate of treated plots then assuming the same magnitude as the control through age 60 (Scenario No. 3). A fourth scenario (Scenario No. 4) was modeled using the above formula for ages one to three to five, but with growth rates of treated plots thereafter decreasing gradually until both treatment plots and control plots achieved the same height, and thereafter the treatment plots then assumed the same growth rate as the control. This scenario utilizes the following formula for projected height in five year increments from age five until treatment heights equal control heights:

$S = 251 \left[\frac{H}{251} \right]^{\left(\frac{A}{25} \right)^{0.38509 + (0.1 * (R - A / R))}}$, where S = site index (base age 25); H = predominant mean

height (98 tallest trees per ha irrespective of species); R= rotation length; and A = total

stand age (personal comm. B. Bullock, NC State University, April 2006; modified from McTague et al 2006).

RESULTS

Total Stand - Species Composition and Stem Density

Across all blocks and treatment plots, the overall species composition of stems greater than 60 cm in height in June 2004 near the beginning of year two growth and the start of fertilizer treatments was: red maple (*Acer rubrum*) 25%, sweetgum (*Liquidambar styraciflua*) 13%, white oak group (*Quercus alba*, *Quercus phellos* and *Quercus prinus*) 11%, redbud (*Cercis canadensis*) 10%, hickory (*Carya ovata*) 10%, red oak group (*Quercus falcate*, *Quercus rubra* and *Quercus coccinea*) 10%, tulip poplar (*Liriodendron tulipifer*) 8%, blackgum (*Nyssa sylvatica*) 5%, black cherry (*Prunus serotina*) 3%, dogwood (*Comus florida*) 2%, and sourwood (*Oxydendrum arboreum*), sassafras (*Sassafras albidum*), American holly (*Ilex opaca*) and loblolly pine (*Pinus taeda*) each about 1%. Only one evergreen stem >60 cm was recorded (Table 1). There were however a large number of loblolly pine seedlings observed that were not recorded due to their small size.

In October of 2005, two full growing seasons after the initial treatments, the overall species composition and percent of stems by species across all blocks greater than 60 cm in height at the end of the third growing season was: loblolly pine 29%, sweetgum 16%, red maple 13%, red oak group 12%, tulip poplar 10%, hickory 6%, white oak group

5 %, and blackgum, black cherry, dogwood , holly, redbud, sassafras, sourwood, and winged sumac (*Rhus copallina*) comprised a total of 11%. There were no statistical differences in the density of stems greater than 60 cm tall among treatments in the June 2004 or October 2005 inventories (Tables 1 and 2). The overall average density of stems over 60 cm tall in October 2005 was 40,000 per ha. There was no blocking effect for stem density.

Stems were grouped into two broad species categories, 1) deciduous hardwoods and, 2) evergreens (loblolly pine and American holly). The percent of evergreen stems per ha two growing seasons after treatment was significantly higher in the *Control* (38%) and lower in the *N+P* treatment (15%) (Table 2). *N* and *N+P+K* treatments had intermediate evergreen percent representation and were not significantly different than the *Control* or *N+P* treatments. There was a significant block effect for percent representation of evergreen stems, with relatively more evergreens in plots with upper slope positions. Hardwood density and percent of total stems were not statistically different among treatments, although the trend was opposite that of evergreens.

Stems were also categorized based on apparent seed versus stump origin. Plots receiving *N+P* treatments had lower percentage of seed origin trees, approximately 28% (10,000 stems/ha), than other treatments, which had about 50% seed origin stems (17,000 to 22,000 stems/ha) (Table 2). Stump sprouts accounted for approximately 72% (24,000 stems/ha) of stems in *N+P* plots and approximately 50% (20,000 stems/ha) in all other treatments. *N+P+K* treatments had the lowest percentage of stump sprouts with approximately 16,000 per ha.

Stems were further categorized by the seven most common species: hickory, loblolly pine, red maple, red oak group, sweetgum, tulip polar and white oak group. Of all the species, only hickory, loblolly pine and sweetgum had significant density and percent representation responses among treatments (Table 2). Hickory stem density in *N* plots was approximately 2,800 stems per ha and in *N+P* plots was approximately 1,200 per ha. Hickory percent of stand did not significantly differ among treatments. The number and percent of loblolly pine stems per ha was the same as indicated previously for all evergreens, given that loblolly pine represented approximately 99% of all evergreen stems. Sweetgum density varied significantly between the *N+P* treatment and all other treatments combined, comprising approximately 41% of total stems (15,000 stems/ha) in *N+P* treatments and approximately 7% (3,000 stems/ha) in all other treatments. Red maple, red oak group, tulip poplar, and white oak group stem density and percent of stand were not significantly different among treatments.

Total Stand - Groundline Diameter (GLD)

Mean *GLD* for all stems combined was significantly greater in *N+P* and *N+P+K* treatments (Table 2), and was 1.4 cm in *Control* plots, 2.1 cm in *N+ P* treatments and 1.9 cm in *N+P+K* plots. The mean *GLD* for all hardwood stems was 30% greater in *N+P* plots (Table 2). Trees in *Control* plots had a mean *GLD* of 1.7 cm in *Control* plots, while in *N+P* plots it was 2.2 cm. Evergreen *GLD* was 37% greater in the *N+P+K* plots (1.6 cm) than in *Control* plots (1.2 cm). *GLD* in other treatment plots for hardwoods and evergreens were intermediate to these extremes and not significantly different from the others (Table 2).

Seed origin stems had GLD that were 21% larger in *N+P* and *N+P+K* treated plots (2.3 cm in both) than seed origin stems in *Control* and *N* plots (Table 2). The mean GLD of stump origin stems did not statistically differ among treatments.

Individual species *GLD* growth response varied by treatment (Table 4). Hickory GLD in *N* and *N+P+K* plots (1.9 cm for both) were 27% smaller than in *Control* plots (2.6 cm). Hickory GLD in *N+P* plots (2.3 cm) was not significantly different from the *Control*. Loblolly pine *GLD* was the same as indicated previously for all evergreens (Table 2). Tulip poplar GLD in *N+P* treated plots was a 115% greater (4.3 cm) than in *Control* plots (1.4 cm), with GLD intermediate in the other treatments. Red maple, red oak group, sweetgum and white oak group *GLD* did not differ among treatments.

Total Stand - Height

Mean tree height among plots in June 2004 before treatment effects were recorded did not significantly vary among block or plots (Table 1). During the October 2005 inventory, mean height varied significantly among treatments (Table 2), with stems in *Control* plots (127.8 cm) being 67% taller than in *N+P* plots (212.4 cm). Mean height in plots receiving *N* and *N+P+K* treatments were intermediate and did not statistically differ among treatments.

Hardwoods increased in height by as much as 50% in *N+P* (232.6 cm) and *N+P+K* (208.8 cm) plots as compared to *Control* plots (155.6 cm) (Table 2). Evergreen mean height was about 28% larger in *N+P+K* (132.8 cm) and *N+P* (127.8 cm) plots than

in *Control* (103.3 cm) plots. *N* plots did not differ among treatments for either category of trees.

Seed origin stem height was increased by as much as a 45% in *N+P* plots (237.6 cm) over *N* (214.8 cm) and *Control* plots (164.2 cm) (Table 2). *N+P+K* plots did not significantly differ from other treatments. Stump sprout mean height increased by as much as 46% in *N+P* (157.7cm) and *N+P+K* (136.5cm) plots than in *Control* plots (108.0cm). *N* plots did not significantly differ from the *Control*.

The mean height of all hickory stems after two growing seasons did not differ among treatments or blocks (Table 4). Loblolly pine mean height among treatments was the same as indicated previously for all evergreens (Table 4). Red maple mean height was 44% larger in the *N+P* plots (201.1 cm) than in the *Control* plots (140.6 cm). Its height in *N* and *N+P+K* treatments did not differ from other treatments. The red oak group had a 32% increase in height in *N+P* plots (227.3 cm) over both the *Control* (171.1 cm) and *N+P+K* (173.7 cm) plots, while in the *N* plots it did not differ among treatments. Sweetgum in plots receiving *N+P* were 51% taller (238.8 cm) than those in *Control* plots (157.6 cm), while in *N* and *N+P+K* plots heights did not significantly differ from the control. Tulip poplar height in the *N+P* plots (324.7 cm) was 103% taller than in the *Control* plots (159.1 cm) while in *N* and *N+P+K* plots it did not significantly differ among treatments. Height of trees in the white oak group height did not significantly differ among treatments.

Total Stand - Stems by Height Class

Stems were put into five categories based on height, and the percent stems by class varied significantly with fertilizer treatment (Table 3). Approximately 44% of the stems in the *Control* plots fell into the 60-100cm category versus 20% in *N*, 22% in *N+P+K* and 12% in *N+P* plots. Stem density in the 101-200 cm class was not significantly different among treatments and accounted for approximately 30% of all stems. Approximately 14% of *Control* plot stems were in the 201-300 cm class compared to about 32% in treated plots. *N* and *N+P* treated plots had 14% of their stems in the 300-400 cm class, while *N+P+K* plots had 8.5% and *Control* plots had 1.6 % of their stems in this class. Seventeen % of the stems in *N+P* plots were in the >400 cm class, while the *Control*, *N* and *N+P+K* plots had 4.7, 0.02, and 10 % of their stems in this class, respectively.

Total Stand - Mean Tree Volume

Mean tree volume or VT_1 for all stems combined varied significantly by treatment (Table 2). *Control* plots averaged 526.8 cm^3 and in *N* plots averaged 1176.8 cm^3 . *N+P+K* and *N+P* plots had a mean tree volume of 1674.5 cm^3 and 2048.0 cm^3 (290% larger than in *Control* plots), respectively.

Mean tree volume for hardwood trees in *N+P* plots was approximately 2500 cm^3 compared to 864 cm^3 in the *Control* plots (189% larger than the *Control*) (Table 2). Mean tree hardwood volume in *N* and *N+P+K* plots were intermediate and did not significantly differ from the other treatments. Mean evergreen tree volume in *N+P+K* plots (571.5

cm³) was significantly greater than in the *Control* plots (256.2 cm³) (119% larger than in the *Control*). Mean evergreen tree volumes in *N* and *N+P* plots were intermediate and did not significantly differ from the others.

The mean tree volume of seed origin trees in *N+P* plots was approximately 2584.1 cm³ compared to 1048.9 cm³ in the *Control* (146% larger than in the *Control*) (Table 2). Mean tree volume was intermediate and did not significantly differ between *N* and *N+P+K* plots. Mean tree volume of stump sprouts increased with the addition of *N+P*, where it had a mean volume of 883.4 cm³, while sprout origin trees in the *Control* plot exhibited an mean volume of 243.1 cm³ (263 % larger than in the *Control*). Mean sprout origin tree volumes in *N* and *N+P+K* plots were intermediate and did not significantly differ from the others.

Mean hickory tree volume had an increase in *N+P* plots over *Control* plots. This species had a mean tree volume of approximately 2,300 cm³ in *N+P* plots compared to approximately 1,700 cm³ in the *Control* plots (32 % larger than the *Control*). Mean hickory tree volume in *N* and *N+P+K* treatments did not significantly differ. Loblolly pine mean tree volume was the same as indicated previously for all evergreens (Table 2). Tulip poplar had a mean volume of 9858.2 cm³ in *N+P+K* treated plots , 9698.1 cm³ in *N+P* treated plots, 4456.1 cm³ in *N* treated plots and 1557.5 cm³ in the *Control* plots (as much as 225% larger than in the *Control*). Red maple, red oak group, sweetgum and white oak group volume was not significantly different among treatments (Table 4).

Total Stand - GL Basal Area

There was no significant difference in overall *GL* basal area between *Control* and fertilizer treated plots (Table 2), with an overall average *GL* basal area across all treatments of approximately 2,500 cm².

Hardwood *GL* basal area was approximately 903.5 cm² in *Control* plots, 1238.2 cm² in *N* plots, 984.6cm² in *N+P+K* plots and 1915.8cm² in *N+P* plots (127% increase over the *Control*). Evergreens did not significantly differ in mean *GL* basal area among treatments.

Seed origin stems did not significantly differ in *GL* basal area by treatment. *GL* basal area of all stump sprouts was approximately 535 cm² in *Control* plots and 1416cm² in *N+P* plots (170% increase over the *Control*), while *N* and *N+P+K* *GL* basal area were intermediate and did not significantly differ among treatments.

Sweetgum *GL* basal area was 651.8cm² in *N+P* plots and 44.0 cm² in *Control* plots (Table 4), while in *N* and *N+P+K* plots it did not differ from *Control* plots. Hickory, loblolly pine, red maple, red oak group, tulip poplar and white oak group *GL* basal area did not significantly differ among treatments for stump sprout origin trees.

Total Stand - Volume per Hectare

Volume per ha increased from 65 m³ in *Control* plots to 169 m³ in *N+P* plots (a 160% increase), while in *N* and *N+P+K* treated plots it did not statistically differ from the *Control*.

Volume per ha of hardwoods was approximately 164 m³ in *N+P* plots and 52 m³ in the *Control* plots (a 217 % increase) (Table 2), while in *N* and *N+P+K* plots it did not significantly differ among treatments. Evergreen stems did not significantly differ in volume per ha among treatments.

Seed origin stems did not significantly differ in volume per ha among treatments. Volume per ha of sprout origin trees in *N+P* stands was 147 m³ versus 47 m³ in *Control* plots (a 212 % increase)(Table 2), while in *N* and *N+P+K* plots it did not differ among treatments. Hickory, loblolly pine, red maple, red oak group, tulip poplar and white oak group were not individually analyzed for total volume.

Total Stand - Herbaceous Cover

Herbaceous understory growth was noticeably higher in fertilized plots than untreated plots (Figure 3). Both muscadine grape and blackberry increased as fertilizer elements were added. Herbaceous cover in *N* plots was similar to *Control* plots, while *N+P* plots had noticeably higher cover of these species. *N+P+K* plots had still higher cover. Muscadine grape vines had a heavy presence in *N+P+K* plots, often girdling and killing woody plants.

Dominant Trees - Size

The species of 16 largest trees per plot varied among treatments and plots, and overall were comprised of blackgum, black cherry, dogwood, hickory, loblolly pine, red

oak group, red maple, redbud, sweetgum, tulip poplar and white oak group. Treatment plots receiving $N+P$ had *GLD* of the 16 largest trees 36% larger (5.2 cm) than in *Control* plots where the 16 largest trees had a mean *GLD* of 3.8 cm. *GLD* in N plots was 4.6 cm and in $N+P+K$ plots it was 4.9 cm. There was a 56% increase in height between *Control* plots (254.3cm) and $N+P$ plots (396.7cm) for the 16 largest trees. For these trees, mean tree volume increased 208% in $N+P$ plots (13495 cm^3) as compared to mean tree volume in *Control* plots (4383 cm^3). Volume per ha of these trees increased 207% between *Control* plots (0.07 m^3) and $N+P$ plots (2.2 m^3), while in N and $N+P+K$ plots it did not significantly differ from the *Control*.

When the ten largest trees per species per plot (from the two October 2005 inventory transects per plot) were considered (Table 5), hickory, loblolly pine, red maple, tulip poplar and white oak group had no *GLD*, height or volume differences among treatments. For these ten trees, red oak group height increased 33% in $N+P$ plots (235.3 cm) over *Control* plots (178.1 cm), while in N and $N+P+K$ treated plots it did not differ. Red oaks did not significantly differ across treatments in *GLD* or volume.

Foliar Analysis

Foliar N concentrations did not differ among treatments for large trees in the red oak group (range 2.26 to 2.45 %) or loblolly pine (range 1.4 to 1.8 %), but differed significantly among treatments in tulip poplar (*Control* = 2.3% to $N\text{ Fert}$ = 2.6%) (Table 6). Foliar P concentrations were the same across treatments for large red oaks (range 0.22 to 0.23 %), but differed significantly in large loblolly pine (*Control* = 0.23% to $N+P+K$ =

0.31%) and tulip poplar ($Nfert = 0.22\%$ to $Control = 0.26\%$). Foliar K concentrations were the same across treatments for red oak group (range 1.02 to 0.91 %) and loblolly pine (range 1.09 to 1.31 %), but differed significantly in tulip poplar ($Control = 1.9\%$ to $N+P+K = 1.66\%$). Foliar Ca concentrations did not differ among treatments for red oaks (range 0.43 to 0.53 %), loblolly pine (range 0.23 to 0.29 %) or tulip poplar (range 0.70 to 0.93 %). Foliar Mg concentrations did not differ among treatments for red oaks (range 0.24 to 0.26 %), loblolly pine (range 0.13 to 0.17 %) or tulip poplar (range 0.30 to 0.35 %). Foliar S concentrations did not differ among treatments for red oaks (range 0.17 to 0.19 %), loblolly pine (range 0.13 to 0.17 %) or tulip poplar (range 0.20 to 0.22 %).

Height Growth Predictions

Projected height growth over time was estimated for the four scenarios using only *Control* and $N+P$ treatment data, as the N and $N+P+K$ plots were generally intermediate and this analysis was limited to the extreme growth responses. The *Control* (Scenario No. 1) was estimated to have an SI 25 of 13.7 m and to reach a height of 22m at 60 years. Under Scenario No. 2 assumptions, $N+P$ treated plots were estimated to have an SI 25 of 16.8 m and are predicted to reach the height of the *Control*, at 60 years, at age 40 (Figure 4). Under Scenario No. 3 assumptions, $N+P$ treated plots were estimated to have an SI 25 of 14.6 m and would reach the height of the *Control*, at 60 years, at age 55 (Figure 5). Under Scenario No. 4 assumptions, $N+P$ treated plots were estimated to have an SI 25 of 15.2 m and were predicted to reach the height of the *Control*, at 60 years, at age 55 (Figure 6).

DISCUSSION

Past research has reported natural hardwood stands to be responsive to silvicultural treatments at a variety of ages. Increased availability of nutrients, particularly nitrogen and phosphorus, through fertilizer application has been found to be a viable method of accelerating stand development and increasing growth on many sites (Auchmoody 1982, Beckjord et al. 1983, Demchik and Sharpe 1999, Dunn et al. 1999, Newton et al. 2001, Schuler and Robison 2006). The results of this study support these findings and demonstrate the use of fertilizer as an effective early intervention technique in NC upland Piedmont mixed species stands.

In the current study, fertilizer treatments were found to have a significant impact on mean stand *GLD*, height and volume (Table 2). When mean height measurements at age one, taken before fertilization impacts, were compared to mean height measured two years later, there was a significant difference in growth rates with *N+P* and *N+P+K* treatments taller than the *Control* (Figure 2). Trees in the *Control* plots gained 39.4 cm in height over two growing seasons while those in *N+P+K* treated plots gained 99.9 cm and in *N+P* plots gained 129.8 cm in height during this time. Treatments consisting of *N+P* and *N+P+K* increased mean *GLD* by as much as 48% and average height growth by as much as 66%. *N+P* treated plots had mean tree volume four times larger than in the *Control* and total stand volume was 290% larger than in the *Control*. These findings indicate that the overall growth of the stand can be accelerated and that N and P in combination are limiting on this site on a stand basis.

The height distribution of trees was heavily influenced by fertilizer treatments (Figure 2), with treated plots containing significantly more large stems. Forty % of stems in *Control* plots were less than one meter in height and only 6% were over 3 m. Stems over 3 m tall comprised over 30% of stems in *N+P* treated plots and over 18% in *N+P+K* plots. In *N* plots, stems over 3 m tall comprised only 13% of all stems. In young even-aged stands, taller trees are more likely to thrive and later form the mature forest canopy than smaller trees. These findings indicate that increasing nutrient availability in this stand through fertilization accelerated stand development, a finding supported by Schuler and Robison (2006) in a study on the same forest.

Evergreens, almost exclusively loblolly pine, demonstrated a positive response to fertilizer treatments (Table 2). Height, *GLD* and volume of *N+P+K* treated pines increased by 30, 45 and 100 % over the *Control*, respectively, while height of *N+P* plots increased by 25% over the *Control*. Plots receiving N alone did not differ from the *Control*. Loblolly pine stem and crown growth has been documented to be highly responsive to fertilizer additions (Albaugh et al. 2004, Martin and Jokela 2004, Allen 2000). When fertilized with N and P, both alone and in combination, Sword et al. (1998) reported a reduction in pine foliar K concentrations that limited stem growth. In the current study where K was added along with N and P, pine growth was greater than with *N+P* only, perhaps by alleviating the K effect that Sword et al. reported.

Deciduous hardwoods in this study also responded vigorously to *N+P* and *N+P+K* fertilization (Table 2). Only the *N+P* treatment produced a significant growth difference over the *Control*. Hardwoods receiving *N+P* fertilization responded with increases in mean *GLD*, height and volume of 29, 150 and 200 %, respectively. Total

stand volume and stand basal area were also increased by over 200% with $N+P$ addition. Past research has shown that many hardwood species are very responsive to N and P additions, but do not respond to potassium addition on many sites (Phares 1971, Lamson 1978, Auchmoody 1982, Burns and Honkala 1990), a finding supported by the current study. However, there are some sites where K additions may be useful for specific hardwoods (Coleman et al. 2003, Jones et al. et al. 1991).

Stem density was reduced with the addition of fertilizer, but the effects were not statistically different among treatments (Table 2). It may be too early in the stand's development to measure statistically significant competition induced mortality in trees over 60 cm tall. Schuler (2005) reported a significant thinning effect in a similar study in the same forest after the second and third growing season, with mortality mainly occurring in trees less than 20 cm in height. The current study did not record stems under 60 cm in height, but there was a noticeable visual reduction of stems less than 60 cm in $N+P$ and $N+P+K$ treated plots during the two years of this study. This suggests that the stem recruitment phase of regeneration was complete.

Stems density was observed to increase for hardwoods and significantly decrease for pines on sites fertilized with $N+P$ (Table 2). There was a significant block effect found for pine density, with more found at higher slope locations. This is attributable to the drier microclimate found higher on the slope, where loblolly pine was probably better able to compete for resources (Burns and Honkala 1990). Despite the block effect, the trend observed was a reduction in pine density with $N+P$ treatments, with pine density as much as 66% lower in the $N+P$ plots than in the *Control*. This suggests that the $N+P$ fertilizer application gave hardwoods a competitive advantage over loblolly pine, a

known pioneer species on low fertility sites. However, surviving pines grew better in the $N+P$ plots (Table 4) and will most likely become one of the dominant species in the mature forest as seen in many mixed pine-hardwood stands (Steinbeck and Kuers 1996). This fertilizer effect on pine density could be a valuable silvicultural tool in manipulating early stand development to influence final species composition.

While overall hardwood stem density was observed to increase with $N+P$ treatments, tulip poplar and oak species were prevalent across this site, accounting for approximately 10% and 12% of the overall stand density. Studies have shown that tulip poplar germination is stimulated by controlled burning by exposing mineral soil (Shearin et al. 1972) and that oak regeneration is resistant to fire (Abrams 1992). The stand in the current study was burned twice during its previous management, in 1997 and 2001, and this may have influenced species density in the current study.

Sprout origin stem density increased by 30% with the addition of $N+P$. Height and volume for these stems also positively responded to $N+P$ (45 and 260 % increase over the *Control*). The well established root systems of this category of trees are probably able to capture more of the added nutrients, allowing for larger growth. Other studies have demonstrated increased stump sprout vigor with the amelioration of soil nutrients (Demchik and Sharpe 2000) and this study corroborates this pattern. The increase in hardwood GL basal area may be positively correlated to the increase in sprout origin stems with nutrient addition, as many of the hardwoods recorded were of sprout origin (Table 2).

Stems of seed origin decreased by 46% with the addition of $N+P$, likely due to the increased competition for resources from accelerated sprout origin stem growth.

However, stems of seed origin in $N+P$ plots did increase in *GLD*, height and mean tree volume (21, 44 and 146 % over the *Control*, respectively). These results follow the trend of past research on stems of seed origin receiving fertilizer treatments in very young stands (Schuler and Robison 2006).

Hardwood individual or group species density and growth responses also varied with fertilizer treatment (Table 4 and Table 7). Overall, hardwood species responded with increased height and volume growth to $N+P$ treatments. There was a small increase in *GLD* growth, but it was not significant. The increase in height growth relative to *GLD* growth may be due to allocation of resources to stem length in response to intense competition for light in high density early stand development (Oliver and Larson 1996).

Hickory doubled its mean volume with the addition of $N+P$, but the number of stems per ha decreased by about 50% with the same treatment (Table 4). Hickory, a relatively slow growing tree (Burns and Honkala 1990), may have experienced high mortality due to competition from vegetation that responded more vigorously to the addition of nutrients.

Red maple increased in height by 30% with $N+P$ treatments, but did not respond in *GLD* or volume growth (Table 4). This is consistent with the generalized growth pattern of red maple, a species that predominantly uses most of its resources for height growth early in the season and does not begin to put on significant *GLD* growth until older (Burns and Honkala 1990). Studies performed on slightly older red maple saplings, ages 7 to 11, found significant increases in *GLD* and height growth (Newton 2003).

Trees of the red oak group had a 32% height increase to $N+P$, but no significant *GLD* or volume increase. Young red oak may be allocating its resources to height growth

in order to compete for light and may not add significant *GLD* growth until later. Lamson (1978) recorded a 20% increase in older sawlog size red oak basal area with the addition of P fertilizer.

Sweetgum increased height growth by 50% with the addition of *N+P* relative to the *Control*, but did not respond with an increase in *GLD* or volume (Table 4). Past research in sweetgum plantations using a Diagnosis and Integrated System analysis found yields to be positively correlated with potassium availability and recommend that potassium fertilization application be investigated for the species at a N:K ratio of less than one (Coleman et al. 2003). The N:K ratio of fertilizer applied to *N+P+K* treatments in the current study was 2:1, and this may have created a potassium imbalance. However, sweetgum did dramatically increase in density in *N+P* plots where it comprised 41% of the stems versus 4% in the *Control*. This dramatic increase in density could be attributed to increased sprouting vigor caused by added nutrients.

Tulip poplar responded to fertilization by increasing, *GLD*, height and volume growth. The application of *N+P* increased *GLD* by 200%, height by 100% and volume by 500%. This species is well known for its vigorous response to fertilizer and studies in young and middle aged natural stands containing tulip poplar have shown similar results (Johnson et al. 1997, Schuler and Robison 2006).

The white oak group did not respond to any of the fertilization regimes applied. Larger, older white oaks have been found to respond to fertilizer treatments, increasing by as much as 48% in basal area with the application of N and P to pole sized trees (Graney and Pope 1978). In the control plots white oaks grew slower than most of the

other common species. Therefore, even with fertilization their capacity to capture site resources under the degree of competition present was restricted in this age class.

Fertilizer treatments of the 16 largest trees per plot (regardless of species) were found to have a significant impact on *GLD*, height and volume (Table 2). *N+P* treatments increased *GLD*, height, and mean tree volume of the 16 largest trees by 36, 56 and 208 % over *Control* plots, respectively. *N* plots had a 47% increase in height over the *Control* for these trees, but did not elicit a growth response in *GLD* or mean tree volume. These findings indicate that the overall growth of the stand was accelerated, for both dominant and minor stems, and that N and P in combination are limiting on this site on a stand basis.

When the response of the 10 largest trees per common timber species per plot were evaluated, there were no size differences found across treatments, except for the red oak group, where the *N+P* treatment enhanced height growth. Red oak has a high resource demand (Graney and Pope 1978) and therefore may exhibit a greater response to resource amelioration. However, red oak showed no treatment differences in foliar concentrations of N, P, K, Ca, Mg, or S (Table 6). Increased height growth of tall representatives of this species may be attributed to the availability of resources other than nutrients, due to the impact of fertilization on the surrounding stems. Enhanced competition for light from other species responding to N and P addition or increased water availability caused by a reduction of stems in *N+P* plots could have induced accelerated height growth. The large red oaks sampled were marginally deficient in foliar calcium, 0.05% below the recommended range (0.55 to 0.83 %) (Jones et al. et al. 1991) but were not deficient in other elements. Past studies have found that the application of

calcium lime to red oak stands can benefit to stem growth (Demchik and Sharpe 2000). Lime in addition to $N+P$ in the current study may have generated a larger growth response. Soils in the Georgeville series, on which the trees in the current study grew, are generally acidic (pH of about 5.2 to 5.7) (Kirby, 1976) and lime may have helped to ameliorate this effect and make other nutrients more available.

The lack of treatment response for large stems of all other common timber species could be attributed to their pre-existing root systems. Trees originating from sprouts have extensive preexisting root systems and are more able to capture below ground resources than smaller stems of seed origin (Zimmerman and Brown 1971). In the case of pines, which do not regenerate from sprouts, growth rates may be a result of site adaptation and genetic interaction in new seedlings (McKeand and Allen 2005). It is important to note that these large common timber trees do not represent the whole stand's response to treatments. Smaller trees from seed origin or sprouts clearly benefited from the amelioration of nutrients (Table 2).

The foliar nutrient data may also be partly explained by the size and origin of the trees sampled. While tulip poplar and loblolly pine foliar elements exhibited small treatment differences, they had adequate foliar concentrations for all of the elements analyzed (Table 6). Therefore these trees apparently already had sufficient access to nutrients and this would also help to explain the general lack of size growth response in these large trees (Table 5). Past research on a similar site recorded N, P and K significant foliar differences in very young tulip poplar of seed origin two growing seasons after fertilizer treatment (Schuler 2005). Foliar samples in the current study were from sprout origin tulip poplar. This suggests that fertilization can ameliorate nutrient deficiencies

and promote accelerated growth in stems without the advantage of older well developed root systems.

Lack of compelling treatment differences in foliar nutrient concentrations could also be due to the sampling method. The methods chosen were recommended for large scale horticultural producers and for tulip poplar and red oak included stem pieces. This may not have provided adequate control of the of the leaf material to allow differences to be detected. In the current study, samples were collected in May due to time constraints and elemental variation may have been high as this is early in the growing season. Generally foliar sample collection for nutrient evaluation is recommended in late summer or early fall. However, in an attempt to minimize foliar nutrient variation in samples, all samples in the current study were taken on the same day. This narrow time period of sampling should have provided reasonable means to compare foliar nutrients across treatments.

Nitrogen as a sole treatment did not elicit significant growth responses or changes in species composition or stem density as compared to the *Control* (Table 7). This suggests that for significant growth responses, N must be applied with P to overcome baseline nutrient limiting factors on this site. This is contrary to some studies that have found nitrogen alone to be the primary limitation in forest soils (Fisher 1984, Powers et al. 1990). However, P alone was not evaluated in the current study and conclusions about the relative importance of N and P cannot be fully drawn. Older stands have demonstrated larger responses to N and P together than as sole elements (Auchmoody 1989). Further research on very young natural stands with the sole application of N, P

and K along with combinations of these elements at varying rates would further explain the role of these elements on early stand development.

Study plots that received an application of $N+P+K$ had a noticeable increase in muscadine grape vine and blackberry. The presence of these weeds may compete with desired forest tree species for available nutrients, sequestering them in their biomass and denying them to other plants. Mixed hardwoods have been found to respond substantially to herbaceous control in young stands (Romagosa and Robison 2003). Grape vine can be particularly damaging, either girdling trees with tendrils or causing malformed stems by restricting the upward growth. As much as 17% of clearcut areas have been observed to be completely covered by grapevine in the Appalachians (McGee and Hooper 1970). Furthermore, it can often take as many as 14 person-hours per ha to remove grape vines from trees before harvesting, adding further costs to management (Smith and McCay 1979). The horticultural literature indicates that both grape and blackberry require phosphorus and potassium for optimum growth and fruiting (Prowling et al. 2003, Pritt and Handley 1989). Furthermore, a study in Michigan showed an increased abundance of understory forest weeds with increased soil fertility and light (Abrams and Dickmann 1983). Fertilizing soon after even-age regeneration harvest no doubt provides optimal light and nutrients for undesired weed species.

Growth projections developed using site index models from McTague et al. (2005) and the various assumptions defined in the Methods section of this study give an estimate of a five to 20 year reduction in the length of time required for mean stand predominant height to reach the mature height of the *Control* (22 m). Auchmoody (1982) suggested that accelerated growth rates from fertilization last for three to five years, after

which the stand returns to similar growth rates as unfertilized areas. He also predicted a 20% increase in volume or a five year decrease in rotation age due to accelerated growth three to five years after fertility treatment, after which the nutrients added are exhausted and growth rates return to that of untreated areas. Findings in the current study corroborate view.

In all of the fertilized stand growth projections, the number of years necessary to reach the mature height of trees in the *Control* at age 60, (perhaps about the time for an even-aged final harvest (e.g., Siry et al. 2004), has been decreased by fertilizer addition at the beginning of year 2. Scenario No. 2 predicts a 33% decrease in the time required to reach a predominant mean height of 22 m from 60 to 40 years. Scenario No's. 3 and 4 predict an 8% decrease (5 years) in the time required to reach 22 m stand height. The outcome of Scenario Nos. 3 and 4 is more probably with only one fertilization treatment early in stand development. If additional subsequent fertility or density reduction treatments were imposed, then higher and/or more sustained increases in growth, such as projected in Scenario 2, would be more probable.

The measured and projected increases in growth in the current study could have substantial economic advantages, if all the costs and benefits provide for an internal rate of return (IRR) better than can be achieved under the *Control* condition. Siry et al. (2003) calculated that typical mixed hardwood stands across the South have an IRR of about 7% without any silvicultural interventions. This IRR would have to be exceeded, perhaps substantially, for landowners to adopt an approach that included early stand fertilization. Stand level fertilization may cost about US\$137 per ha (Dubois et al. 2003), which is a substantial sum to be invested at a very early age. Bullard (2002) surveyed

private landowners in the Southeast and found that most would be reluctant to invest in any natural stand intervention if the IRR was predicted to be less than 10% in timber investments lasting over 25 years. Despite these cautions, the assumptions and analyses of Siry et al. (2004) suggested that circumstances could be envisioned where silvicultural intervention in very young natural stands could enhance growth and economic value.

There are a number of factors which are not accounted for in the current study which preclude an economic analysis projection, including lack of information to calculate volume and growth projections, and uncertainty about species composition changes and species' timber values in the future. Results from the current study suggest that such changes, as well as accelerated stand growth, are likely to occur as a result of fertilization. Published growth and yield projection models and even-aged stocking guides that could apply to mixed species natural stands like the one studied here are limited to stands with mean *GLD* of about 10 cm and/or minimum age of about 5 years (McTague et al. 2006, Rauscher et al. 2000, Schuler and Robison 2006). This makes it difficult to predict the growth of very young stands and to conduct credible economic analyses.

The results of the current study indicate that substantial density and growth gains can be readily achieved in these kinds of stands, but that species composition and the longevity and value of these changes cannot yet be predicted with confidence. Continued research over longer periods of time will be important.

CONCLUSION

The objectives of this study were to evaluate the impact of broadcast N , $N+P$, $N+P+K$ fertilization (at a single rate per treatment) on stand density, species composition, and total stand and individual species growth in a rising two-year-old naturally regenerated mixed species upland Piedmont stand in North Carolina. Two growing seasons after treatment, stem density (≥ 60 cm in height) did not differ among treatments. Sprout origin stems increased and seed origin density decreased with the addition of $N+P$. Loblolly pine and hickory density decreased significantly with $N+P$ fertilization, while sweetgum density increased. Loblolly pine density showed a blocking effect likely caused by the drier microclimate of uphill plots, but the overall trend was a reduction in pine stems in plots receiving $N+P$ fertilizer. The density of red and white oaks, red maple and tulip poplar were unaffected by treatments. This indicates that stand composition and stem origin can be manipulated at an early age by the addition of fertilizer on this site.

On a total stand basis, $N+P$ fertilization had a significant positive impact on GLD, height, mean tree volume and volume per ha for stems of both seed and stump origin. All hardwood species had an increase in growth with $N+P$ addition. Red maple, red oak group and sweetgum all increased in height, hickory increased in GLD and volume, and Tulip poplar increased in GLD, height and volume with the addition of $N+P$. Loblolly pine responded positively to $N+P+K$ fertilizer in GLD, height and volume growth. N fertilization alone produced no significant growth increases compared to the *Control* for any category of trees, with the sole exception being a height response of the 16 largest

trees per plot. This indicates that fertilizer treatments of $N+P$ and $N+P+K$ increased height growth for both pines and hardwoods, while $N+P$ increased diameter growth of hardwoods and but $N+P+K$ was required for diameter growth of pines to be enhanced.

The 16 largest trees per plot (equivalent to 988 trees per ha, regardless of species origin) followed the same trend as the total stand with GLD, height and mean tree volume growth positively responding to $N+P$ fertilization. However, growth of the 10 largest trees per species per plot did not generally respond to fertilizer treatments, with only trees in the red oak group increasing in height growth with the addition of $N+P$. Foliar concentrations of the largest loblolly pine, red oak and tulip poplar showed slight treatment differences, but were not at levels indicating deficiency. The general lack of foliar nutrient response to treatments in these large trees could be attributed to extensive root systems and their ability to capture more below ground resources than small stems, regardless of the treatment.

This study indicates that stand composition and growth on this site can be manipulated at a very young age through fertilizer treatments. Stand composition can be influenced toward a hardwood or pine majority with the addition or delay of $N+P$ fertilizer, and fertilization with the compounds and rates used here benefit the overall stand more so than the growth of individual large stems within the context of many thousands of small stems. Overall stand volume growth was raised by as much as 290% in the current study and height growth projections based on published site index models suggested a potential estimate a 5 to 20 year decrease in harvest age with the application of $N+P$ than in the *Control*. Therefore it seems that in this situation, fertilization can contribute to stand development and earlier achievement of trees suitable for timber

harvest, through the process of accelerated stand competition and eventual self-thinning, more so than through the enhanced growth of already large stems. Fertilizer coupled with the release of larger stems may further accelerate stand development and dominant tree growth.

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Table 1. One-year-old mean stand density and size measurements (\pm SD, n=4), for stems \geq 60 cm in height taken during the initial stand inventory in June 2004 on an upland NC Piedmont natural even-aged mixed species stand. Stems/ha are displayed in the 1,000's. Interactive effects were not statistically different and are not reported.

<i>Attributes</i>	<i>Control</i>	<i>N Fert</i>	<i>N+P Fert</i>	<i>N+P+K Fert</i>	<i>ANOVA</i>
<i>Total Stems/ha</i>	3.6 \pm 0.64	3.7 \pm 0.8	3.8 \pm 0.7	2.9 \pm 0.5	F=0.89; P _{Blk.} =0.21; P _{Trt.} =0.52
<i>Hardwood Stems/ha</i>	3.6 \pm 0.64	3.7 \pm 0.8	3.7 \pm 0.7	2.9 \pm 0.5	F=0.90; P _{Blk.} =0.25; P _{Trt.} =0.55
<i>Height (cm)</i>	121.5 \pm 29.6	137.7 \pm 49.1	160.3 \pm 76.9	148.1 \pm 64.7	F=0.43; P _{Blk.} =0.17; P _{Trt.} =0.76

Note: Means within a row were considered statistically different at P = 0.10 by Tukey's separation procedure following significant ANOVA of P \leq 0.15.

Table 2. Mean stand density and size measurements (\pm SD, n=4), for stems \geq 60 cm in height, measured in October 2005, two growing seasons after fertilizer treatment on an upland NC Piedmont natural even-aged mixed species stand. Stems/ha are displayed in the 1,000's. Interactive effects were not statistically different and are not reported.

<i>Attributes</i>	<i>Control</i>	<i>N Fert</i>	<i>N+P Fert</i>	<i>N+P+K Fert</i>	<i>ANOVA</i>
Total Stand					
<i>Composition</i>					
Total Stems/Ha	51.9 \pm 31.5	39.3 \pm 3.9	34.6 \pm 8.8	36.5 \pm 16.0	F=0.95; P _{Blk.} =0.22; P _{Trt.} =0.46
% Hardwood	62.1 \pm 25.9	71.4 \pm 13.4	86.7 \pm 13.2	69.4 \pm 29.1	F=1.74; P _{Blk.} =0.12; P _{Trt.} =0.24
% Evergreen	38.0 \pm 25.8 a	28.5 \pm 13.4 ab	15.1 \pm 11.6 b	30.5 \pm 29.0 ab	F=2.52; P _{Blk.} =0.03; P _{Trt.} =0.12
% Sprout Origin	42.9 \pm 20.7 a	55.3 \pm 15.7 a	71.8 \pm 18.0 b	50.9 \pm 23.3 a	F=3.86; P _{Blk.} =0.01; P _{Trt.} =0.05
% Seed Origin	57.0 \pm 20.7 a	44.6 \pm 15.7 a	28.1 \pm 18.0 b	49.0 \pm 23.3 a	F=3.86; P _{Blk.} =0.01; P _{Trt.} =0.05
% Hickory	5.4 \pm 3.3 a	7.2 \pm 3.6 a	3.9 \pm 2.7 b	6.6 \pm 6.5 a	F=2.34; P _{Blk.} =0.14; P _{Trt.} =0.13
% Loblolly Pine	38.0 \pm 25.8 a	28.5 \pm 13.4 ab	15.1 \pm 11.6 b	30.5 \pm 29.0 ab	F=2.52; P _{Blk.} =0.03; P _{Trt.} =0.12
% Red Maple	8.6 \pm 4.6	16.3 \pm 10.5	14.7 \pm 6.4	11.0 \pm 8.4	F=0.92; P _{Blk.} =0.24; P _{Trt.} =0.47
% Red Oak	13.1 \pm 11.0	6.9 \pm 11.2	11.4 \pm 15.9	17.2 \pm 16.6	F=0.52; P _{Blk.} =0.09; P _{Trt.} =0.68
% Sweetgum	4.2 \pm 3.1 a	8.37 \pm 8.7 a	41.61 \pm 25.7 b	7.93 \pm 5.6 a	F=6.72; P _{Blk.} =0.18; P _{Trt.} =0.01
% Tulip Poplar	8.6 \pm 10.0	8.7 \pm 3.4	10.3 \pm 10.9	13.6 \pm 15.2	F=0.32; P _{Blk.} =0.11; P _{Trt.} =0.81
% White Oak	2.5 \pm 0.6	6.6 \pm 4.1	6.0 \pm 5.2	4.6 \pm 3.9	F=0.69; P _{Blk.} =0.90; P _{Trt.} =0.58
<i>Size</i>					
GLD (cm)	1.45 \pm 0.8 a	1.74 \pm 1.1 ab	2.1 \pm 1.3 c	1.9 \pm 1.2 bc	F=6.79; P _{Blk.} =0.02; P _{Trt.} =0.01

Table 2. (Continued).

Attributes	<i>Control</i>	<i>N Fert</i>	<i>N+P Fert</i>	<i>N+P+K Fert</i>	<i>ANOVA</i>
Height (cm)	127.8 ± 54.9 a	173.4 ± 91.0 ab	212.4 ± 99.4 b	176.5 ± 97.5 b	F=6.08; P _{Blk.} =0.07; P _{Trt.} =0.01
Volume (cm ³)	526.8 ± 1324.4 a	1176.8 ± 3070.7 a	2047.9 ± 4483.4 b	1674.5 ± 6000.1b	F=3.27; P _{Blk.} =0.06; P _{Trt.} =0.07
Total Volume/ha (m ³)	65 ± 43 a	108 ± 43 a	169 ± 56 b	147 ± 73 b	F=4.71; P _{Blk.} =0.07; P _{Trt.} =0.03
<i>GL</i> Basal Area (cm ²)	2840.0 ± 2583.1	2080.6 ± 500.6	2423.7 ± 443.2	2263.8 ± 1115.6	F=0.78; P _{Blk.} =0.32; P _{Trt.} =0.78
<i>Hardwoods</i>					
Mean <i>GLD</i> (cm)	1.7 ± 1.0 a	1.8 ± 1.9 ab	2.2 ± 1.4 b	2.1 ± 1.4 ab	F=4.23; P _{Blk.} =0.06; P _{Trt.} =0.04
Mean Height (cm)	155.6 ± 61.3 a	194.9 ± 96.8 ab	232.6 ± 100.1 b	208.8 ± 111.6 b	F=5.56; P _{Blk.} =0.07; P _{Trt.} =0.02
Mean Tree Volume (cm ³)	864.4 ± 605.8 a	1498.7 ± 734.8 ab	2496.5 ± 600.6 b	2350.3 ± 906.5 ab	F=4.41; P _{Blk.} =0.06; P _{Trt.} =0.04
Total Volume/ha (m ³)	52 ± 117 a	104 ± 47 ab	164 ± 60 b	130 ± 91 ab	F=4.99; P _{Blk.} =0.21; P _{Trt.} =0.02
<i>GL</i> Basal Area (cm ²)	903.5 ± 200.9 a	1238.2 ± 520.2 a	1915.8 ± 465.9 b	984.6 ± 531.5 a	F=4.43; P _{Blk.} =0.05; P _{Trt.} =0.03
<i>Stand Volume: Evergreen</i>					
<i>GLD</i> (cm)	1.2 ± 0.5 a	1.4 ± 0.6 ab	1.5 ± 0.5 ab	1.6 ± 0.7 b	F=4.01; P _{Blk.} =0.09; P _{Trt.} =0.04
Height (cm)	103.4 ± 29.9 a	119.3 ± 38.5 ab	127.8 ± 32.8 b	132.8 ± 41.7 b	F=6.24; P _{Blk.} =0.59; P _{Trt.} =0.01
Volume (cm ³)	256.2 ± 259.3 a	364.9 ± 485.8 ab	399.9 ± 369.3 ab	571.5 ± 671.3 b	F=6.24; P _{Blk.} =0.85; P _{Trt.} =0.03
Total Volume/ha (m ³)	21 ± 17	34 ± 5.2	4.3 ± 5.6	17 ± 17	F=0.85; P _{Blk.} =0.49; P _{Trt.} =0.51
<i>GL</i> Basal Area (cm ²)	785.9 ± 1401.6	130.4 ± 74.5	459.4 ± 598.0	459.4 ± 598.0	F=2.45; P _{Blk.} =0.01; P _{Trt.} =0.13

Table 2. (Continued).

Attributes	<i>Control</i>		<i>N Fert</i>		<i>N+P Fert</i>		<i>N+P+K Fert</i>		<i>ANOVA</i>
<i>Seed Origin</i>									
Mean <i>GLD</i> Diameter (cm)	0.9 ± 1.1	a	2.0 ± 1.2	ab	2.3 ± 1.4	b	2.3 ± 1.6	b	F=2.62; P _{Blk} =0.65; P _{Tr} =0.1
Mean Height (cm)	164.2 ± 63.7	a	214.8 ± 98.3	a	237.6 ± 98.9	b	228.6 ± 119.5	ab	F=8.51; P _{Blk} =0.1; P _{Tr} =0.01
Mean Volume (cm ³)	1048.9 ± 2016.7	a	1854.4 ± 3972.7	ab	2584.1 ± 4989.4	c	3202.3 ± 8819.6	bc	F=5.73; P _{Blk} =0.2; P _{Tr} =0.01
Total Volume/ha (m ³)	21 ± 13		13 ± 4.7		21 ± 17		26 ± 17		F=0.86; P _{Blk} =0.05; P _{Tr} =0.5
<i>GL</i> Basal Area (cm ²)	2298.7 ± 2531.1		1151.3 ± 347.4		1007.6 ± 634.6		1618.1 ± 1347.9		F=0.81; P _{Blk} =0.16; P _{Tr} =0.5
<i>Sprout Origin</i>									
Mean <i>GLD</i> (cm)	1.2 ± 0.5		1.3 ± 0.6		1.3 ± 0.6		1.5 ± 0.7		F=3.29; P _{Blk} =0.05; P _{Trt} =0.07
Mean Height (cm)	108.0 ± 36.7	a	121.8 ± 42.0	ab	157.8 ± 75.0	b	136.5 ± 46.4	b	F=4.15; P _{Blk} =0.12; P _{Trt} =0.04
Mean Volume (cm ³)	243.1 ± 522.1	a	330.7 ± 473.0	ab	883.7 ± 773.0	b	495.5 ± 810.3	ab	F=2.59; P _{Blk} =0.07; P _{Trt} =0.11
Total Volume/ha (m ³)	47 ± 8	a	99 ± 47	ab	147 ± 60	b	121 ± 91	ab	F=3.51; P _{Blk} =0.07; P _{Trt} =0.06
<i>GL</i> Basal Area (cm ²)	533.5 ± 160.1	a	935.8 ± 517.6	ab	1416.1 ± 343.8	b	642.42 ± 295.1	ab	F=6.46; P _{Blk} =0.16; P _{Trt} =0.01

Table 2. (Continued).

Attributes	<i>Control</i>	<i>N Fert</i>	<i>N+P Fert</i>	<i>N+P+K Fert</i>	<i>ANOVA</i>
16 Largest Trees/Plot (0.04 ha)					
Mean <i>GLD</i> (cm)	3.8 ± 1.0 b	4.6 ± 1.2 ab	4.6 ± 1.2 ab	4.9 ± 1.9 a	F=2.76; P _{Blk.} =0.06; P _{Trt.} =0.1
Mean Height (cm)	254.4 ± 58.7 a	375.7 ± 98.2 b	396.8 ± 88.7 b	381.4 ± 138.4 b	F=3.78; P _{Blk.} =0.1; P _{Trt.} =0.52
Mean Volume (cm ³)	4383 ± 3718 a	9456 ± 7529 ab	13497 ± 17288 b	9456 ± 7529 ab	F=3.84; P _{Blk.} =0.07; P _{Trt.} =0.05
Total Volume/ha (m ³)	0.7 ± 0.2 a	1.5 ± 0.7 ab	2.0 ± 0.9 b	2.2 ± 1.7 ab	F=2.9; P _{Blk.} =0.12; P _{Trt.} =0.09

Note: All data reported is non-transformed. Raw data was transformed as needed for statistical analysis as follows: % Evergreen: square root transformed, % of All Stems Sprout Origin: Log10 transformed, % of All Stems: Hickory: Log 10 transformed, % of All Stems Loblolly Pine: Square Root transformed, Evergreen Basal Area: log10 transformed, Seed Origin Mean Volume: Log10 transformed, 16 Largest Trees/Plot Mean Volume: log10 transformed and 16 Largest Trees/Plot Total Volume: Log10 transformed. Means within a row followed by different letters were statistically different at P = 0.10 by Tukey's separation procedure following significant ANOVA of P ≤ 0.15. *GLD*= ground line diameter, *GL*= ground line.

Table 3. Percent (\pm SD, n=4) distribution of all stems by height class two growing seasons after fertilizer treatments (measured October 2005) on an upland NC Piedmont natural even-aged mixed species stand. Interactive effects were not statistically different and are not reported.

Height Class	<i>Control</i>	<i>N Fert</i>	<i>N+P Fert</i>	<i>N+P+K Fert</i>	<i>ANOVA</i>
24-100 cm	43.9 \pm 25.1 a	19.6 \pm 16.3 ab	11.7 \pm 6.6 b	21.7 \pm 15.2 ab	F=3.48; P _{Bik.} =0.31; P _{Ttt.} =0.06
101-200 cm	35.8 \pm 22.8	34.2 \pm 7.5	25.6 \pm 12.8	31.9 \pm 8.5	F=1.12; P _{Bik.} =0.58; P _{Ttt.} =0.38
201-300 cm	13.8 \pm 8.1 a	32.1 \pm 8.3 b	31.3 \pm 8.1 b	27.7 \pm 9.9 b	F=2.39; P _{Bik.} =0.42; P _{Ttt.} =0.13
301-400 cm	1.6 \pm 1.6 a	13.9 \pm 5.8 b	13.8 \pm 8.5 ab	8.4 \pm 4.9 a	F=4.17; P _{Bik.} =0.44; P _{Ttt.} =0.04
≥ 401 cm	4.7 \pm 5.1 a	0.02 \pm 0.04 a	17.3 \pm 17.1 b	10.1 \pm 11.8 ab	F=3.60; P _{Bik.} =0.11; P _{Ttt.} =0.05

Note: All data reported is non-transformed. Raw data was transformed for statistical analysis as needed as follows: 24-100 cm class and 201-300cm class: square root transformed. Means within a row followed by different letters were statistically different at P = 0.10 by Tukey's separation procedure following significant ANOVA of $P \leq 0.15$.

Table 4. Mean size measurements (\pm SD, n=4) for all stems of common timber species, ≥ 60 cm in height, measured in October 2005, two growing seasons after fertilizer treatment on an upland NC Piedmont natural even-aged mixed species stand. Interactive effects were not statistically different and are not reported.

<i>Species / Attribute</i>	<i>Control</i>	<i>N Fert</i>	<i>N+P Fert</i>	<i>N+P+K Fert</i>	<i>ANOVA</i>
<i>Hickory</i>					
GLD (cm)	2.6 \pm 1.3 a	1.9 \pm 0.9 b	2.3 \pm 1.6 ab	1.9 \pm 0.9 b	F=3.82; P _{Blk.} =0.52; P _{Trt.} =0.05
Height (cm)	155.7 \pm 68.5	154.5 \pm 68.3	172.5 \pm 99.1	160.6 \pm 65.4	F=0.29; P _{Blk.} =0.56; P _{Trt.} =0.83
Volume (cm ³)	1751.3 \pm 2301.5 a	961.5 \pm 1516.3 ab	2306.2 \pm 4101.3 b	902.8 \pm 1228.7 ab	F=3.2; P _{Blk.} =0.31; P _{Trt.} =0.03
GL Basal Area (cm ²)	16.2 \pm 14.8	16.0 \pm 17.6	4.4 \pm 3.9	5.3 \pm 3.5	F=1.37; P _{Blk.} =0.26; P _{Trt.} =0.31
<i>Loblolly Pine</i>					
GLD (cm)	1.1 \pm 0.5 a	1.4 \pm 0.6 ab	1.5 \pm 0.5 ab	1.6 \pm 0.6 b	F=3.84; P _{Blk.} =0.09; P _{Trt.} =0.05
Height (cm)	101.4 \pm 29.9 a	119.3 \pm 38.5 ab	129.8 \pm 32.8 b	131.8 \pm 41.7 b	F=6.21; P _{Blk.} =0.59; P _{Trt.} =0.01
Volume (cm ³)	258.2 \pm 66.3 a	385.9 \pm 76.8 ab	378.9 \pm 59.3 b	572.5 \pm 57.2 b	F=4.25; P _{Blk.} =0.85; P _{Trt.} =0.03
GL Basal Area (cm ²)	785.9 \pm 1001.6	130.3 \pm 74.5	55.2 \pm 63.7	459.4 \pm 598.0	F=2.4; P _{Blk.} =0.01; P _{Trt.} =0.13
<i>Red Maple</i>					
GLD (cm)	1.4 \pm 0.7	1.6 \pm 0.8	1.6 \pm 0.9	1.5 \pm 0.7	F=.023; P _{Blk.} =0.96; P _{Trt.} =0.87
Height (cm)	140.6 \pm 15.7 a	191.0 \pm 14.0 ab	201.1 \pm 14.0 b	171.8 \pm 16.0 ab	F=3.25; P _{Blk.} =0.44; P _{Trt.} =0.06
Volume (cm ³)	534.8 \pm 1196.4	900.0 \pm 1442.3	929.0 \pm 1669.9	670.5 \pm 929.1	F=0.89; P _{Blk.} =0.95; P _{Trt.} =0.47
GL Basal Area (cm ²)	15.5 \pm 14.7	73.1 \pm 89.3	45.1 \pm 51.7	29.9 \pm 30.2	F=1.03; P _{Blk.} =0.19; P _{Trt.} =0.42

Table 4. (Continued).

<i>Species / Attribute</i>	<i>Control</i>	<i>N Fert</i>	<i>N+P Fert</i>	<i>N+P+K Fert</i>	<i>ANOVA</i>
<i>Red Oak</i>					
<i>GLD</i> (cm)	2.4 ± 1.5	1.9 ± 0.7	2.8 ± 1.3	2.03 ± 0.9	F=1.99; P _{Blk.} =0.50; P _{Trt.} =0.20
Height (cm)	173.7 ± 81.1 a	193.4 ± 69.3 ab	227.3 ± 63.5 b	171.1 ± 68.1 a	F=3.66; P _{Blk.} =0.43; P _{Trt.} =0.01
Volume (cm ³)	2111.3 ± 4367.7	963.9 ± 849.3	2661.9 ± 2793.1	1016.2 ± 955.8	F=2.47 P _{Blk.} =0.55; P _{Trt.} =0.40
<i>GL</i> Basal Area (cm ²)	53.2 ± 49.8	30.6 ± 60.1	83.6 ± 141.3	104.8 ± 121.0	F=0.24; P _{Blk.} =0.31; P _{Trt.} =0.86
<i>Sweetgum</i>					
<i>GLD</i> (cm)	1.6 ± 1.1	2.0 ± 1.2	2.3 ± 1.2	2.0 ± 1.2	F=0.8; P _{Blk.} =0.69; P _{Trt.} =0.52
Height (cm)	157.6 ± 64.2 a	206.4 ± 85.0 ab	238.8 ± 83.5 b	195.1 ± 85.8 ab	F=3.96; P _{Blk.} =0.55; P _{Trt.} =0.05
Volume (cm ³)	950.2 ± 2435.6	1760.6 ± 3155.5	2116.9 ± 3453.1	1633.1 ± 2586.3	F=1.02; P _{Blk.} =0.76; P _{Trt.} =0.43
<i>GL</i> Basal Area (cm ²)	4.4 ± 3.7 a	38.5 ± 60.4 a	651.8 ± 97.6 b	44.3 ± 79.1 a	F=3.22; P _{Blk.} =0.56; P _{Trt.} =0.09
<i>Tulip Poplar</i>					
<i>GLD</i> (cm)	1.4 ± 0.7 a	2.7 ± 2.0 ab	4.3 ± 2.2 b	3.5 ± 2.5 ab	F=3.39; P _{Blk.} =0.09; P _{Trt.} =0.07
Height (cm)	159.1 ± 63.5 a	240.7 ± 158.3 ab	324.7 ± 142.2 b	279.0 ± 185.7 ab	F=2.78; P _{Blk.} =0.11; P _{Trt.} =0.06
Volume (cm ³)	1557.5 ± 2354.3 a	4456.1 ± 2243.8 a	9698.2 ± 2410.7 b	9858.1 ± 2308.1 b	F=9.25; P _{Blk.} =0.14; P _{Trt.} =0.01
<i>GL</i> Basal Area (cm ²)	21.0 ± 34.14	54.1 ± 56.9	98.1 ± 154.5	110.4 ± 151.6	F=0.16; P _{Blk.} =0.91; P _{Trt.} =0.91

Table 4. (Continued).

<i>Species / Attribute</i>	<i>Control</i>	<i>N Fert</i>	<i>N+P Fert</i>	<i>N+P+K Fert</i>	<i>ANOVA</i>
<i>White oak</i>					
<i>GLD</i> (cm)	2.2 ± 1.1	1.7 ± 1.0	2.1 ± 0.8	1.9 ± 1.0	F=1.38; P _{Blk.} =0.22; P _{Trt.} =0.31
Height (cm)	170.0 ± 66.4	148.4 ± 61.8	183.5 ± 69.4	165.7 ± 72.4	F=1.03; P _{Blk.} =0.39; P _{Trt.} =0.42
Mean Volume (cm ³)	1315.2 ± 1572.1	843.8 ± 1177.8	1185.4 ± 1326.1	1116.6 ± 1575.0	F=0.92; P _{Blk.} =0.37; P _{Trt.} =0.31
<i>GL</i> Basal Area (cm ²)	3.23 ± 0.9	14.96 ± 23.2	16.01 ± 23.7	8.62 ± 12.7	F=0.39; P _{Blk.} =0.83; P _{Trt.} =0.76

Note: All data reported is non-transformed. Raw data was transformed as needed for statistical analysis as follows: Loblolly Pine Basal Area: log10 transformed. Means within a row followed by different letters were statistically different at P = 0.10 by Tukey's separation procedure following significant ANOVA of P ≤ 0.15. *GLD*= ground line diameter, *GL*= ground line.

Table 5. Mean size measurements (\pm SD, n=4) for the 10 largest trees per common timber species per plot, ≥ 60 cm in height, measured in October 2005, two growing seasons after fertilizer treatment on an upland NC Piedmont natural even-aged mixed species stand. Interactive and block effects were not statistically different and are not reported.

<i>Species / Attribute</i>	<i>Control</i>	<i>N Fert</i>	<i>N+P Fert</i>	<i>N+P+K Fert</i>	<i>ANOVA</i>
<i>Hickory</i>					
<i>GLD</i> (cm)	3.0 \pm 0.30	2.3 \pm 0.3	2.2 \pm 0.3	2.1 \pm 0.3	F=1.98; P _{Trt.} =0.18
Height (cm)	178.5 \pm 20.3	173.5 \pm 19.5	169.6 \pm 20.4	164.8 \pm 21.1	F=0.08; P _{Trt.} =0.96
Volume (cm ³)	2287.0 \pm 482.2	2242.0 \pm 528.8	1329.1 \pm 449.6	1066.1 \pm 492.6	F=1.86; P _{Trt.} =0.20
<i>Loblolly Pine</i>					
<i>GLD</i> (cm)	2.6 \pm 0.2	2.4 \pm 0.2	2.3 \pm 0.2	1.9 \pm 0.2	F=2.04; P _{Trt.} =0.22
Height (cm)	173.5 \pm 17.7	172.1 \pm 16.9	153.8 \pm 16.9	140.8 \pm 18.8	F=1.31; P _{Trt.} =0.35
Volume (cm ³)	1692.5 \pm 220.7	1137.7 \pm 200.9	913.4 \pm 200.9	732.7 \pm 231.9	F=0.56; P _{Trt.} =0.56
<i>Red Maple</i>					
<i>GLD</i> (cm)	2.5 \pm 0.3	2.3 \pm 0.4	2.3 \pm 0.3	1.9 \pm 0.3	F=0.52; P _{Trt.} =0.67
Height (cm)	261.5 \pm 28.3	259.9 \pm 28.3	229.8 \pm 32.7	171.0 \pm 28.3	F=2.22; P _{Trt.} =0.14
Volume (cm ³)	2183.5 \pm 647.1	2057.4 \pm 647.1	1580.9 \pm 747.2	947.6 \pm 647.1	F=0.75; P _{Trt.} =0.54
<i>Red Oak</i>					
<i>GLD</i> (cm)	2.8 \pm 0.3	2.6 \pm 0.25	2.1 \pm 0.30	2.08 \pm 0.38	F=1.55; P _{Trt.} =0.27
Height (cm)	178.1 \pm 12.4 a	193.3 \pm 15.0 ab	235.3 \pm 14.7 b	176.5 \pm 18.6 ab	F=3.43; P _{Trt.} =0.08
Volume (cm ³)	2518.5 \pm 1023.2	2453.1 \pm 872.3	1882.5 \pm 982.2	1059.0 \pm 1234.8	F=0.36; P _{Trt.} =0.78

Table5. (Continued).

<i>Species / Attribute</i>	<i>Control</i>	<i>N Fert</i>	<i>N+P Fert</i>	<i>N+P+K Fert</i>	<i>ANOVA</i>
<i>Sweetgum</i>					
<i>GLD</i> (cm)	3.7 ± 0.7	2.8 ± 0.6	2.5 ± 0.6	2.0 ± 0.715	F=0.93; P _{T_{rit}} =0.27
Height (cm)	307.1 ± 40.8	252.7 ± 36.0	245.5 ± 35.7	183.4 ± 41.0	F=1.53; P _{T_{rit}} =0.08
Volume (cm ³)	6308.7 ± 1787.1	3385.6 ± 1601.7	2763.3 ± 1584.21	1498.9 ± 1806.2	F=1.37; P _{T_{rit}} =0.78
<i>Tulip Poplar</i>					
<i>GLD</i> (cm)	4.5 ± 1.1	4.5 ± 1.0	3.6 ± 1.0	1.7 ± 1.1	F=1.35; P _{T_{rit}} =0.13
Height (cm)	355.0 ± 78.8	345.1 ± 78.1	323.0 ± 77.9	152.1 ± 80.3	F=2.14; P _{T_{rit}} =0.16
Volume (cm ³)	16887.0 ± 5273.8	12769.0 ± 5151.7	8489.2 ± 5088.7	1131.1 ± 5458.7	F=.2.26; P _{T_{rit}} =0.15
<i>White Oak</i>					
<i>GLD</i> (cm)	2.5 ± 0.4	2.3 ± 0.4	2.1 ± 0.4	1.9 ± 0.4	F=.0.48; P _{T_{rit}} =0.71
Height (cm)	215.0 ± 23.9	179.2 ± 27.2	175.2 ± 23.9	159.3 ± 23.4	F=.0.98; P _{T_{rit}} =0.43
Volume (cm ³)	1646.5 ± 530.8	1457.6 ± 532.9	1195.8 ± 605.4	1031.6 ± 519.6	F=.0.26; P _{T_{rit}} =0.85

Note: Means within a row followed by different letters were statistically different at P = 0.10 by Tukey's separation procedure following significant ANOVA of P ≤ 0.15. *GLD*= ground line diameter, *GL*= ground line.

Table 6. Mean percent (\pm SD, n=4) foliar nutrient concentrations for northern red oak, loblolly pine and tulip poplar at the start of the third growing season after fertilizer treatment on an upland NC Piedmont natural even-aged mixed species stand. Samples were collected on 10 May 2006. Interactive effects were not statistically different and are not reported.

<i>Species / Nutrient</i>	<i>Control</i>	<i>N Fert</i>	<i>N+P Fert</i>	<i>N+P+K Fert</i>	<i>ANOVA</i>	<i>Critical Foliar Value (%)</i>
<i>Red Oak</i>						
Foliar N (%)	2.26 \pm 0.38	2.45 \pm 0.39	2.3 \pm 0.2	2.38 \pm 0.24	F=0.3; P _{Blk.} =0.38; P _{Trt.} =0.30	1.90 (Reference 1)
Foliar P (%)	0.23 \pm 0.04	0.22 \pm 0.03	0.22 \pm 0.03	0.23 \pm 0.03	F=0.35; P _{Blk.} =0.12; P _{Trt.} =0.79	0.11 (Reference 1)
Foliar K (%)	1.02 \pm 0.09	0.97 \pm 0.1	0.91 \pm 0.12	1.0 \pm 0.08	F=1.68; P _{Blk.} =0.16; P _{Trt.} =0.24	0.50 (Reference 1)
Foliar Ca (%)	0.53 \pm 0.04	0.5 \pm 0.1	0.43 \pm 0.11	0.5 \pm 0.14	F= 1.37; P _{Blk.} =0.09; P _{Trt.} =0.31	0.55 (Reference 1)
Foliar Mg (%)	0.24 \pm 0.05	0.23 \pm 0.04	0.22 \pm 0.07	0.26 \pm 0.05	F=0.75; P _{Blk.} =0.08; P _{Trt.} =0.54	0.12 (Reference 1)
Foliar S (%)	0.17 \pm 0.03	0.19 \pm 0.02	0.17 \pm 0.02	0.19 \pm 0.02	F=1.63; P _{Blk.} =0.16; P _{Trt.} =0.25	Na
<i>Loblolly Pine</i>						
Foliar N (%)	1.4 \pm 0.16	1.75 \pm 0.41	1.59 \pm 0.31	1.84 \pm 0.1	F=2.09; P _{Blk.} =0.38; P _{Trt.} =0.17	1.20 (Reference 2)
Foliar P (%)	0.23 \pm 0.03a	0.22 \pm 0.02a	0.25 \pm 0.03a	0.31 \pm 0.03 b	F=8.19; P _{Blk.} =0.60; P _{Trt.} =0.01	0.12 (Reference 2)
Foliar K (%)	1.09 \pm 0.19	1.09 \pm 0.08	1.15 \pm 0.31	1.31 \pm 0.1	F=1.8; P _{Blk.} =0.06; P _{Trt.} =0.21	0.30 (Reference 2)
Foliar Ca (%)	0.23 \pm 0.03	0.27 \pm 0.09	0.25 \pm 0.07	0.29 \pm 0.06	F=0.68; P _{Blk.} =0.20; P _{Trt.} =0.58	0.15 (Reference 2)
Foliar Mg (%)	0.13 \pm 0.02	0.13 \pm 0.01	0.14 \pm 0.03	0.17 \pm 0.02	F= 2.54; P _{Blk.} =0.77; P _{Trt.} =0.12	0.08 (Reference 2)
Foliar S (%)	0.13 \pm 0.02	0.15 \pm 0.03	0.14 \pm 0.03	0.17 \pm 0.02	F=2.05; P _{Blk.} =0.53; P _{Trt.} =0.17	0.10 (Reference 2)

Table 6. (Continued).

<i>Species / Nutrient</i>	<i>Control</i>	<i>N Fert</i>	<i>N+P Fert</i>	<i>N+P+K Fert</i>	<i>ANOVA</i>	<i>Critical Foliar Value (%)</i>
<i>Tulip Poplar</i>						
Foliar N (%)	2.3 ± 0.1 a	2.67 ± 0.27 b	2.55 ± 0.05 b	2.31 ± 0.25 a	F=5.33; P _{Blk.} =0.11; P _{Trt.} =0.02	1.90 (Reference 3)
Foliar P (%)	0.26 ± 0.02a	0.22 ± 0.03 b	0.24 ± 0.03 ab	0.25 ± 0.02 ab	F=3.99; P _{Blk.} =0.12; P _{Trt.} =0.04	0.10 (Reference 3)
Foliar K (%)	1.94 ± 0.2 a	1.56 ± 0.17 ab	1.5 ± 0.18 ab	1.66 ± 0.24 b	F=3.63; P _{Blk.} =0.74; P _{Trt.} =0.05	0.90 (Reference 3)
Foliar Ca (%)	0.93 ± 0.14	0.69 ± 0.29	0.87 ± 0.37	0.7 ± 0.21	F=2.41; P _{Blk.} =0.01; P _{Trt.} =0.13	0.30 (Reference 3)
Foliar Mg (%)	0.35 ± 0.04	0.35 ± 0.06	0.36 ± 0.04	0.3 ± 0.03	F=2.03; P _{Blk.} =0.37; P _{Trt.} =0.18	0.10 (Reference 3)
Foliar S (%)	0.22 ± 0.03a	0.22 ± 0.02 ab	0.2 ± 0.02 b	0.2 ± 0.01 b	F=4.15; P _{Blk.} =0.42; P _{Trt.} =0.04	0.15 (Reference 3)

Note: Means within a row followed by different letters were statistically different at P = 0.10 by Tukey's separation procedure following significant ANOVA of P ≤ 0.15. Critical foliar (%) value defined here as is the minimum concentration of an element at which the plant is not deficient and thereby normal growth is not limited. Reference 1= Jones et al. 1991, Reference 2= Allen et al. 1987 and Reference 3 = A&L labs, Memphis Tennessee 2006.

Table 7. Significance of total stand growth and density response (for all stems, species groups and categories and for the 16 largest trees per inventory) two growing seasons after fertilizer treatments for upland NC Piedmont natural even-aged mixed species stand.

Attributes	-----Total Stand-----			16 Largest Trees	-----Total Stand (all stems by species)-----						
Treatment	All Stems	Pine Stems	Hardwood Stems		Hickory	Loblolly Pine	Red Maple	Red Oak	Sweetgum	Tulip Poplar	White Oak
Height Response											
N	ns	ns	ns	++	ns	ns	ns	ns	ns	ns	ns
N+P	+++	+	++	++	ns	+	++	++	+++	++++	ns
N+P+K	++	++	++	+++	ns	++	ns	ns	ns	ns	ns
GLD Response											
N	ns	ns	ns	ns	00	ns	ns	ns	ns	ns	ns
N+P	++	ns	++	++	ns	ns	ns	ns	ns	++++	ns
N+P+K	++	++	ns	++	00	++	ns	ns	ns	ns	ns
Density Response											
N	ns	ns	ns	--	ns	ns	ns	ns	ns	ns	ns
N+P	ns	00	ns	--	00	00	ns	ns	++++	ns	ns
N+P+K	ns	ns	ns	--	ns	ns	ns	ns	ns	ns	ns

Note: + = statistically significant response to fertilizers and up to 25% larger than the Control; ++ = statistically significant response and 26 to 50 % larger than the Control; +++ = statistically significant response and 51 to 100 % larger than the Control; ++++ = statistically significant response and >100% larger than the Control; 0 = statistically significant response up to 25 % smaller than the Control; 00 = statistically significant response and 26 to 50 % smaller than the Control; and ns = not significantly different from the control. *GLD*= ground line diameter.

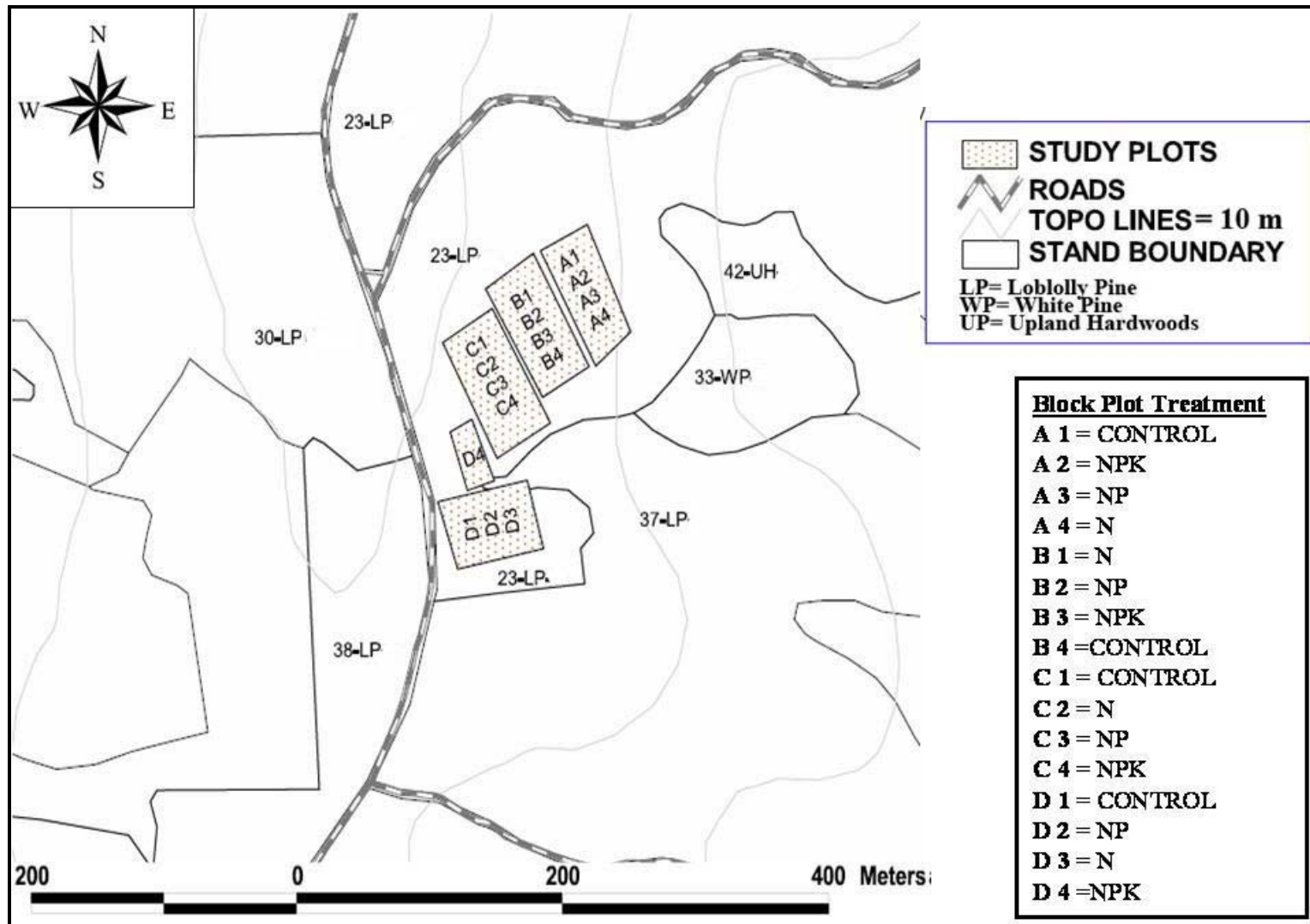


Figure 1. Map and layout of the current study site: Hill Forest, Durham County, North Carolina.

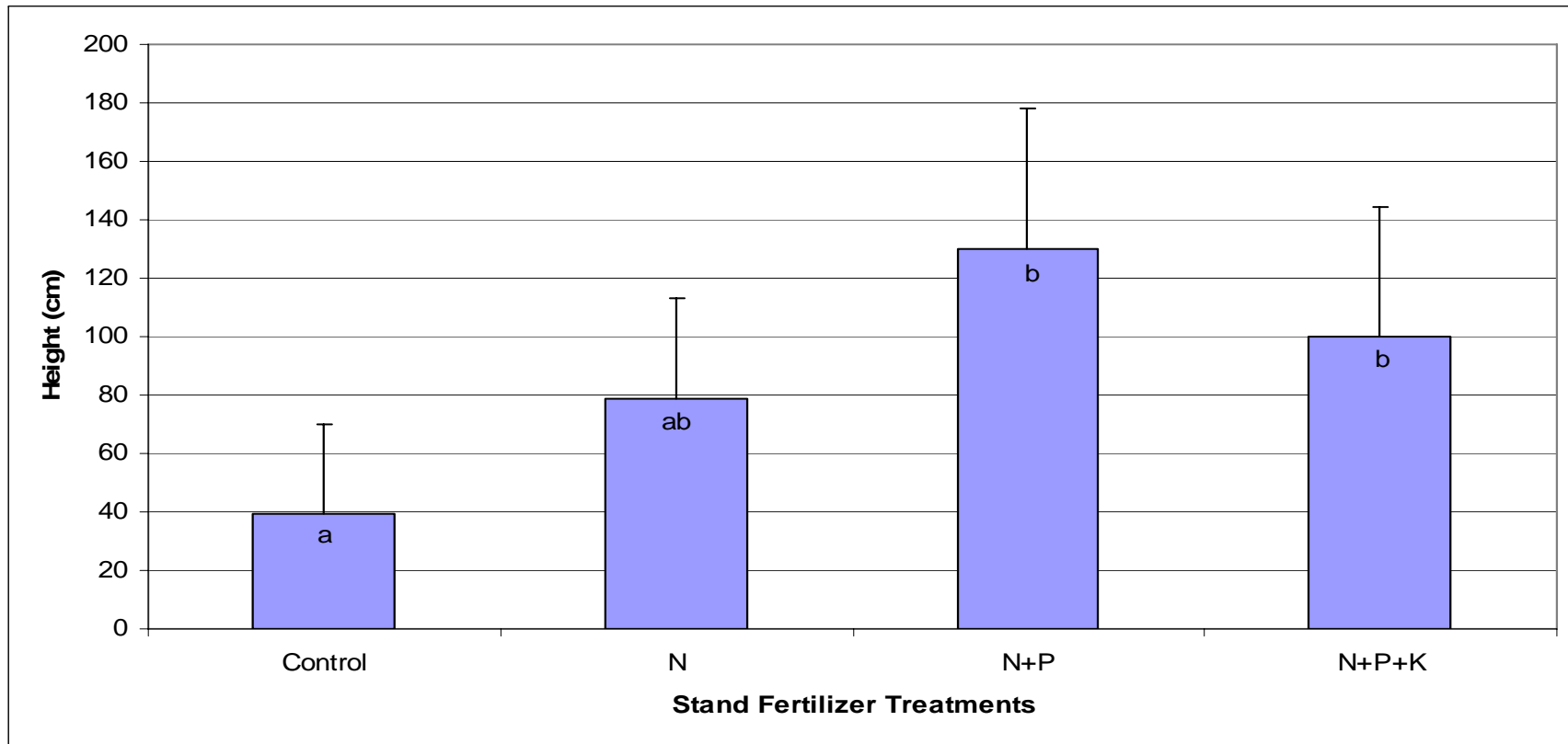


Figure 2. Change in mean height (\pm SD, $n=4$) of all stems ≥ 60 cm tall after two growing seasons, years 2 and 3 of stand growth, on an upland NC Piedmont natural even-aged mixed species stand. ANOVA= $F=5.43$; $P_{\text{Blk.}}=0.07$ $P_{\text{Trt.}}=0.02$. Means within a row followed by different letters were statistically different at $P = 0.10$ by Tukey's separation procedure following significant ANOVA of $P \leq 0.15$.

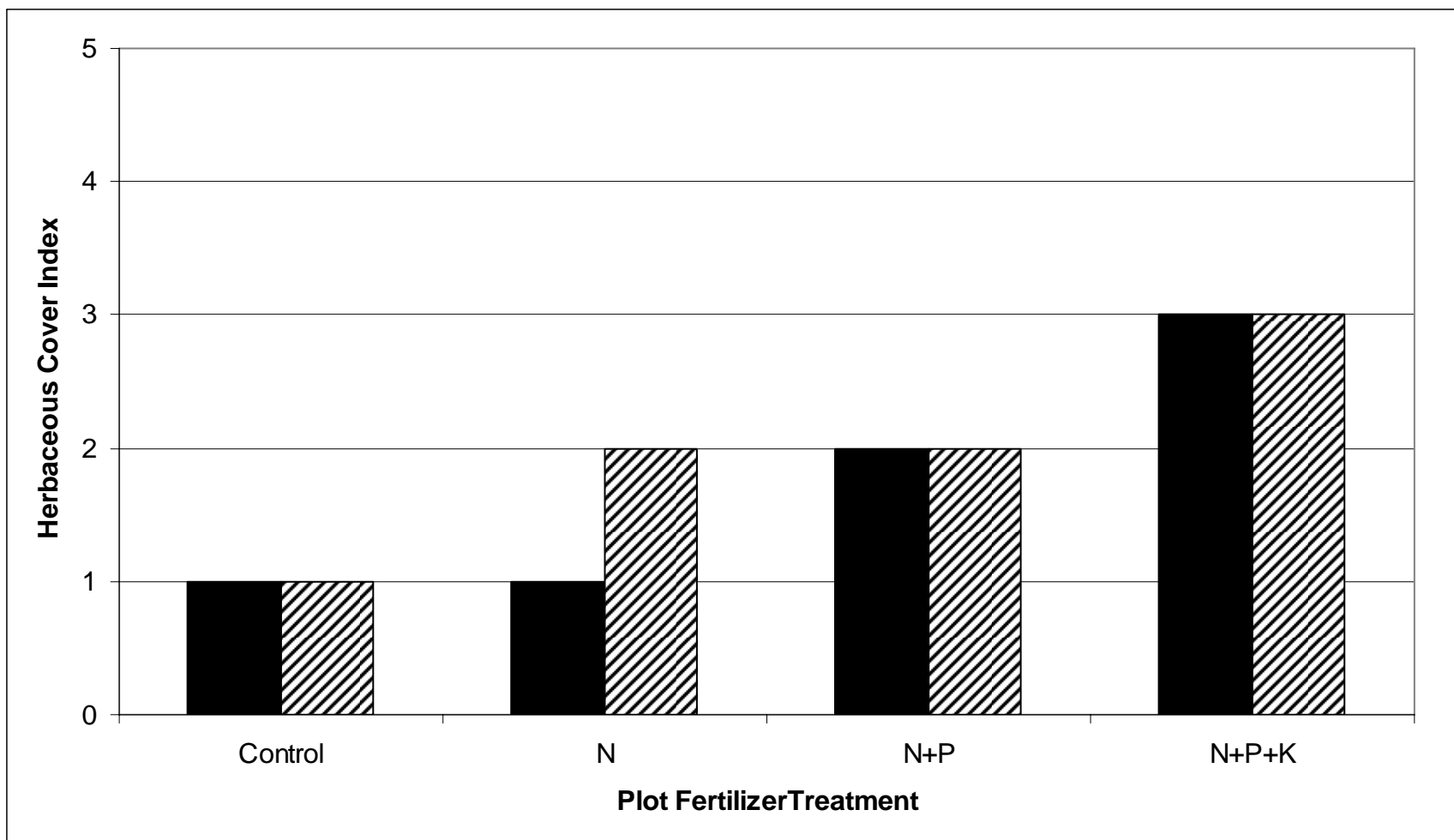


Figure 3. Mean visual estimates (n=4) of muscadine grape (*Vitis rotundifolia*), cross-hatched bars, and blackberry (*Rubrus spp.*), solid black bars, cover (methodology described in the text). Low density = cover index of 1, mid density = cover index of 2 and high density = cover index of 3. No statistical analysis was performed.

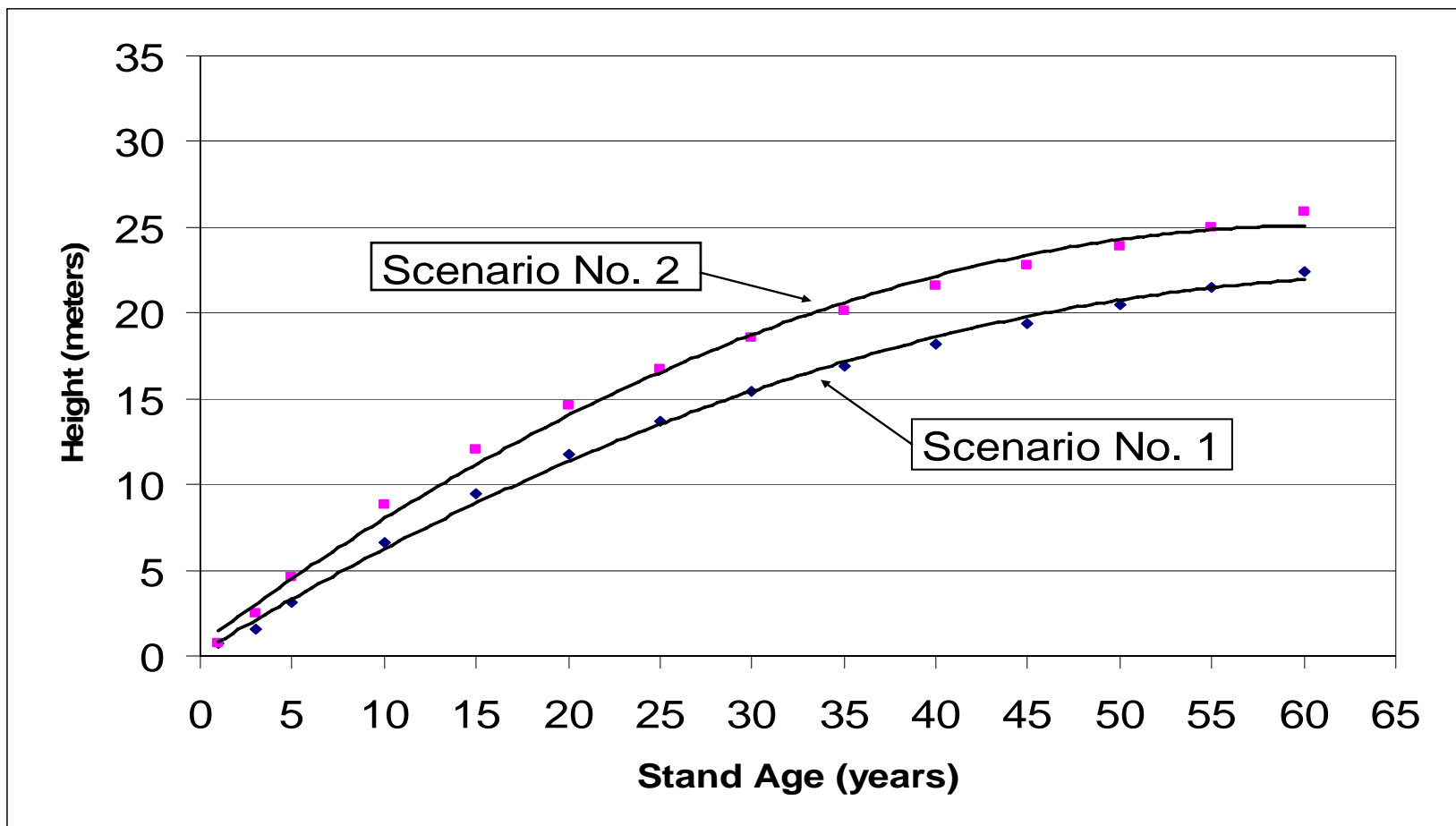


Figure 4. Modeled upland NC Piedmont natural even-aged mixed species stand height over time using a site index formula (see text for description; from McTague et al. 2006) based on experimental data from the current study for ages 1 and 3, and predicted through age 60 (calculated in 5 year increments). In Scenario No. 1, data from age three was the untreated control and its height projection is the basis for comparison. In Scenario No. 2, the data from age three was from the *N+P* treated plots and the increase in growth rate between ages 1 and 3 is assumed to continue without change through age 60.

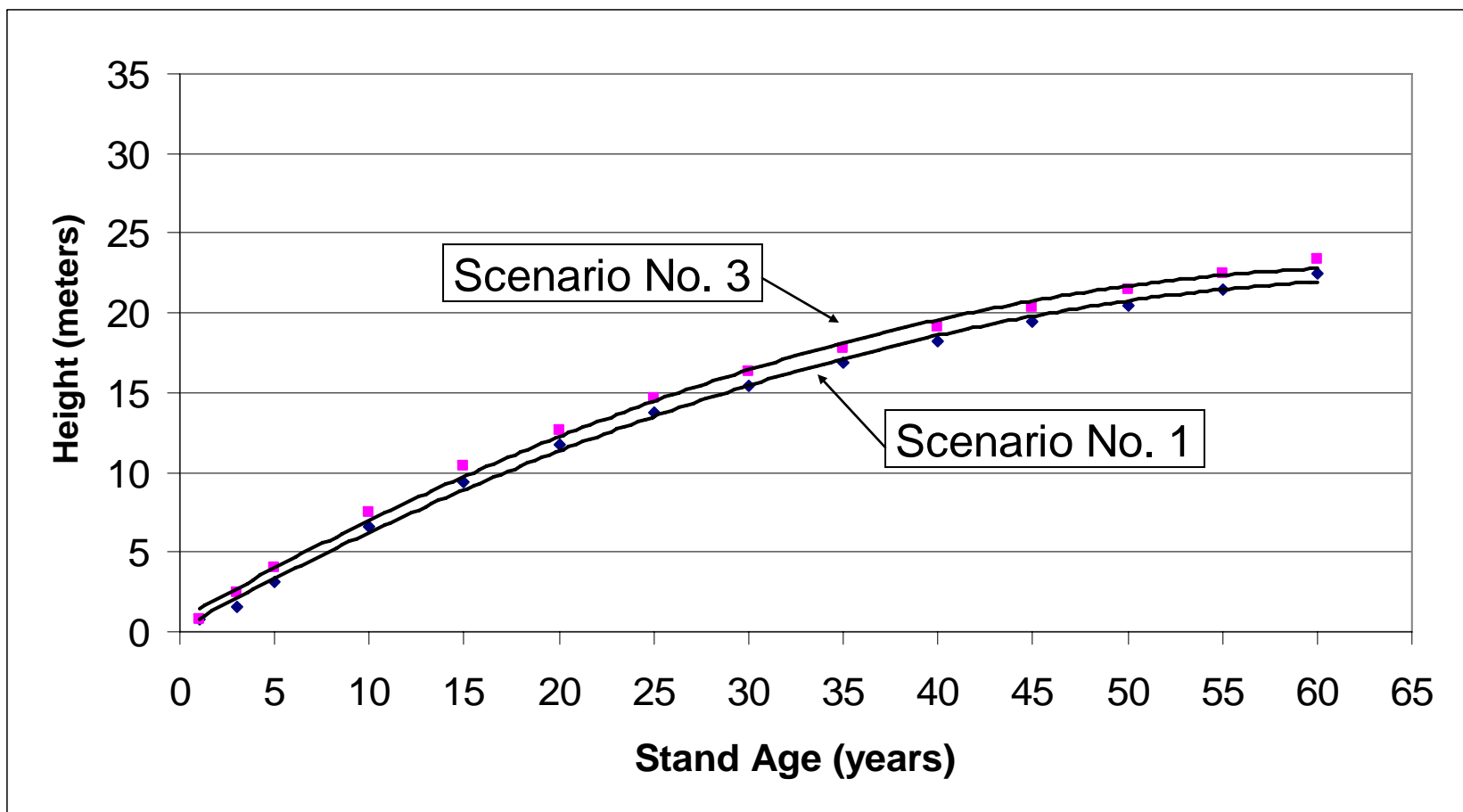


Figure 5. Modeled upland NC Piedmont natural even-aged mixed species stand height over time using a site index formula (see text for description; from McTague et al. 2006) based on experimental data from the current study for ages 1 and 3, and predicted through age 60 (calculated in 5 year increments). In Scenario No. 1, data from age three was the untreated control and its height projection is the basis for comparison. In Scenario No.3, the increase in growth rate due to the *N+P* fertilizer treatment between age 1 and 3 is assumed to continue without change until age five, with the growth rate then assuming the same magnitude as Scenario No. 1 through age 60.

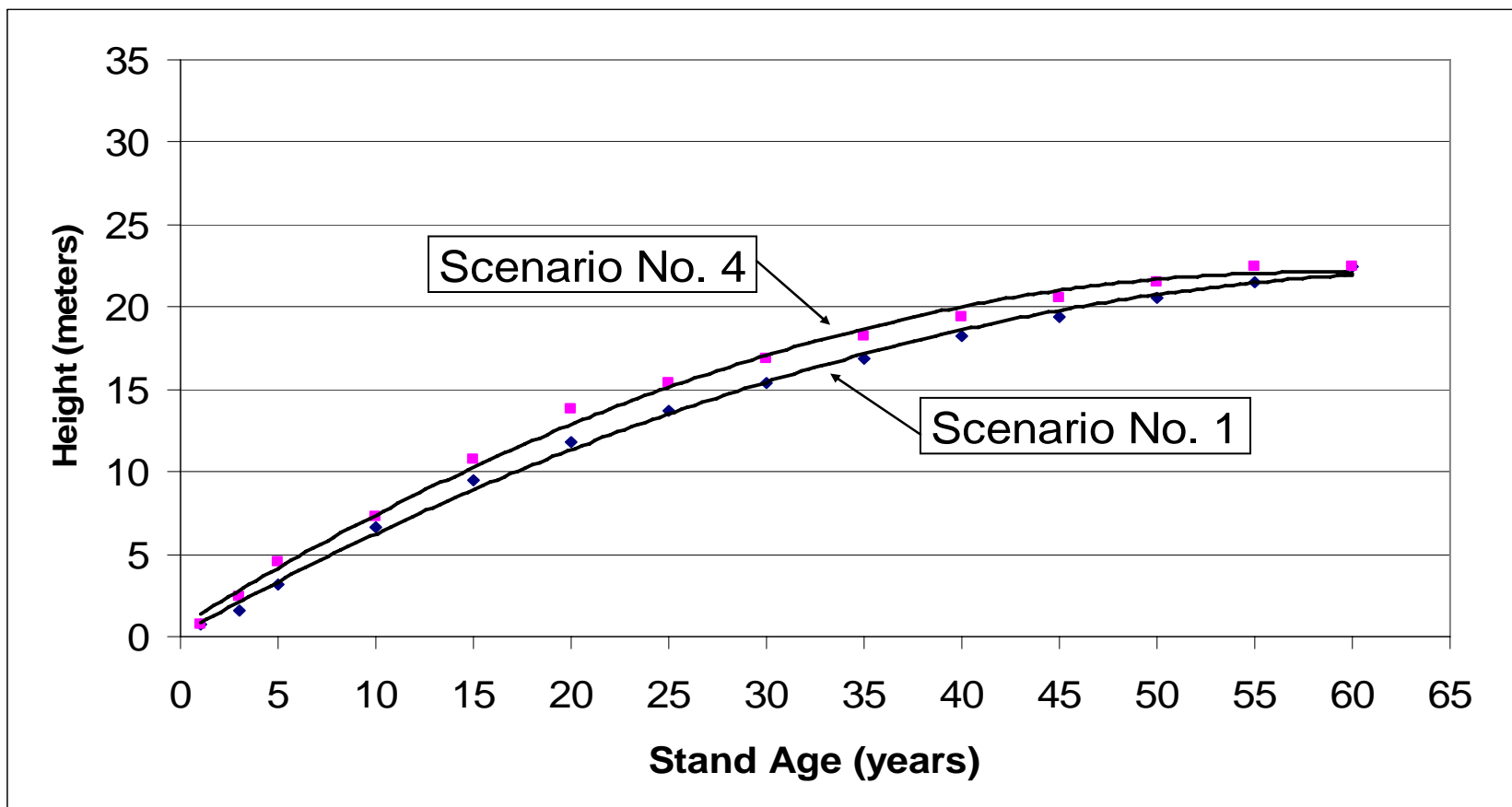


Figure 6. Modeled upland NC Piedmont natural even-aged mixed species stand height over time using site index formulas (see text for description; from McTague et al. 2006) based on experimental data from the current study for ages 1 and 3, and predicted through age 60 (calculated in 5 year increments). In Scenario No. 1, data from age three was the untreated control and its height projection is the basis for comparison. In Scenario No.4, the increase in growth rate due to the $N+P$ fertilizer treatment between age 1 and 3 is assumed to continue without change until age five, with growth rates thereafter decreasing gradually until both Scenario No. 4 and Scenario No.1 achieve the same height, and thereafter Scenario No. 4 then assuming the same growth rate as Scenario No. 1 through age 60.

APPENDICES

Appendix 1. Preliminary (see note below) financial analysis of height growth projections using net present value (NPV) and initial rate of return (IRR).

Financial estimates based on height growth projection scenarios, as described in text.

Financial Estimates	<i>Scenario 1</i>	<i>Scenario 2</i>	<i>Scenario 3</i>	<i>Scenario 4</i>
NPV (R=10%)	17.6	5.2	-84.8	-84.8
IRR	15.0%	9.8%	6.5%	6.5%

Note: A generalized yield of 308 green tons per hectare (GTH) at age 60 typical of naturally grown mixed pine-hardwood stands in the piedmont (142 GTH hardwood saw timber, 34 GTH pine sawtimber, five GTH pine chip-and-saw, 100 GTH hardwood pulpwood and 27 GTH pine pulpwood) was used as the estimated final volume in calculations (Siry et al 2004). Current prices from Timbermart (accessed May 10th of 2006) were used to calculate the gross profit of US\$5360 per ha from final stand harvest. Initial investment was estimated at US\$137.2 per hectare, the average cost of fertilization in the southeast US (Dubois et al 2003), at year 2. This estimate assumes that initial investment costs and timber prices remain constant throughout the length of the rotation. Harvest age of all scenarios was reached when projected height equaled the final projected height of the *Control* (at 60 years). $NPV = \frac{C}{(1+R)^N} - \frac{A}{(1+R)^I}$; where C= gross

profit from final harvest; A= initial investment; R= Interest Rate; N= harvest age; and I= year of Investment; $IRR = \sqrt[N]{\frac{C}{A}} - 1$; where C= gross profit from final harvest; A= initial

investment; and N= harvest age. Harvest age for both NPV and IRR was 60 for Scenario No.1, 40 for Scenario No.2, 55 for Scenario No.3, and 55 for Scenario No.4. This estimate is not included in the text as it assumes similar species composition across treatments at the end of the rotation. The final species composition at year 60 of *Control* and *N+P* treated plots cannot be determined at this young age and were likely influenced by fertilizer application. The growth projections are also based solely on height and do not account for diameter growth, making it difficult to project final volume. This estimate was created to be used as a comparison to future financial predictions of this stand.