ABSTRACT

SCHULER, JAMIE LEE. Stand Dynamics and Ecological Constraints on Growth in Young, Naturally Regenerated Hardwood Stands. (Under the direction of Dr. Daniel J. Robison)

In the southern U.S., forests are generally managed as even-aged entities, and commonly regenerated using a clearcut reproduction method. Alternatives to clearcutting, namely low- and medium-density shelterwood methods, were assessed in North Carolina, South Carolina and West Virginia. Results suggested that the alternative methods afforded little to no advantage over traditional clearcut methods.

Weeding, fertilization and thinning treatments were employed post-harvest on rising 1-yr-old Hill Forest and rising 3-yr-old Duke Forest upland Piedmont sites. Stems at both sites responded to fertilization. Individual stem volumes increased 2 to 3-fold after three years. Weeding-alone increased growth on the Hill Forest. The response to weeding and fertilization treatments was usually additive. Thinning-alone had little effect on stem growth. However, thinning + weeding treatments simulated large increases in stem growth. For thinned stems, weeding generally had a greater affect on growth than fertilization at both sites.

Stems on the rising 1-yr-old Hill Forest site were tagged (>3000 stems) and monitored over three years. Stem survival was greatly affected by the weeding and fertilization treatments. Fertilization reduced survival for most species, especially for the lower initial height and diameter size classes. Weeding, by contrast, tended to increase survival in the small initial size classes. The survival data indicated that some of the growth response associated with fertilization might be due to mortality in the smaller sized stems.

Three-year growth and survival models based on initial stem size were generated for each species and treatment combination at the Hill Forest site. Comparisons were made between treatments for each species, and between *Liriodendron tulipifera* L. and *Cornus florida* L., *Prunus serotina* Ehrh., *Pinus* spp., *Acer rubrum* L. and *Quercus alba* L. for each treatment. Generally, most species responded favorably to weeding and fertilization treatments, although these responses were not always statistically significant. However, individual species differed in respect to their ability to increase growth and survival, although yellow-poplar ranked among the fastest growing species in every treatment after 3 years. These last data can be used to develop floristic models to predict species composition for other upland stands.

STAND DYNAMICS AND ECOLOGICAL CONSTRAINTS ON GROWTH IN YOUNG, NATURALLY REGENERATED HARDWOOD STANDS

by

JAMIE LEE SCHULER

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APPROVED BY:

Daniel J. Robison Chair of Advisory Committee	H. Lee Allen
Charles B. Davey	Douglas J. Frederick

BIOGRAPHY

Jamie Schuler was born in Rome, NY on June 13, 1974. He was enrolled in public schools in the Rome City School District until mid-way through his high school junior year. He and his family then moved to Blossvale, NY where he completed his high school education in Camden, NY.

Jamie obtained an A.S. degree in conservation from Finger Lakes Community College in Canandaigua, NY in 1994. He then transferred to SUNY College of Environmental Science & Forestry at Syracuse, NY, and subsequently earned his B.S. and M.S. degrees in 1997 and 1999, respectively.

In 1999, he moved to Raleigh to pursue a Ph.D. with Dr. Daniel J. Robison of the Hardwood Research Cooperative, Department of Forestry and Environmental Resources, North Carolina State University. In 2001, Jamie began working full-time for the Hardwood Research Cooperative as its Assistant Director.

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Study Objectives

The objectives of the research contained within this dissertation are to explore regeneration difficulties and management activities on moderately productive sites, instead of the highly productive Appalachian and bottomland sites that are the focus of much of the more resent research in hardwood forest management. This dissertation is divided into four chapters. Each chapter deals with a different component of the forest stand regeneration process.

In the first chapter, I evaluate three even-aged stand reproduction methods on the quantity and development of natural hardwood reproduction on three distinct site types in the U.S. I also compare the growth rates and the effects of harvesting on residual tree quality.

The second chapter includes a focus on how fertility, competing vegetation, and overstocking affect growth and development of newly established regeneration in very young, naturally regenerated hardwood stands. By implementing treatments that alter resource availability (weeding, fertilization, and thinning), growth constraints in young stands may be minimized allowing opportunities to change stand development patterns and ultimately increase longterm growth rates.

In the third chapter, I seek to highlight the actual mechanisms that produced changes in growth rates that were uncovered in the previous chapter. I examine the effects of intensive silvicultural treatments on leaf characteristics and seasonal growth patterns of individual stems within two very young naturally regenerated hardwood stands in order to better define the growth altering mechanisms. Yellow-poplar (*Liriodendron tulipifera* L.) was selected as the species of study because of its prevalence throughout the region, and because of its sensitivity to resource availability.

My objective in the final chapter is to determine how seedlings of co-occurring species on a newly regenerated upland hardwood site respond to gradients of resource availability induced by weeding and fertilization treatments. This final chapter shows that regeneration can be managed post-harvest by altering resource availability to match the requirements of individual species.

Literature Review

According to recent assessments, the South, from Virginia to Texas, contains about 215 million acres of forest, with slightly more than 200 million acres considered timberland (Conner and Hartsell, 2002). The hardwood resource is approximately 67% of the total timberland, with the largest forest-type group being oak-hickory at 55%. Hardwood timber production is highest in Mississippi, North Carolina, Georgia, Alabama, and Virginia.

The Southern Forest Resource Assessment has indicated that while hardwood stocks are plentiful, the inability to dramatically improve growth rates or expand their coverage will result in a declining hardwood inventory after twenty to thirty years (Prestemon and Abt, 2002). And for North Carolina, a steady increase in pine plantation acreage and conversion to urban and sub-urban uses are projected to decrease privately owned natural forest types (including natural hardwood and pine forests) by 30%.

As with all forestlands, southern hardwood forests will be expected to increase supply, but on fewer hectares. Given current growth rates, concerns of a declining hardwood resource are warranted. Compared to pine and hardwood plantations, growth rates in natural stands are considerably under-producing. Intensively managed pine plantations typically average 10-15 $m^3\ ha^{-1}\ yr^{-1}$, with some stands capable of growth rates over 25 $m^3\ ha^{-1}\ yr^{-1}$ (Allen et al., 1990). Sweetgum (*Liquidambar styraciflua* L.) and sycamore (Platanus occidentalis L.) plantations generally average 17 and 8 $m^3\ ha^{-1}\ yr^{-1}$, with some capable of 27 and 19 $m^3\ ha^{-1}\ yr^{-1}$, respectively, for 11-19 year old stands (Porter, 1997). By contrast, natural hardwood and hardwood-pine upland forests throughout the South have been plagued by poor growth rates. Growth rates for mature forest stands range from 4 to 7 $m^3\ ha^{-1}\ yr^{-1}$, whereas more productive cove and bottomland sites range from 5 to 10 m^3 ha^{-1} yr^{-1} (Roeder and Gardner, 1984).

Obviously, if the supply of natural hardwoods is to keep pace with projected demands, management has to change to meet the needs of a growing population. Many productive hardwood forests have been relegated to stands containing poor growing stock with low value as a result of repeated partial cuttings that removed favored species and/or trees over a certain diameter, without consideration of the residual growing stock (Fajvan et al., 1998). As a result, many stands are understocked in acceptable growing stock, and dominated by undesirable species and low merchantability.

Other historical activities have contributed to low growth rates in southern hardwood forests. From the late 1600s until the early 1900s, approximately one-third of the forestland was converted to other landuses. Much of this loss in forest cover was attributed to agriculture, transforming much of the Coastal Plain and Piedmont regions into croplands and pastures. Repeated cultivation and poor soil conservation practices have taken their toll on the soil resource. Large areas were rendered infertile through annual crop removals, while others lost massive amounts of topsoil from soil erosion, especially in the Piedmont regions. Some of the early hardwood site classification work demonstrated that hardwood productivity is related to the depth of the soil A horizon; deeper A horizons equated to higher site index (Coile, 1952). Consequently, large areas of the Southeast have been converted from fertile, productive soils capable of growing high quality hardwoods to loblolly pine plantations (*Pinus taeda* L.), which are better suited to these degraded soils. However, despite having older, degraded soils the southern U.S. does still support an important hardwood resource, and many highly productive hardwood sites remain. A challenge for the future is to develop and apply the appropriate technologies necessary to accelerate productivity on under-producing and productive sites alike, and to manipulate species composition to balance economic, wildlife, aesthetic, and diversity concerns.

Silvicultural Systems in the Southern U.S.

Uneven-aged systems have been shown to work well in the Northeast and Lake States (Eyre and Zillgitt, 1953; Nyland, 1987). Cutting cycles typically range from 15 to 25 years, leaving 19.4 and 14.8 m^2 ha^{-1} (Hansen and Nyland, 1987). These types of management scenarios favor shade tolerant, high value species like sugar maple (*Acer saccharum* Marsh.) and red maple (*A. rubrum* L.), with a few scattered white ash (*Fraxinus americana* L.), yellow birch (*Betula alleghaniensis* Britton), and black cherry (*Prunus serotina* Ehrh.) in larger openings, such as those attained using group selection.

Instances of successful uneven-aged silviculture are rare in the South. More common are partial cuttings or incomplete harvests (Fajvan et al., 1998), which are often conducted under the guise of single tree selection systems to justify the removal of mature timber to allocate growing space to suppressed and intermediate position individuals (*i.e.*, high-grading) (Nyland, 1992). Ironically, some of these types of harvests, particularly diameter-limit and selective cuts, result in an aesthetic appearance which is pleasing to the public, more so than the appearance following clearcutting, despite the negative impacts they have on future stand growth and value (Sheppard and Harshaw, 2001). Della-Bianca and Beck (1985) demonstrated that Appalachian hardwoods managed under a selection system failed to produce an adequate recruitment of saplings and poles of desirable species to maintain a balanced system. In fact, undesirable saplings (*e.g.*, dogwood (*Cornus florida* L.), red maple, blackgum (*Nyssa sylvatica* Marsh.), and hophornbeam (*Ostrya virginiana* K. Koch.)) outnumbered desirable species more than 3 to 1. Reports have shown that red oaks (Quercus spp.), some of the most valuable and desired species, have difficulty regenerating following single tree selection systems (Clatterbuck and Meadows, 1993), and question whether the regeneration that does develop is capable of growing into larger pole and sawtimber size classes (Goelz and Meadows, 1995).

Aside from regeneration concerns, managing stands using uneven-age methods will likely result in more damage to residual trees. Even minor wounds will be infection sites for disease and entrance sites for insects, leading to decay and discoloration that will further degrade log quality. In any circumstance where residuals are intended for harvest, these kinds of damages will dramatically reduce the value of these trees. In short, uneven-aged forest stands require more effort, and often time and money, to create, maintain, and manage.

As a result of these concerns associated with uneven-age management, southern hardwoods are generally managed under an even-aged silvicultural system. The recommended method for improving timber quality in mature degraded forest stands is clean (silvicultural) clearcutting (Kellison et al., 1981; 1988). Numerous reports have advocated its use in hardwood stands, and documented adequate stand development (fully stocked, desired species) following its application on bottomland (Bowling and Kellison, 1983; Krinard and Johnson, 1986), upland Piedmont (McKinney, 1997) and Southern Appalachian sites (Beck and Hooper, 1986). Contrary to many commercial clearcuts that leave non-merchantable trees occupying the site, clean clearcuts result in control of all trees larger that a given diameter, *e.g.*, 2 inches dbh. This condition facilitates rapid regeneration and full site occupancy by a variety of species, including a strong preference for shade intolerant species.

Regeneration is dependent on existing advance regeneration, stump sprouting and root suckering, and the seed bank (Johnson, 1993; Kelty, 1988). These sources also vary by species (Loftis, 1989; Schweitzer et al., 2004) and site quality (Kays et al., 1985). Non-sprout origin stems regenerate from either newly germinated seed or carry over from the previous stand as advance regeneration (Table 1). Sprout origin stems initially grow faster than newly established germinants of the same species (Schweitzer et al., 2004). Research has suggested that the primary source of regeneration, especially for recalcitrant species (*e.g.*, red and white oaks), is seedling- and stump sprouting (Kays et al., 1988).

Despite the overall effectiveness of clearcutting as a regeneration method, some drawbacks exist. On good to high quality sites without adequate advanced regeneration, desirable species with medium shade tolerance, particularly oaks are absent or occur in low numbers in the future stand due to competition from shade intolerant species like yellow-poplar (*Liriodendron tulipifera* L.) (Beck and Hooper, 1986; Brose et al., 1999; Loftis, 1989). Experience has also shown that a carefully controlled partial harvest, *e.g.,* shelterwood, can perpetuate both seedling and advance regeneration of species with moderate shade tolerance, whereas these species often fail under a clearcut system. According to Loftis (1990a), the key to producing a stand with a significant proportion of oak stems is having adequate numbers of advance reproduction present before removing the overstory. Since oak seedlings allocate more photosynthate for root development at the expense of shoot elongation, they are generally at a disadvantage during their first years of development. On good to high quality hardwood sites, species like yellow-poplar and red maple outgrow and quickly dominate oaks on newly regenerated sites. Foresters have realized this for many years, and have come to rely on advance regeneration to provide the necessary head start oak seedlings need to compete on productive sites. Even in young, regenerating stands, the growth of more shade intolerant species, i.e. maple and yellow-poplar, quickly relegates oaks to an understory position. This is especially notable when the competitors are largely sprout origin.

Light levels under mature hardwood canopies are generally below the light compensation point for red oaks (Hodges and Gardiner, 1993). Promoting advanced regeneration prior to harvesting by controlling mid- and understory vegetation several years ahead of applying the reproduction method is required in many instances. Using chemical or mechanical means to remove undesirable midstory trees to promote and maintain advanced regeneration is essential in maintaining oak on productive sites (Carvell and Tryon, 1961; janzen and Hodges, 1984; Loftis, 1985, 1990a).

The mere presence of advance regeneration, however, does not guarantee that oaks will continue to be a large component of the future stand. Even with about 2,200 to 10,000 stems ha^{-1}, Arend and Scholz (1969) suggested that the stocking of oak was inadequate because most seedlings were too small to compete with other regenerated species. Much research effort has been devoted towards determining what size regeneration is necessary to have stems in a dominant or co-dominant position in the canopy. Loftis (1990b) notes a dramatic increase in the probability of survival for advance regeneration with increasing basal diameter and decreasing site index. A minimum of 546 oak seedlings per hectare $\geq$1.37 m tall is recommended to insure adequate stocking (Sander et al., 1976). Regardless of the desired species, more larger advance regeneration will clearly improve the chances that regeneration goals will be met.

Constraints on Growth

Light is often assumed as the most limiting factor constraining plant growth. Janzen and Hodges (1984) hypothesized that the increase in oak advanced regeneration was likely due to increased light levels reaching the forest floor. Hence, understory and/or mid-story removal treatments are often prescribed to encourage advance regeneration. Other research has also flagged aboveground competition for light as a major factor in the performance of field planted seedlings (Lorimer, 1981).

However, as Coomes and Grubb (1999) and McPhee and Aarssen (2001) highlight in their reviews on root competition, it is very difficult to separate above- and belowground competition. Several experiments, beginning as early as the 1920's, showed tree seedlings and other forest plants could grow under the dark canopy of mature forest stands (Toumey, 1929). Toumey's experiments used trenching as a means to reduce root competition for what was presumed to be water limitations, but probably also nutrient deficiencies. Since then, several authors have used these root exclusion barriers (trenches), often with plastic liners, to demonstrate the effects of root competition for water and nutrients (see McPhee and Aarssen, 2001)

Repeating works of Toumey and others, Korstian and Coile (1938) showed that understory development on lower Piedmont soils in NC was again not limited solely by light. In their trenching experiment, Korstain and Coile found that understory vegetation develops rapidly under full canopies following trenching. This they attributed to increased soil moisture and nutrient uptake.

Competition belowground for water and nutrients probably constrain growth more than any other factors in the Southeast. Nutrient limitations have been well documented to limit tree growth in the eastern U.S. (Allen, 2000), with the first formal forest fertilization studies beginning in the early 1930's with Wyman (1936) and Mitchell and Chandler (1939). Most of the reported research has focused on southern pines with comparatively little interest in hardwood trees. Concern for shortages in hardwood fiber has prompted research into fertilization studies in hardwood plantations, notably cottonwood (*Populus* spp.), sycamore (*Platanus occidentalis* L.), and sweetgum (*Liquidambar styraciflua* L.) in the South. However, there is still a lag in fertilization studies in natural hardwood stands.

Nitrogen and phosphorus fertilization trials have demonstrated increased height and diameter growth in seedlings, and increased radial and volume growth in pole and sawtimber-sized timber. A number of nitrogen fertility studies show a nitrogen effect lasting 5-7 years (Graney and Pope, 1978; Lamson, 1978; Beck and Della-Bianca, 1981). Phosphorus usually will last for longer periods, even rotations (Allen, 2000).

Nitrogen and phosphorus have increased above and belowground seedling biomass in 5 yr old saplings in black cherry, oak spp. and yellow-poplar (Broadfoot and Ike, 1968; Farmer et al., 1970; Auchmoody, 1972; Beckjord et al., 1983, Netwon et al., 2003). Auchmoody (1972) noted that individually nitrogen produces a greater response than phosphorus alone. Together, nitrogen and phosphorus generally have a synergistic effect. However, the impact of increased nutrient capital on seedling growth has been inconsistent under natural field conditions. Studies with planted seedlings under good vegetation control have been successful, while those with little or no vegetation control have failed. With natural regeneration, red oaks have not responded well to N and NP treatments largely because of competition from more aggressive seedlings and sprouts (Graney and Rogerson, 1985).

Water limitations are common for young germinants and newly planted seedlings, as young seedlings have reduced root biomass impairing their ability to capture necessary resources (Dougherty and Gresham, 1988). While water alone is essential for survival, it also functions to transport nutrients into plants. Therefore, water limitations will also cause nutrient limitations (Haines and Haines, 1978). As Canham et al. (1996) note, nitrogen fertilization benefits seedling growth when there is sufficient soil moisture.

The effects of weeding treatments in hardwood plantations have been well-studied. Weed control clearly aids plantation establishment and growth (Zutter et al., 1987; Nelson, 1985; Schuler et al., 2004). The effects of competing woody and non-woody vegetation in newly regenerated natural stands are less clear, and the studies that are available report on short-term results (*i.e.*, 1 to 3 years). The removal of competing vegetation has been shown to promote increased growth on upland stands (Romagosa and Robison, 2003), while other studies show less consistent results (McGill and Brenneman, 2002).

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Table 1. Regeneration sources for various southern forest stands, excluding sprout origin stems.

From Seed Following Harvest	From Advance Regeneration
Birches (*Betula* spp.)	American beech (*Fagus grandifolia* Ehrh.)
black cherry (*Prunus serotina* Ehrh.)	basswood (*Tilia heterophylla* Vent.)
yellow pines (*Pinus* spp.)	black cherry (Prunus serotina Ehrh.)
yellow-poplar (*Liriodendron tulipifera* L.)	black locust (*Robinia psuedoacacia* L.)
	buckeye (*Aesculus octandra* Marsh.)
	cucumbertree (*Magnolia acuminata* L.)
	eastern hemlock (*Tsuga canadensis* (L.) Carr.)
	flowering dogwood (*Cornus florida* L.)
	hickories (*Carya* spp.)
	maples (*Acer* spp.)
	oaks (*Quercus* spp.)
	Silverbell (*Halesia carolina* L.)
	sourwood (*Oxydendrum arboreum* DC)
	white ash (*Fraxinus americana* L.)
	white pine (*Pinus strobus* L.)

Adapted from Loftis (1989)

Chapter I: Response of Reproduction and Residual Overstory Trees to Even-aged Regeneration Methods in Southern Hardwoods

Jamie L. Schuler

North Carolina State University, Hardwood Research Cooperative, Department of Forestry and Environmental Science, Raleigh, NC 27695-8008

Abstract

Southern hardwood forests have been degraded as the result of mismanagement, leaving them with poor desirable species composition and growth rates. The common prescription to rejuvenate these degraded stands is clean clearcutting. The regeneration and residual tree response of these forest stands to shelterwood reproduction methods, as compared to clean clearcutting, has not been well documented in large research trials.

In this study we compare two silviculturally appropriate alternatives to clean clearcutting, low- and medium-density shelterwood methods, across three physiographic regions: a North Carolina Piedmont forest, a South Carolina bottomland forest, and a West Virginia Appalachian slope forest. The residual overstory assessment immediately following treatment application determined that logging damage was generally minor. The 5-6 years post-harvest inventories of the low- and medium-density shelterwood treatments indicated that epicormic branching was often prolific on residual stems, and growth rates of the residual overstory averaged 0.15 to 0.66 cm yr^{-1} dbh. Regeneration height, abundance, and composition indicated that 5-6 years following harvests stem densities varied little among harvest treatments, and that average stem height decreased linearly with increased residual overstory basal area. Species composition was evaluated based on importance values (IV). For each site, IVs varied greatly depending on pre-harvest conditions and overstory

treatment. These techniques offer reasonable alternatives to clearcutting, but with some caution for slower regeneration growth rates, residual tree damage, epicormic branching, and species composition.

Introduction

Hardwood forests comprise about 75 million ha from Virginia to Texas in the southeastern U.S. (Conner and Hartsell, 2002). Much of the mature forestland contains poor quality sawtimber as a result of prior mismanagement (Fajvan, 1994). Incomplete harvests are often conducted under the guise of single-tree selection methods. In these incomplete harvests the removal of select individuals from even-aged mature timber is often justified as allocating growing space to suppressed and intermediate position individuals. These harvests are usually in the form of diameter-limit cuts and selective cuts where only the best and largest trees are repeatedly harvested, eventually leaving only undesirable and cull trees. Without a specific intent to regenerate new age classes and to tend existing ones, these practices amount to high-grading (Nyland, 1992). Ironically, some of these types of harvests result in an aesthetic appearance which is pleasing to the public, despite the negative impacts they have on future stand growth and value (Herrick and Rudis, 1994; Sheppard and Harshaw, 2001).

One recommendation for improving mature degraded hardwood forest stands is to regenerate them using clearcut regeneration methods (Kellison et al., 1981; 1988). Numerous reports have advocated its use, and documented adequate stand development (fully stocked, desired species) following its application (Bowling and Kellison, 1983; Johnson and Krinard, 1983; Beck and Hooper, 1986; Johnson and Krinard, 1988; Kennedy and Meadows 1993). Compared to many commercial clearcuts that leave non-merchantable trees occupying the site, clean clearcuts result in control of all trees larger than a given diameter, *e.g.*, 5 cm dbh. This condition facilitates rapid regeneration and full site occupancy by a variety of species (often similar to the composition of the previous stand (Messina et al., 1997; Rapp et al., 2001)), including a strong preference for shade intolerant species, with stems emerging from seed and sprout origins.

Despite the overall effectiveness of clearcutting as a regeneration method, some drawbacks exist. Regeneration is dependent on existing advance regeneration, stump sprouting and root suckering, and the seed bank (Johnson, 1993; Kelty, 1988). Without adequate advance regeneration, desirable species with intermediate shade tolerance, particularly oaks (*Quercus* spp.), are absent or occur in low numbers in the future stand due to competition from shade intolerant species like yellow-poplar (*Liriodendron tulipifera L.*) (Beck and Hooper, 1986; Loftis, 1989; Brose et al., 1999). Research in the southern Appalachians suggests that small, established oak seedlings can develop into advance reproduction with treatments that reduce basal area 60 to 70 % (Loftis, 1990). A carefully controlled partial harvest, *e.g.,* shelterwood, can perpetuate both seedling and advance regeneration of species with moderate shade tolerance, whereas these species often fail under a clearcut system (Loftis, 1983; 1989).

While the application of various even-age reproduction methods (*i.e.*, clearcut, high- and low-density shelterwood) generally produce similar numbers of stems per hectare (Young et al., 1993; McKinney, 1996), differences can occur in species composition and growth rates. These differences are often a function of the amount of residual basal area retained in the overstory (Young et al., 1993), and the variation in the species and origin of regeneration present at the time of harvesting.

Very few natural regeneration studies have incorporated the advantage of large, representative treatment blocks (≥2 ha), coupled with baseline preharvest data, and long-term (> 4 yr) monitoring of overstory and regeneration post-harvest response. This paper describes a case study that evaluates the application of three of the same even-aged stand regeneration methods on the quantity and development of natural hardwood reproduction during the stand establishment phase in large treatment blocks on three distinct site types in the U.S. Growth rates and the effects of harvesting on residual tree quality were also compared.

Methods

This study was initiated in late 1994 on three southern hardwood stands located in North Carolina (NC), South Carolina (SC), and West Virginia (WV), USA. Each stand was 50-70 yr old, relatively uniform, and contained a mixture of naturally regenerated hardwood species. The advantage this study has was the large size of the treatment blocks. The 2 to 5.25 ha blocks plus a 40 m buffer were extensive enough that the measurement plots were not influenced by edge effects. However, the large treatment blocks required a minimum of 8 ha (plus buffers) of reasonably uniform hardwood forest, which for practical reasons precluded the installation of treatment replications at each site. Since each site was unique in terms of physiographic location, productivity, and species composition, they could not be combined to test for differences in species composition or other variables.

Treatment Description

Each stand was divided into four equal treatment plots, ranging from 2 to 5.25 ha depending on tract size. Each treatment plot was randomly assigned to one of the treatment plots (non-replicated). A 40 m buffer was left between treatment plots. The treatments imposed in the winter of 1994/95 were:

(1) control- no harvesting;

(2) silvicultural clean clearcut- all merchantable stems greater than 3.8 cm were cut or deadened;

(3) medium-density shelterwood- stocking reduced to about 11.5 $m^2 ha^{-1}$, commercially important trees of good vigor were left in a well-spaced pattern; and

(4) low-density shelterwood- stocking reduced to about 7.0 $m^2 ha^{-1}$, commercially important trees with good vigor were left in a well-spaced pattern.

Site Descriptions

North Carolina

This upland site was located in the Piedmont region in Durham Co., on the NC State University Hill Demonstration Forest. Soils were representative for the area, Herndon silt loam (fine, kaolinitic, thermic Typic Kanhapludults) on gently rolling topography within the Carolina Slate Belt. Inherent soil productivity is moderate, *i.e.*, SI_{50} 23 m for northern red oak (*Quercus rubra* L.). The even-aged stand was 50-55 years old with a pretreatment basal area of 30 $m^2 ha^{-1}$ when treatments were installed.

South Carolina

This bottomland site was located in Colleton Co. on MeadWestvaco Corporation land. Inherent soil productivity was high, *i.e.* about SI_{50} 30-33.5 m for loblolly pine (*Pinus taeda* L.) (no site index was available for oak). The site was classified as a blackwater bottomland hardwood forest growing on the second terrace of the Edisto River. The soil was Lumbee loamy sand (fine-loamy over sandy or sandy-skeletal, siliceous, subactive, thermic Typic Endoaquults). The stand was primarily even-aged, 60-65 years old, with a few apparently older stems. Pretreatment basal area was 27 m^2 ha^{-1}.

West Virginia

This upland site was located in Greenbrier Co. on MeadWestvaco Corporation land. The site was a south-facing southern Appalachian slope hardwood forest, located 1036 m above msl. Soils were of the series Dekalb cobbly sandy loam (loamy-skeletal, siliceous, active, mesic Typic Dystrudept) and Gilpin channery silt loam (fine-loamy, mixed, active, mesic Typic Hapludult) (McKinney, 1996). The study area was generally very stony with 5 to 20 % slopes. Inherent soil productivity was moderate, *i.e.,* SI_{50} 21 m for northern red oak. The stand was 74 years old when treatments were installed, with a pretreatment basal area of 27 m^2 ha^{-1}.

<u>Measurements</u>

Measurement protocols varied slightly among sites. Prior to harvest in late 1994, 17-20 permanent 0.01 ha plots (NC), 24 permanent 0.01 ha plots (SC), and 12 permanent 0.02

ha plots (WV) were installed across each treatment block to determine initial overstory conditions. All subsequent overstory measurements were obtained in these same plots. All stems over 14 cm dbh were tallied by species in these plots. Overstory measurements of each residual stand were taken immediately following the shelterwood treatments, and five years after the harvest treatment for SC and WV, and six years after harvest for NC. Logging damage and epicormic branching on overstory stems $\geq$30 cm dbh were also assessed during post-harvest inventories. Epicormic branching was recorded as present or absent on the first 4.9 m section of the bole or butt log. In addition, bole and crown damage, *e.g.,* broken branches and bark sloughing, were noted as present or absent on each tree.

Preharvest advance reproduction ($\leq$3.8 cm dbh) was inventoried in late 1994. Preharvest data for the WV Appalachian and NC Piedmont sites were obtained from McKinney (1996). The measurement protocol in WV and NC consisted of 36 to 48 sample points with two 1-m^2 subplots in which each stem was tallied by species (no height measurements taken). The SC bottomland site was assessed using 48 to 60 4-m^2 plots within each treatment block. Stems in SC were tallied by species, and height class ($<$1.2 m or $\geq$1.2 m) recorded for all individuals $\leq$3.8 cm dbh.

Postharvest regeneration was assessed five (SC, WV) or six years (NC) after cutting using two 4-m^2 plots located 3 m to the north and south of the plot center of each permanent overstory plot. Species, stem origin (seed vs. sprout), and height to nearest 30 cm were recorded for seedling- and sapling-sized trees in NC and WV. On the SC site, species and stem height (tallied as $<$1.2 m or $\geq$1.2 m) were recorded.

Data Analysis

Pseudo-replication among treatments at each site prevented statistical comparison of treatment means for the overstory and regeneration data. Instead, descriptive statistics were used to report the overstory and regeneration response to the treatments. Mean regeneration height and abundance, calculated from the average of two plots per overstory measurement plot, were used to described the regeneration response to the harvest treatments. Also, species richness was calculated as the total number of species identified on the regeneration subplots per treatment. The response of the residual overstory trees in both shelterwood treatments was described using the average residual overstory basal area, stems ha^{-1} and quadratic mean stand diameter (QMD). Pre-harvest, immediately post-harvest and 5-6 years post-harvest values were compared. Residual stem damage estimates for both shelterwood treatments were based on the total number of individual trees sampled per treatment block.

The effect of residual overstory basal area on the amount and size of regeneration was analyzed using simple linear regression by site. The residual basal area immediately post-harvest for each 0.1 ha overstory plot was regressed on the 5-year (6-yr for NC) regeneration height and density averages. The regeneration data associated with each overstory plot was the average height and density of the two subplots. This analysis provides an examination for each site as an independent case study.

Post harvest importance values (IV) for regeneration for each treatment were calculated for NC and WV as the sum of relative abundance (RA), relative dominance (RD), and relative frequency (RF), where relative refers to the contribution of an individual species to the total (Curtis and McIntosh, 1951). The relative dominance for SC was calculated as the average percent of stems of individual species ≥1.2 m tall compared to the maximum average percent ≥1.2 m, since height classes were tallied at this site.

Results

North Carolina

The preharvest stand contained an average of 373 stems ha^{-1} and 30.3 m^2 ha^{-1} of basal area (Table 1), with a quadratic mean diameter (QMD) of 32 cm across all treatment blocks. The range in preharvest stem density and basal area among the treatment plots was 79 trees ha^{-1} and 3.7 m^2ha^{-1}, respectively. Yellow-poplar and hickory (all species scientific names are contained in Table 2) comprised about 50% of the initial species composition of stems 14 cm or larger across the stand (Table 2). The clearcut, low- and medium-density shelterwood treatments removed 100, 77 and 57 %, respectively, of their initial basal areas. After six years, the control and low-density shelterwood treatment blocks lost an additional 0.8 and 0.3 m^2 ha^{-1}, respectively, while the medium-density shelterwood stand gained <0.2 m^2 ha^{-1}. The control and both shelterwood treatments had lower stem densities by the sixth year (Table 1). The QMD of overstory trees increased 1.8, 1.8 and 3.8 cm for the control, low- and medium-density shelterwood blocks, respectively, over the same period.

Residual tree degrade was recorded as incidence of epicormic branching, stem damage from felling or machinery, and crown breakage. At least one epicormic branch was recorded on the first 4.9 m log on 71, 38 and 10 % of the sawtimber-sized trees (≥30 cm dbh) for low- and medium-density shelterwoods and control trees, respectively. The majority of these branches occurred above the lowest 2.4 m stem section. Hickory and sweetgum, both minor components, and white oak exhibited the most epicormic sprouting, with 100, 75 and

75 % incidence, respectively. Stem damage, putatively from logging activities, occurred on 44% of sawtimber stems within the medium-density shelterwood treatment, and 29% of stems in the low-density shelterwood treatment. Crown breakage was 29% in the low-density shelterwood treatment. The proportion of trees 30 cm dbh or larger that were damaged (*i.e.*, having either stem or crown damage or epicormic branches on the first 4.9 m log) was 88, 69 and 22 % for the low- and medium-density shelterwoods and control treatments, respectively.

Each of the four treatment blocks had similar numbers of stems before harvest, ranging from about 96,000 to 116,000 stems ha^{-1} (Table 3). Red maple was the most prevalent species. Hackberry, even though absent as a canopy species, was very common as advance regeneration. Other common species included American beech, American holly, flowering dogwood, hophornbeam, and white ash.

After six years, the uncut control stand had about one-third fewer seedlings and saplings than prior to harvest. However, it still had abundant numbers of seedlings and saplings (over 32,000 stems ha^{-1}), although most were small stems of non-commercial species (Table 3). Seedling and sapling densities within clearcut, low- and medium-density shelterwood treatments changed +37, -26 and –7 % six years after harvest, respectively. A negative linear trend (P=0.1078, R^2=0.80) is apparent when stem density is regressed on residual basal area of all treatments including the control (Fig. 1). However, no trends were identified that predicted stand density using residual basal area for just the three regeneration treatments.

A significant negative linear relationship (P=0.0053, R^2=0.99) between average height of regeneration and residual basal area across all four treatments was also found.

After six years, the average height of regeneration was 2.0, 1.9 and 1.5 m for the clearcut, low- and medium-density treatments, respectively, compared to 0.9 m for seedlings (as advance reproduction) in the control. Excluding the control treatment, there was still a negative linear tend, albeit non-significant (P=0.1334, R^2=0.96), between regeneration density and residual basal area.

Harvesting increased tree species diversity. Inventories six years following the clearcut, low- and medium-density shelterwood regeneration cuts identified a total of 30, 25 and 24 species, respectively, compared to 19 in the control. Shade tolerant species dominated the understory in the uncut control plots, and the harvested areas were dominated by more shade intolerant species (*e.g.,* yellow-poplar). The highly shade intolerant yellow-poplar ranged from 29 to 57 % of all stems across clearcut, low- and medium-density shelterwood treatments, respectively, after 6 years (Table 4), whereas in the uncut control they represented only about 1% of the advance regeneration.

Importance values were calculated for each species within each treatment for the regeneration plots (Table 3). The clearcut block was dominated by yellow-poplar. For the low-density shelterwood treatment, yellow-poplar was again dominant, but sweetgum, hophornbeam, red bud and red maple were also abundant. For the medium-density shelterwood, species with the highest IVs were again yellow-poplar, red bud, red maple, but also included American beech.

A comparison of the non-harvested control seedlings versus all harvesting treatments combined showed increased levels of importance for laurel/willow oak, hophornbeam, pines, red bud, red oak, sassafras, sweetgum and yellow-poplar among overstory treatments. American holly was the only species that had a large decrease in importance as regeneration as a result of the harvesting treatments (Table 3). American beech, blackgum and hornbeam increased in importance with increasing residual overstory basal area. By contrast, pines and sweetgum had their highest importance with decreased residual overstory basal area. The magnitude of yellow-poplar dominance was similar between the clearcut and medium-density shelterwood treatments, and both were greater than the low-density shelterwood treatment. Yellow-poplar still maintained the highest IV for each harvest treatment, while hophornbeam and white oak attained their greatest dominance under the low-density shelterwood treatment.

The number of sprout-origin stems can influence the overall competitiveness of a species. American beech, American holly, dogwood, hickory, and red and white oaks showed high percentages of sprouting stems (Table 4). By contrast, yellow-poplar and black cherry regenerated mainly through newly germinated seed.

South Carolina

The preharvest stand contained approximately 336 stems ha^{-1} and 27.1 m^2 ha^{-1} of basal area (Table 1), with a QMD of 32.5 cm across all treatment blocks. The range in preharvest stem density and basal area among treatment blocks was 111 trees ha^{-1} and 10.3 m^2 ha^{-1}. Initial species composition consisted of willow oak (30%), swamp chestnut oak (13%), sweetgum (12%), and 17 additional species (Table 2). Regeneration treatments left 0, 17 and 38 % of the original basal area for clearcut, low- and medium-density shelterwood treatment blocks, respectively. After five years, the low- and medium-density shelterwood and control block overstories gained 0.7 to 2.1 m^2 ha^{-1}. The SC partial cut blocks retained all of their residual overstory stems during this period, while the control stand added some stems through ingrowth. The QMD of the residual trees changed –0.25, +2.5 and +3.3 cm for the control, low- and medium-density shelterwood treatments over the same period, respectively (Table 1).

The five-year post-harvest inventory indicated severe epicormic branching on the overstory leave trees ($\geq$30 cm dbh) for both shelterwood treatments. Almost one-half of the residual trees in the medium-density shelterwood treatment had visible epicormic branches on the first 4.9 m section of sawtimber sized trees, while over three-quarters of the sawtimber sized trees in the low-density shelterwood treatment had epicormic sprouting. Epicormic sprouts were especially prominent on sweetgum and water/willow/laurel oaks. About 80% of the sweetgum and 63% of the water/willow/laurel oak stems developed sprouts on the first 4.9 m log. Felling and extraction activities only damaged one leave tree on the site.

The control, clearcut, and medium-density shelterwood treatment blocks had similar pre-treatment numbers of advance regeneration, from 143,300 to 190,300 stems ha^{-1} (Table 5). Water/willow/laurel oak (combined because of difficulties separating very small seedlings) were by far the most prevalent species, ranging from 49,400 to 133,400 stems ha^{-1} across all treatments. The low-density shelterwood treatment block had substantial numbers of water/willow/laurel oak, with about 500,000 stems ha^{-1} tallied across the treatment plot. However, all but 208 of these oak stems ha^{-1} were less than 1.2 m tall (data not shown). Other well-represented commercial species included river birch, sweetgum, red maple, and some swamp chestnut oak (Table 5).

There was no linear trend for stem density related to residual basal area across all harvest treatments and the control (P=0.7757, R^2=0.05) (Fig. 1), nor were trends found among the harvest treatments (excluding the control). After five years, the amount of regeneration varied from 37,100 to 58,100 stems ha^{-1} among treatments (Table 5). However, differences in the development of regeneration were apparent. Of the total number of seedling/saplings present on the uncut control block, only 25% were at least 1.2 m tall. About 50% of the advance regeneration contained in both shelterwood treatments was at least 1.2 m tall, while the clearcut had the greatest proportion with 71% of the advance regeneration at least 1.2 m tall.

Harvesting did not appreciably alter the tree species diversity, except for plots within the low-density shelterwood treatment. Inventories performed five years after the treatments were imposed identified a total of 18 species on each of the clearcut, medium-density shelterwood and control blocks, while only 11 on the low-density shelterwood cut. Of the species initially present in the overstory, four species were absent on the medium-density shelterwood and control regeneration plots, while six and seven species were absent from the clearcut and low-density shelterwood regeneration plots, respectively, after 5 years (Table 5).

Importance values indicated that water/willow/laurel oak complex dominated the non-harvested control plots (Table 5). Yellow-poplar, sweetgum, and red maple were the most important species following clearcutting. Sweetgum and water/willow/laurel oak were most pronounced following the low-density shelterwood cut, while yellow-poplar, sweetgum and water/willow/laurel oak were most important species present following the medium-density shelterwood seed cut.

A comparison of regeneration between the non-harvested control and all harvesting treatments combined identified few species (*e.g.*, cherrybark oak, hickory) as having reduced IVs with harvesting. However, their contribution as advance regeneration was notably limited (Table 5). Pines, red maple, sweetgum and yellow-poplar all increased their IVs following harvest compared to the control.

Among harvesting treatments, the medium-density shelterwood treatment had higher IVs for cherrybark and water oak than the clearcut or low-density shelterwood treatments. Southern magnolia, pines, red maple and black willow had larger IVs after clearcutting. Clearcutting and medium-density shelterwood methods generally produced greater IVs than the low-density shelterwood treatment.

The inventory on this bottomland site showed that the number of stems developing from stump and seedling sprouts was relatively low (Table 4). Those that did demonstrate a high percentage of sprout-origin stems generally had little contribution to the overall stem count (*e.g.*, green ash).

West Virginia

The preharvest stand contained about 346 stems ha^{-1} and 27.6 m^2 ha^{-1} of basal area (Table 1), with a QMD of 31.5 cm across all treatment blocks. Overstory species composition consisted of red oak (24%), red maple (19%), chestnut oak (15%), Fraser and cucumber magnolia (11%) and 12 other species (Table 2). Harvesting reduced basal area by 75 and 67 % in the low- and medium-density shelterwood regeneration treatments, respectively. Over five years, residual overstory stem density in the control and shelterwood treatments remained relatively constant. The QMD of these trees increased 1.0, 1.5 and 0.8 cm for the control, low- and medium-density shelterwood blocks, respectively, over the same period (Table 1).

After five years, some degrade in the residual overstory stem quality was evident. Felling and extraction damages were minimal, occurring on about 5% of the residual stems in both shelterwood treatments. Epicormic branches were found on 24 and 20 % of the overstory stems in the low- and medium-density shelterwood stands, respectively. This epicormic branching occurred entirely on the various species of oak, which accounted for almost 75% of the residual overstory. When felling and extraction damages were included, 29 and 27 % of the residual stems had some form of damage in the low- and medium-density shelterwood treatments, respectively, compared to 2% for the control.

Preharvest inventories indicated similar numbers of advance regeneration across all treatments, ranging from 42,000 to 51,900 stems ha^{-1} (Table 6). White ash was the most common species, but red maple, sugar maple, and red oak were also found in high numbers. Five years following the harvests, residual basal area significantly affected regeneration density across all treatments (P=0.0717, R^2=0.86, Fig. 1). The regeneration treatments had greater numbers of seedlings and saplings than the control (Table 6), whereas there was no linear relationship among the regeneration treatments themselves (excluding the control), which ranged from just over 34,600 to slightly less than 43,200 stems ha^{-1}.

After five years, the height of regeneration for clearcut, low- and medium-density shelterwood, and control treatments averaged 1.6, 1.3, 1.2 and 1.4 m, respectively. With the control treatment included, no obvious trend related to residual basal area was evident (Fig. 1). However, among regeneration treatments, a clear linear trend is present (P=0.1311, R^2=0.96).

Harvesting increased tree species diversity. Clearcut, low- and medium-density shelterwood reproduction methods resulted in a total of 19, 18 and 17 species, respectively, compared to 7 species in the control treatment. Of the species initially present in the overstory, four species were absent on the medium-density shelterwood and clearcut regeneration plots, while five and eight species were absent from the low-density shelterwood and control regeneration plots, respectively, after 5 years (Tables 2 and 6).

Importance values calculated for the WV site (Table 6) showed that plots in the control treatment were dominated by shade tolerant sugar maple, with a lesser component of striped maple. The blocks regenerated by clearcut and shelterwood methods contained largely mixed stands of black birch, white ash, sugar maple and cherry.

A comparison between the control and all harvesting treatments combined identified black birch, black and pin cherry, white ash, and yellow-poplar with sizeable increases in importance in the regenerated stands, while sugar and striped maple had reduced IVs associated with harvesting. Within the harvest treatments, red maple and sassafras both attained greatest importance on the low-density shelterwood treatment. Striped maple, a competitor to more valuable species, was most important on both shelterwood plots, and yellow birch developed higher IVs following clearcut and medium-density shelterwood treatments.

The number of sprout-origin stems compared to putatively seed-origin stems is small (Table 4). While red oak in the medium-density shelterwood treatment had only about 2,500 stems ha^{-1} after 5 years, about 50% were sprouts and likely at a competitive advantage over most seed-origin stems. Sugar maple was the other species present in high numbers, and with roughly 50% sprout frequency.

Discussion

Residual Stands

Growth rates of the control stands were typical of degraded, mature hardwood stands throughout the southeastern U.S. (Roeder and Gardner, 1984). In almost every case, the control stands on our three study sites grew <0.23 $m^2 ha^{-1} yr^{-1}$. Periodic annual increment was less than 0.25 cm QMD for the SC and WV sites. The NC site averaged 0.30 cm yr^{-1} QMD, but the slightly improved growth rate was likely due in part to the loss of 20 overstory trees from the lower end of the diameter distribution, presumably due to exposure (Table 1).

The shelterwood overwood on all three sites grew only moderately even though many of these reserve trees were species that respond well to release, *e.g.* red oak (Meadows and Goelz, 2002). Many of the leave trees had restricted crowns prior to release that were slow to expand, which may indicate a need for a preparatory cut 5-10 yrs prior to the regeneration cut to improve tree vigor.

The NC site was the only one that had a substantial decrease in the number of overstory trees in the cut areas surviving until remeasurement. Two growing seasons after treatments were imposed Hurricane Fran (6 September 1996) swept through the region, causing considerable damage. The result was that control and both shelterwood treatment blocks had no net gain in basal area over the six-year period and losses in the number of overstory trees. Residual overstory trees on shelterwoods are inherently at high risk for windthrow, especially on vulnerable sites (Ruel, 1995).

Epicormic branch development is a serious problem for the future marketability of leave trees (Kellison et al., 1981; Kellison et al., 1988; Smith et al. 1989). New branches will be expressed as a defect in the new sapwood if the residual shelterwood is not harvested in a few years. Epicormic branching was found on the first 4.9 m log of 20 to 80 % of the trees on each of the low- and medium-density shelterwood treatments on all sites. Studies on bottomland sites in AL and SC documented very similar results (Stubbs, 1986; Meadows and Burkhardt, 2001). Smith and others (1989) also documented similar incidences after applying a seed tree cut in a WV Appalachian stand, where 45 and 33 % of red and white oak stems, respectively, developed branches, while under similar conditions yellow-poplar developed few epicormic sprouts (Della-Bianca, 1972; Johnson et al., 1998; Smith, 1977). These results highlight the need to account for the propensity of various species, tree ages, and sites to produce epicormic sprouts, as a criterion for selecting leave trees if optimizing their timber value is an objective.

Whenever residual trees are to be left during harvest operations, there is also potential for significant damage to them from logging activities (Egan, 1999). The higher incidence of logging damage on the NC site was probably due to poor contractor performance on public lands (highest bidder), whereas on industrial lands selected contractors have demonstrated quality operations. Logging damage breaks the integrity of the bark, often low on the bole, and results in grade reductions and substantial loss of value. These wounds will be infection sites for disease and entrance sites for insects, leading to decay and discoloration that will further degrade log quality. Shigo (1972) demonstrated that 100% of logging wounds on oak were infected by stain or decay fungi. Shortle and Cowling (1978) showed that the development of fungi can be rapid, 0.9 m of stem in two years for yellow-poplar. If residual overstory trees are not intended for later extraction and value realization, then toppling, top breakage, epicormic sprouts, and logging damage matter little. However, in any circumstance where residuals are intended for harvest, these kinds of damage will dramatically reduce the value of these trees, especially if shelterwood reserve systems are to be implemented.

Regeneration

The NC Piedmont, SC bottomland, and WV Appalachian hardwood forest stands reported here were responsive to stand disturbances, as expected for eastern hardwood forests (Barrett 1995). Each of the three regeneration techniques successfully produced a new cohort of regeneration with densities that were within or greater than published ranges (Johnson and Krinard, 1988; Smith et al., 1989; Waldrop, 1997; Young et al., 1993).

The amount and species composition of regeneration that develops following disturbance is at least partly dependent on the disturbance intensity. The stand regeneration methods employed in this study represent a disturbance intensity continuum from moderate (medium-density shelterwood) to severe (clearcut). With increased disturbance intensity, a greater area is available for new and existing regeneration and more site resources become available to support their growth. Some authors report that under a wide range of residual basal areas, stem density is little affected (Young et al., 1993). Our data for the clearcut and shelterwood treatments also demonstrate this. However, plots of stem density against residual basal area (control included) show trends of decreasing stem density with increasing residual basal area (Fig. 1), but the exact point at which residual basal area affects regeneration density is still unclear.

Height growth development was also affected by treatment. For both the NC and WV sites, clearcutting resulted in the tallest regeneration, whereas the medium-density shelterwood produced the shortest average regeneration of the three methods assessed. For the SC site, clearcutting produced a greater percentage of stems greater than 1.2 m tall (71%)

compared to shelterwood treatments (ca. 50%). Whether this or stem density differences will have longterm effects on stand development is unknown.

Species richness has been reported to change (*e.g.*, McKinney, 1996; Wang and Nyland, 1993), or remain similar (*e.g.*, Messina et al., 1997; Rapp et al., 2001), following disturbance. Species richness in the current study was not appreciably different across the three sites and among the three regeneration treatments, except for the low-density shelterwood in SC which had only 11 species five years following harvest. Most dramatic was how the treatments altered the relative contribution of each species (Table 3, 5 and 6).

In the current study, both red and white oaks regenerated almost exclusively as sprouts. Species like red maple, American beech, American holly, and dogwood are generally less desirable for timber, and also appeared to persist due to coppicing (Table 4). The propensity of individual trees to sprout is not only different among species, but has also been shown to decrease with tree age and size (Sander et al., 1976). The lack of sprouts, especially for the SC bottomland site (Table 4), may indicate that species composition in conjunction with tree maturation and a lack of smaller diameter stems resulted in conditions that were not conducive for stump sprouting, and therefore did not contribute much as a source of regeneration. Stump and seedling sprouts are important sources of reproduction in many hardwood stands (Petruncio and Lea, 1985; Zahner and Myers, 1984), which practitioners have come to rely on to perpetuate certain species for timber, and for heavy seeded-large mast producing species for wildlife.

Across study sites, yellow-poplar, pines, birch, and red bud apparently established themselves from seed fall and bank, since they had little to no advance regeneration present prior to treatments. The origin of sweetgum was difficult to isolate because of its propensity to root sucker, as well as regenerate from seed and stump sprouts. Regardless of origin, the new germinants of yellow-poplar and sweetgum had little difficulty capturing a competitive advantage in each of the regenerated treatment blocks.

Despite the large number of species regenerated across all three sites, the forest products industry, wildlife managers, and non-industrial landowners alike, have favored oak species. However, the ability of managers to successfully regenerate oak species has been poor, especially on good to excellent sites (Johnson and Krinard, 1983; Loftis, 1989). In spite of comprising about 25% of the overstory in WV, red oaks did not produce many stump sprouts, and few of the preharvest seedlings and saplings survived to 5 years after the overstory removal. Red oak's best IV ranking was sixth with the shelterwood treatment in WV. This result is a common occurrence on Appalachian sites (Loftis and McGee, 1993). The need to develop and maintain oak as advance regeneration on moderate to high quality upland sites has been well documented. Control of less desirable species in the understory and mid-canopy prior to harvest may be necessary in certain cases to promote preferred species regeneration (Brose et al., 1999; Crow, 1988; Kelty and Nyland, 1981; Loftis, 1990). For the NC site, oak species accounted for 10% of the overstory composition, and the percent of oak regenerated in the low-density shelterwood increased slightly over preharvest levels. However, the longterm oak contribution to these stands will likely be minimal due to their small size (Loftis, 1990; Sander, 1972; Sander et al., 1976). In fact, of the oaks found, 43, 27 and 57 % are already less than the average height of all regeneration for clearcut, low- and medium-density shelterwood treatments, respectively.

By contrast, the water/willow/laurel oak complex was well-represented on the SC bottomland site five years after harvest on all treatments. The dense cover of oak advance regeneration on this site, almost all being less than 1.2 m tall, coupled with putatively newly germinated seed-origin stems (Table 4), was successful in perpetuating these oak species in the new stand.

Conclusions

Southern hardwood forests are flexible in their regeneration requirements. After five to six years, clearcut and shelterwood regeneration methods produced stands with economically desirable species on all sites. On the NC Piedmont site, yellow-poplar dominated each of the harvested blocks following the regeneration treatments. The SC bottomland site largely contained yellow-poplar and sweetgum on the clearcut and medium-density shelterwood compartments, and a strong component of sweetgum and laurel oak using the low-density shelterwood method. The WV Appalachian site was composed of mainly black birch and sugar maple irrespective of the regeneration treatment.

As documented by previous work in these forest types, the overstory does not necessarily provide a good indication of the subsequent community composition when following an even-aged management system. As this study demonstrates, while there may not be a change in the number of species, there often are large changes in their relative contributions. A case in point is red oak, which accounted for 25% of the WV overstory. Importance values indicate this species will likely be a minor component in the developing stand, across all regeneration techniques used.

The residual overstory stems in both shelterwood treatments experienced degrade in the form of epicormic branching. Roughly one-half of these leave trees had epicormic branches after five or six years, and was very pronounced for species like hickory, sweetgum, and white oak. Logging damage from felling and extraction was minimal except on the NC site. These damages and degrades can be minimized by using skilled logging contractors and through judicious selection of leave trees. Under the stand conditions described in this study, the application of low- and medium-density shelterwood regeneration methods did not provide any distinct regeneration advantage over the clearcut regeneration method. Furthermore, the shelterwood treatments resulted in shorter regeneration after five or six years, indicating that the residual overstories should have been removed sooner than was planned (10 yrs for the medium density shelterwood). Also, these methods will likely be more costly due to quality losses in the residual overstory, and because they require an additional stand re-entry.

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Table 1. Overstory basal area and stem density (stems >14 cm dbh) on three study sites pre- and post-harvest, and 5 or 6 years after three regeneration treatments.

	Stem Density			Basal Area		
Regeneration Method	Preharvest	Residual	5 or 6 Yr[a]	Preharvest	Residual	5 or 6 Yr[a]
NC	------(stem/ha)------			------(m^2/ha)------		
Control	390	390	341	29.9	29.9	29.1
Clean clearcut	418	0	0	32.6	0.0	0.0
Low-density shelterwood	339	104	88	29.0	6.7	6.4
Medium-density shelterwood	348	94	78	29.7	12.8	12.9
SC						
Control	371	371	391	26.4	26.4	27.5
Clean clearcut	259	0	0	22.1	0.0	0.0
Low-density shelterwood	371	45	45	30.3	5.3	6.1
Medium-density shelterwood	341	91	91	32.4	12.4	14.4
WV						
Control	326	321	314	27.1	28.2	29.2
Clean clearcut	321	0	0	22.8	0.0	0.0
Low-density shelterwood	353	70	69	26.4	6.7	7.4
Medium-density shelterwood	395	82	69	32.9	10.8	10.8

[a] The NC site remeasurement period was six years following initial harvest, SC and WV were after five years.

Table 2. Preharvest species composition (stems ≥ 14 cm dbh) across all treatments and three site types: a NC upland Piedmont, a SC bottomland, and WV Appalachian.

Species	Site		
	NC	SC	WV
	-------------------%------------------		
American beech (*Fagus grandifolia* Ehrh.)	11.0	1.5	6.0
American holly (*Ilex opaca* Ait.)	-	0.9	-
basswood (*Tilia americana* Vent.)	-	-	2.2
blackgum (*Nyssa sylvatica* Marsh.)	4.2	10.2	-
black birch (*Betula lenta* L.)	-	-	1.2
black cherry (*Prunus serotina* Ehrh.)	-	-	4.6
chestnut oak (*Quercus montana* Willdenow)	-	-	15.3
elm (*Ulmus spp.*)	-	0.3	-
Fraser/cucumber magnolia (*Magnolia fraseri* Walt., *M. acuminata* L.)	-	-	10.9
green ash (*Fraxinus pennsylvanica* (Borkh.)Sarg.)	-	2.0	-
hickory (*Carya spp.*)	23.3	2.3	1.4
persimmon (*Diospyros virginiana* L.)		0.3	-
pine (loblolly, Virginia) (*Pinus taeda* L., *P. virginiana* Mill.)	1.3	1.2	-
red maple (*Acer rubrum* L.)	5.5	4.4	18.8
red oak[a]	0.8	2.1	23.6
river birch (*B. nigra* L.)	-	0.3	-
southern magnolia (*M. grandiflora* L.)	-	5.3	-
sugar maple (*A. saccharum* Marsh.)	-	-	9.7
swamp chestnut oak (*Q. michauxii* Nutt.)	-	10.5	-
sweetgum (*Liquidambar straciflua* L.)	8.9	16.1	-
white ash (*Fraxinus americana* L.)	-	-	2.0
white oak (*Q. alba* L.)	11.0	3.2	1.0
willow/laurel oak (*Q. phellos* L., *Q. laurifolia* Michx.)	0.4	30.4	-
yellow birch (*B. alleghaniensis* Britton)	-	-	0.4
yellow-poplar (*Liriodendron tulipifera* L.)	23.7	4.7	2.4
other	9.7	4.4	0.8

[a] Includes black (*Q. velutina* Lam.), cherrybark (*Q. pagoda* Raf.), northern red (*Q. rubra* L.), scarlet (*Q. coccinea* Muench.), and southern red oaks (*Q. falcata* Michx.).

Table 3. Advance regeneration and reproduction response to various regeneration methods in an upland Piedmont mixed hardwood stanc
in Durham Co., NC.

	Clean clearcut			Low-density shelterwood			Medium-density shelterwood			Control		
Species	Preharvest	Postharvest	IV[a]	Preharvest	Postharvest	IV	Preharvest	Postharvest	IV	Preharvest	Postharvest	IV
	-------------%------------			-------------%------------			-------------%------------			-------------%------------		
American beech	2.0	4.9	80	0.5	1.7	38	5.7	15.4	135	6.1	15.9	105
American holly	4.0	1.2	33	0.7	1.4	35	0.7	0.8	21	2.6	13.6	123
black cherry	0.9	0.9	69	1.8	1.6	83	0.7	1.4	73	2.2	4.0	74
blackgum	0.6	1.0	26	1.8	1.7	65	3.1	3.2	95	1.1	3.5	38
dogwood[b]	14.3	1.4	46	6.8	5.2	91	3.3	2.6	59	8.8	14.0	85
elm	0.3	0.1	6	0.2	0.1	8	0.2	0.1	8	0.2	0.0	0
fringetree[c]	0.0	0.0	0	0.2	0.0	0	0.0	0.0	0	0.0	0.0	0
hackberry	17.1	0.0	0	18.6	0.0	0	27.3	0.0	0	16.7	0.0	0
hickory	4.6	1.5	49	6.1	3.4	86	4.3	2.6	71	2.2	2.9	46
hophornbeam[e]	0.3	1.2	38	11.6	9.9	144	0.0	0.9	44	0.9	1.9	35
hornbeam[f]	0.3	0.2	19	2.5	3.6	68	0.2	1.4	77	1.3	1.1	37
laurel/willow oak	0.0	0.1	12	0.0	1.2	32	0.0	0.3	16	0.0	0.0	0
mulberry[g]	0.3	0.0	5	0.0	0.0	0	0.0	0.0	0	0.7	0.0	0
pine	0.0	0.9	63	0.0	0.3	13	0.0	0.1	6	0.0	0.0	0
red bud[h]	0.0	5.2	140	0.0	8.1	125	0.0	6.5	128	0.0	8.4	84
red cedar[i]	0.0	0.0	3	0.0	0.4	22	0.2	0.1	8	0.0	0.0	0
red maple	40.9	4.3	99	33.3	7.4	113	27.3	8.1	126	48.0	15.6	118
red oak[o]	1.4	3.4	83	3.2	2.0	58	1.9	3.8	99	1.8	4.1	53
sassafras[j]	1.4	1.2	51	0.0	0.9	49	0.5	2.3	74	0.2	0.0	0
serviceberry[k]	0.0	0.0	0	0.0	0.0	0	0.0	0.0	0	0.2	0.0	0
sourwood[l]	0.6	0.4	22	0.0	0.7	23	0.2	0.6	21	0.4	0.9	16
spicebush[m]	0.9	0.0	0	0.0	0.0	0	0.0	0.0	0	0.7	0.0	0.0
sweetgum	0.9	11.4	127	2.0	14.7	153	0.7	6.6	117	0.2	0.3	7
sycamore[n]	0.0	0.0	4	0.0	0.0	0	0.0	0.1	6	0.0	0.0	0
white ash	7.7	1.7	92	1.1	1.1	46	21.3	2.4	88	2.2	2.5	45
white oak	0.9	0.5	26	6.6	4.6	83	0.9	0.4	21	1.3	2.8	26
yellow-poplar	2.9	57.2	213	2.9	29.5	159	1.4	40.5	181	2.2	0.7	11
other	0.0	1.2	38	0.0	0.2	3	0.0	0.0	0	0.0	7.8	75
Stems ha^{-1}	97,221	133,091	--	116,053	85,835	--	105,499	113,147	--	114,000	32,432	--

[a] Importance values are the summation or relative abundance, relative dominance, and relative frequency for a maximum of 300 units.
[b] Cornus florida L., [c] Chionanthus virginicus L., [d] *Celtis occidentalis* L., [e] *Ostrya virginiana* K. Koch, [f] *Carpinus caroliniana* Walt., [g] *Morus spp.*,
[h] *Cercis canadensis* L., [i] *Juniperus virginiana* Mill., [j] *Sassafras albidum* (Nutt.) Nees., [k] *Amelanchier sp.*, [l] *Oxydendrum arboreum* DC.,
[m] , [n] *Platanus occidentalis* L.
[o] Includes black, cherrybark, northern red, scarlet, and southern red oak.

Table 4. Percent of regenerated stems that are of stump- and/or seedling-sprout origin on three southern hardwood sites in response to three even-aged reproduction methods.

	North Carolina			South Carolina			West Virginia		
Species	CC[a]	LDS	MDS	CC	LDS	MDS	CC	LDS	MDS
	---------------%--------------			---------------%--------------			---------------%--------------		
American beech	79	62	91	0	-	22	25	15	29
American chestnut	-	-	-	-	-	-	-	100	-
American holly	88	80	86	36	-	19	-	-	-
black cherry	7	5	24	0	-	0	0	8	0
black walnut	-	-	-	-	-	-	75	-	-
blackgum	0	39	15	0	0	0	0	0	0
chestnut oak	-	-	-	-	-	-	100	-	-
Fraser/cucumber magnolia	-	-	-	-	-	-	0	0	56
dogwood	57	49	46	-	-	-	-	-	-
green ash	-	-	-	-	100	-	-	-	-
hickory	57	81	100	-	-	60	-	-	-
hophornbeam	69	33	17	-	-	-	-	-	-
hornbeam	33	72	48	-	-	-	0	0	0
other	0	0	-	20	35	17	-	-	-
red bud	14	19	13	-	-	-	-	-	-
red maple	11	36	33	0	30	0	78	0	0
red oak	95	95	94	-	-	-	0	0	58
sassafras	22	0	25	0	-	-	0	0	-
serviceberry	-	-	-	-	-	-	100	0	0
sourwood	83	38	75	-	-	-	-	-	-
striped maple	-	-	-	-	-	-	0	40	40
sugar maple	-	-	-	-	-	-	47	32	74
swamp chestnut oak	-	-	-	5	0	9	-	-	-
sweet bay	-	-	-	43	0	0	-	-	-
sweetgum	18	17	3	4	4	3	-	-	-
water/willow/laurel oak	50	0	100	0	0	17	-	-	-
white ash	21	33	2	-	-	-	0	-	14
white oak	88	86	100	0	-	0	-	-	-
yellow-poplar	52	21	17	0	0	1	46	0	0

[a] CC=Clean clearcut, LDS=Low-density shelterwood, MDS=Medium-density shelterwood

Table 5. Advance regeneration and reproduction response to various regeneration methods in a blackwater bottomland hardwood site in Colleton Co., South Carolina

Species	Clean clearcut			Low-density shelterwood			Medium-density shelterwood			Control		
	Preharvest	Postharvest	IV[a]	Preharvest	Postharvest	IV	Preharvest	Postharvest	IV	Preharvest	Postharvest	IV
	-------------%--------------			-------------%--------------			-------------%--------------			-------------%--------------		
American beech	0.6	0.3	2	0.0	0.0	0	1.5	1.7	19	0.0	0.7	2
American holly	3.0	4.0	38	0.1	0.0	0	1.9	3.1	37	1.9	6.0	30
autumn olive[b]	4.2	0.0	0	0.0	0.0	0	3.5	0.0	0	12.6	0.0	0
black cherry	0.2	0.9	21	0.0	0.0	0	0.9	0.3	2	0.1	0.7	2
blackgum	0.1	1.8	38	0.1	3.1	28	0.7	2.2	24	1.0	1.3	4
cherrybark oak	0.0	0.0	0	0.0	0.0	0	0.0	1.7	19	0.0	6.7	27
elm	0.0	0.0	0	0.1	0.0	0	0.0	0.0	0	0.0	0.0	0
green ash	0.0	0.0	0	0.0	0.5	7	0.0	0.0	0	0.0	0.0	0
hickory	0.5	0.0	0	0.0	0.0	0	0.3	0.8	10	0.7	2.7	9
horsesugar[c]	16.5	0.0	0	0.0	0.0	0	11.5	0.0	0	2.5	0.0	0
loblolly pine	0.1	5.2	66	0.0	3.1	24	0.1	1.4	29	0.0	0.7	2
magnolia	0.7	4.3	42	0.0	0.0	0	0.9	0.6	5	0.1	1.3	5
persimmon	0.1	0.3	7	0.1	0.0	0	0.0	0.0	0	0.1	0.0	0
red bay[d]	0.0	0.0	0	0.9	0.0	0	0.0	0.0	0	0.0	0.0	0
red maple	9.3	12.5	109	1.4	18.1	91	6.4	8.7	78	1.9	2.0	13
red oak	0.7	0.0	0	0.0	0.0	0	0.0	0.0	0	0.3	0.0	0
river birch	14.9	0.0	0	0.0	0.0	0	30.5	0.0	0	3.4	0.0	0
sassafras	0.1	0.9	17	0.0	0.0	0	0.0	0.0	0	0.0	0.0	0
southern red oak	0.0	0.0	0	0.0	0.0	0	0.0	0.0	0	0.0	2.7	10
sweet bay[e]	0.8	1.2	21	0.0	0.5	2	1.3	0.8	12	0.3	2.7	12
swamp white oak	0.0	0.0	0	0.0	0.0	0	0.1	0.0	0	0.0	0.0	0
swamp chest. oak	0.7	3.7	38	0.0	1.0	4	3.6	6.4	67	1.1	3.3	14
sweetgum	2.7	18.7	177	0.1	33.7	167	2.2	19.6	157	2.6	4.7	23
white oak	0.1	2.8	23	0.0	0.0	0	0.3	0.3	2	1.6	4.0	14
willow[g]	0.0	3.7	43	0.0	0.0	0	0.0	0.3	7	0.0	0.0	0
water[f]/willow/laurel oak	44.5	7.1	75	97.1	29.0	147	34.4	12.0	102	69.7	28.0	120
yellow-poplar	0.1	18.0	180	0.0	4.7	37	0.0	20.4	186	0.1	0.7	8
other	0.1	14.7	117	0.0	6.2	33	0.0	19.6	115	0.0	32.0	100
Stems ha^{-1}	144,499	45,714	--	513,542	37,579	--	143,542	57,965	--	191,250	37,374	--

[a] Importance values are the summation or relative abundance, relative dominance, and relative frequency for a maximum of 300 units.
[b] *Elaeagnus umbellata* Thunberg, [c] *Symplocos tinctoria* (L.) L'Herit., [d] *Persea borbonia* Spreng., [e] *Magnolia virginiana* L., [f] *Quercus nigra* L., [g] *Salix sp.*

Table 6. Advance regeneration and reproduction response to various stand regeneration methods on an Appalachian upland hardwood site in Greenbriar Co., WV.

	Clearcut			Low-density shelterwood			Medium-density shelterwood			Control		
Species	Preharvest	Postharvest	IV[a]	Preharvest	Postharvest	IV	Preharvest	Postharvest	IV	Preharvest	Postharvest	IV
	-------------%--------------			-------------%--------------			-------------%--------------			-------------%--------------		
American beech	2.2	5.5	79	2.0	9.0	72	2.0	3.0	14	1.6	1.2	26
American chestnut	0.0	0.0	0	0.0	0.2	13	0.0	0.0	0	0.0	0.0	0
basswood	0.4	0.0	0	0.0	0.0	0	0.0	0.0	0	0.0	0.0	0
birch spp.	2.6	-	-	0.0	-	-	1.0	-	-	0.0	-	-
black birch	-	11.5	137	-	17.8	112	-	6.5	90	-	1.6	7
yellow birch	-	10.0	64	-	0.0	0	-	1.2	26	-	0.0	0
cherry spp.	3.4	-	-	2.4	-	-	10.3	-	-	4.4	-	-
black cherry	-	3.4	54	-	12.2	111	-	8.8	96	-	3.5	21
pin Cherry[b]	-	3.9	100	-	7.8	90	-	1.3	50	-	0.0	0
blackgum	1.7	0.4	12	0.0	0.6	9	0.5	0.2	6	0.0	0.0	0
black locust[c]	0.0	0.0	0	0.4	0.0	0	0.0	0.6	23	0.0	0.0	0
black walnut[d]	0.0	0.7	17	0.0	0.0	0	0.0	0.0	0	0.0	0.0	0
chestnut oak	1.7	3.2	15	0.8	0.0	0	0.0	0.0	0	0.5	0.0	0
magnolia spp.	0.0	-	-	0.4	-	-	0.5	-	-	0.0	-	-
cucumber magnolia	-	0.8	15	-	0.7	22	-	4.3	33	-	0.0	0
Fraser magnolia	-	0.0	0	-	0.2	5	-	0.7	19	-	0.0	0
hornbeam	0.0	0.5	11	0.0	0.6	16	0.0	1.0	9	0.0	0.0	0
red maple	21.1	3.2	22	12.7	5.3	89	31.5	1.1	19	11.5	9.7	29
red oak	9.1	3.3	28	7.9	3.8	56	4.4	7.1	56	15.3	2.6	22
red Pine[e]	0.0	0.2	9	0.0	0.2	8	0.0	0.0	0	0.0	0.0	0
sassafras	0.0	1.3	22	0.0	3.8	60	0.0	0.0	0	1.6	0.0	0
serviceberry	0.0	0.5	13	0.0	0.7	7	0.0	0.5	9	2.7	0.0	0
sugar maple	19.4	19.7	108	6.7	20.4	124	18.7	19.9	149	10.4	55.7	196
striped maple[f]	1.7	0.2	8	3.2	5.5	74	8.9	2.9	26	3.3	25.7	84
white ash	34.9	18.6	115	61.9	7.7	65	20.2	24.5	111	45.9	0.0	0
witchhazel[g]	0.9	0.0	0	0.4	0.0	0	0.5	0.0	0	1.1	0.0	0
yellow-poplar	0.9	13.0	93	1.2	3.5	63	1.5	16.4	79	1.6	0.0	0
Stems ha^{-1}	48,333	36,756	--	52,500	42,934	--	42,292	34,903	--	38,125	9,061	--

[a] Importance values are the summation or relative abundance, relative dominance, and relative frequency for a maximum of 300 unit

[b] *Prunus pensylvanica* L., [c] *Robinia pseudoacacia* L., [d] *Juglans nigra* L., [e] *Pinus resinosa* Ait., [f] *Acer pensylvanicum* L., [g] *Hamamelis virginiana* L.

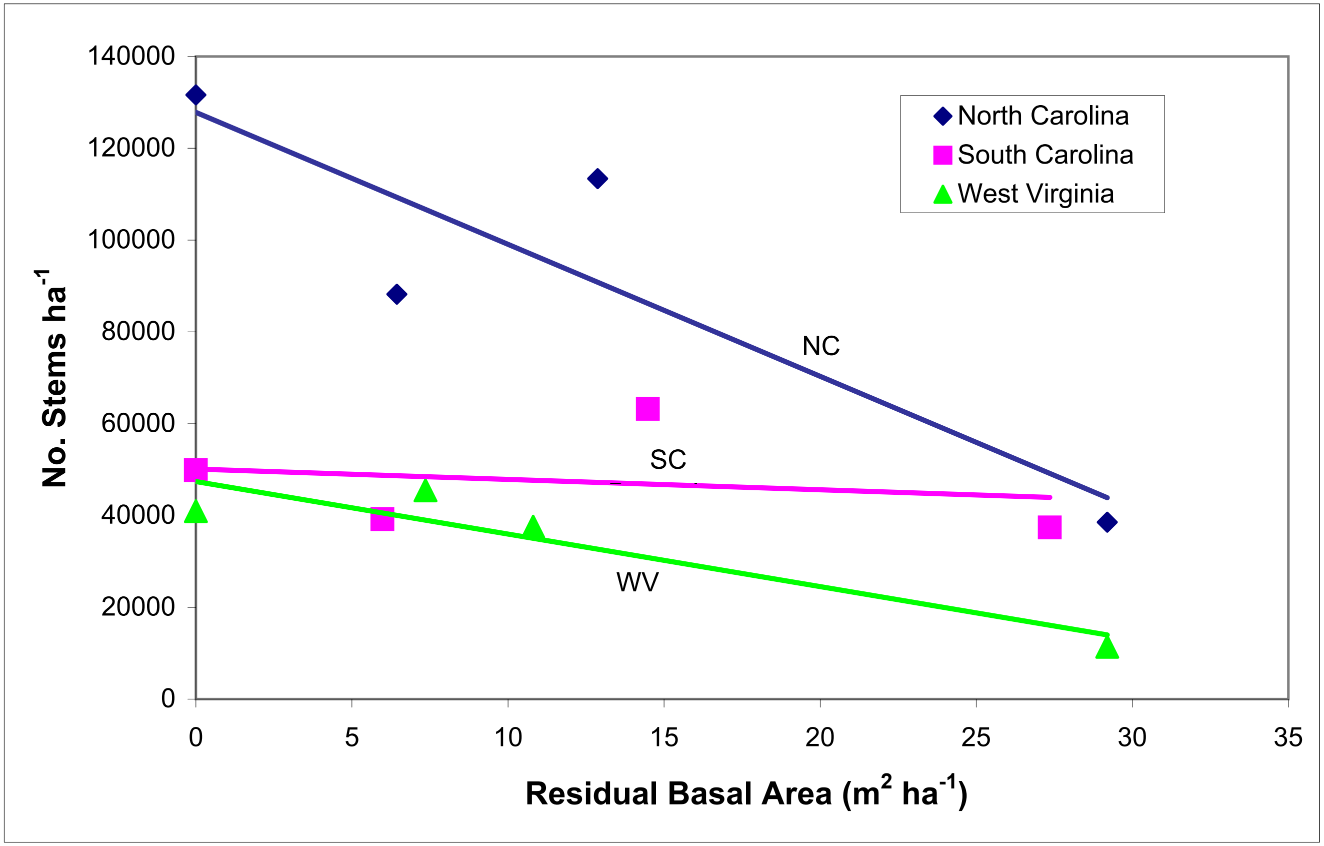

Figure 1. The effects of harvest intensity on the number of stems regenerated on three southern hardwood sites.

Chapter II: Stand Development and Growth Responses of 1 to 5 Year-old Natural Upland Hardwoods to Silvicultural Treatments

Jamie L. Schuler

North Carolina State University, Hardwood Research Cooperative, Department of Forestry, Raleigh, NC 27695-8008

Abstract

Intense competition for growth resources between herbaceous and woody vegetation is considered a major constraint to the growth and development of newly regenerated forest stands. However, very few studies have explored silvicultural opportunities to manage these constraints. In this study, the effects of fertilization, thinning and weed control on rising 1- and 3-yr-old upland mixed species Piedmont stands were monitored for three years following the imposition of treatments. Broadcast fertilization proved very beneficial in accelerating stem growth and promoting self-thinning at both sites. Weeding treatments without thinning had no effect on total stem height. At both sites, substantial gains in growth were noted for yellow-poplar and oak spp. when thinning and weeding treatments were combined. A significant fertilization effect on thinned plots was also noted for oak spp. These results demonstrate that stem growth and stand development are constrained by the availability of site growth resources, and can be silviculturally managed to promote stand development.

1. Introduction

Southern hardwoods are the most prevalent forest community type in the southern U.S. (Conner and Hartsell, 2002). The high demand for quality solid wood products, hardwood fiber, and wildlife benefits make them extremely valuable resources. Naturally regenerated mixed species hardwood and hardwood-pine forests, commonly oak-hickory forest types, dominate a large portion of the Piedmont region that extends from Virginia through Georgia (Conner and Hartsell, 2002).

Low productivity characterizes many of these upland hardwood forests in the Piedmont. Most of this region has suffered from severe soil erosion that has depleted natural soil fertility levels. In addition, many stands have been repeatedly subjected to selective harvesting with few if any improvement cuttings. As a result most of these upland stands have average growth rates of about 5 m^3/ha/yr (Roeder and Gardner, 1984).

Increased harvesting of hardwood stands is predicted in the Piedmont because of an expected increased market demand for hardwood roundwood and chips (Prestemon and Abt, 2002). The region has an imbalanced age class structure heavily weighted to sawtimber-sized stands, which originated during the early 1900s as former agricultural lands became unprofitable for row-cropping. With increased harvesting, many thousand hectares of newly regenerated stands are being created that will produce mixed species stands starting with 40,000 to 100,000 stems/ha (Schuler et al., 2004a). Another three or four decades will typically pass before the next treatment, usually a commercial thinning. By this time, one-third to one-half the rotation may have passed without any attempt to improve productivity or species composition, thereby increasing the likelihood of a continued cycle of sub-optimal productivity and without timber stand improvement a high-representation of low-value species. Incentives to find alternative non-forest uses will also be reduced if stand growth rates and values can be enhanced.

Hardwood plantations can be a viable alternative to natural stand management. High growth rates on upland sites are possible through the application of intensive cultural treatments, proper species selection and genetic improvement (Robison et al., 1999), but usually require the high costs associated with site preparation, seedling and planting costs, repeated weed control and fertilization, making plantations unattractive for most private landowners (Spetich et al., 2004). However, some of these management techniques may make natural hardwood management practices more affordable and profitable (Siry et al., 2004). Young natural stands (<15 yr) can be very responsive to silvicultural activities and site manipulations to improve species composition, increase growth rates, and shorten rotations. In young natural stands, the low productivity of Southern hardwoods has generally been attributed to overstocking (Kellison et al., 1981) and the delayed onset of crown closure due to intense competition from competing vegetation (Romagosa and Robison, 2003). Managing stem density and competing vegetation has led to positive effects on individual tree growth in young stands (Pham, 1985; Johnson et al., 1998; Robison et al., 2004).

Soil nutrient management has received substantial attention in the southern U.S. Over 500,000 ha of pine plantations are fertilized annually (NCSFNC, 2002). Studies have also shown that fertilization, especially with nitrogen and phosphorus, can be very beneficial for hardwood stands by increasing growth rates and accelerating self-thinning (Haines and Sanderford, 1976; Auchmoody, 1985; Newton et al., 2002; Schuler and Robison, 2002). However, detailed fertilization regimes are only available for a select few hardwood species, and only for those grown in plantations (*e.g.*, cottonwood, *Populus* spp., and sweetgum, *Liquidambar styraciflua*) (Scott et al., 2004).

Recent economic modeling activities indicate investments upwards of US$320/ha in year 1 in natural hardwoods are potentially profitable investments if productivity can rise from 4.7 to 6.9 tons/ha/yr due to management activities (assuming IRR=7.3%) (Siry et al., 2004). These projections indicate that investments such as broadcast weed control and fertilization (Dubios et al., 2003) made soon after regeneration treatments (*e.g.*, yr 1 to 3) are financially feasible under these assumptions.

The objective of this study was to assess how fertility, competing vegetation, and overstocking affect growth and development of very young mixed species Piedmont stands of naturally regenerated hardwoods. By manipulating factors that potentially constrain resource availability, opportunities to increase productivity in upland Piedmont stands may be realized.

2. Methods

Two upland sites in the North Carolina Piedmont were studied. Site one is on the Hill Demonstration Forest (Hill), located in Durham Co., is owned by North Carolina State University, and was formerly a natural 2 ha loblolly and Virginia pine (*Pinus taeda* L. and *P. virginiana* Mill., respectively) stand with a lesser component of mixed hardwoods. This site was regenerated through clean clearcutting in winter 1998-1999. Site two on the Duke Forest (Duke), located in Orange Co., is owned by Duke University, and was formerly a 5 ha mature natural mixed oak (*Quercus spp.*) stand. This site was regenerated following a salvage clean clearcut operation in the winter 1996-1997 following damage from Hurricane Fran (6 September 1996). The two sites are approximately 24 km apart.

The Hill site has Georgeville silt loam soils with mainly north-facing aspect on slopes less than 5% (Kirby, 1976). The Duke site has Wedowee sandy loam soils with a north-facing aspect on a 2-10 percent slope (personal communication, 2004, Judson Edeburn, Duke Forest Manager).

Durham and Orange counties have an average annual temperature of about 16°C, and about 200 days of growing season from April through October (Kirby, 1976; Dunn, 1977). The longterm average precipitation near the Hill site (Rougemont, NC) is 112 cm/yr. The longterm average precipitation near the Duke site (Durham, NC) is 116 cm/yr (http://www.nndc.noaa.gov, accessed 21 July 2004). Precipitation is generally evenly distributed throughout the year. Monthly precipitation totals during the study years are illustrated in Figure 1.

Thirty-two 10-m^2 circular plots with an additional 1-meter treated border were located on each site with the criteria that each plot contained at least two yellow-poplar (*Liriodendron tulipifera*) and two oak (*Quercus* spp.) stems (putatively seed or seedling-sprout origin), no obvious stump sprouts, and were not in heavy slash concentrations or on skid trails. For each site, eight treatments were replicated in four blocks based on topography. The treatments began in June 1999 and continued through the end of the 2001-growing season. The study was installed as a 2x2x2 factorial design with or without the following main factors.

1) Weeding- repeated hand removal of the aboveground portion of all non-arborescent vegetation in years 1-3 as needed.

2) Fertilization- in June 1999 with 90 kg N/ha and 100 kg P/ha applied as diammonium phosphate, and in March 2001 with 100 kg N/ha as urea and 100 kg K/ha as muriate of potash.

3) Cleaning (thinning)- woody stem density reduced to 4 stems/plot (equivalent to 4,000 stems/ha), consisting of two yellow-poplars and two red or white oaks (*Q. alba*, *Q. falcata*, *Q. rubra*, *Q. stellata* or *Q. veluntina*; depending on their availability in the treatment plots). Resprouting cut stems were clipped as needed.

Stem heights (±1 cm) and basal diameters (±0.1 mm) were recorded for all arborescent species in spring 1999 prior to the installation of treatments on all plots. However, on the plots designated to be thinned to 4 stems/plot, measurements were taken only on the four trees marked to be left (thinned stems). Stem heights and diameters were again measured on all plots at the end of the 2000 and 2001 growing seasons, and 2 and 3 years after treatments were imposed, respectively. Stem volumes were calculated as conical volume. Each stem at the Hill Site was permanently marked with an aluminum tag embossed with a unique identification number prior to the initiation of treatments. Additional stems that emerged over the duration of the study were tagged at each measurement cycle. The presence and survival of individual stems was used to assess patterns of recruitment and mortality.

Stem densities and stem height, diameter, and volume were analyzed using analysis of variance (ANOVA) (SAS, 1990) with the respective initial measurement parameter as a covariate. Therefore, reported means are based on least-squares estimators. Main effects and interactions were evaluated for significance at $P \leq 0.1$. Logarithmic transformations were applied to volume data to correct for heteroscadasticity. ANOVAs were conducted separately for all non-thinned plots, and for all thinned plots, so there are no treatment responses compared between thinned and non-thinned plots (e.g. Tables 4 and 5). This was necessary because the stems selected to be left in the thinned plots were by design among the largest stems present, not of average size, given that a thinning operation would logically favor larger stems.

3. Results

Hill Forest

All Species Combined- Stem Density

Only the non-thinned plots were evaluated for all species combined. All plots were dominated by yellow-poplar, which ranged from 51 to 69 % of the total composition. Pretreatment stem densities on these plots averaged from 130,000 to 206,000 stems ha^{-1} with over 20 species represented (Table 1). However, no statistical differences were detected in initial stem densities.

Although species composition varied little throughout the three-year study, stem densities changed markedly, mostly as a result of stem mortality (Table 1). Stem density on control plots increased during the second (2GS) and third growing seasons (3GS). Weeded-only and weeded + fertilizer treatments resulted in fairly consistent reductions in densities in years 2 and 3, respectively. By contrast, stem numbers declined dramatically (>50%) by the end of the second growing season on the fertilized-only plots, and then slightly thereafter. Stem density was affected by a weeding and fertilization interaction following 2GS (P=0.015) and 3GS (P=0.049). Stem density on fertilized-only plots was significantly less than on all other treatment plots after the 2GS, and less than the control and weeded plots after the 3GS.

The recruitment of new stems at the end of years 2 and 3 (Table 2) was recorded by tagging. The number of new individuals ranged from 13 to 30 and from 4 to 12 stems/plot during year 2 and 3, respectively. The number of newly tagged stems after year 2 was significantly reduced by fertilization when expressed as a percent of total stem density. For the non-fertilized plots, the recruitment of new stems was +19% of the 2GS stem density, while in fertilized plots the number of new stems increased by 11% after 2GS (P=0.013). A similar fertilization trend, with fertilization reducing recruitment, was found for the 3GS and for 2GS and 3GS combined (total recruitment), although differences were not statistically significant. No significant weeding effect was detected for the second or third growing season individually or combined.

Recruitment was grouped into 20-cm height classes to elucidate treatment differences by size class for each growing season (Table 2). The only significant treatment effects at the end of the 2GS were for weeding in the 61-80 cm height class (P=0.027) and for fertilization in the 141-160 cm height class (P=0.082). These differences amounted to less than 2 stems/plot. There were no treatment effects on stem recruitment by height class after year 3.

Cumulative stem mortality among treatments was 19% (25 stems), 37% (87 stems), 20% (38 stems) and 20% (33 stems) of the initial stem density after the 2GS (P=0.091), and 25, 47, 29 and 34 % of the initial stem density after the 3GS for the control, fertilized, weeded, and weeded + fertilized treatments, respectively (Fig. 2). Over the three year study, the total mortality among stems present pretreatment was affected by a weeding and fertilization interaction (*P*=0.086). Total mortality averaged 37, 114, 67 and 59 stems/plot on control, fertilized, weeded, and weed + fertilized treatment plots.

Stem mortality among all treatments was generally restricted to the small size classes. The average median initial height for stems that died was from 19, 21, 20 and 26 cm for the control, fertilized, weeded, and weed + fertilized treatments, and did not differ significantly among treatments. The mean initial height for stems that died was 20, 24, 23 and 30 cm for the control, fertilized, weeded, and weed + fertilized treatments, respectively. With mortality separated into 20-cm height classes, fertilization increased stem mortality in the 0 to 20 and 21 to 40 cm height classes (Fig. 2), but variation was to too great to detect statistical differences. Significant treatment differences in stem mortality in the 81 to 100 and 101 to 120 cm height classes, but differences amounted to less than 4 stems/plot over the three year period.

All Species Combined - Stem Growth

No significant pretreatment differences were detected for height, diameter or volume on plots delineated to become control, fertilized, weeded, or weeded + fertilized plots (Table 3). As a main effect, fertilization produced a 21 and 53 % increase in stem height and volume, respectively, over non-fertilized stems for year 2. Following year 3, stem height on fertilized plots increased 22%, while diameter increased 29% over non-fertilized stems. Weeding was effective in increasing stem diameter in both growing seasons following the initial treatment applications, but did not significantly affect stem height or volume. Compared to non-weeded plots, diameters of weeded stems were 18 and 29 % greater after the 2 and 3GS, respectively.

Yellow-Poplar-Stem Growth

Initial stem heights were significantly different between thinned and non-thinned plots at the Hill Forest (P<0.0001). Thinned treatments averaged 54 cm tall, 8 mm in diameter and 15 cm^3 in volume, whereas non-thinned seedlings averaged 27 cm, 4 mm and 11 cm^3 for height, diameter, and volume (Table 4). This reflects the intended bias in selecting larger stems to be left in the thinned plots and the reason why treatment differences between thinned and non-thinned conditions are not compared statistically (see methods). Within thinned and non-thinned treatments at the start of the experiment in 1999, there were no significant differences for either the weeding or fertilization effects (Table 4).

On non-thinned plots, weeding and fertilization treatments had a negative interaction for stem height in the 2GS (Table 4). The yellow-poplar stems in the fertilize-only treatment were significantly taller than all other treatments, while the average height for stems in the weed + fertilization treatment was significantly greater than stems in the weed-only and control treatments. After 3GS, fertilization was the only significant factor affecting stem height, with fertilized stems being about 30% taller than non-fertilized stems. Fertilization and weeding treatments significantly increased stem diameter in the 2GS and 3GS about 3 mm over the respective non-fertilized and non-weeded stems (Table 4). The significant volume responses to fertilization and weeding in the 2GS disappeared by the 3GS, although differences among the control and the other treatments ranged from 2- to over 3-fold.

On the thinned plots, weeding had a significant impact on stem height and diameter (Table 4). Weeding increased height 80 and 121 %, and diameter 135 and 179 %, over non-weeded treatments for years 2 and 3, respectively. Weeding and fertilization treatments had a negative interaction for volume for both growing seasons. In each case, weed-only treated stems had about twice the volume as weed + fertilization treated stems, although this difference was not statistically different. The effects of both treatments were, however, statistically greater than the thin-only control and fertilize-only stems (Table 4). The difference between the best treatment (weed-only) and the thin-only was 22- and 34-fold for years 2 and 3, respectively.

Red and White Oaks

Initial height, diameter and volume were significantly different between thinned and non-thinned treatments for oaks, as described in the methods. Stem height averaged 55 cm for thinned and 32 cm for the non-thinned seedlings (P=0.0002). Stem diameter and volume averaged 7 mm and 7 cm^3 for thinned oak stems, whereas the non-thinned stems averaged 5 mm and 2 cm^3 (P=0.0098, P=0.0014, respectively). No differences for fertilization and weeding factors were present within thinned or non-thinned treatments at the time of initial measurements (Table 5).

For the non-thinned plots, height was enhanced with the fertilization-only treatment after years 2 and 3, but only significantly after year 2. There were no differences among the control, weeded, and weeded + fertilization treatments (Table 5). Stem diameter and volume were increased due to the effects of fertilization on non-thinned plots in years 2 and 3, by 37 and 26 %, respectively for diameter, and 175% in year 2 for volume.

Thinned oak stems had a significant response to fertilization with a 31 and 43 % increase in total height, and a 22 and 44 % increase in diameter, for years 2 and 3, respectively (Table 5). Likewise, weeding treatments improved total height 31% in year 3, and diameter 86 and 72 %, respectively for the years 2 and 3. In all cases on the thinned plots, oaks had a synergistic response to the weeding and fertilization treatments, being 3 to 4-fold larger than weeding- or fertilization-only after year 3 for volume, as an example (Table 5).

Duke Forest: Age 3

All Species Combined - Stem Growth

Only the non-thinned plots were evaluated with all species combined. Pretreatment stem densities on plots delineated to remain non-thinned ranged from 79-104 stems per 10 m^2 plot among treatments, with over 20 species recorded (Table 6). No pretreatment statistical differences existed among plots.

Individual stems were not tagged at this site, making it impossible to specify specific recruitment and mortality patterns. Nonetheless, plot inventories revealed stem density patterns associated with the treatments (Table 6). Fertilization appeared to reduce stem density and weeding to increase stem density 2 and 3 years after treatment, although not always significantly for both growing seasons. The weeding x fertilization interaction was not significant.

Species composition was similar to the Hill site, with yellow-poplar comprising 49 to 71 % of the total species composition (Table 6). White oaks were also common, comprising 10 to 38 % of the total number of stems. Species composition varied little from establishment through year 3.

Fertilization significantly increased stem growth 2 and 3 years (4GS and 5GS) after initial treatments were imposed (Table 3). Responses to fertilization following the 5GS for height, diameter and volume averaged 35, 19 and 86 % over non-fertilized stems, which averaged 155 cm, 18 mm and 21 cm^3 for height, diameter and volume, respectively. After the 4GS stem height also increased as a result of weeding treatments, but this response was restricted to the 4GS only.

Yellow-Poplar - Stem Growth

Selection of stems to remain after the thinning treatments resulted in a significant difference for initial height between the thinned and non-thinned treatments with total stem height averaged 100 cm for thinned stems and 77 cm for non-thinned stems (P=0.001) (Table 4). On non-thinned plots, there was an initial difference for stem volume, where the stems on the designated control plots were about 60% greater than stems on plots designated for other treatments. No initial differences existed among thinned plots prior to the application of the weeding and fertilization treatments.

For yellow-poplar stems growing on non-thinned plots, fertilization increased stem height, diameter and volume over non-fertilized stems for both post-treatment inventories (Table 4). After 5GS, stems increased by 57 cm in height, by 3 mm in diameter, and 128 cm^3 in volume on fertilized plots over non-fertilized plots. The weeding effect that was present after 4GS for height and volume diminished by the end the 5GS.

Thinned yellow-poplar responded to the effects of weeding and fertilization during both the 4 and 5GS (Table 4). The thinned stems appeared more responsive to weeding than to fertilization. Height growth increased 36% from weeding and 20% from fertilization after 5GS on these plots. Diameter increased 67% and 33%, and volume increased 3- and 2.5-fold, on thinned plots due to weeding and fertilization, respectively.

Red and White Oak Species

Significant initial differences existed between thinned and non-thinned stems for height, diameter, and volume ($P<0.0001$) due to stem selection procedures for the thinned plots (Table 5). Thinned oak stems averaged 99 cm in height, 15 mm in diameter, and 54 cm^3 in volume, while their non-thinned counterparts averaged 48 cm, 8 mm, and 5 cm^3, respectively. No initial pretreatment differences existed within non-thinned or thinned plots designated for fertilization or weeding treatments.

On non-thinned plots, height growth was not significantly affected by any treatment until 5GS, at which time fertilized stems were about 30% taller and had about twice the volume as non-fertilized oak stems. The fertilizer treatment effects for stem diameter disappeared by the 5GS. Weeding non-thinned plots had no effect on stem growth for either growing season.

Thinned oak stems had greater height, diameter and volume than the control treatments after 4GS and 5GS due to fertilize-only, weed-only and weed + fertilize treatments (Table 5). However, the only significant treatment effect was fertilization.

3. Discussion

Many natural hardwood stands have been reported to be responsive to a variety of early stand interventions. Site modification treatments have generally focused on improving nutrient availability through fertilization, largely with nitrogen and phosphorus, and have been shown beneficial for many species and sites (Auchmoody, 1972; Beckjord et al., 1983; Kolb et al., 1990; Demchik and Sharpe, 1999; Newton et al., 2002). Vegetation control treatments that remove competing herbaceous and undesirable woody species and/or overtopping residuals have also been beneficial in certain circumstances (Petruncio and Lea, 1985; Leak, 1988; Young et al., 1993; Romagosa and Robison, 2002). Results from this study corroborate these findings, demonstrating that in NC Piedmont hardwoods certain fertilization and weeding treatment combinations were very successful in increasing growth and accelerating early stand development (see Tables 3 - 5).

In the current study, broadcast fertilization generally produced a large and sustained increase in height, diameter and volume on non-thinned plots. On non-thinned plots, the collective species response to nutrient additions was a 2- to 3-fold increase in individual stem volume. This type of response to fertilization is expected on many Piedmont sites, which have experienced severe soil erosion over the last century (Daniels et al., 1999), leaving many of the soils with a thin surface horizon overlaying a thicker Bt horizon, and consequently are generally low in organic matter, nitrogen and other nutrients (Della-Bianca and Wells, 1967).

Concurrent with increased growth, stem densities were reduced on fertilized plots even with the short time span of this study. This suggests other essential growth resources have very quickly become limiting (*e.g.*, water and/or light) among tree stems, or that non-arborescent vegetation out-competed the tree stems for these other resources. The data also suggest that the large response to the fertilization was due, in part, to mortality at the lower end of the initial height distribution indicating the expected relationship between competition, growth and density reductions. For the fertilization-only treatment, a larger proportion of mortality occurred in the smaller height classes (*i.e.*, 0-20 cm) compared to the other treatments (Figure 2). The establishment of new stems, either from seed or sprouts, also appears retarded under fertilization treatments, although the variation among treatments was large. Therefore, the large increase in stem size in the fertilization-only treatments may not be completely attributable to enhanced growth rates, but enhanced mortality and reduced recruitment of smaller stems, thereby providing more site resources to fewer stems.

Weeding treatments increase the availability of light, water and nutrients, and allocate these resources that would otherwise be utilized by competing vegetation to tree stems. The benefits of weeding hardwood plantations have been well documented (e.g., Fitzgerald et al., 1975; Nelson, 1985; Schuler et al., 2004b). However, few studies have reported the effects of competing vegetation on young naturally regenerated hardwood stands (McGill and Brenneman, 2002; Romagosa and Robison, 2002). In general, weeding had a limited effect on stem growth on the non-thinned plots. The all stems combined group and yellow-poplar stems did respond with increased diameters following year 3 at the Hill Forest site (Tables 3 - 4), while the Duke Forest site had no significant response in height, diameter or volume after the 5GS. It is also likely, but not quantified, that the weed biomass at the Hill Forest site was greater, and therefore, more competitive than at the Duke Forest site due to the younger age of the Hill stand. The stem height and volume response to weeding treatments reported for this study differed from those of Romagosa and Robison (2002), who reported significant growth responses to weeding-alone on similar sites but with lower initial densities and large shifts in species dominance (Schuler and Robison, 2002). No large shift in species composition at the Hill or Duke Forest sites was noted through the 3 years of this study (Tables 1 and 6).

Weed control treatments may improve tree growth in part through improved soil moisture availability. The effect of weeding treatments is also subject to variation in annual precipitation (wet vs. dry years), with the impact of vegetation control generally more pronounced on dry sites and years (Powers and Reynolds, 1999). The monthly precipitation patterns for the Hill and Duke Forest sites (Fig. 1) were normal or slightly above normal during the 2000 and 2001 growing seasons. The 1999 growing season had a 10 cm precipitation deficit in May (based on longterm average) that could have affected growth and survival, especially for small, newly germinated seedlings with under-developed root systems.

It is uncertain whether the effects of weeding on non-thinned plots will be realized since the treatment did not appear to produce a height benefit (Tables 3 - 5), and the majority of stems were not shade tolerant species. The response to weeding may be an increase in the number and size of gaps between tree stems created with the removal of competing vegetation. Since diameter is well correlated with crown size (Goelz, 1996), weeding may ultimately result in crown expansion, and therefore increased diameter as found for all stems and yellow-poplar at the Hill site (Tables 3 and 4). The weeding + fertilization treatments produced little to no additional benefit over fertilization-alone, suggesting that non-arborescent vegetation, by itself, was not severely limiting the availability of growth resources.

In contrast to non-thinned plots, weeding on thinned plots greatly enhanced yellow-poplar and oak stem growth. Following thinning, competing woody and herbaceous plants invaded newly liberated growing space, essentially negating most of the benefits of release. Maintaining weed-free conditions on thinned plots generally resulted in a 30-120 % increase in total height over thinned seedlings without weed control. When thinned plots were weeded, stem growth responses were impressive, especially when contrasted against non-thinned data. However, since initial seedling selections on thinned plots were biased towards larger stems, direct comparisons between thinned and non-thinned plots were not made.

Broadcast fertilization in thinned stands was beneficial to oak stems on both sites, and for the yellow-poplar at the Duke Forest site. Apparently, the older stems at the Duke site were of sufficient size to overcome the effects of increased weed competition normally associated with fertilizing young stands (Pysek and Leps, 1991), whereas stems on the Hill Forest site were initially shorter and more affected by competition.

Fertilization + weeding treatment interactions were significant only for the Hill Forest site (Tables 4 - 5). The volume response of yellow-poplar from fertilization + weeding on thinned plots was significantly less than the additive response due to fertilization- and weeding-alone for 2GS and 3GS, whereas volume response was largely additive among non-thinned plots. For oak stems at the Hill Forest site, the volume response to fertilization + weeding treatments was synergistic in the 4GS and additive in the 5GS.

Conclusions

These data clearly demonstrate that even the youngest naturally regenerated upland forest stands in the NC Piedmont are not achieving their maximum individual tree growth potential. On these Piedmont sites, young stands are overstocked and growing on soils deficient in soil nutrients. Reducing competing woody and herbaceous vegetation produced a tremendous response for yellow-poplar and oaks, with or without fertilization. Broadcast fertilization without thinning greatly accelerated growth, and provided an added benefit of reducing stem density. Although further work on larger study plots will be required to determine whether these responses can be maintained in the future on these upland sites, there does appear to be opportunities to manage regeneration in newly established stands.

Future work will be needed to assess whether fertilization and vegetation control treatments can modify species composition in such a way that favors more desirable species (*i.e.*, the positive response of oak spp. to fertilization). The use of species-specific fertilizer mixes and rates may be useful if we can show preferential uptake and use among hardwood tree species. Similarly, with herbicides becoming more target specific, more species selection opportunities may be available within mixed hardwood stands.

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Table 1. Species composition (percent of all stems) at the Hill Forest site. Age 0 is the pretreatment composition of a rising 1-yr-old naturally regenerated, upland North Carolina Piedmont stand.

Common name	Scientific name	Control			Fertilized			Weeded			Weed+Fertilized		
		Age 0	Age 2	Age 3	Age 0	Age 2	Age 3	Age 0	Age 2	Age 3	Age 0	Age 2	Age 3
		-----------%------------			-----------%------------			-----------%------------			-----------%----------		
Yellow-poplar	*Liriodendron tulipifera* L.	61.8	54.4	50.9	66.1	63.9	57.3	69.2	65.8	61.4	57.3	53.1	52.2
River birch	*Betula nigra* L.	8.9	11.3	12.6	1.6	0.4	0.9	5.7	5.7	6.8	0.7	0.8	0.6
Sumac	*Rhus* spp.	6.0	4.6	5.0	5.4	3.0	3.9	4.5	3.7	5.7	5.4	5.6	6.3
Red maple	*Acer rubrum* L.	4.1	4.2	4.2	2.8	3.6	3.7	6.0	7.9	8.0	3.4	4.4	4.9
Dogwood	*Cornus florida* L.	3.3	4.0	5.2	6.4	6.2	6.0	2.6	2.7	2.8	11.4	11.8	10.6
Black cherry	*Prunus serotina* Ehrh.	2.7	3.3	4.0	4.0	6.3	7.2	1.6	1.7	1.7	3.9	4.2	4.4
White oak group[a]	*Quercus* spp.	2.3	2.9	2.6	3.0	2.4	3.0	0.4	0.4	0.5	2.9	3.3	3.6
Blackgum	*Nyssa sylvatica* Marsh.	2.1	2.1	2.2	-	-	-	1.2	1.7	1.3	1.5	1.7	1.9
Pine group[b]	*Pinus* spp.	1.9	2.7	2.6	4.4	5.4	6.7	2.7	4.2	5.0	1.3	0.6	0.4
White ash	*Fraxinus americana* L.	1.9	1.5	1.6	2.4	2.6	3.2	0.9	0.8	0.9	1.8	1.9	1.9
Sweetgum	*Liquidambar straciflua* L.	1.4	2.1	2.4	0.6	1.2	1.4	1.2	1.1	1.4	6.0	6.8	7.2
Mulberry	*Morus* spp.	1.0	0.6	0.8	0.5	0.8	1.4	0.4	0.6	0.5	0.8	1.2	1.5
Red oak group[c]	*Quercus* spp.	1.0	2.1	2.2	1.1	1.8	2.1	1.1	0.8	0.9	0.2	0.2	-
American beech	*Fagus grandifolia* Ehrh.	0.6	0.6	0.6	-	0.2	0.2	-	-	-	-	-	-
American holly	*Ilex opaca* Ait.	0.4	2.3	1.8	0.4	0.6	0.7	0.5	0.6	0.6	1.5	1.9	2.3
Hickory	*Carya* spp.	0.2	0.2	0.2	0.4	0.4	0.5	0.3	0.3	0.3	0.2	0.2	0.2
Persimmon	*Diospyros virginiana* L.	0.2	0.2	0.2	0.1	0.2	0.2	0.7	1.1	1.6	0.3	0.6	0.2
Sycamore	*Platanus occidentalis* L.	0.2	0.2	0.2	-	-	-	-	-	-	-	-	-
Elm	*Ulmus* spp.	-	0.6	0.6	0.4	0.6	0.7	0.3	0.4	0.3	1.3	1.4	1.5
Hophornbeam	Ostrya virginiana K. Koch.	-	-	-	0.2	0.6	0.7	-	0.1	0.2	-	0.2	-
Juniper	*Juniperus virginiana* L.	-	-	-	-	-	-	0.1	0.1	0.2	-	-	-
Sassafras	*Sassafras albidum* (Nutt.) Nees.	-	0.2	0.2	0.2	-	-	0.4	0.1	-	0.2	0.2	0.2
	Total Number (stems/10 m^2)	130	152	151	206	98	87	184	166	151	159	143	125

[a] Includes post oak (*Q. stellata* Wang.) and white oak (*Q. alba* L.).

[b] Includes loblolly pine (*P. taeda* L.), shortleaf pine (P. echinata Mill.) and Virginia pine (*P. virginiana* Mill.).

[c] Includes black oak (*Q. velutina* Lamarck), red oak (*Q. rubra* L.), scarlet oak (*Q. coccinea* Muench.), and willow oak (*Q. phellos* L.).

Table 2. The number and distribution of newly recruited stems by height class (cm) and growing season for the Hill forest site on 10 m^2 plots.

	End of 2nd Growing Season				End of 3rd Growing Season			
	Treatments				Treatments			
Height Class	Control	Fertilized	Weeded	Weed+Fert	Control	Fertilized	Weeded	Weed+Fert
1 - 20	15.0	4.0	16.0	5.5	0.3	0.0	1.3	0.0
21 - 40	3.3	5.0	8.3	2.0	2.0	0.5	3.0	0.8
41 - 60	3.0	3.5	2.5	1.8	5.0	0.0	1.5	1.0
61 - 80	2.5	3.0	1.3	0.5	2.3	1.3	0.5	0.3
81 - 100	1.0	1.3	1.0	0.5	1.0	0.8	0.3	0.3
101 - 120	0.3	1.0	0.8	0.5	1.0	0.3	0.0	1.0
121 - 140	0.3	0.5	0.0	0.5	0.3	0.3	0.0	1.0
141 - 160	0.0	0.3	0.0	0.3	0.0	0.0	0.3	0.5
161 - 180	0.0	0.0	0.0	0.5	0.3	0.3	0.5	0.3
180 - 200	0.0	0.0	0.0	0.3	0.3	0.3	0.0	0.3
201 - 220	0.0	0.5	0.0	0.5	0.0	0.5	0.3	0.0
All	25.3	19.0	29.8	12.8	12.3	4.0	7.5	5.3

Note: Significance at $P \leq 0.10$ was detected for height class 61-80 for the main effect of weeding, and for height class 141-160 for the main effect of fertilization.

Table 3. The effect weeding and fertilization treatments on a rising 1-year-old stand (Hill Forest) and on a rising 3-year-old stand (Duke Forest) on non-thinned naturally regenerated upland NC Piedmont stands for all species combined.

HILL FOREST
Non-thinned

		Height			Diameter			Volume[a]		
		Age 0	Age 2	Age 3	Age 0	Age 2	Age 3	Age 0	Age 2	Age 3
	Treatment	(cm)			(mm)			(cm^3/seedling)		
	Control	29.7	70.4	103.2	4.6	7.6	10.3	1	7	14
	Fertilized	32	93.3	137.7	4.5	9.1	13.5	1	12	36
	Weeded	31.4	75.0	119.2	4.2	9.2	12.4	1	10	28
	Weed + Fert	37.2	84.3	133.5	4.6	10.5	15.7	1	14	42
Main Effects	Fertilization	—	0.053	0.023	—	—	0.035	—	0.089	—
	Weeding	—	—	—	—	0.085	0.015	—	—	—

DUKE FOREST
Non-thinned

		Height			Diameter			Volume		
		Age 3	Age 4	Age 5	Age 3	Age 4	Age 5	Age 3	Age 4	Age 5
	Treatment	(cm)			(mm)			(cm^3/seedling)		
	Control	77.2	126.2	155.5	10.1	14	17.6	14	38	65
	Fertilized	63.5	140.2	212.4	8.9	14.5	20.8	8	48	141
	Weeded	63.2	103.8	154.2	8.7	13.2	19.2	8	27	76
	Weed + Fert	70.9	133.1	205.4	9.3	16.7	22.9	12	62	153
Main Effects	Fertilization	—	0.015	<.001	—	0.035	0.025	—	0.01	<.001
	Weeding	—	0.07	—	—	—	—	—	—	—

[a] All volumes were analyzed using $\log_e$ transformed data. The reported least-square means were back-calculated for ease of interruptation.

Table 4. The three year effects of weeding and fertilization treatments on a rising 1-yr-old stand (Hill Forest) and on a rising 3-yr-old stand (Duke Forest) on naturally regenerated yellow-poplar seedlings on upland NC Piedmont sites.

HILL FOREST		Height			Diameter			Volume		
Non-thinned		Age 0	Age 2	Age 3	Age 0	Age 2	Age 3	Age 0	Age 2	Age 3
	Treatment	(cm)			(mm)			(cm³/seedling)		
	Control	24.3	57.8	87.7	4.2	6.6	8.7	1	5	12
	Fertilized	26.6	85.9	128.2	4.3	8.3	11.2	1	11	30
	Weeded	26.0	62.4	106.0	3.9	8.4	10.8	1	8	25
	Weed + Fert	30.6	75.3	123.8	4.2	10.7	15.2	1	16	43
Main Effects	Fertilization	—	na	0.018	—	0.025	0.078	—	0.008	—
	Weeding	—	na	—	—	0.017	0.039	—	0.023	—
Interaction		—	0.064	—	—	—	—	—	—	—
Thinned	Control	51.0	81.4	112.1	8.8	9.5	16.1	9	18	76
	Fertilized	52.9	107.7	165.2	8.0	14.4	20.4	8	46	147
	Weeded	56.9	188.4	329.7	7.1	29.8	55.5	6	390	2619
	Weed + Fert	56.5	151.7	283.5	8.7	26.5	46.4	10	226	1331
Main Effects	Fertilization	—	—	—	—	—	—	—	na	na
	Weeding	—	0.009	<.001	—	<.001	<.001	—	na	na
Interaction		—	—	—	—	—	—	—	0.079	0.093

DUKE FOREST		Height			Diameter			Volume		
Non-thinned		Age 3	Age 4	Age 5	Age 3	Age 4	Age 5	Age 3	Age 4	Age 5
	Treatment	(cm)			(mm)			(cm³/seedling)		
	Control	86.4	146.1	190.9	11.2	15.7	20.4	21	68	140
	Fertilized	71.6	163.4	252.1	9.7	16.8	24.1	13	98	302
	Weeded	75.7	125.8	186.6	9.5	15.5	22.6	13	57	183
	Weed + Fert	74.1	147.9	240.3	9.4	17.6	25.5	14	84	277
Main Effects	Fertilization	—	0.011	<.001	—	0.016	0.048	na	0.002	0.005
	Weeding	—	0.014	—	—	—	—	na	0.084	—
Interaction		—	—	—	—	—	—	0.050	—	—
Thinned	Control	104.0	128.0	216.1	14.2	22.3	30.4	53	146	507
	Fertilized	92.6	178.6	302.2	14.2	26.6	46.8	39	332	1679
	Weeded	94.1	205.1	339.0	15.2	32.5	58.2	55	489	2404
	Weed + Fert	110.9	210.5	364.4	14.1	41.0	71.0	56	997	4966
Main Effects	Fertilization	—	—	0.046	—	0.005	0.02	—	0.007	0.002
	Weeding	—	0.052	0.070	—	<.001	<.001	—	<.001	<.001
Interaction		—	—	—	—	—	—	—	—	—

Note: Significance for main effects are listed when the interaction term was not significant at $\alpha = 0.10$. Main effects were not applicable (na) when interaction term was significant. "—" indicates non-significant effects.
Volumes were analyzed using $\log_e$ transformed data. The reported least-square means were back-calculated for ease of interpretation.

Table 5. The three year effects of weeding and fertilization treatments on a rising 1-yr-old stand (Hill Forest) and on a rising 3-yr-old stand (Duke Forest) on naturally regenerated red and white oak seedlings on upland NC Piedmont sites.

HILL FOREST		Height			Diameter			Volume		
Non-thinned		Age 0	Age 2	Age 3	Age 0	Age 2	Age 3	Age 0	Age 2	Age 3
	Treatment	(cm)			(mm)			(cm^3/seedling)		
	Control	34.1	54.4	85.8	6.2	7.2	8.6	3	5	8
	Fertilized	32.4	89.0	117.5	4.9	11.9	13.2	2	22	34
	Weeded	25.7	58.8	80.4	4.3	8.4	12.4	1	7	28
	Weed + Fert	35.7	61.8	90.5	4.8	9.4	13.1	2	11	29
Main Effects	Fertilization	—	na	—	—	0.053	0.064	—	0.03	na
	Weeding	—	na	—	—	—	—	—	—	na
Interaction		—	0.08	—	—	—	—	—	—	0.01
Thinned	Control	37.8	85.6	105.9	5.1	12.1	19.2	2	62	59
	Fertilized	60.3	118.8	180.8	7.7	16.1	25.0	8	79	261
	Weeded	60.0	117.6	166.8	8.3	24.2	30.0	9	91	343
	Weed + Fert	63.4	148.0	208.5	8.2	28.1	46.1	8	292	991
Main Effects	Fertilization	—	0.096	0.025	—	0.008	0.017	—	na	0.006
	Weeding	—	—	0.068	—	<.001	0.003	—	na	0.002
Interaction		—	—	—	—	—	—	—	0.074	—

DUKE FOREST		Height			Diameter			Volume		
Non-thinned		Age 3	Age 4	Age 5	Age 3	Age 4	Age 5	Age 3	Age 4	Age 5
	Treatment	(cm)			(mm)			(cm^3/seedling)		
	Control	62.6	83.2	94.0	11.2	10.3	13.0	9	11	19
	Fertilized	45.4	100.1	131.0	6.9	12.5	16.4	3	21	47
	Weeded	37.3	70.2	95.6	6.3	10.6	13.8	3	10	20
	Weed + Fert	48.4	92.7	115.0	7.3	13.7	15.5	4	29	32
Main Effects	Fertilization	—	—	0.046	—	0.056	—	—	0.075	0.079
	Weeding	—	—	—	—	—	—	—	—	—
Interaction		—	—	—	—	—	—	—	—	—
Thinned	Control	75.4	141.4	186.6	12.7	25.9	39	23	212	610
	Fertilized	97.5	156.9	236	13.6	29.9	43	41	330	1029
	Weeded	101.8	155.3	211.3	16.3	29.3	41.2	64	307	827
	Weed + Fert	121.1	179.3	232.9	17.5	29.7	48.3	87	355	1237
Main Effects	Fertilization	—	—	0.06	—	—	—	—	—	—
	Weeding	—	—	—	—	—	—	—	—	—
Interaction		—	—	—	—	—	—	—	—	—

Note: Significance for main effects are listed when the interaction term was not significant at $\alpha = 0.10$. Main effects were not applicable (na) when interaction term was significant. "—" indicates non-significant effects.
Volumes were analyzed using $\log_e$ transformed data. The reported least-square means were back-calculated for ease of interpretation.

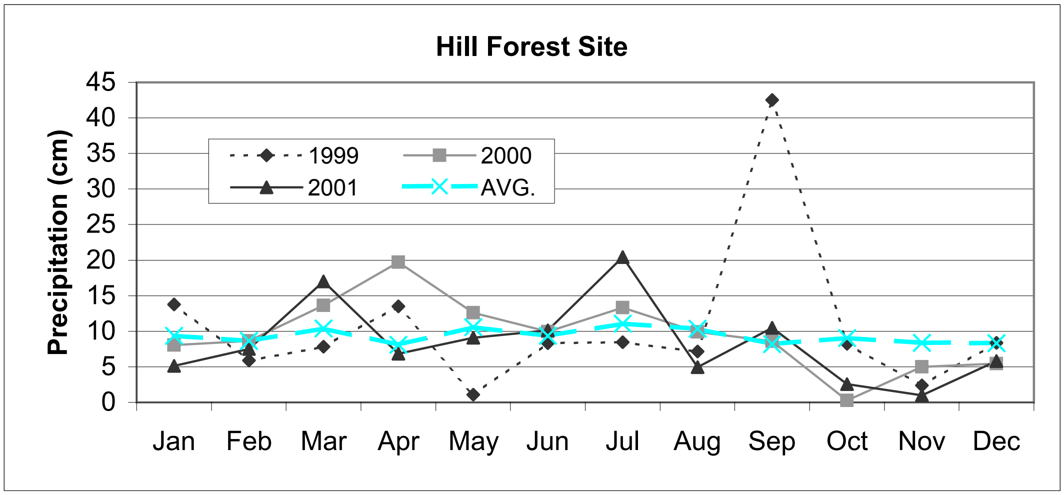
Table 6. Species composition (percent of all stems) at the Duke Forest site. Age 3 represents pretreatment composition in a rising 3-yr-old naturally regenerated, upland North Carolina Piedmont stand.

		Control			Fertilized			Weeded			Weeded+Fertilized		
Common name	Scientific name	Age 3	Age 4	Age 5	Age 3	Age 4	Age 5	Age 3	Age 4	Age 5	Age 3	Age 4	Age 5
		--------------%------------			-------------%-------------			-------------%-------------			-----------%------------		
Yellow-poplar	*Liriodendron tulipifera* L.	63.1	60.8	59.8	49.0	52.4	46.4	59.2	53.1	52.2	68.5	70.9	68.5
White oak[c]	*Quercus alba* L.	13.1	18.2	13.0	28.5	31.1	38.0	28.5	31.3	35.6	9.5	11.9	11.0
Dogwood	*Cornus florida* L.	6.1	2.8	2.2	5.1	4.9	2.8	1.4	2.7	1.8	3.8	1.8	1.1
Red oak[b]	*Quercus rubra* L.	5.7	4.5	8.3	6.3	3.2	5.0	2.8	4.6	3.7	8.1	8.3	10.2
Hickory	*Carya* spp.	3.8	5.2	4.2	2.4	2.9	1.5	2.5	2.4	2.0	2.0	1.4	2.8
Red maple	*Acer rubrum* L.	3.2	4.9	6.1	1.9	1.2	1.7	3.4	2.4	1.4	2.0	2.2	2.2
Blackgum	*Nyssa sylvatica* Marsh.	1.9	0.3	1.4	3.9	0.3	1.3	-	-	0.2	2.0	0.7	1.1
Pine[a]	*Pinus* spp.	1.6	1.0	1.7	0.2	0.3	0.4	0.3	0.5	0.2	1.2	1.4	0.8
Black cherry	*Prunus serotina* Ehrh.	0.3	0.3	0.6	1.0	1.2	0.9	1.1	0.7	1.4	0.6	0.7	0.6
American holly	*Ilex opaca* Ait.	0.3	-	0.6	-	-	-	-	-	-	-	-	-
Sassafras	*Sassafras albidum* (Nutt.) Nees.	0.3	-	-	-	-	-	-	-	-	-	-	-
Sourwood	*Oxydendrum arboreum* DC.	0.3	0.3	-	0.5	-	0.4	0.6	-	-	0.3	0.4	0.6
Sumac	*Rhus* spp.	0.3	0.3	0.6	0.7	0.6	-	-	0.2	-	0.6	-	-
Sycamore	*Platanus occidentalis* L.						0.2			-			-
Elm	*Ulmus* spp.	-	-	0.3	-	-	-	-	0.2	0.2	-	-	-
Juniper	*Juniperus virginiana* L.	-	0.3	0.6	-	0.3	0.4	-	0.2	0.2	-	-	-
Mulberry	*Morus* spp.	-	-	-	0.2	0.3	0.2	-	-	-	-	-	-
Persimmon	*Diospyros virginiana* L.	-	0.7	-	-	1.2	0.7	-	0.7	0.4	0.9	-	0.6
River birch	*Betula nigra* L.	-	-	-	0.2	-	-	-	-	-	-	-	-
Sweetgum	*Liquidambar straciflua* L.	-	-	0.8	-	0.3	-	-	0.7	0.6	0.6	0.4	0.6
	Total Number (stems/10m^2)	79	80	107	104	77	94	90	102	123	87	72	95

[a] Includes post oak (*Q. stellata* Wang.) and white oak (*Q. alba* L.).

[b] Includes loblolly pine (*P. taeda* L.), shortleaf pine (P. echinata Mill.) and Virginia pine (*P. virginiana* Mill.).

[c] Includes black oak (*Q. velutina* Lamarck), red oak (*Q. rubra* L.), scarlet oak (*Q. coccinea* Muench.), and willow oak (*Q. phellos* L.).



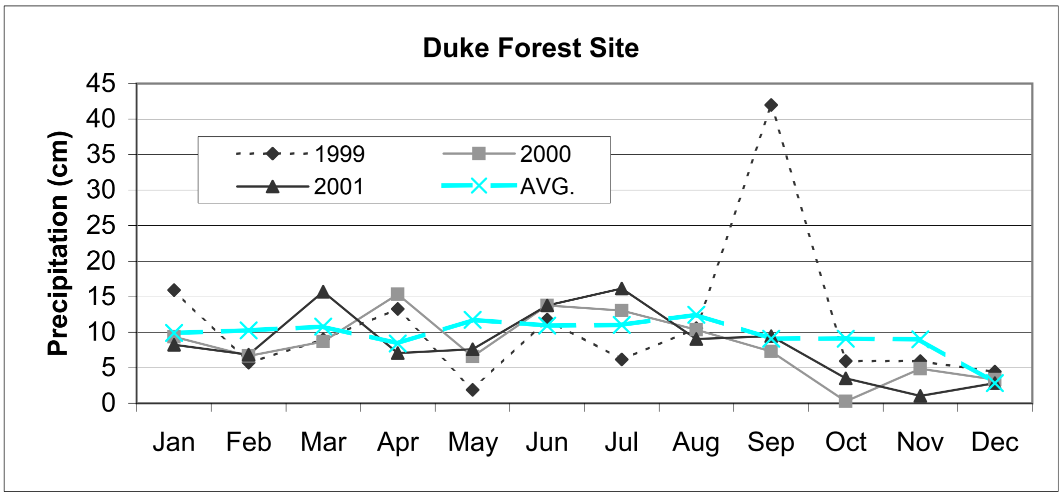


Figure 1. Monthly precipitation patterns for the Hill Forest (Rougemont, NC) and Duke Forest (Durham, NC) during the study years from 1999-2001. The average precipitation data are based on the 100 yr longterm average.

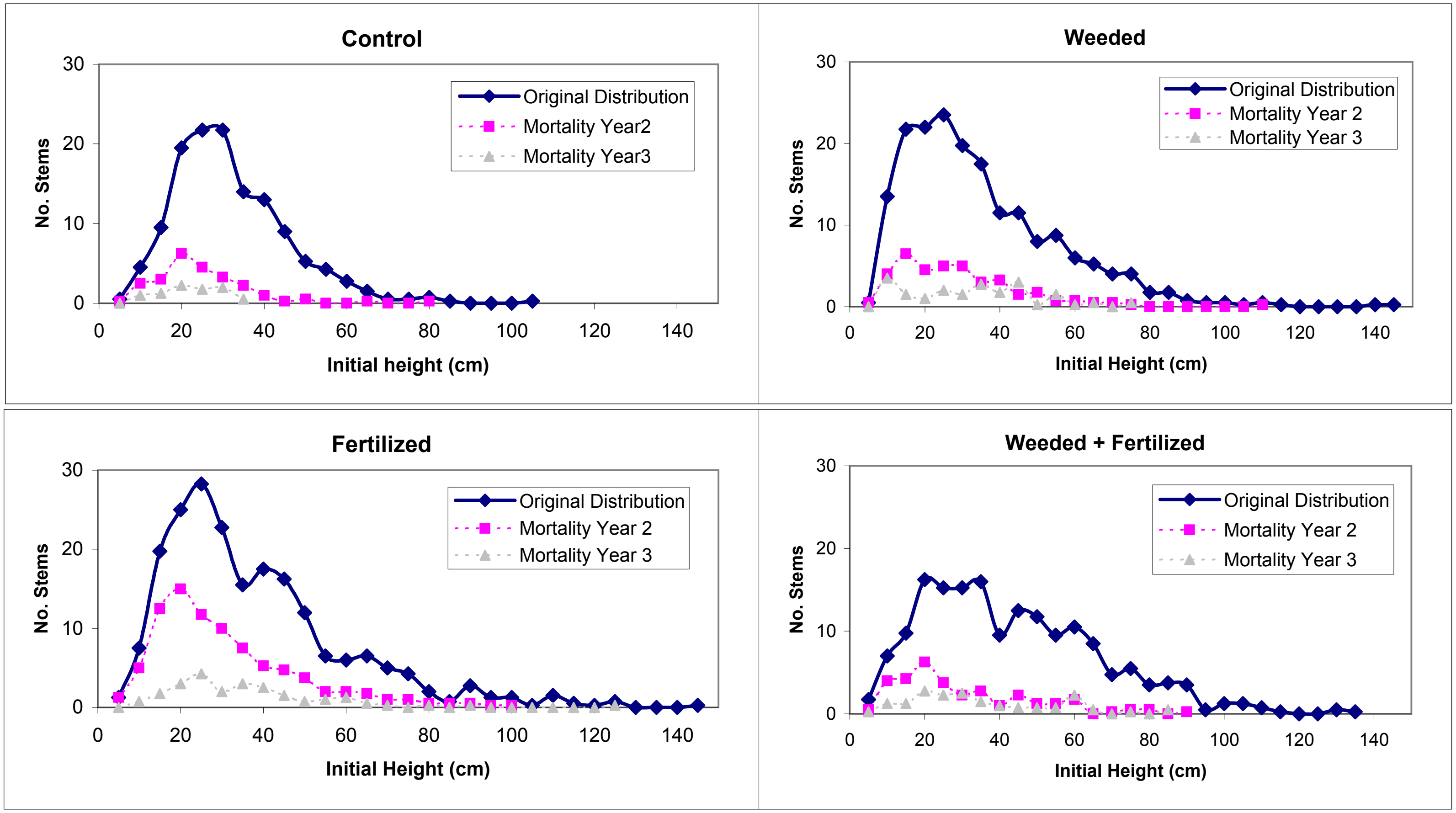


Figure 2. The initial distribution of rising 1-yr-old stems (solid line, by 5-cm height classes) and subsequent mortaility (dashed lines) at the end of the second and third growing seasons at the Hill Forest site.

Chapter III: Weeding, Fertilizing, and Thinning Affect Leaf Characteristics and Growth Phenology of Very Young Naturally Regenerated Yellow-Poplar on Two Upland Sites.

Jamie L. Schuler

North Carolina State University, Hardwood Research Cooperative, Department of Forestry, Raleigh, NC 27695-8008

Abstract

Yellow-poplar is one of the more commonly regenerated species in upland Piedmont stands following clearcut reproduction methods. Recent studies show that a variety of silvicultural activities affect the growth of yellow-poplar seedlings. However, the mechanisms responsible for these changes in growth have not been documented in detail. This study reports the effects of weed control, fertilization and thinning treatments on yellow-poplar stem growth and monthly growth patterns for two recently clearcut stands ages 1 to 3 and 3 to 5. Leaf physical and chemical parameters were compared by treatment, and also correlated with stem growth. Vector analysis was used to illustrate changes in leaf area and foliar nutrient concentrations in relation to plant nutrient status.

1. Introduction

The application of intensive silvicultural treatments like fertilization and weed control are commonplace in intensive hardwood and pine plantation culture in the southern U.S. (Zutter et al., 1987; Lockaby et al., 1997; NCSFNC, 2002). However, their application to young natural hardwood stands has been limited, partly due to an insufficient understanding of the factors that constrain the growth and development of very young, naturally regenerated forest stands.

Recent research activities have demonstrated that intensive practices are effective in promoting accelerated growth and development in very young naturally regenerated hardwood stands (Schuler, this thesis). Competing vegetation, animal herbivory, disease, soil quality and overstocking have been identified as constraints on growth in young even-aged hardwood stands in the North Carolina Piedmont and upper coastal plain regions (Newton et al., 2002; Schuler and Robison, 2002; Ramogosa and Robison, 2003). Intensive silvicultural treatments to manage competing vegetation and herbivory have resulted in 5-fold increases in volume production compared to non-managed hardwood stands at ages 1 to 3 (Ramogosa and Robison, 2003). Broadcast fertilization-alone has produced 3-fold gains in volume in young stands on similar sites (Newton et al., 2002; Schuler, this thesis). However, none of these studies has provided insight to the ecophysiological mechanisms that fostered these significant growth responses, which is the goal of this paper.

Previous research has demonstrated that growth responses are related to a seedling's aptitude to capture incoming solar radiation, which is related to leaf area and plant nutrition (Miller, 1995), and the subsequent use of the light energy in the synthesis of biomass (Cannell, 1989). Studies show that increases in nutrient and/or water availability can increase leaf areas and foliar biomass through changes in leaf size (Kuers and Steinbeck, 1998), leaf number (Coyne and Van Cleve, 1977), or both (Myers and Landsberg, 1989). Fertilization and competition control treatments may increase leaf area and leaf duration (Kuers and Steinbeck, 1998). Substantial increases in hardwood stem biomass have been recorded from nitrogen (N) and phosphorus (P) fertilization (e.g., Graney and Murphy, 1993; Nelson et al., 1995; Lockaby et al., 1997; Chang, 2003), as well as from other nutrient additions (Burke and Raynal, 1998).

Detailed fertilization prescriptions are only available for a select few hardwood species grown in plantations (*e.g.*, black walnut, cottonwood, eucalptus, and sweetgum) (Ponder et al.,1979; Leech and Kim, 1981; Coleman et al., 2003; Scott et al., 2004), and none are available for natural stands. A number of methods to describe nutrient deficiencies in forest trees has been examined using soil and plant tissue analyses. Soil analysis has not been a reliable test for diagnosing plant nutrient deficiencies because of the dynamic nature of soil nutrient availability for plant uptake, and the lack of strong empirical basis for the relation between soil nutrients, testing and plant growth. Analysis of plant tissues, especially foliage, is an accepted and widely used approach for characterizing nutritional status (Bowen and Nambiar, 1984; Binkley, 1986). Critical level approaches to diagnose nutrient deficiency/sufficiency using foliar concentrations are unable to detect nutrient induced changes in foliar nutrient contents resulting from increases in the number and/or size of leaves (leaf area). Approaches that assess foliar nutrient status and leaf biomass simultaneously may provide a more sensitive diagnostic test (Haase and Rose, 1995), especially for species and forest systems for which data on this is limited.

In addition to foliar characteristics, analysis of seasonal growth patterns can also aid in the identification of resource limitations in tree species. For example, late summer and early fall soil moisture shortages have been implicated in late season growth declines on many sites in the southeastern U.S. (Ferrell, 1953; Dougherty and Gresham, 1988).

Increases in late season soil moisture availability (*e.g.*, through vegetation control treatments) have led to an alteration of growth patterns, longer growing seasons, and improved growth rates in pines (Allen and Wentworth, 1993), and it is likely that hardwood seedlings would respond to treatments that improve resource availability since most hardwood species are more demanding compared to pine (Davey, 1973).

The objectives of this study were to examine the effects of intensive silvicultural treatments on leaf characteristics and seasonal growth patterns of individual stems within two very young naturally regenerated hardwood stands in order to better define the growth altering mechanisms. Yellow-poplar (*Liriodendron tulipifera* L.) was selected as the species of study because of its prevalence throughout the region (Beck, 1990), and because of its sensitivity to resource availability (Hay et al., 1987; Kolb and Steiner, 1990).

2. Methods

2.1. Site Descriptions

Two upland sites in the North Carolina Piedmont were selected for study. The first site, on the Hill Demonstration Forest (Hill), is located in Durham Co., and owned by North Carolina State University. This 2 ha site was previously a natural loblolly (*Pinus taeda* L.) and Virigina pine (*P. viriginiana* Mill.) stand with a small component of mixed hardwoods. The Hill site was regenerated by clean clearcutting in the winter 1998/99. The second site, on the Duke Forest (Duke), is located in Orange Co., and owned by Duke University. It was formerly a 5 ha mixed oak (*Quercus spp.*) stand. The Duke site was regenerated by clean clearcutting in the winter 1996/97. Both sites occur within the Carolina Slate Belt soil system of NC (Daniels et al., 1999). Soils at the Hill site were classified as a Georgeville silt loam, with a mainly north-facing aspect on slopes less than 5% (Kirby, 1976). Soils at the Duke site were classified as a Wedowee sandy loam on a north-facing aspect with 2-10% slopes (J. Edeburn, Duke Forest Manager, personal comm., 2004). Both sites have an average site index (SI_{50}) of 24.3 m for loblolly pine (*Pinus taeda* L.), and are located about 24 km apart.

Both forested areas have about 200 days of growing season from April through October (Kirby, 1976; Dunn, 1977). Annual precipitation is very similar between sites. The longterm average for Rougemont, NC (station approx. 3 km from the Hill site) is 112 cm yr^{-1}. The longterm average for Durham (station approx. 5 km from the Duke site) is 116 cm yr^{-1} (http://www.nndc.noaa.gov, accessed 21 July 2004). Monthly deviations from the long-term precipitation patterns during the 2001 study year are illustrated in Figure 1.

2.2. Experimental Design

Ten square meter circular plots (3.58 m diameter) with treated 1 m radius borders were located so that each plot contained at least two yellow-poplar and two red or white oak seedlings (*Quercus* spp.) on both sites. No plots contained discernable stump sprouts or heavy concentrations of logging slash. At each site, eight treatments were arranged in a 2x2x2 factorial arrangement and installed with four replications in a randomized complete block design. Weeding, fertilization, and thinning represented the main treatment factors, and are described below.

(1) The weeding treatment removed all non-arborescent vegetation. Plots were hand weeded beginning in June 1999, and maintained weed-free at least every other week through the 2001-growing season.

(2) The fertilization treatment consisted of broadcast application of 90 kg N ha^{-1} and 100 kg P ha^{-1} applied as diammonium phosphate in June 1999. Fertilizer was re-applied in the spring prior to the 2001 growing season at a rate of 100 kg N ha^{-1} as urea, and 100 kg K ha^{-1} as muriate of potash.

(3) The thinning treatment reduced stem density to four stems per plot (the equivalent of 4,000 stems ha^{-1}). Thinned plots consisted of two yellow-poplar and two oak seedlings that were well-spaced to minimize crowding.

2.3. Stem and Leaf Measurements

Height, diameter and volume increments for the yellow-poplar stems were recorded for the 2001 growing season (three years after treatments were first imposed, and the 3rd (3GS) and 5th growing seasons (5GS) for the Hill and Duke stands, respectively). Monthly height measurements were also recorded at each site. For non-thinned plots, repeated measurements were performed on a random subsample of the same 10 to 12 yellow-poplar seedlings per treatment plot. Both yellow-poplar seedlings were measured on thinned plots at each interval.

Leaf duration was estimated using the same individuals identified for the monthly height measurement record. Leaf duration for each seedling was defined in days, as the time beginning with leaf expansion and ending with leaf abscission, and rated every 14 days. The beginning of leaf expansion was set at the time when 50% of the 10 uppermost terminal buds had visually identifiable leaves protruding through the expanding bud. Leaf abscission was set as the point when an individual seedling lost all of its leaves from 9 of the 10 uppermost buds.

Yellow-poplar leaves were collected from the upper crown and composited for each treatment plot in late August 2001. Leaf size (cm^2, without petioles) was determined using Delta T scanning equipment (Delta-T Devices, Cambridge, UK) within 8 hr of collection, or when fresh leaves could not be scanned the same day, the leaves were photocopied for later measurement. Leaves were then dried to a constant weight at 60°c and then weighed. Specific leaf area (SLA, $cm^2\ g^{-1}$) was calculated as the leaf size divided by the dry weight of each sample. Foliar nutrient status was assessed from the same leaf samples after SLA determination. Chemical analyses were performed according to standard methods (Westerman, 1990). Total nitrogen concentration was determined using a NC 2100 Soil Analyzer (ThermoQuest Italia S.p.A., Milan, Italy). Phosphorus and potassium were analyzed colorimetrically using an inductively coupled plasma spectrophotometer.

Total leaf area (TLA) and leaf biomass were estimated for yellow-poplar on all treatment plots. On thinned plots one of the released yellow-poplar stems, and on non-thinned plots two average sized yellow-poplar stems per plot were enclosed in nylon netting with 2 x 2 cm holes, which allowed the seedlings to continue to photosynthesize normally while still capturing senescent leaves. Abscised leaves were collected starting in late August 2001 and collected periodically until all leaves were collected. Leaves were weighed, and TLA and the number of leaves were calculated from SLA.

Vector analysis (Haase and Rose, 1995) was used to describe nutrient limitations in yellow-poplar stems. This analysis allowed for the simultaneous evaluation of total foliar biomass and nutrient concentration and content response to each treatment.

2.4 Statistical Analysis

All statistical procedures were preformed using SAS (SAS Institute Inc., Cary, NC) with each site evaluated separately. ANOVAs were used to test for treatment differences in growth rates and leaf characteristics. Repeated measures procedures within ANOVA were used to analyze monthly growth data. Simple linear regressions were fitted to the growth data regressed over leaf area, with stem volumes $\log_e$ transformed to account for unequal variances. Pearson's correlations were used to examine relationships between growth variables and leaf characteristics. All statistics were considered significant at α=0.10.

3. Results

3.0 Stem Growth

Overall mean stem height increment for the 2001 growing season for yellow-poplar ranged from 25 to 142 cm at the Hill (3GS), and from 47 to 169 cm at the Duke site (5GS) (Table 1). A weeding and thinning treatment interaction significantly affected height increment at the Hill (P<0.001) and Duke sites (P=0.010). The combination of weeding + thinning increased yellow-poplar height growth 3.6- and 2.6-fold over the effects of weeding and thinning treatments alone, respectively. At the Duke site, fertilization resulted in 1.5 times more height growth during the 5GS than the non-fertilized condition (P<0.001) (Table 1).

At the Hill site, weeding and thinning treatment interaction generated a 20.0 mm diameter increase, whereas weeding and thinning individually produced 1.0 and 3.5 mm increases, over non-weeded and non-thinned conditions (Table 1). At the Duke site, weeding and thinning interacted positively, resulting in 2.2-fold increase over the additive effects of weeding- and thinning-only. Fertilization and thinning also produced a synergistic interaction, increasing diameter growth 1.6 times over the additive effects of fertilization and thinning individually.

The weeding and thinning interaction for volume growth at the Hill site resulted in stems in the weeding + thinning plots having 2.4 times more volume than the treatments individually (Table 1). The yellow-poplar volume increment for the fifth year at the Duke site responded significantly to fertilization and exhibited a weeding and thinning interaction. Fertilization produced a 1.1-fold gain in volume over non-fertilized stems. Weeding and fertilization had significant synergy, contributing to a 2.3-fold increase in volume over non-weeded and non-fertilized conditions.

3.1. Monthly Stem Height Growth

Depending on the treatment, 55 to 80 % of yellow-poplar's annual height growth for three-year-old regeneration was completed by the end of June at the Hill site (Fig. 2a). For the Hill site, fertilized trees grew proportionally less in July, but then had increased growth in August compared to non-fertilized stems. A weeding and thinning treatment interaction (P<0.001) is evident in the relatively stable height growth pattern through

August under these treatments, which contrasted with the other treatments that peaked in June followed by a precipitous drop in height growth in July through October.

At the Duke site, 64 to 86 % of the total height growth for 5-year-old yellow-poplar (in 2001) was completed by the end of June (Fig. 2b). The yellow-poplar stems for each treatment followed similar growth patterns. Growth rates peaked in June followed by a sharp decline in growth in July to October. Fertilization, weeding, and thinning treatments interacted over time (P=0.052). Thinned treatments tended to have a lower proportion of growth during May than non-thinned treatments, and the weeded + thinned treatment produced 15 to 20 % more growth in June than the other treatments. At the Hill site cumulative height growth through May accounted for about 20% of the total seasonal growth, whereas at the Duke site growth through May accounted for about 30% of the total seasonal growth (Fig. 2).

3.2 Leaf Measurements

Leaf Duration

For the Hill site, yellow-poplar displayed leaves from late April/early May until October for an average of 190 days, and ranged from 187-197 days (Table 2). Weeding as a treatment factor significantly affected leaf duration. Stems in the weeded treatment retained their leaves an average 6 days longer than non-weeded stems. Yellow-poplar stems at the Duke site flushed several weeks before those at the Hill site. Many yellow-poplar had discernable leaves in mid-April and they persisted into October. Leaf duration at the Duke site averaged 200 days, and ranged from 194 to 207 days (Table 2). Stems in the thinned treatment displayed leaves an average 8 days longer than non-thinned stems (P<0.001).

Leaf Physical Characteristics

Leaf size was influenced by a weeding and thinning treatment interaction at the Hill site (*P*=0.044) (Table 2). Thinning without weeding resulted in a 20 cm^2 decrease, and weeding without thinning produced a 20 cm^2 increase in average leaf size over non-weeded and non-thinned leaves, although these differences were not significant. With thinning and weeding combined, there was a synergistic increase of 40 cm^2 in average leaf size over yellow-poplar leaves from non-weeded and non-thinned plots (*P*=0.004).

Specific leaf area (SLA) ranged from 183 to 267 cm^2/g and 163 to 216 cm^2/g among treatments at the Hill and Duke sites, respectively (Table 2). Thinning significantly reduced yellow-poplar SLA at both sites. For all thinned plots combined, SLA averaged 200 and 166 cm^2/g, compared to 260 and 202 cm^2/g, for non-thinned plots at the Hill and Duke sites, respectively.

The number of leaves per stem was recorded at the Hill site only (Table 2). The control treatment had fewest leaves per stem, while the thin + weed and thin + weed + fertilization treatments had the greatest number. Weeding and thinning treatments interacted to produce about 3 times more leaves per yellow-poplar stem than all other weeding and thinning treatment combinations. All weeded plots without thinning and all non-thinned plots with or without weeding did not differ statistically for the number of leaves per stem.

<u>Foliar Nutrients</u>

At the Hill site, foliar nitrogen concentrations were affected by a weeding and thinning treatment interaction (*P*=0.075). Foliar N levels on all weeded and thinned plots increased 0.25% N over foliar N concentrations on all non-weeded plots without thinning. Foliar N concentrations at the Duke site ranged from 2.1 to 2.5 %, however, there were no statistically significant treatment differences.

Phosphorus concentrations at the Hill site were affected by a negative fertilization and weeding interaction (*P*=0.009). Foliar P concentrations on fertilized plots without weeding averaged 0.212%, which was significantly greater than the three other treatment combinations. Foliar P concentration on non-fertilized plots without weeding were 0.150%, on weeded plots without fertilization they were 0.163%, and on plots combined with fertilization and weeding combined they averaged 0.177%. At the Duke site, foliar P concentrations averaged 0.165% on fertilized plots, compared to 0.140% on the non-fertilized plots.

For the Hill site, foliar K concentrations were significantly affected by a fertilization and weeding treatment interaction (Table 2). Foliage on all non-fertilized plots with weeding and all fertilized plots without weeding had increased K concentrations compared to foliage from all non-fertilized and non-weeded plots. When fertilization and weeding were combined, however, K concentrations were less than additive, although still elevated when compared to non-weeded and non-fertilized seedlings. Also at the Hill site, thinning resulted in an 18% reduction in foliar K levels compared to non-thinned seedlings. At the Duke site, weeded plots had 20% greater foliar K concentrations than foliage from non-weeded plots.

Vector analysis was used to interpret the foliar nutrient response of yellow-poplar to the silvicultural treatments at the Hill site (Fig. 3). Vector analyses were separated by thinning treatments due to a 10-fold difference in leaf biomass, although the trends were similar between non-thinned (Fig. 3a) and thinned (Fig. 3b) groups. Foliar nutrient responses for N, P and K are plotted for each treatment relative to the untreated control. Increases in relative foliar biomass and nutrient concentration (collectively relative nutrient content) indicate pretreatment deficiency. For non-thinned plots (Fig. 3A), N was deficient for each treatment. Stems responded to fertilization, weeding, and the combined treatment by increasing foliar nitrogen concentration and content and leaf biomass. Yellow-poplar response to weeding and weeding+fertilization in the absence of thinning demonstrated a deficiency in K, whereas P was sufficient in the weed-only plots.

Vector analysis also showed that thinned yellow-poplar have foliar deficiencies for N in all treatments (Fig. 3B). Phosphorus was limiting for stems that were thinned-only, thin + fertilized, and thin + weed + fertilized conditions, but not thin + weed treatments. Potassium was not limiting for stems on the thin + weeded and thin + fertilized + weeded treatments, and limiting for the stems that were the thin-only and thin + fertilized treatments.

3.3. Relationships Between Stem Growth and Foliar Characteristics

Each of the foliar characteristics was correlated with stem growth for yellow-poplar at each of the two sites (Table 3). With few exceptions, third year height, diameter and volume growth increments were significantly correlated with yellow-poplar leaf physical characteristics. Third year height, diameter and volume growth were positively related to leaf duration and leaf size at both sites, and also with the number of leaves at the Hill site. SLA consistently demonstrated negative relationships with growth, regardless of site. Although most correlations between stem growth and leaf physical parameters were significant, some were not strong, with coefficients ranging from 0.33 to 0.75 for the significant correlations. Stem growth increments were best correlated with the number and size of leaves at the Hill site, and leaf duration at the Duke site.

Foliar nutrient concentrations were poorly correlated with third year stem growth at both sites (Table 3). Nitrogen was correlated with height, diameter and volume, although coefficients ranged from 33 to 34 % for the significant correlations. Potassium and phosphorus were not significantly correlated with any stem growth parameter.

Total leaf area ($\log_e$ transformed) was used to predict growth rates for the third year of the study (Fig 4). Total leaf area explained 55, 61 and 82 % of the variation in yellow-poplar stem height, diameter and volume ($\log_e$ transformed) increments for all treatments combined, respectively. Separating yellow-poplar stems by thinning treatment improved the fit of the diameter increment model for non-thinned stems (r^2=0.90), and thinned stems (r^2=0.68) over the combined model. Using separate thinned and non-thinned models for height and volume did not appreciably improve model fit over their respective combined models.

4. Discussion

Growth rates of very young, natural upland hardwood stands on many NC Piedmont sites are sub-optimal (Romagosa and Robison, 2002), and true for the sites reported here. Natural regeneration at the Hill and Duke Forest sites was subjected to weeding, fertilization, and thinning treatments beginning at ages 1 and 3, respectively. Third year growth increments were compared with seasonal height growth patterns, leaf morphological characteristics, and foliar nutrient data to elucidate growth constraints for yellow-poplar. Growth rates differed among treatments, but trends were similar between sites (Table 1). On both sites, growth rates were enhanced through a synergistic response to weeding and thinning treatments. In addition, fertilization with N, P and K was beneficial at the Duke site.

Monthly growth rates were used to highlight treatment effects that altered seasonal growth patterns. Changes in growth patterns may be indicative of temporal changes in resource availability (Allen and Wentworth, 1993). Monthly growth rates for yellow-poplar expressed relative to the annual growth increment (Fig. 2) depicted trends that are consistent with previous work (Kramer, 1943). Yellow-poplar growth began with bud burst in April, and essentially stopped stem elongation in August, well before the first frosts arrived in the fall. This early cessation of aboveground growth is indicative of late summer water shortages that are common in the Southeast (Dougherty and Gresham, 1988). Monthly growth rates for yellow-poplar at the Hill site were altered by complete vegetation control (weeding + thinning treatments). For the younger stems on the Hill site, weeding and thinning treatments combined increased the proportion of August height growth (Fig. 2a). This response coincided with a 6 cm water deficit during the month of August (Fig. 1). Water stress among very young yellow-poplar is likely during late summer months, especially since yellow-poplar is generally more sensitive to dry conditions than many other hardwood species (Auge et al., 1998).

Mean monthly height growth at the Duke site did not appear to be affected by any single treatment factor (Fig. 2b). Since monthly growth was assessed during the fifth growing season at the Duke site, competition from herbaceous and semi-woody (e.g., *Rubus* spp.) vegetation was less compared to arborescent competition, as compared to the younger Hill site forest. Thinning treatments, however, did not noticeably affect growth different from the other treatments, except for a peak in the weeding + thinning treatment in June and a more moderate growth rate for the thinning + weeding + fertilized treatment throughout the growing season.

Early emergence and longer periods of leaf display are generally considered advantageous and can lead to increase growth (Tharakan, 1999). The period of leaf display did correlate positively, although not strongly, with increased growth rates (Table 3), with thinned and weeded stems having the greatest growth rates and longest leaf duration. However, monthly height growth patterns did not indicate that longer leaf duration leads to longer periods of seasonal height growth (Fig. 2). However, having longer leaf duration may foster larger periods of diameter growth and /or belowground growth, both not measured here. Late-season photosynthesis rates are often considerably lower than early and mid growing season rates (Herrick and Thomas, 2003), and therefore the extended leaf duration would likely contribute little to the overall carbon gain. The lack of nearby branches from competitor stems to detach partially abscised leaves may also be a factor in explaining the longer leaf retention in the thinned plots.

Foliar nutrient concentrations are often used to identify potential nutrient deficiencies, reasons for poor growth and to quantify fertilization responses (Binkley, 1986). However, there are very few minimum response thresholds that have been studied in detail for natural hardwood stands (Mitchell and Chandler, 1937), and well-tested critical values are only available for the more commonly grown plantation species (Coleman et al., 2003; Scott et al., 2004). A challenge in relying on foliar concentrations to diagnose nutrient deficiency is determining whether elevated nutrient levels are responses to actual deficiencies being corrected through fertilization, or are due to luxury consumption by the plant. Nitrogen, P and K foliar concentrations did not predict growth responses for yellow-poplar in the current study (Table 3). An important factor not considered when using the critical threshold method is whether seedlings used the increased resource availability to alter the number and size of individual leaves (or leaf area). Vector analysis allowed for comparisons of nutrient concentrations and leaf biomass responses simultaneously (Fig. 3). Based on the foliar nutrient concentration and leaf biomass response by treatment, nitrogen and phosphorus were in most cases limiting, and all treatments resulted in increased foliar biomass over the control stems. This suggests that leaf area per stem was constrained.

Leaf area is generally a good predictor of tree growth for many hardwood species (Bacon and Zedaker, 1986). For all treatments combined, leaf area explained 55 to 82 % of the variation in stem growth at the Hill site. Leaf area was not a precise predictor for third year height and diameter increments, but it did predict volume increment reasonably well. The leaf physical measurements data (Table 2) also show that weeding in combination with thinning significantly increased leaf area by increasing the size of leaves, and more substantially the number of leaves per stem. Weeding and thinning made growth resources more available to the yellow-poplar stems that otherwise would be acquired by other vegetation.

Conclusions

For upland NC Piedmont forested sites supporting very young mixed hardwoods, results indicate that growth resources are not being acquired and/or allocated in a way that maximizes the growth of individual stems. Stems that were released via weeding and thinning treatments with or without fertilization had the greatest growth rates. These responses suggest that maximum growth enhancement is possible from inherent site resources that are focused on individual stems. Without thinning, the response of yellow-poplar to fertilization suggests that inherent site resources are not suitable for maximum growth potential.

Seasonal height growth patterns varied among treatments. The 3-yr-old yellow-poplar stems (Hill site) growing under thinned + weeded conditions with or without fertilization had a greater percentage of growth later in the summer compared to the other treatments. The older stems at the Duke site appeared to not only have longer leaf duration than at the Hill site, but also to have accumulated more height growth by May than at the Hill site.

Vector analysis of N, P and K responses to fertilization, weeding and thinning treatments demonstrated that yellow-poplar responded to ameliorations of N and P deficiencies. Potassium levels were sufficient in six of the eight treatments. Fertilization-only and thin-only treatments resulted in large increases in foliar K concentrations consistent with deficiency. The largest increases in leaf biomass were coincident with increases in foliar N and P.

Regardless of treatment, total leaf area was a good predictor of stem volume, but less so for height and diameter growth. Total leaf area was highly correlated with third year diameter growth for non-thinned stems. Other foliar characteristics like leaf number, leaf size and nitrogen concentration were positively correlated with stem growth.

These data show that yellow-poplar growth rates can be greatly enhanced by manipulating the existing or supplementing deficient growth resources to enhance leaf area, leaf duration and photosynthesis, and hence growth.

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Table 1. Height, diameter and volume growth rates for the third year following treatment initiation for two regenerating NC Piedmont stands. The Hill Forest site (Durham Co.) was a rising 1-yr-old stand and the Duke Forest site was a rising 3-yr-old stand at the time treatments were imposed. Only significant (P<0.10) treatment effects are listed.

Site	Treatment	Height (cm)	Diameter (mm)	Volume (cm^3)
Hill Forest	None	25.2	2.4	82
	Fert	30.7	2.4	161
	Weed	35.0	3.1	228
	Weed+Fert	43.4	3.8	405
	Thin	29.3	6.0	298
	Thin+Fert	56.9	5.8	493
	Thin+Weed	142.4	24.7	9389
	Thin+Weed+Fert	132.8	20.4	6708
	Sign. ANOVA Effects			
	Weed x Thin	<.001	<.001	0.072

Site	Treatment	Height (cm)	Diameter (mm)	Volume (cm^3)
Duke Forest	None	47.1	5.3	960
	Fert	87.4	7.1	1442
	Weed	60.6	6.9	1042
	Weed+Fert	91.8	7.7	1819
	Thin	88.6	8.7	1502
	Thin+Fert	122.6	19.7	5929
	Thin+Weed	124.9	23.6	9548
	Thin+Weed+Fert	169.0	29.3	17500
	Sign. ANOVA Effects			
	Weed x Thin	0.010	<.001	<.001
	Fert x Thin	-	0.013	-
	Fertilization	<.001	-	<.001

Table 2. Mean foliage characteristics three years after treatments were initiated for 3- and 5-yr-old yellow-poplar growing in two naturally regenerated NC Piedmont forest stands on the Hill and Duke Forests, respectively. Only signifcant ANOVA effects ($P \leq 0.10$) are listed.

Site	Treatment	Leaf Duration (days)	Leaf Size (cm^2)	Specific Leaf Area (cm^2/g)	No. Leaves per Tree	Nitrogen Conc. (%)	Phosphorus Conc. (%)	Potassium Conc. (%)
Hill Forest	Control	186	78.9	243.5	20	2.20	0.163	1.03
	Fert	188	108.2	266.7	29	2.69	0.22	1.61
	Weed	189	120.6	267.3	33	2.52	0.157	1.67
	Weed+Fert	190	109.0	261.9	28	2.63	0.185	1.30
	Thin	185	67.8	201.2	28	2.26	0.141	0.96
	Thin+Fert	191	80.7	205.6	53	2.31	0.203	1.34
	Thin+Weed	197	128.6	183.6	326	2.77	0.169	1.10
	Thin+Weed+Fert	197	138.7	209.1	358	2.72	0.169	1.24
Sign.	**ANOVA Effects**							
	FERT	-	-	-	-	-	<0.001	-
	THIN	-	-	0.004	0.013	-	-	0.031
	WEED	0.032	<0.001	-	0.012	0.005	-	-
	FERT*WEED	-	-	-	-	-	0.009	0.015
	WEED*THIN	-	0.043	-	0.010	0.093	-	-

Site	Treatment	Leaf Duration (days)	Leaf Size (cm^2)	Specific Leaf Area (cm^2/g)	No. Leaves per Tree	Nitrogen (%)	Phosphorus (%)	Potassium (%)
Duke Forest	Control	194	108.9	201.3	na	2.03	0.136	0.89
	Fert	197	138.5	216.5	na	2.27	0.165	1.13
	Weed	196	121.7	189.1	na	2.17	0.136	0.89
	Weed+Fert	198	133.4	201.3	na	2.23	0.157	0.90
	Thin	202	94.8	171.8	na	2.31	0.156	1.07
	Thin+Fert	204	128.4	163.4	na	2.25	0.177	1.04
	Thin+Weed	205	127.0	162.2	na	2.27	0.136	0.89
	Thin+Weed+Fert	207	137.3	167.6	na	2.48	0.161	0.85
Sign.	**ANOVA Effects**							
	FERT	-	0.042	-	na	-	0.003	-
	THIN	0.005	-	<.001	na	-	-	-
	WEED	-	-	-	na	-	-	0.094

Table 3. Pearson correlation coefficients (and P-value) between 2001 yellow-poplar stem growth and foliar characteristics. Treatments were initiated in 1999 on rising 1- and 3-yr-old yellow-poplar growing in two naturally regenerated NC Piedmont forest stands on the Hill and Duke Forests, respectively.

Site	3rd Yr Growth Increment	Leaf Duration	Leaf Size	No. Leaves	SLA	% N	% P	% K
Hill Forest	Height Inc.	0.54 (0.001)	0.69 (<0.001)	0.72 (<0.001)	-0.42 (0.017)	0.34 (0.0674)	0.04 ns	-0.15 ns
	Diameter Inc.	0.51 (0.003)	0.67 (<0.001)	0.75 (<0.001)	-0.46 (0.008)	0.24 ns	-0.08 ns	-0.29 ns
	Volume Inc.	0.62 (<0.001)	0.74 (<0.001)	0.72 (<0.001)	-0.47 (0.006)	0.33 (0.073)	0.03 ns	-0.14 ns
Duke Forest	Height Inc.	0.59 (<0.001)	0.49 (0.005)	- -	-0.38 (0.039)	0.27 ns	0.04 ns	-0.15 ns
	Diameter Inc.	0.60 (<0.001)	0.26 ns	- -	-0.53 (0.003)	0.34 (0.062)	0.08 ns	-0.13 ns
	Volume Inc.	0.65 (<0.001)	0.24 ns	- -	-0.53 (0.003)	0.33 (0.069)	0.13 ns	-0.13 ns

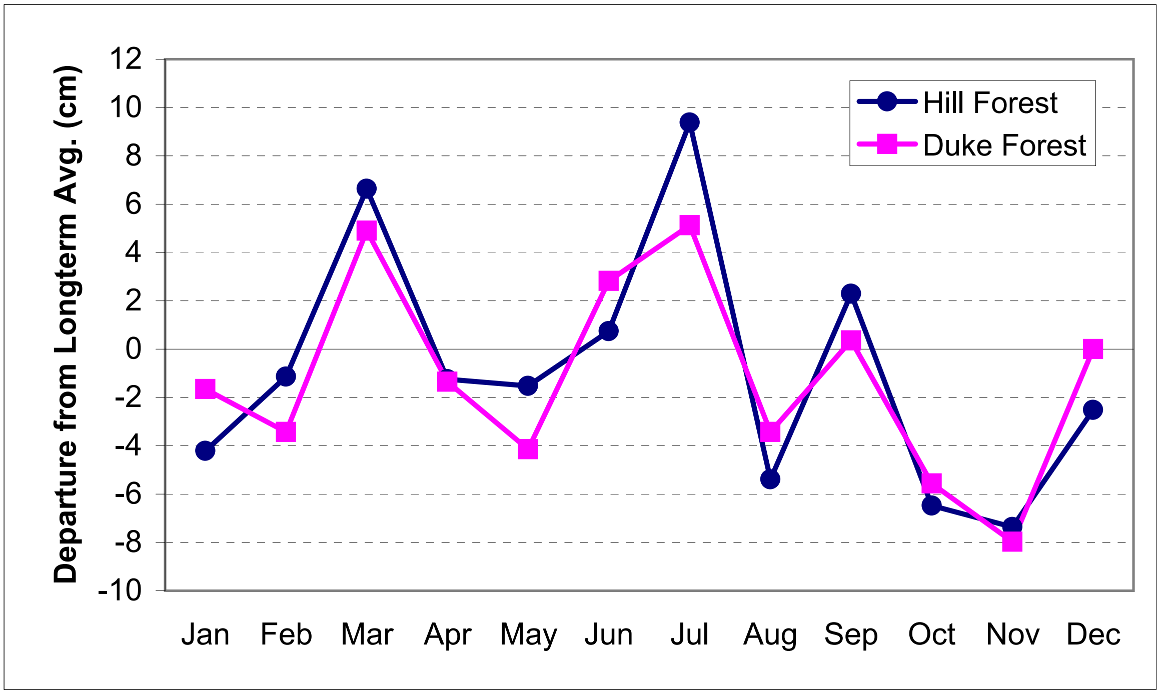


Figure 1. Monthly precipitation patterns for the Hill Forest (Rougemont, NC) and Duke Forest (Durham, NC) during the third growing season (2001) based on the 100 yr longterm average.

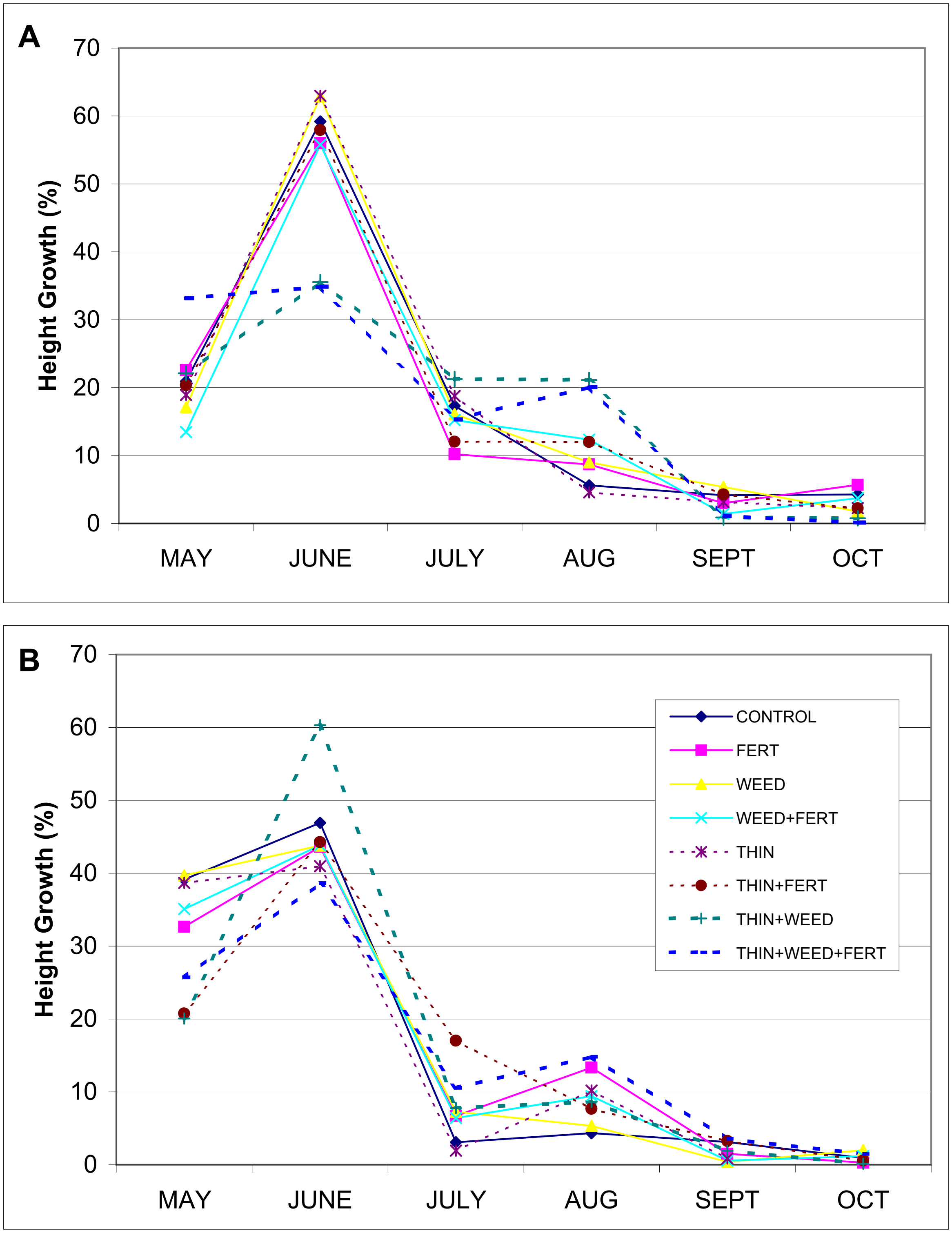


Figure 2. Monthly height growth in 2001 for yellow-poplar as a percent of the 2001 total height growth. Year 2001 was the third growing season for the Hill Forest (A) in Durham Co., NC and the fifth growing season for the Duke Forest (B) in Orange Co., NC, and 3 years since treatments were initiated at both sites.

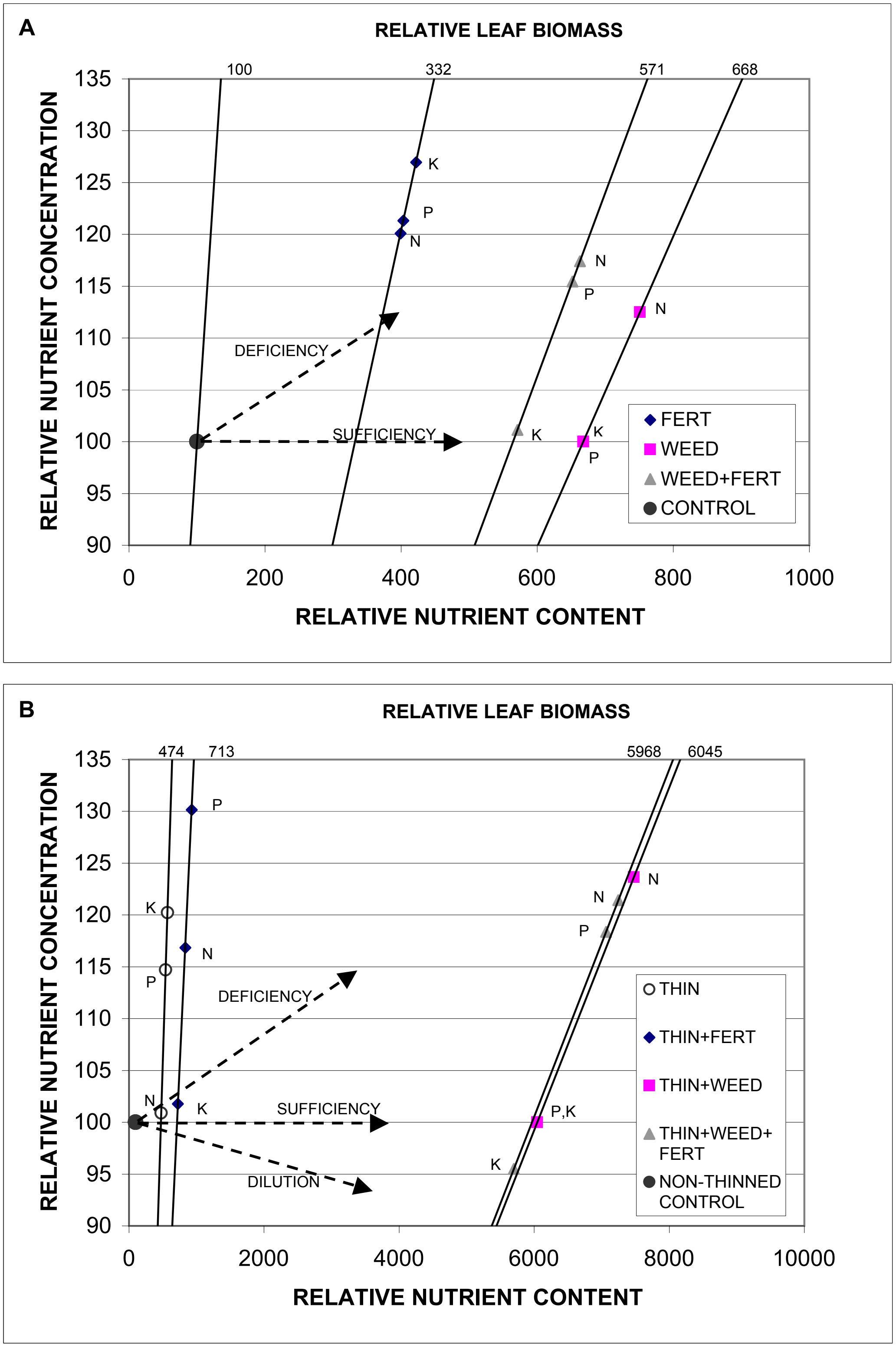
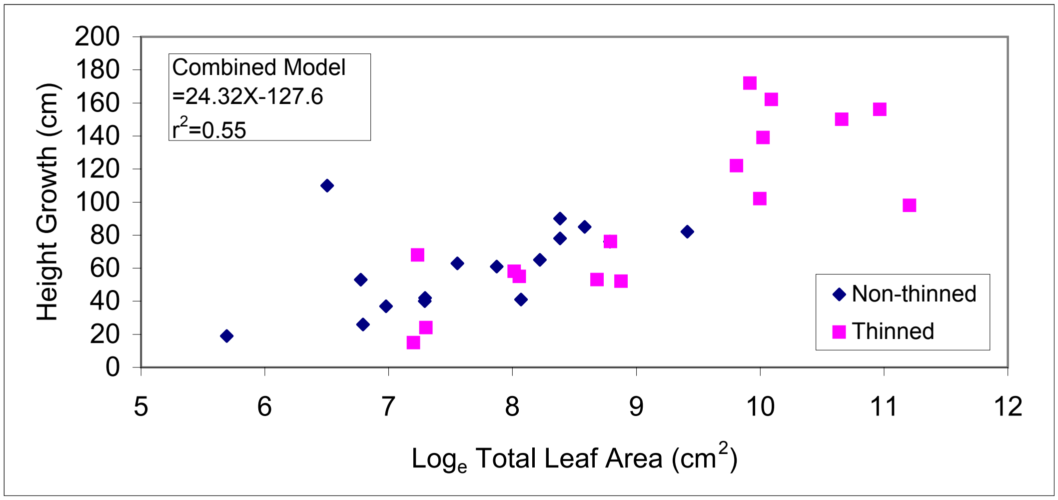
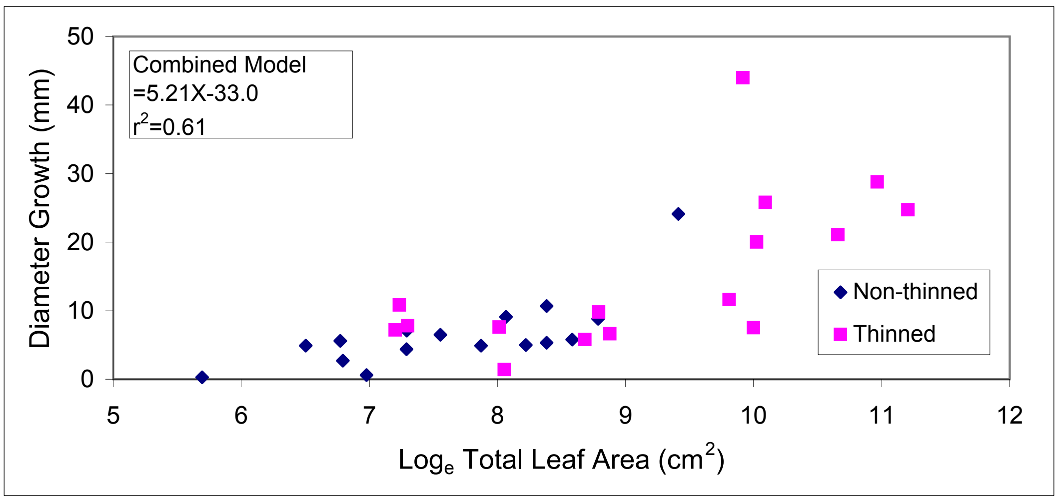


Figure 3. The relative abundance of nutrients (N,P,K) and leaf biomass for non-thinned (A) and thinned (B) yellow-poplar subjected to weeding and fertilization treatments at the Hill Forest site. The data were collected during the third growing season, three years after treatments were initiated.





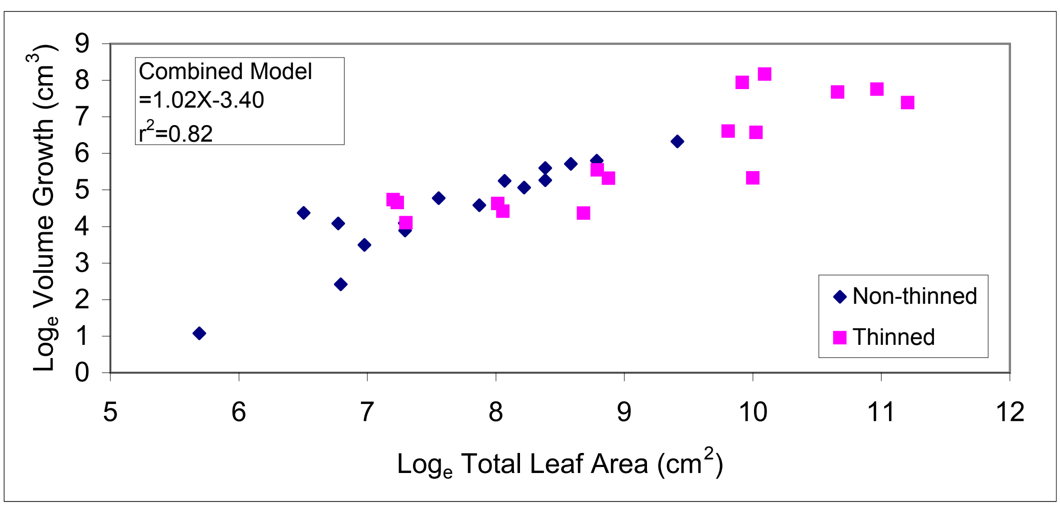


Figure 4. Total leaf area relationship to third year growth increment from a three-yr-old upland hardwood stand at the Hill Forest, Durham Co., NC. The combined model is for non-thinned and thinned conditions jointly.

Chapter IV: Three-year Growth Response and Survival Probabilities for Very Young Co-occurring Upland Tree Species Subjected to Fertilization and Weed Control Treatments

Jamie L. Schuler

Department of Forestry and Environmental Resources, North Carolina State University, Raleigh, NC 27695-8008

Abstract

Difficulties in regenerating economically desirable tree species, notably oak spp., have intensified interest in managing regeneration post-harvest in order to alter species composition by manipulating growth rates and survival of individual species. Weed control and fertilization treatments were applied to stems on a rising 1-yr-old mixed hardwood-pine stand. Over 3,000 individual stems were tagged and monitored for three years. Height, diameter and volume equations predicting three-year stem growth from initial stem size measurements were generated for each species/treatment combination. Initial stem measurements were also used to construct three-year survival probability models by species. Growth and survival models were compared between yellow-poplar (the most prevalent species) and black cherry, flowering dogwood, pine spp., red maple and white oak. The results highlight the interactions of treatment differences and species growth characteristics. This paper also demonstrates that species composition in very young stands can be affected using weed control and fertilization treatments.

1. Introduction

In the southern U.S., upland hardwoods represent 35% of the timberland, or roughly 26 million ha in 1999 (Conner and Hartsell, 2002). These stands are often regenerated using clearcut and shelterwood regeneration methods to produce even-aged stands (Kirkham, 1988). By contrast, single tree selection and group selection regeneration methods to produce uneven-aged stands are not widely applied because of the difficulties associated with distributing the cut and a propensity to regenerate shade tolerate species, making them poor choices to regenerate economically desirable Southern hardwood species which tend to be moderately tolerant to intolerant of shade (e.g. red oak, *Quercus* rubra L., white oak, *Q. alba* L., and yellow-poplar, *Liriodendron tulipifera* L.) (Della-Bianca and Beck, 1985).

Published literature concerning natural hardwood regeneration under even-aged silvicultural systems has largely focused on the role of different sources of regeneration (*i.e.*, seed, advance regeneration, and stump or seedling sprouts), pre-harvest treatments that facilitate control of undesirable species and promote advance regeneration, and the temporal and spatial manipulation of overstory light levels. This information has been used to develop regeneration strategies to re-establish new forests with high proportions of desirable species. Barring disturbances during the regeneration phase such as wildfire or severe insect damage, upland sites typically regenerate to well-stocked and diverse stands, regardless of the even-aged regeneration method used (Beck and Hooper, 1986; Schuler et al. 2005), although the preferred representation of specific species can be difficult to achieve. There is, however, a paucity of information available to make decisions about how to manage regeneration post-harvest to accelerate growth and to favor certain species. The complex mixture of seed- and sprout-origin stems, commercial and non-commercial species, as well as other competing vegetation, make improving growth rates and altering species composition in naturally regenerated forests challenging.

Stand development (*i.e.*, self-thinning) is often constrained due to site and temporal resource limitations (Harper, 1977). Intense competition for growth resources (light, water, nutrients, etc.) limits growth (Newton et al., 2002; Romagosa and Robison 2003) and may predispose certain species to increased mortality in seedling and sapling-size classes (Newton, 2003) in multi-species upland stands. Given that forest stands generally attain their highest level of species richness at the time of crown closure (Wang and Nyland, 1993), early interventions may also offer the greatest potential for altering species composition.

Post-harvest regeneration management practices that can affect the availability of growth resources include weed control, nutrition management, stem density reduction, and microsite modification treatments. Treatments like fertilization and woody and herbaceous vegetation control following stand establishment are common in the southeastern U.S., but generally limited to pine dominated stands. There are, however, some reports which indicate these treatments are beneficial in very young hardwood stands (Safford and Filip, 1974; Auchmoody, 1983, 1985; Leak, 1988). In Pennsylvania, broadcast fertilization resulted in 1.8 m and 1.7 cm gain in height and diameter respectively, for black cherry (*Prunus serotina* Ehrh.), over non-fertilized seedlings after five years (Auchmoody, 1983). Recent studies in young North Carolina upland hardwood stands report two- to five-fold increases in average stem volume following broadcast fertilizer applications of nitrogen and phosphorus (Newton et al., 2002; Schuler, this thesis), and up to a 2.5-fold increase in stem height due to weeding (Romagosa and Robison, 2003; Schuler, this thesis), all prior to age 11.

Despite the potential to significantly accelerate tree growth in natural stands at young ages, there is limited information available on how early stand treatments can alter species composition. Since growth rates tend to vary among species, and tree species vary in their ability to acquire and process site resources, not all species are likely to respond to the same treatment equally. For example, in Arkansas, advance regeneration and stump sprout black cherry and white ash (*Fraxinus americana* L.) stems responded to both increased light and fertility levels, whereas red and white oaks did not respond to either (Graney and Rogerson, 1985).

With the large amount of acreage in the Southeast that is fertilized and weeded annually [101,000-121,000 ha yr^{-1} from 2000-2004 (NCSFNC, 2004)], there may be efficient opportunities to apply these types of treatments commercially to young, developing hardwood stands, if it can be demonstrated that such treatments can produce desirable results (*i.e.*, alter species composition and improve growth rates) in Southern hardwoods. The objective of this study is to determine how stems of co-occurring species on a newly regenerated upland hardwood site respond to gradients of resource availability induced by weeding and fertilization treatments.

2. Methods

2.1 Site descriptions

An upland site in the North Carolina Piedmont, clearfelled in Fall/Winter 1998, was studied. The site was located in Durham Co., NC on North Carolina State University's Hill Demonstration Forest. The site was formerly a 2-ha natural loblolly pine stand with a component of mixed hardwoods. Soils were typical for the area, Georgeville silt loam, with mainly a north-facing aspect on slopes less than 5% (SI_{50} 80 ft for loblolly pine, *Pinus taeda* L.). More details on the site are found in Schuler (this thesis).

2.2 Experimental design

Sixteen 10 m^2 circular plots (3.57 m diameter), each with an additional 1 m radius border, were randomly located with the constraint that no plots contained obvious stump sprouts, slash piles or skid trails, and were well stocked with advance regeneration (including seedling sprouts) or newly germinated stems. The appropriate sample plot size was calculated experimentally by Romagosa and Robison (2003) for similar sites.

In June 1999, during the site's first growing season post-harvest (1GS), plots were treated as follows: non-treated control, weeding, fertilization, and weeding + fertilization (n=4). The fertilization treatment consisted of broadcast application of 90 kg N ha^{-1} and 100 kg P ha^{-1} applied as diammonium phosphate. In March 2001, and prior to the start of the third growing season (3GS), 100 kg N ha^{-1} as urea, and 100 kg K ha^{-1} as muriate of potash were applied to maintain nutrient availability. For the weeding treatment, all non-arborescent vegetation was periodically removed through hand weeding to maintain weed-free conditions through the 3GS. The combined weeding + fertilization treatment was the application of the weeding and fertilization, as described above, on the same treatment plot.

2.3 Measurements and Data Analyses

Prior to treatment, all stems were permanently marked with aluminum tags embossed with a unique number in order to follow the growth and survival of individual stems. More than 3000 stems were tagged during the study. Total height (±1 cm) and basal diameter (±0.1 mm) were measured for each stem in June 1999 and at the end of the third growing season (3GS) in Nov. 2001.

Model coefficients [β_0 (y-intercept), β_1(slope)] were generated using simple linear regressions of initial measurements (height, diameter and conical volume) against the 3GS data for each treatment by species. Three-year survival probabilities were developed for each species and treatment using the PROC LOGISTIC regression procedure based on initial stem measurements. Only the logistic models that achieved convergence are reported. McFadden's R^2 (R^2_{MF}) (Menard, 2000) was used to describe the model fit to the logistic function:

$$\text{Three-year Survival Probability} = [e^{\beta_0+\beta_1(\text{initial measurement})}] / [1+ e^{\beta_0+\beta_1(\text{initial measurement})}], \quad [1]$$

where e is the natural logarithm, β_0 (intercept) and β_1 (slope) are model coefficients, and initial measurements refer to the June 1999 (early 1GS) measurement of stem height, diameter or volume.

Since many species had relatively few data points for each treatment, species comparisons for survival and growth model coefficients were made between black cherry, dogwood (Cornus florida L.), pine spp. (Pinus spp.), red maple (Acer rubrum L.), and white oak to yellow-poplar only. Contrast statements (in PROC GLM / PROC LOGISTIC) were used for comparisons between species, and for comparing treatment effects by species (SAS, 1990). Yellow-poplar was selected because of its prevalence and because it tends to be the major competitor for all other species.

For all treatment comparisons, weeding x fertilization treatment interactions were evaluated first, and when not significant, the significance of the weeding and fertilization main effects was assessed. Statistical significance for all tests was assessed at the 90% probability level.

3. Results

3.1 Comparisons of growth within individual species by treatment

Linear regression models were generated for each species and treatment combination to predict height, diameter and volume from ages 1 to 3 (Tables 1-3). Not every species was represented on each treatment block due to natural variation. Yellow-poplar dominated every plot, representing 57 to 69 % of the initial stem count (Schuler, this thesis, Chap. 2).

Within the height models, species with significant weeding and fertilization treatment interactions for intercept coefficients were white ash (P=0.0285) and winged sumac (P=0.0142). Ash had higher intercepts with the control and weeded + fertilization treatments, and the intercept on fertilized plots was the same as on the weeded + fertilization treatment (Table 1). Fertilized winged sumac exhibited the largest y-intercept among the four treatments. Winged sumac's response to weeding + fertilization was non-additive, and similar to that of the control. Weeding as a main effect (weeded and weeded + fertilized treatments) resulted in smaller intercept coefficients for dogwood (P=0.0799), red maple (P=0.0704) and yellow-poplar (P=0.0108) compared to non-weeded stems (control and fertilized treatments). By contrast, intercept coefficients for pine (P=0.0429) and yellow-poplar (P<0.0001) were increased by fertilization (fertilized and weeded + fertilized treatments).

Among slope coefficients of height models, no weeding x fertilization interactions existed for an individual species. For weeded treatments, dogwood (P=0.0799), red maple (P=0.0386), yellow-poplar (P=0.0051) and winged sumac (P=0.0305) had greater slope coefficients than on non-weeded treatments. Fertilized pine (P=0.0472), yellow-poplar

(*P*<0.0001) and winged sumac (*P*=0.0449) each had smaller slopes, and hence slower growth rates (per cm of initial height) than non-fertilized stems (control and weeded treatments).

For diameter growth models (Table 2), a weed x fertilize treatment interaction in red maple (*P*=0.0346) resulted from synergy among treatments. The effect of weeding increased intercepts for dogwood and yellow-poplar, while the black cherry had a smaller intercept coefficient on weeded plots. Compared to non-fertilized stems, fertilized mulberry had a greater intercept coefficient (*P*=0.0378), while fertilized yellow-poplar (*P*=0.0708) had a smaller intercept.

Weed x fertilize treatment interactions for diameter models occurred for the slope coefficients in dogwood, mulberry, pine, red maple and yellow-poplar (Table 2). The weeded + fertilized treatment produced a significantly smaller slope than weeding alone for dogwood (*P*=0.0941) and red maple (*P*=0.0346). For pine spp. and yellow-poplar, the weeded + fertilized treatment resulted in slope coefficients that were the smallest of the four treatments (*P*=0.0719 and *P*=0.0171, respectively). Mulberry demonstrated a synergistic response to weeding and fertilization (*P*=0.0378).

For the volume models (Table 3), pine spp. had greater intercept coefficients for weeding (*P*=0.0769) and fertilization (*P*=0.0167) effects compared to non-weeded and non-fertilized treatments, respectively. Yellow-poplar also had a greater intercept coefficient with fertilized treatments (*P*=0.0099). Significant treatment differences in volume slope coefficients were detected for black cherry, dogwood, pine spp., red maple, yellow-poplar and winged sumac. Dogwood (*P*=0.0717) and yellow-poplar (*P*<0.0001) slope coefficients displayed negative interactions among weeding and fertilization treatments, but there was a synergistic response in black cherry. Winged sumac (*P*=0.0202) and red maple (*P*=0.0506) showed a positive response to weeding treatments. Red maple also showed a positive slope response to fertilization (*P*=0.0062), while pine spp. had a smaller slope (*P*=0.0149) compared to non-fertilized treatments.

3.2 Comparison of growth among species by treatment

Six species were selected, based on their representation and local importance, to examine how each treatment affected subsequent growth and species composition. Slopes and intercepts for yellow-poplar three-year growth were compared to black cherry, dogwood, pine spp., red maple and white oak. Graphical data are shown for height (Fig. 1), not diameter or volume, to illustrate species interaction.

For height models (Fig. 1), black cherry and red maple slope coefficients on non-fertilized plots were significantly less than yellow-poplar (*P*=0.0275 and *P*<0.0001, respectively). Pine spp. had a significantly greater intercept than yellow-poplar on non-fertilized plots. Slope coefficients for fertilized yellow-poplar were greater than fertilized dogwood (*P*=0.0976). Y-intercept coefficient for yellow-poplar differed only from pine spp. (*P*=0.0987). On non-weeded plots, dogwood had a smaller slope, but a larger intercept coefficient than yellow-poplar. Pine spp. had a larger y-intercept, while red maple had a smaller slope (= growth rate) than yellow-poplar. The same responses for dogwood, red maple and pine spp. were noted for weeded plots, except that the dogwood y-intercept was no different than for yellow-poplar.

For diameter models, no interactions among weeding and fertilization treatments existed. Non-fertilized pine had greater intercepts, and non-fertilized black cherry and red maple had smaller slopes compared to yellow-poplar. Fertilized pine spp. also had a larger intercept, while dogwood had a smaller slope compared to fertilized yellow-poplar. For non-weeded stems, dogwood had a greater intercept, but a smaller slope than non-weeded yellow-poplar. Weeding resulted in significantly larger slope coefficients for dogwood but smaller slopes for red maple, and a greater intercept for pine compared to weeded yellow-poplar.

For volume growth models, species interacted with weeding and fertilization treatments for slope and intercept terms. Yellow-poplar had significantly smaller slopes than dogwood and pine spp. on the control plots, than black cherry, pine spp. and white oak on fertilized plots, and pine spp. on weeded plots. Yellow-poplar had larger slopes than black cherry on control plots, than dogwood and red maple on fertilized plots, than black cherry and red maple on weeded plots, and than black cherry on weeded and fertilized plots. Y-intercepts were greater for pine spp. on control, fertilized and weeded plots compared to yellow-poplar. Black cherry was had a greater intercept on weeded and weed + fertilized plots than yellow-poplar.

3.3 Survival probabilities

Logistic regression models were used to predict survival as a function of initial height, diameter and volume. Models for all species that met the criteria of model convergence are listed for initial height, diameter and volume (Tables 4-6). In most cases, initial heights and diameters were more significant predictors of survival than was initial volume. Initial height and diameter components of the logistic function had the highest level of probability (lowest *P*-value) of three measurements in 27 and 22 cases, respectively, compared to only 6 cases for models using initial volume.

Survival probabilities for yellow-poplar were highly significant (*P*<0.0001) based on the initial height, diameter and volume measurement for each treatment. Using initial height to predict yellow-poplar survival (Table 4, Fig. 2), weeding resulted in a smaller slope (*P*=0.0013), but greater intercept (*P*<0.0001) coefficients compared to non-weeded treatments. Analysis of the fertilization main effect did not indicate differences relative to slope of the survival function between fertilized and non-fertilized stems. However, the survival model for fertilized yellow-poplar by initial height did have a smaller intercept coefficient (*P*=0.0111) than the non-fertilized model.

Survival models for yellow-poplar with initial diameter as the continuous independent variable had no significant differences in slope coefficients among treatments. However, fertilization treatments had different intercept coefficients (*P*=0.0551), with the fertilized treatment model having the smaller intercept (lower survival) (Table 4).

Survival probabilities for yellow-poplar generated from initial volume as the continuous independent variable indicated significant weeding and fertilization effects in both slope (*P*=0.0133 and 0.0462) and intercept (*P*<0.0001 and *P*=0.0249) coefficients. Fertilization resulted in substantially lower survival for small volume individuals, whereas weeding increased survival probabilities for smaller volume individuals (Table 5).

Survival probabilities also varied by species (Tables 4-6). Graphical data are shown for height (Figs. 3 and 4), not diameter or volume, to illustrate species interaction. Non-fertilized dogwood and red maple had larger slopes (*P*=0.0676 and *P*=0.0054, respectively) and smaller intercepts (*P*=0.0484 and *P*=0.0180, respectively) than yellow-poplar for height models (Fig. 3). Fertilized black cherry and dogwood had smaller slopes (*P*=0.0039 and *P*=0.0769, respectively) and larger intercepts (*P*=0.0206 and *P*=0.0769, respectively) than yellow-poplar (Fig. 3). Slope coefficients for non-weeded yellow-poplar were greater than for black cherry (*P*=0.0051), and smaller than for red maple (*P*=0.0883) (Fig. 4). Black cherry also had a smaller intercept (*P*=0.0105) than yellow-poplar. For weeded plots, red maple had a larger slope coefficient (*P*=0.1000), while dogwood had a smaller intercept coefficient (*P*=0.0387), than yellow-poplar (Fig. 4).

Discussion

Sites in the Piedmont regions of the southeastern U.S. commonly have over 20 tree species in one forest stand. Management of regeneration following silvicultural reproduction methods is a difficult and often overlooked task. Pre-harvest prescriptions (e.g., mid-story release and understory vegetation herbicide treatments) are commonly used to modify species composition by favoring and/or eliminating advance regeneration (Loftis 1985, Horsley 1988, Lorimer 1994, Wender 1998, Brose et al. 1999). The results the current study demonstrate that common silvicultural treatments can be successfully applied to post-harvest regeneration to accelerate stand development, alter species composition and improve productivity through increased growth rates and stem mortality.

The results of this study show that individual species respond to weeding and fertilization treatments differently. Among co-occurring species, the magnitude of the treatment response also varies depending initial size (*e.g.*, Fig. 2). These shifts in dominance are not new concepts. Researchers have long known about differences in species performance due to silvicultural practices like fertilization and thinning, especially in older stands (Mitchell and Chandler, 1939; Farmer et al. 1970; Robison et al. 2004). In their 1939 fertilization study, Mitchell and Chandler suggested that tree species fall into one of three categories: nitrogen tolerant, moderately N tolerant, and nitrogen demanding. The tolerant species being capable of its best performance in areas with limited nitrogen availability, moderately tolerant species out-compete tolerant species in areas with moderate supply of resources, while the demanding species outgrow all others on the best sites and have limited representation on the poorest sites. On this Piedmont site, most species responded positively to fertilization (e.g., black cherry, red maple and yellow-poplar). However, not all species responded as well as others, indicating competitive advantage differences among species (Fig. 1). For example, fertilization resulted in a large rank change for white oak.

Weeding treatments are often employed under plantation culture. Weeding experiments in natural hardwood stands have few examples in published literature (e.g., McGill and Brenneman, 2002; Romagosa and Robison 2003). Other examples of hardwood regeneration response to weeding can be found in the pine plantation herbicide literature. Miller et al. (1991) showed an 3-fold increase in hardwood basal area following herbaceous vegetation control in a pine plantation. Cain (1991) showed a doubling of height for hardwood seedlings following herbaceous weed control in pine plantations. In this study yellow-poplar was very responsive to weeding, with height, diameter and volume increasing with increasing size (Tables 1-3).

Yellow-poplar was a dominant species on all plots under these treatments, although pine spp. and white oak appeared to successfully compete with it (growth-wise) on the control plots, assuming similar initial sizes, through year 3 (Fig. 1). Black cherry and pine spp. with fertilization, and pine with weeding, grew at an almost identical rate as yellow-poplar (Fig. 1). For height growth, very few species x initial height interactions existed. Within those treatments where yellow-poplar grew at different rates than the other species, few examples of rank change were found. Yellow-poplar differed with respect to slopes for red maple in the control and weeded treatments, and dogwood in the fertilized and weed + fertilized treatments. As an example of rank change, dogwood on fertilized plots is one of the largest stems after three years if initial stem size is under 40 cm (Fig. 1) (assuming all other stems are of similar size); however, if the initial height is greater than 100 cm tall, dogwood would have one of the smallest three-year heights of any species on fertilized plots (Fig. 1).

While growth rates determine dominance in young stands, survival ultimately determines future species composition. Survival probabilities have been studied in detail for several hardwood species. Many of the current oak regeneration protocols are designed to factor in survival probabilities in order to determine the expected stand composition several years into the future (Loftis 1990). Others have used survival, based on initial size, to determine how many seedlings to plant for enrichment planting purposes to provide the desired number of competitive trees in the future (Spetich et al. 2002).

The data in the current study show survival probabilities increase with initial stem size (Figs. 3-4). Survival probabilities for each of the treatment factors tend to converge toward 1.0 beginning around 60 cm for yellow-poplar (Fig. 2). Other species attain near maximum 3 yr survival at much smaller sizes (*e.g.*, red maple, Fig. 3a), and still others never reached the asymptote under the initial range of data (*e.g.*, black cherry and dogwood, Fig. 3b). The weeding and fertilization treatments demonstrate that silvicultural prescriptions influence survival, and hence species composition. While yellow-poplar survival was generally well over 95% for initial stem sizes greater than 60 cm (Figs. 3-4), species like black cherry and dogwood had decreased survival on weeded and fertilized plots compared to yellow-poplar in larger size classes. Still other species, especially at smaller sizes, had elevated survival compared to yellow-poplar. Red maple, black cherry and white oak on fertilized plots, and white oak and red maple on weeded plots demonstrated greater survival than yellow-poplar.

Collectively, growth and survival predictions can be used to ascertain whether weeding and fertilization treatments in young, naturally regenerated, upland forests can result in the desired outcome: greater stem growth and higher percentages of desirable species. For large advance regeneration (*e.g.*, >1 m), survival does not appear to a major factor affecting species composition. Large stems generally have survival probabilities near 1.0 up to age 3. However, differences in growth rates may alter a seedling's competitiveness in the future. For example, after three years stem heights differed by 50 cm on fertilized plots for stems with 70 cm initial heights (Fig. 1).

This study has shown that individual species have different growth trajectories and survival probabilities based on the inherent characteristics of this site. I also show that silvicultural manipulation of site resources, through weeding and fertilization, can impact growth and survival differently among species. Little variation in growth rates by initial size classes were detected that would influence the overall three yr dominance (*i.e.*, no rank change compared to yellow-poplar). Growth and survival was affected by the treatments, and was dependent on species. Yellow-poplar showed rapid increases in survival probability with increased stem size. Yellow-poplar became more competitive with pine spp. on weeded and/or fertilized plots. White oak did not respond as favorably to weeding and fertilization treatments as did the other species, which reduced its competitive ability. Black cherry, by contrast, did respond to increases in resource availability. Fertilization treatments increased growth relative to yellow-poplar. Fertilization also increased survival of stems <40 cm tall at the start of 1GS. However, weeding treatments did not have any impact on black cherry growth, but did reduce survival probabilities.

Even though this study is of limited time frame, it does however indicate that there may be significant potential to alter natural stand dynamics and development using relatively simple to apply silvicultural manipulations of site resources to favor certain species. Further monitoring of this study will provide data that can be used to validate and/or modify existing predictive regeneration models (*e.g.*, Loftis 1989) or develop new ones.

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Table 1. Linear functions predicting third-year heights (cm) by species and treatment in a newly regenerated Piedmont upland stand according to the model: $Height_{Yr3} = B_0 + B_1(Height_{Yr0})$. Treatment details are described in the text.

Treatment	Species	N	B_1	B_0	R^2	P-value	Initial Ht. Range (cm)	Mean Initial Ht. (cm)	Mean Ht. Yr 3 (cm)
Control	American beech (*Fagus grandifolia* Ehrh.)	3	0.5060	34.5317	0.55	0.4698	39-59	48	59
Control	American holly (*Ilex opaca* Ait.)	2	4.8182	-59.5455	1.00	-	6-14	36	112
Control	black cherry (*Prunus serotina* Ehrh.)	11	2.0084	-2.7000	0.85	<0.0001	31-105	54	106
Control	blackgum (*Nyssa sylvatica* Marsh.)	9	2.1669	-3.3630	0.55	0.0711	26-65	43	91
Control	dogwood (*Cornus florida* L.)	11	1.2226	67.1985	0.07	0.4407	21-52	37	113
Control	mulberry (*Morus rubra* L.)	2	0.2500	60.0000	1.00	-	20-24	22	66
Control	pine spp. (*Pinus* spp.)	9	3.1708	36.5726	0.65	0.0085	16-50	32	137
Control	red maple (*Acer rubrum* L.)	16	0.6714	35.7129	0.22	0.0664	17-53	30	56
Control	red oak (*Quercus rubra* L.)	5	2.1885	-4.9490	0.50	0.1837	14-56	36	73
Control	river birch (*Betula nigra* L.)	39	2.4230	65.1670	0.25	0.0005	20-59	36	154
Control	sumac (*Rhus typhina* L.)	7	1.2450	53.7470	0.24	0.2641	28-57	42	107
Control	sweetgum (*Liquidambar styraciflua* L.)	5	-0.3666	81.3379	0.05	0.7269	21-36	28	71
Control	white ash (*Fraxinus americana* L.)	7	1.2291	87.4100	0.73	0.0139	21-61	42	139
Control	white oak (*Quercus alba* L.)	11	2.3757	15.2736	0.44	0.0252	16-74	32	91
Control	winged sumac (*Rhus copallina* L.)	13	1.8772	37.5088	0.39	0.0189	16-74	49	130
Control	yellow-poplar (*Liriodendron tulipifera* L.)	223	2.3300	20.6530	0.35	<0.0001	5-59	28	87
Fertilized	American holly	3	1.0962	13.7692	0.93	0.0350	6-14	9	24
Fertilized	black cherry	26	1.9647	86.6446	0.62	<0.0001	19-113	74	232
Fertilized	dogwood	23	1.2758	92.8455	0.20	0.0313	21-80	51	159
Fertilized	hickory (*Carya* spp.)	2	4.3864	-85.0000	1.00	-	44-88	66	205
Fertilized	hophornbeam (*Ostrya virginiana* K.Koch)	2	6.5333	-53.7333	1.00	-	22-37	30	139
Fertilized	mulberry	4	2.0382	45.0582	0.34	0.4160	25-62	38	122
Fertilized	pine spp.	22	1.8919	93.5722	0.56	0.0001	17-62	38	165
Fertilized	red maple	15	1.6097	51.7531	0.54	0.0014	20-107	49	131
Fertilized	red oak	5	2.9819	40.7500	0.76	0.0557	28-49	41	164
Fertilized	river birch	3	0.7228	112.3150	0.62	0.4235	42-75	64	158
Fertilized	sumac	5	1.2570	92.6242	0.35	0.2928	21-98	54	160
Fertilized	sweetgum	3	2.9885	40.4470	0.98	0.0986	19-56	39	157
Fertilized	white ash	11	1.8733	9.3368	0.78	0.0002	14-122	46	96
Fertilized	white oak	11	1.3577	53.0212	0.17	0.2021	17-71	43	111

Table 1 (Cont'd).

Treatment	Species	N	B_1	B_0	R^2	P-value	Initial Range (cm)	Mean Initial Ht. (cm)	Mean Ht. Yr 3 (cm)
Fertilized	winged elm	2	1.9167	120.4167	1.00	-	29-65	47	211
Fertilized	winged sumac	10	0.1146	261.6759	0.01	0.8362	23-141	94	272
Fertilized	yellow-poplar	225	2.3400	52.4270	0.43	<0.0001	8-107	35	137
Weed	American holly	4	3.0383	-23.7847	0.69	0.0055	5-44	27	58
Weed	black cherry	10	2.5706	-6.3317	0.67	0.0036	43-86	68	170
Weed	blackgum	6	1.0125	52.1715	0.51	0.1110	14-142	79	133
Weed	dogwood	12	3.2820	-20.5235	0.80	<0.0001	17-74	44	125
Weed	hickory	2	4.7143	-29.1429	1.00	-	10-17	14	35
Weed	persimmon (*Diospyros virginiana* L.)	5	0.3393	137.8605	0.26	0.3777	76-137	91	169
Weed	pine spp.	19	2.6800	59.2838	0.46	0.0014	12-41	25	126
Weed	red maple	35	2.0127	9.0639	0.68	<0.0001	11-75	38	85
Weed	red oak	6	3.8533	-26.9059	0.80	0.0158	8-40	25	68
Weed	river birch	36	4.0117	-13.7590	0.58	<0.0001	39-98	58	218
Weed	sumac	7	4.3308	-16.2742	0.69	0.0203	18-65	41	163
Weed	sweetgum	7	1.8473	7.9587	0.42	0.1136	22-81	54	108
Weed	white ash	6	7.2347	-99.5624	0.81	0.0138	18-29	26	87
Weed	white oak	3	-6.1429	188.4762	1.00	0.0427	19-24	32	53
Weed	winged sumac	12	2.7109	27.9344	0.72	0.0004	16-98	47	156
Weed	yellow-poplar	321	3.5420	1.3310	0.64	<0.0001	6-94	30	107
Weed+Fert	American holly	9	2.4193	4.9801	0.69	0.0007	5-44	18	49
Weed+Fert	black cherry	20	2.5040	43.5731	0.52	0.0010	34-132	82	249
Weed+Fert	blackgum	7	1.8208	31.1437	0.49	0.0804	12-61	34	94
Weed+Fert	dogwood	38	2.0268	18.2570	0.67	<0.0001	14-98	46	112
Weed+Fert	pine spp.	2	0.5862	130.5172	1.00	-	23-52	38	153
Weed+Fert	red maple	16	2.3917	6.8464	0.66	0.0004	15-106	51	128
Weed+Fert	river birch	2	0.0556	155.1111	1.00	-	34-52	43	158
Weed+Fert	sumac	15	1.5481	88.2581	0.37	0.0153	15-101	49	165
Weed+Fert	sweetgum	30	2.5482	35.1812	0.23	0.0156	12-105	61	191
Weed+Fert	white ash	8	1.8665	67.4838	0.49	0.0530	17-79	51	163
Weed+Fert	white oak	13	2.3966	13.1628	0.55	0.0037	13-61	34	95
Weed+Fert	winged sumac	4	1.9833	61.6654	1.00	0.0019	16-108	40	141
Weed+Fert	yellow-poplar	222	2.6810	22.7610	0.46	<0.0001	3-87	41	136

Table 2. Linear functions predicting third-year basal diameters (mm) by species and treatment in newly regenerated upland Piedmont stands according to the model: $Diameter_{Yr3} = B_0 + B_1(Diameter_{Yr0})$. Treatment details are described in the text.

Species	Treatment	N	B_1	B_0	R^2	P-value	Initial Dia. Range (mm)	Mean Initial Dia. (mm)	Mean Yr 3 Dia. (mm)
American beech	Control	3	1.2662	0.3373	0.97	0.1066	5.9-10.7	8.0	10.5
American holly	Control	2	-4.8333	33.5500	1.00	-	4.5-5.1	4.8	10.4
black cherry	Control	11	1.8272	0.8523	0.75	0.0006	2.2-10.6	5.8	10.9
blackgum	Control	8	2.8121	-3.2685	0.80	0.0029	3.0-10.5	5.6	12.1
dogwood	Control	8	3.1807	-1.0160	0.67	0.0132	2.1-6.5	6.0	11.3
mulberry	Control	2	3.6875	-3.4063	1.00	-	1.9-3.5	2.7	6.6
pine spp.	Control	9	4.1378	5.6334	0.73	0.0036	1.8-7.5	4.1	22.6
red maple	Control	17	0.9193	3.1822	0.48	0.0019	1.9-7.1	4.3	6.8
red oak	Control	3	5.3023	-14.6930	0.91	0.1966	3.6-6.7	6.0	11.3
river birch	Control	40	1.8559	5.3608	0.19	0.0053	0.9-4.8	3.0	11.1
sumac	Control	7	0.6273	10.0937	0.18	0.3414	3.0-9.9	6.5	14.2
sweetgum	Control	5	0.5795	4.6893	0.88	0.0186	2.7-7.3	4.2	7.1
white ash	Control	7	1.3027	5.4019	0.63	0.0597	4.1-10.7	7.6	14.0
white oak	Control	9	2.1758	0.5586	0.64	0.0098	2.5-10.4	5.4	10.9
winged sumac	Control	13	0.5937	8.2469	0.09	0.3110	2.6-8.5	5.7	11.7
yellow-poplar	Control	216	2.0985	-0.1086	0.60	<0.0001	1.5-12.1	4.3	8.8
American holly	Fertilized	2	0.8684	0.6316	1.00	-	1.0-4.8	3.4	3.5
black cherry	Fertilized	26	2.8740	1.4317	0.63	<0.0001	1.7-14.9	7.1	21.7
dogwood	Fertilized	24	1.1839	6.3775	0.27	0.0088	3.0-13.5	5.4	13.1
hickory spp.	Fertilized	2	6.5769	-49.6423	1.00	-	10.3-12.9	11.6	27.7
hophornbeam	Fertilized	2	10.2727	-30.9273	1.00	-	3.4-4.5	4.0	9.7
mulberry	Fertilized	4	1.6508	0.0238	0.73	0.1485	2.6-3.8	3.1	5.1
pine spp.	Fertilized	22	2.0364	13.7801	0.22	0.0284	2.5-8.1	4.8	23.5
red maple	Fertilized	15	2.5657	-2.8502	0.83	<0.0001	1.8-10.1	5.3	10.8
red oak	Fertilized	5	1.5818	6.7815	0.49	0.1858	3.5-8.4	6.2	16.6
river birch	Fertilized	3	0.4638	6.7813	0.51	0.4923	3.9-7.1	5.0	9.1
sumac	Fertilized	5	0.5099	9.7126	0.20	0.4557	3.8-12.2	6.8	13.2
sweetgum	Fertilized	3	2.6054	0.9530	0.98	0.1000	2.5-9.1	5.0	14.1
white ash	Fertilized	12	1.6308	0.6461	0.83	<0.0001	2.5-17.4	6.5	10.6
white oak	Fertilized	12	5.1792	-15.3105	0.75	0.0003	3.9-9.3	5.3	12.5
winged elm	Fertilized	2	0.9242	5.2576	1.00	-	3.4-10.0	6.7	11.5
winged sumac	Fertilized	10	1.4527	8.0120	0.36	0.0673	4.2-13.4	8.2	19.9
yellow-poplar	Fertilized	229	2.2659	0.3593	0.51	<0.0001	2.0-11.1	5.3	12.3

Table 2 (Cont'd)

Species	Treatment	N	B_1	B_0	R^2	P-value	Initial Range (mm)	Mean Initial Dia. (mm)	Mean Yr 3 Dia. (mm)
American holly	Weeded	4	0.8325	5.0087	0.37	0.3934	2.2-8.9	5.3	9.4
black cherry	Weeded	10	0.5397	18.3678	0.05	0.5218	3.7-12.3	8.5	23.0
blackgum	Weeded	6	1.6671	2.1792	0.62	0.0648	3.8-17.3	9.9	18.6
dogwood	Weeded	12	2.7297	1.0939	0.74	0.0003	1.5-8.5	4.7	13.6
hickory spp.	Weeded	2	-2.5000	16.4500	1.00	-	3.7-4.1	3.9	6.7
mulberry	Weeded	3	-1.1757	13.3833	0.99	0.0590	2.9-5.1	3.7	9.0
persimmon	Weeded	5	-0.0063	23.0555	0.00	0.9944	8.5-15.4	12.0	23.0
pine spp.	Weeded	19	5.3776	3.1181	0.47	0.0012	1.5-6.5	3.2	20.3
red maple	Weeded	35	1.5552	2.5012	0.62	<0.0001	1.8-10.8	4.9	9.9
red oak	Weeded	6	3.8168	-4.8116	0.86	0.0075	2.0-6.4	3.7	9.2
river birch	Weeded	36	3.0822	1.7413	0.42	<0.0001	2.5-8.9	4.4	15.2
sumac	Weeded	8	2.1926	5.4190	0.29	0.1662	1.5-7.8	4.1	15.6
sweetgum	Weeded	6	2.1335	2.8435	0.39	0.1873	3.2-9.9	6.2	14.9
white ash	Weeded	6	-0.3496	17.4112	0.00	0.9246	4.8-6.8	5.8	10.6
white oak	Weeded	3	-4.5165	27.8154	0.94	0.1627	3.4-4.5	4.0	8.9
winged sumac	Weeded	12	2.3570	2.8042	0.61	0.0027	2.5-10.5	5.9	16.8
yellow-poplar	Weeded	325	2.7879	0.4686	0.45	<0.0001	1.6-11.5	4.2	12.3
American holly	Weed+Fert	9	2.4206	0.9861	0.85	0.0004	1.8-7.6	3.5	7.6
black cherry	Weed+Fert	20	2.5423	7.4869	0.27	0.0200	2.5-14.0	7.1	25.6
blackgum	Weed+Fert	6	1.9175	0.5859	0.47	0.1319	3.0-8.9	5.7	9.8
dogwood	Weed+Fert	32	2.3747	0.0179	0.60	<0.0001	2.3-13.1	4.5	9.7
mulberry	Weed+Fert	2	10.5000	-29.6500	1.00	-	3.3-3.5	3.4	6.1
pine spp.	Weed+Fert	2	-3.0882	42.8677	1.00	-	1.9-5.3	3.6	31.8
red maple	Weed+Fert	15	2.3274	3.1664	0.70	0.0001	1.1-11.9	5.1	14.6
river birch	Weed+Fert	2	2.2000	4.1200	1.00	-	2.9-3.9	3.4	11.6
sumac	Weed+Fert	15	1.6595	7.7100	0.33	0.0242	2.5-15.2	6.1	17.8
sweetgum	Weed+Fert	28	2.9104	3.6796	0.22	0.0125	3.5-12.9	6.8	22.2
white ash	Weed+Fert	9	1.8394	3.3857	0.19	0.2349	4.3-8.3	6.6	16.4
white oak	Weed+Fert	14	2.4879	-0.3413	0.52	0.0038	2.1-9.4	4.9	12.3
winged elm	Weed+Fert	4	-0.1391	18.2363	0.03	0.8215	4.5-10.1	6.6	17.3
winged sumac	Weed+Fert	4	2.6219	-1.6327	0.98	0.0087	3.6-10.7	5.6	13.1
yellow-poplar	Weed+Fert	226	1.9857	3.2198	0.27	<0.0001	1.0-12.2	5.2	13.5

Table 3. Linear functions predicting third-year volumes (cm^3) by species and treatment in a newly regenerated upland Piedmont stand according to the model: $Volume_{Yr3} = B_0 + B_1(Volume_{Yr0})$. Treatment details are described in the text.

Species	Treatment	N	B_1	B_0	R^2	P-value	Initial Vol. Range (cm^3)	Mean Initial Vol. (cm^3)	Mean Yr 3 Vol. (cm^3)
American beech	Control	3	1.6772	2.9131	0.97	0.0329	3.6-17.7	9.2	18.4
American holly	Control	2	249.8950	-492.8009	1.00	-	2.0-2.2	2.1	34.0
black cherry	Control	11	8.2678	-1.2378	0.97	<0.0001	0.4-30.9	6.8	53.1
blackgum	Control	8	11.0818	16.2547	0.73	0.0068	0.9-18.7	5.2	71.3
dogwood	Control	8	32.5912	3.7198	0.75	0.0052	0.3-5.7	5.4	56.0
mulberry	Control	2	23.0573	-2.1526	1.00	-	0.2-0.8	5.0	8.9
pine spp.	Control	9	85.2905	71.1552	0.71	0.0046	0.1-7.4	2.2	254.7
red maple	Control	15	2.2034	4.5137	0.36	0.0185	0.2-4.2	1.8	7.6
red oak	Control	3	21.1808	5.2904	0.33	0.6125	0.9-6.6	4.1	59.6
river birch	Control	39	41.4170	18.1440	0.46	<0.0001	0.1-3.5	1.0	60.8
sumac	Control	7	2.0250	48.9797	0.06	0.6057	0.9-14.6	5.5	60.1
sweetgum	Control	5	2.0869	6.3221	0.99	0.0002	0.4-3.9	1.5	9.5
white ash	Control	6	8.6545	32.0239	0.61	0.0681	1.5-14.4	7.6	81.9
white oak	Control	9	11.5852	26.2650	0.70	0.0049	0.3-20.9	4.2	62.5
winged sumac	Control	13	1.6502	45.4539	0.04	0.5376	0.3-12.2	5.0	53.7
yellow-poplar	Control	214	11.9058	9.4914	0.53	<0.0001	0.1-25.3	7.9	31.5
American holly	Fertilized	3	1.9746	0.3089	0.65	0.4004	0.0-0.7	0.4	1.0
black cherry	Fertilized	26	29.1533	28.1947	0.71	<0.0001	0.2-65.6	13.5	421.3
dogwood	Fertilized	23	7.6487	58.2128	0.28	0.0100	0.9-28.6	5.2	98.3
hickory spp.	Fertilized	2	33.8377	-320.8493	1.00	-	12.2-38.3	25.3	534.5
hophornbeam	Fertilized	2	86.0100	-53.4893	1.00	-	0.7-2.0	1.3	59.5
mulberry	Fertilized	4	6.1656	3.0779	0.60	0.2251	0.5-2.3	1.1	9.6
pine spp.	Fertilized	22	35.8750	176.0124	0.29	0.0097	0.3-10.6	3.0	283.4
red maple	Fertilized	15	10.8008	11.0161	0.74	<0.0001	0.2-28.5	6.0	76.3
red oak	Fertilized	5	17.4081	44.8691	0.53	0.1649	0.9-8.9	5.0	131.8
river birch	Fertilized	3	2.2281	24.0931	0.74	0.3435	1.7-9.9	4.9	35.0
sumac	Fertilized	5	1.4559	73.5420	0.09	0.6325	1.0-34.6	12.2	91.4
sweetgum	Fertilized	3	28.3751	1.9356	1.00	0.0350	0.3-12.1	4.6	132.4
white ash	Fertilized	11	7.6418	-12.2798	0.93	<0.0001	0.2-96.6	13.0	86.5
white oak	Fertilized	11	34.5485	-30.0372	0.63	0.0035	0.8-13.8	3.8	101.7
winged elm	Fertilized	2	6.3413	26.9427	1.00	-	0.9-17.0	8.9	83.7
winged sumac	Fertilized	10	7.5418	184.7736	0.29	0.1079	1.6-3.5	19.7	333.8
yellow-poplar	Fertilized	226	18.2085	20.8104	0.51	<0.0001	0.1-30.9	3.5	83.8

Table 3 (Cont'd).

Species	Treatment	N	B_1	B_0	R^2	P-value	Initial Vol. Range (cm^3)	Mean Initial Vol. (cm^3)	Mean Yr 3 Vol. (cm^3)
American holly	Weeded	4	5.6017	6.0319	0.27	0.4796	0.2-6.2	3.0	22.6
black cherry	Weeded	10	7.8506	160.2513	0.09	0.4132	1.6-26.9	15.5	282.0
blackgum	Weeded	6	3.1825	94.1485	0.41	0.1734	0.5-111.2	34.3	203.3
dogwood	Weeded	11	15.7841	46.8743	0.61	0.0046	0.1-14.0	4.3	109.2
hickory spp.	Weeded	2	30.2015	-11.4783	1.00	-	0.4-0.6	0.5	4.4
mulberry	Weeded	3	-34.3099	82.8745	0.70	0.3665	0.9-1.8	1.3	38.3
persimmon	Weeded	5	0.9356	209.1925	0.05	0.7146	15.3-76.4	37.5	244.4
pine spp.	Weeded	19	99.1495	103.9757	0.25	0.0305	0.1-4.5	0.9	196.6
red maple	Weeded	34	7.6515	7.8398	0.67	<0.0001	0.1-20.4	4.0	37.3
red oak	Weeded	6	38.5225	-9.1925	0.76	0.0242	0.1-3.6	1.4	44.2
river birch	Weeded	36	53.3160	-2.1544	0.71	<0.0001	0.7-20.3	3.4	179.5
sumac	Weeded	7	8.6029	180.7763	0.01	0.8167	0.1-9.1	3.1	207.4
sweetgum	Weeded	6	14.3652	26.2932	0.32	0.2441	0.6-20.8	7.8	127.1
white ash	Weeded	6	16.7159	23.1123	0.15	0.4430	1.6-3.5	2.3	61.7
white oak	Weeded	3	-33.6807	44.3926	0.93	0.1753	0.6-1.2	0.9	13.0
winged sumac	Weeded	12	40.7660	-67.9052	0.65	0.0015	0.3-27.7	7.3	230.5
yellow-poplar	Weeded	321	41.1825	3.1116	0.56	<0.0001	0.1-32.5	2.0	86.7
American holly	Weed+Fert	9	16.6946	-1.2992	0.87	0.0003	0-.6.6	1.3	20.5
black cherry	Weed+Fert	20	33.3449	273.9479	0.30	0.0126	0.7-66.6	14.1	745.4
blackgum	Weed+Fert	5	4.2694	42.2097	0.12	0.5621	0.3-12.6	4.8	44.5
dogwood	Weed+Fert	31	12.3475	19.8760	0.50	<0.0001	0.3-40.4	4.6	69.3
mulberry	Weed+Fert	2	26.2779	-24.6627	1.00	-	1.1-1.6	1.4	11.0
pine spp.	Weed+Fert	2	-61.0269	529.2978	1.00	-	0.2-3.8	2.0	406.0
red maple	Weed+Fert	15	18.9028	21.9734	0.89	<0.0001	0.0-39.3	7.5	161.5
river birch	Weed+Fert	2	16.1879	33.1931	1.00	-	0.7-2.1	1.4	56.0
sumac	Weed+Fert	15	5.7837	170.3681	0.10	0.2514	0.2-61.0	8.9	222.2
sweetgum	Weed+Fert	28	45.6131	191.7129	0.32	0.0019	0.4-45.7	9.6	596.3
white ash	Weed+Fert	8	7.1515	89.1044	0.08	0.5056	1.1-14.2	6.6	136.5
white oak	Weed+Fert	13	19.1660	4.1166	0.73	0.0002	0.1-14.1	3.3	67.1
winged elm	Weed+Fert	4	1.6741	124.0741	0.02	0.8664	2.1-11.5	5.3	133.0
winged sumac	Weed+Fert	4	15.4295	7.9280	1.00	0.0001	0.5-32.3	8.6	140.7
yellow-poplar	Weed+Fert	221	21.6564	36.4984	0.28	<0.0001	0.0-25.8	3.9	121.3

Table 4. Three year survival probability models for tree stems in a newly regenerated upland Piedmont stand. Models based on initial height at year 0 by species and treatment for the model: Survival (%) at Year 3 =$[e^{(B0 + B1*Initial\ Height)}] / [1 + e^{(B0 + B1*Initial\ Height)}] * 100$. Treatment details are described in the text.

Treatment	Species	N	B_1	B_0	P-value	R^2_{MF}	Initial Ht. Range (cm)	Mean Yr 3 Surv. (%)
Control	black cherry	14	0.1342	-3.1840	0.4836	0.13	31-105	93
Control	blackgum	11	0.1181	-2.5268	0.7331	0.25	26-65	82
Control	dogwood	17	0.2148	-6.0080	0.0673	0.30	21-52	65
Control	red maple	21	0.3327	-5.4392	0.1019	0.45	17-53	86
Control	river birch	46	0.1169	-1.7625	0.0739	0.12	20-59	87
Control	sumac	12	0.3183	-10.1347	0.0790	0.55	28-61	67
Control	sweetgum	7	-0.1695	6.3061	0.2166	0.27	21-36	71
Control	white ash	10	0.0152	0.2599	0.6653	0.02	21-61	70
Control	winged sumac	19	0.0667	-1.9855	0.0806	0.16	16-74	68
Control	yellow-poplar	320	0.1236	-2.0073	<.0001	0.18	5-78	71
Fertilized	black cherry	33	0.0054	0.9294	0.1371	0.00	19-113	79
Fertilized	dogwood	53	0.0260	-1.3836	0.0778	0.05	21-80	45
Fertilized	pine spp.	28	0.0167	-0.5388	0.6083	0.01	17-62	50
Fertilized	red maple	23	0.1080	-2.6128	0.0564	0.31	20-107	65
Fertilized	river birch	13	0.1165	-7.2082	0.0743	0.38	42-75	23
Fertilized	sumac	8	0.0080	0.1121	0.7445	0.17	21-98	63
Fertilized	sweetgum	5	0.0726	-1.8918	0.3435	0.01	19-56	60
Fertilized	white ash	20	0.0751	-1.5538	0.1227	0.21	14-122	70
Fertilized	white oak	25	0.0360	-1.3363	0.1371	0.07	16-74	46
Fertilized	winged sumac	36	0.0666	-5.8809	0.0048	0.33	23-141	28
Fertilized	yellow-poplar	543	0.1227	-3.4765	<.0001	0.30	8-107	42
Weed	black cherry	12	0.1229	-4.8199	0.2281	0.35	43-86	83
Weed	blackgum	9	0.0089	0.0378	0.6666	0.02	14-142	67
Weed	dogwood	19	0.0680	-1.6010	0.0912	0.17	17-74	68
Weed	red maple	44	0.1839	-2.8713	0.0113	0.36	11-75	82
Weed	red oak	7	0.1335	-0.5349	0.4743	0.18	8-40	86
Weed	river birch	42	0.0961	-3.1073	0.0397	0.16	39-98	86
Weed	sumac	12	0.0300	-0.3310	0.3964	0.25	18-65	67
Weed	sweetgum	9	0.0901	-2.4552	0.2563	0.05	22-81	78
Weed	white ash	7	0.2555	-4.3553	0.3734	0.15	18-29	86
Weed	winged sumac	21	0.0630	-1.9076	0.0816	0.18	16-98	57
Weed	yellow-poplar	510	0.0783	-1.0924	<.0001	0.17	6-94	64
Weed+Fert	black cherry	24	0.0192	0.1815	0.3780	0.04	34-132	83
Weed+Fert	blackgum	9	0.4206	-5.1288	0.3758	0.47	12-61	89
Weed+Fert	dogwood	70	0.0413	-1.1397	0.0040	0.12	14-98	57
Weed+Fert	mulberry	5	0.4480	-18.2039	0.3582	0.49	5-44	40
Weed+Fert	pine spp.	7	-0.0461	-0.5708	0.6465	0.05	23-52	14
Weed+Fert	red maple	21	0.0359	-0.3061	0.2191	0.09	15-106	76
Weed+Fert	river birch	4	-0.0178	0.8040	0.7795	0.01	34-52	50
Weed+Fert	sumac	27	0.0071	-0.1122	0.6471	0.01	15-101	56
Weed+Fert	sweetgum	37	0.0696	-1.7878	0.0136	0.26	12-105	81
Weed+Fert	white ash	11	0.0854	-1.8301	0.2078	0.23	17-79	82
Weed+Fert	white oak	18	0.0424	-0.0187	0.4113	0.04	13-61	78
Weed+Fert	winged sumac	6	0.0012	0.6482	0.9652	0.00	16-108	67
Weed+Fert	yellow-poplar	351	0.0798	-1.4664	<.0001	0.17	3-87	65

Table 5. Three year survival based on initial basal diameter by species and treatment for the model: Survival at Year 3 = [exp(B_0 + B_1*Initial Diameter)] / [1 + exp(B_0 + B_1*Initial Diameter) x 100

Treatment	Species	N	B_1	B_0	P-value	R^2_{MF}	Initial Range (mm)
Control	black cherry	14	1.6584	-3.6459	0.2527	0.38	2.2-10.6
Control	blackgum	11	1.2218	-3.1591	0.2354	0.29	3.0-10.5
Control	dogwood	17	0.1253	-0.0413	0.4738	0.00	2.1-6.5
Control	mulberry	5	-0.4485	0.8358	0.7899	0.01	3.6-9.5
Control	red maple	21	1.2158	-2.0336	0.1202	0.24	1.9-7.1
Control	river birch	46	-0.679	4.1925	0.0948	0.08	0.9-4.8
Control	sumac	12	0.8765	-3.9902	0.094	0.33	3.0-9.9
Control	sweetgum	7	0.8531	-2.0418	0.4806	0.11	2.7-7.3
Control	white ash	10	0.4342	-1.7926	0.1503	0.22	4.1-10.7
Control	white oak	12	0.5911	-0.01059	0.5008	0.12	2.5-10.4
Control	winged sumac	19	0.6426	-2.2718	0.0695	0.19	2.6-8.5
Control	yellow-poplar	320	0.619	-1.4283	<.0001	0.11	1.5-12.1
Fertilized	black cherry	33	-0.0499	1.6764	0.7114	0.00	1.7-14.9
Fertilized	dogwood	53	0.2789	-1.4218	0.0375	0.08	3.0-13.5
Fertilized	pine spp.	28	0.4671	-1.7557	0.1073	0.08	2.5-8.1
Fertilized	red maple	23	0.888	-2.852	0.0376	0.26	1.8-10.1
Fertilized	river birch	13	1.2086	-5.838	0.1113	0.33	3.9-7.1
Fertilized	sumac	8	0.1598	-0.4724	0.576	0.03	3.8-12.2
Fertilized	sweetgum	5	0.1658	-0.3547	0.7004	0.02	2.5-9.1
Fertilized	white ash	20	0.1271	0.1177	0.4803	0.02	2.5-17.4
Fertilized	white oak	25	0.2894	-1.4477	0.2016	0.05	3.9-9.3
Fertilized	winged sumac	36	0.707	-5.3508	0.0051	0.35	4.2-13.4
Fertilized	yellow-poplar	543	0.6495	-3.1432	<.0001	0.17	2.0-11.1
Weeded	black cherry	12	0.8935	-3.6028	0.2111	0.38	3.7-12.3
Weeded	blackgum	9	0.3896	-2.1129	0.2259	0.23	3.8-17.3
Weeded	dogwood	19	0.4578	-0.9532	0.1673	0.11	1.5-8.5
Weeded	pine spp.	18	-0.9587	6.7604	0.2469	0.20	1.5-6.5
Weeded	red maple	44	0.9207	-1.6008	0.0287	0.23	1.8-10.8
Weeded	river birch	42	0.8982	-1.6577	0.1141	0.10	2.5-8.9
Weeded	sumac	12	-0.1788	1.4792	0.4983	0.03	1.5-7.8
Weeded	winged sumac	21	0.8001	-2.9095	0.0863	0.27	2.5-10.5
Weeded	yellow-poplar	510	0.6044	-1.6265	<.001	0.10	1.6-11.5
Weed+Fert	black cherry	24	0.9205	-2.9293	0.0627	0.34	2.5-14.0
Weed+Fert	dogwood	70	0.6972	-2.0399	0.0024	0.16	2.3-13.1
Weed+Fert	pine spp.	7	-1.4205	1.6573	0.5224	0.23	1.9-5.3
Weed+Fert	red maple	21	-0.0742	1.6002	0.4783	0.30	1.1-11.9
Weed+Fert	river birch	4	2.2661	-6.8011	0.3434	0.02	2.9-3.9
Weed+Fert	sumac	27	0.0476	-0.0555	0.7152	0.00	2.5-15.2
Weed+Fert	sweetgum	37	0.6201	-1.9928	0.0812	0.14	3.5-12.9
Weed+Fert	white ash	11	2.444	-10.4864	0.2211	0.55	4.3-8.3
Weed+Fert	white oak	18	1.4008	-3.9555	0.0999	0.27	2.1-9.4
Weed+Fert	winged sumac	6	0.357	-0.9654	0.5657	0.08	3.6-10.7
Weed+Fert	yellow-poplar	351	0.7476	-2.4443	<.0001	0.20	1.0-12.2

Table 6. Three year survival models based on initial volume by species and treatment for the model: Survival at Year 3 = [exp(B_0 + B_1(Initial Volume))] x 100

Treatment	Species	N	B_1	B_0	P-value	R^2_{MF}	Initial Range (cm^3)
Control	black cherry	14	0.0214	-0.8920	0.2594	0.42	0.4-30.9
Control	blackgum	11	0.0161	-0.8106	0.2949	0.28	0.9-18.7
Control	dogwood	17	0.0013	0.1907	0.4135	0.05	0.3-5.7
Control	mulberry	5	-0.2877	-0.2877	0.9412	0.01	0.2-0.9
Control	red maple	21	0.0378	-0.5850	0.1971	0.31	0.2-4.2
Control	river birch	46	-0.0029	2.2198	0.5410	0.01	0.1-3.5
Control	sumac	12	0.0104	-2.1388	0.1223	0.03	0.9-14.6
Control	sweetgum	7	0.0045	0.3580	0.6289	0.43	0.4-3.9
Control	white ash	10	0.0006	0.4823	0.6377	0.02	1.5-14.4
Control	white oak	12	0.0236	0.4751	0.6054	0.25	0.3-20.9
Control	winged sumac	19	0.0025	-0.1004	0.2001	0.10	0.3-12.2
Control	yellow-poplar	320	0.0087	-0.0596	<.0001	0.11	0.1-25.3
Fertilized	black cherry	33	-0.0002	1.6182	0.4717	0.01	0.2-65.6
Fertilized	dogwood	53	0.0001	-0.2463	0.6736	0.00	0.9-28.6
Fertilized	pine spp.	28	0.0016	-0.2676	0.5156	0.01	0.3-10.6
Fertilized	red maple	23	0.0088	-0.7424	0.1016	0.25	0.2-28.5
Fertilized	river birch	13	0.0107	-3.4871	0.1707	0.38	1.7-9.9
Fertilized	sumac	8	0.0007	-0.0166	0.4373	0.08	1.0-34.6
Fertilized	sweetgum	5	0.0025	-0.2066	0.5169	0.12	0.3-12.1
Fertilized	white ash	20	0.0010	0.3962	0.4622	0.07	0.2-96.6
Fertilized	white oak	25	0.0006	-0.2664	0.5693	0.01	0.8-13.8
Fertilized	winged sumac	36	0.0024	-3.0030	0.0085	0.38	1.6-3.5
Fertilized	yellow-poplar	543	0.0046	-1.1865	<.0001	0.13	0.1-30.9
Weed	black cherry	12	0.0044	-0.7101	0.4242	0.38	1.6-26.9
Weed	blackgum	9	0.0009	-0.4424	0.3589	0.23	0.5-111.2
Weed	dogwood	19	0.0082	-0.4326	0.1963	0.20	0.1-14.0
Weed	pine spp.	18	-0.0091	4.4236	0.1984	0.22	0.1-4.5
Weed	red maple	44	0.0240	-0.2873	0.1052	0.28	0.1-20.4
Weed	river birch	42	0.0089	-0.0789	0.0843	0.15	0.7-20.3
Weed	sumac	12	0.0000	0.7004	0.9900	0.00	0.1-9.1
Weed	sweetgum	9	0.0494	-3.6241	0.4887	0.58	0.6-20.8
Weed	winged sumac	21	0.0085	-1.1431	0.1352	0.28	0.3-27.7
Weed	yellow-poplar	510	0.0030	0.1613	<.0001	0.04	0.1-32.5
Weed+Fert	black cherry	24	0.0045	-0.6450	0.1052	0.33	0.7-66.6
Weed+Fert	dogwood	70	0.0038	-0.3571	0.0233	0.13	0.3-40.4
Weed+Fert	mulberry	5	0.1183	-13.7477	0.4407	0.52	0.5-1.6
Weed+Fert	pine spp.	7	-0.0251	-0.6002	0.6456	0.20	0.1-6.0
Weed+Fert	red maple	21	-0.0001	1.2620	0.1012	0.00	0-39.3
Weed+Fert	river birch	4	0.0069	-0.8402	0.6173	0.05	0.2-2.1
Weed+Fert	sumac	27	0.0001	0.1247	0.7011	0.00	0.2-61.0
Weed+Fert	sweetgum	37	0.0057	-0.6246	0.0640	0.28	0.4-45.7
Weed+Fert	white ash	11	0.0118	-1.4890	0.2471	0.41	1.1-14.2
Weed+Fert	white oak	18	0.0143	-0.4160	0.2105	0.19	0.1-14.1
Weed+Fert	winged sumac	6	0.0009	0.3374	0.6024	0.08	0.5-32.3
Weed+Fert	yellow-poplar	351	0.0041	-0.2162	<.0001	0.13	0-25.8

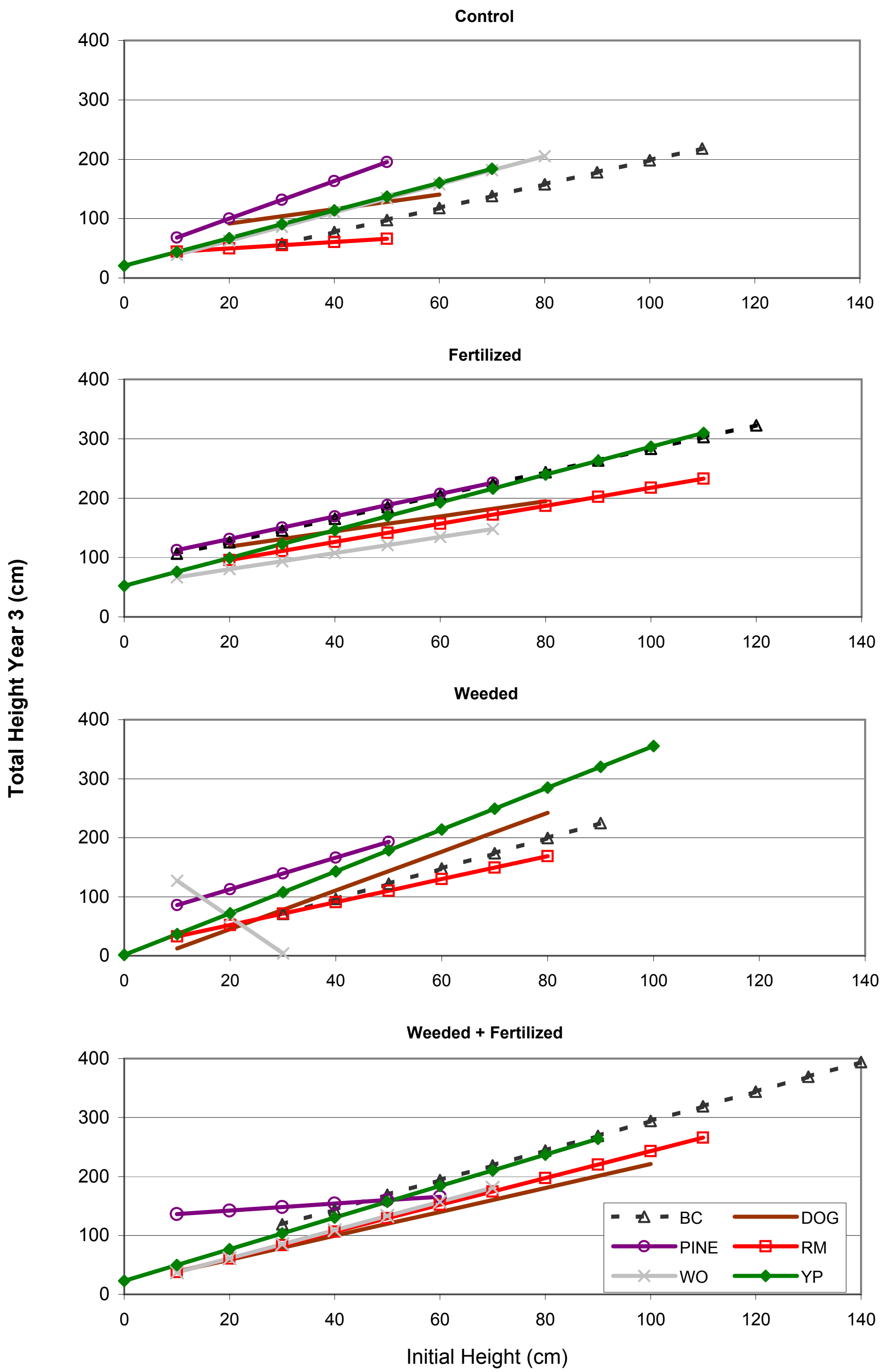

Figure 1. Linear regression lines depicting growth trends for select newly regenerated upland Piedmont tree species. Initial height is the total height in June of the first growing season. Growth equations for each species are listed in Table 1. Treatments details are described in the text. Species key: BC= black cherry, DOG= dogwood, PINE= pine spp., RM= red maple, WO= white oak, YP= yellow-poplar.

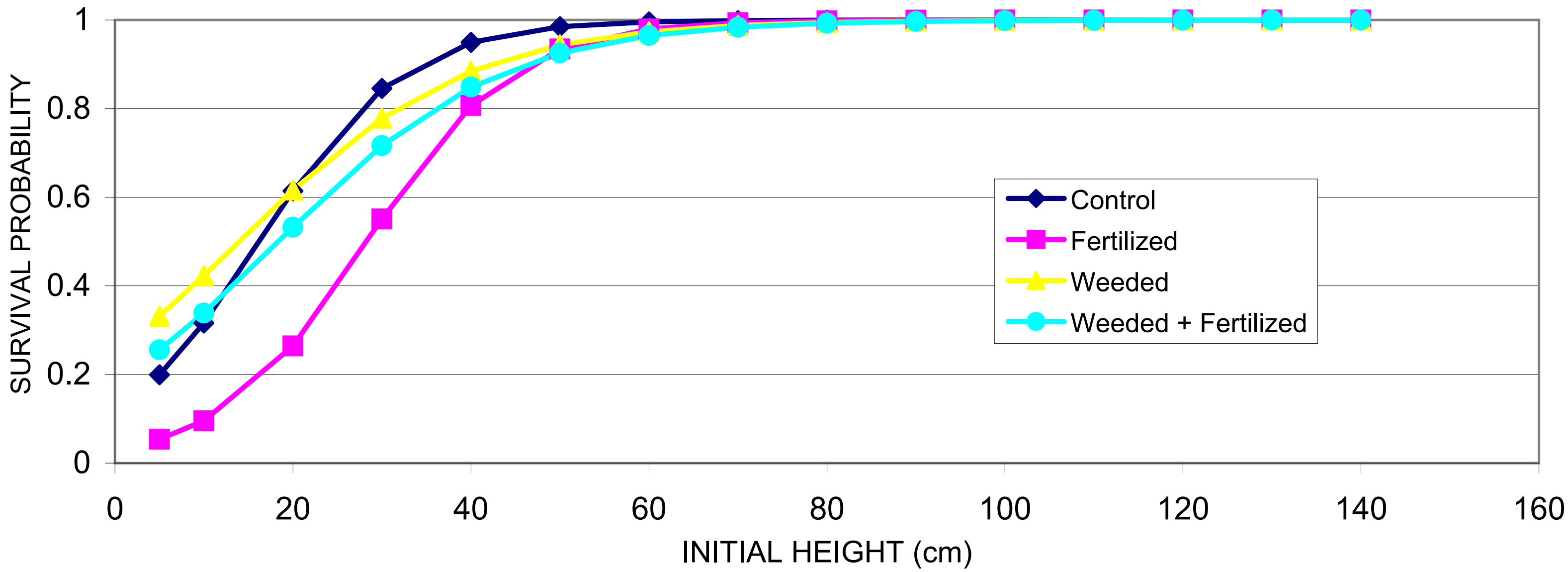

Figure 2. Three-year survival probabilities for yellow-poplar based on initial stem heights for a rising 1-yr-old upland Piedmont stand. Treatment details are described in the text.

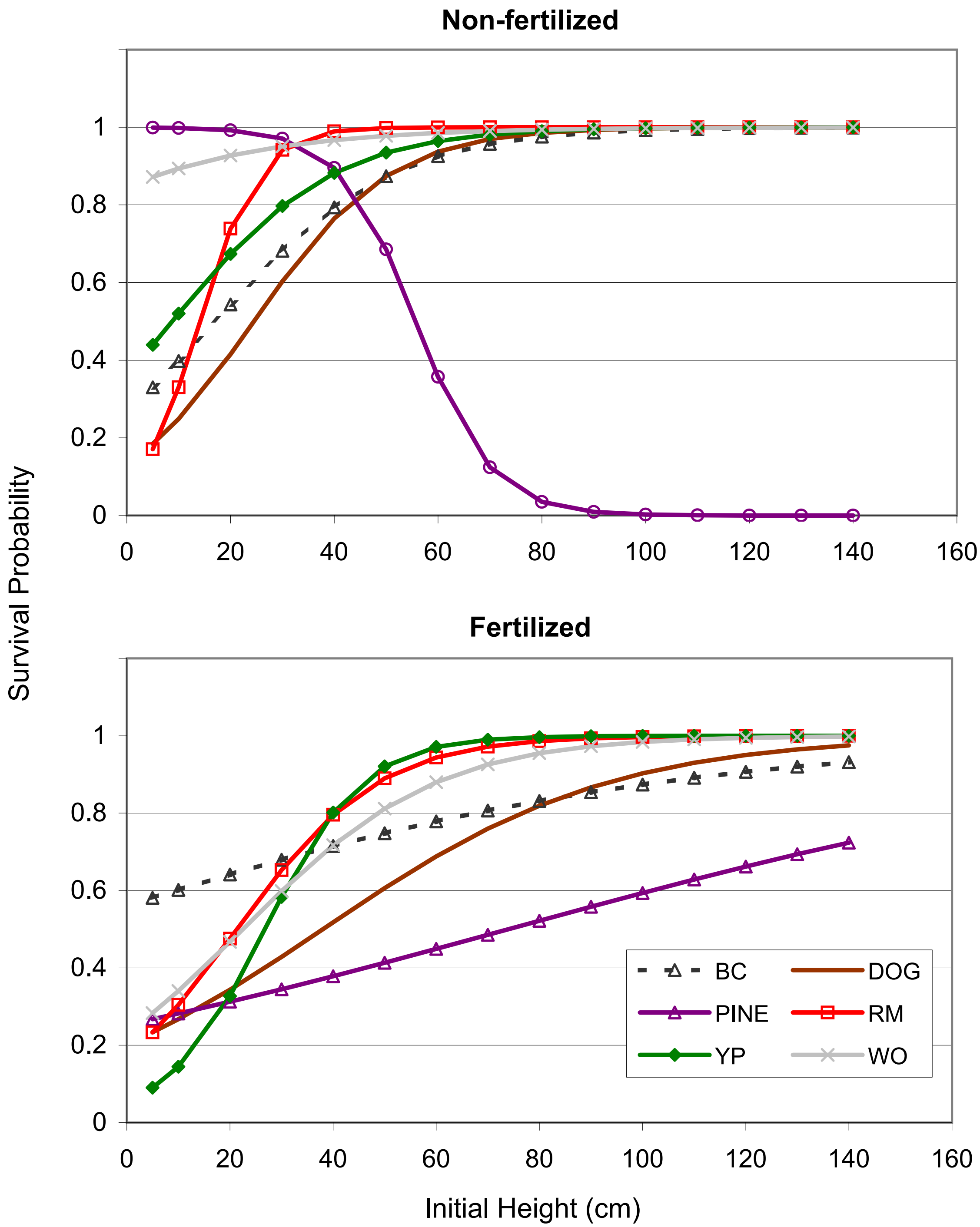

Figure 3. The effect of fertilization on three-year survival probability for select newly regenerated upland Piedmont tree species. Initial height is the total height in June of the first growing season. Survival equations for each species are listed in Table 4. Treatments details are described in the text. Species key: BC= black cherry, DOG= dogwood, PINE= pine spp., RM= red maple, WO= white oak, YP= yellow-poplar.

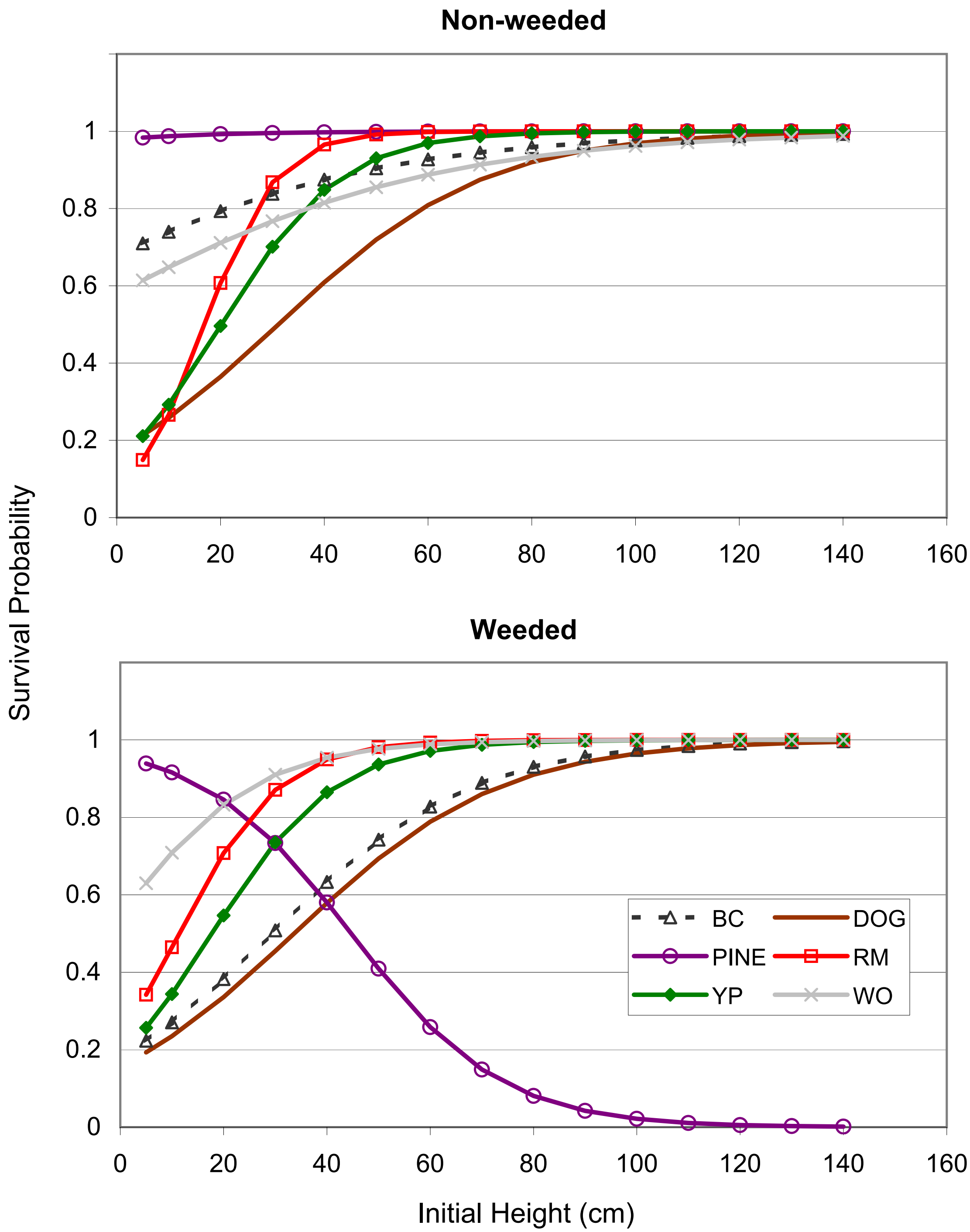

Figure 4. The effect of weeding on three-year survival probability for select newly regenerated upland Piedmont tree species. Initial height is the total height in June of the first growing season. Survival equations for each species are listed in Table 4. Treatments details are described in the text. Species key: BC= black cherry, DOG= dogwood, PINE= pine spp., RM= red maple, WO= white oak, YP= yellow-poplar. Note that the survival probability model for pine spp. is constructed from 7 individuals.

Dissertation Summary

Southern hardwood forests are very resilient to natural or anthropogenic disturbances. The response of three distinct forest types to varying levels of disturbance (harvesting) was explored in Chapter 1. The regeneration response was profuse, but often dissimilar to the overstory.

- Low- and medium density shelterwood and clearcut reproduction methods each regenerated about the same number of stems ha^{-1}.
- The residual overwood from the shelterwood treatments depressed height growth compared to the clearcut treatment after 5 years for SC and WV or 6 years for NC.
- Species richness was little affected by the three harvesting treatments, excluding the non-harvested control. However, the relative contribution of each species (or IV) did vary by treatment. Oak generally decreased in importance on the NC and WV upland sites following harvest treatments, while species like birch, pine, red maple, and yellow-poplar increased.
- Across each of the three sites and harvest treatments, sprouting was a major source of regeneration after 5-6 years. Certain species like American holly, American beech, dogwood, hickory, red oak, sourwood and white oak regenerated almost exclusively as seedling- and/or stump sprouts.

The diameter growth response of residual overstory for the shelterwood treatments was variable across all sites, and was likely affected by species composition.

- For NC, the residual stems in the medium-density shelterwood treatment increased 2.0 cm dbh in 6 years over the control. The low-density treatment resulted in no diameter response relative to the control.
- For SC, the low- and medium-density shelterwood treatments increased diameter 2 and 3 cm dbh over the control after 5 years.
- For WV, stem diameters on the medium-density shelterwood treatment decreased relative to the control, while stems in the low-density treatment increased 0.5 cm dbh after 5 years compared to the control.

Residual tree damage and/or degrade resulting, from epicormic branching and felling and extraction activities, is a potentially serious problem.

- At least one epicormic branch was recorded on the lower butt log for 20 to 80 % of the sawlogs in the low- and medium-density shelterwood treatments.
- Epicormic branching was most common on hickory, sweetgum and white oak, while few branches were noted on yellow-poplar.
- For the NC and SC sites, over half of the residual stems on the shelterwood treatments experience damage from either felling and extraction or epicormic branching. Residual stem damage occurred on less than 30% of the stems for the WV site.

In Chapter 2, I evaluated an applied research question: can relatively simple to apply treatments (weeding, fertilization, and thinning) be implemented in newly regenerated upland Piedmont stands (rising 1-yr-old Hill Forest and rising 3-yr-old Duke Forest) to accelerate stem growth and stand development.

- For all species combined, fertilization-only increased height growth by 22 and 40% after 3GS for the Hill Forest. After 3GS, the only significant weeding effect was increased basal diameter.
- Stem mortality was greatest in the smallest size classes at the Hill Forest. Fertilization resulted in a large increase in mortality in stems ≤30 cm compared to the other treatments. Individual stems were not monitored at the Duke site.

Yellow-poplar was the most prevalent species on all plots. Weeding, fertilization and thinning treatment produced the following results:

- For yellow-poplar on non-thinned plots on the Hill Forest, fertilized stems were 30% taller than non-fertilized stems after 3GS. Stem diameter was improved by both weeding and fertilization effects. Individual stem volumes for fertilization and weeding treatments were 2- to 3.5-fold greater than the control after 3GS.
- For thinned plots on the Hill Forest, weeding greatly enhanced yellow-poplar height, diameter and volume following 3GS.
- For non-thinned plots on the Duke Forest, fertilization increased yellow-poplar height, diameter and volume after 3GS (age 5). No significant weeding effects existed after 3GS.

- On thinned plots on the Duke site, fertilization and weeding treatments greatly increased stem height, diameter and volume after 3GS.

Oak regeneration has been reported to compete poorly with regenerating stems of other tree species. The effects of weeding, fertilization and thinning treatments were also examined for oak species to identify growth constraints.

- On non-thinned plots at the Hill Forest, no significant weeding or fertilization treatments effects existed for oak spp. after 3GS. Stem diameter increased in response to fertilization. For individual stem volume, the weeding x fertilization treatment interaction was negative. Fertilization-alone produced the greatest volume after 3GS.
- On non-thinned plots at the Duke site, fertilization increased height, diameter and volume for oak spp. after 3GS. No response to weeding was detected.
- On thinned plots, oak spp. increased stem height, diameter and volume in response to weeding and fertilization treatments after 3GS at the Hill site. By contrast, no treatment differences were detected after 3GS at the Duke Forest.

In Chapter 3, I examined the effects of weeding, fertilization and thinning on leaf characteristics and seasonal growth patterns of individual yellow-poplar stems within the Duke and Hill Forest sites in order to better define the mechanisms for the improved growth rates seen in Chapter 2. The parameters investigated include monthly height growth patterns, leaf duration, leaf physical characteristics and foliar nutrient levels.

- Height growth patterns were altered by complete vegetation control treatments (weeded + thinned treatments) at the Hill site. The proportion of monthly growth was more stable throughout the growing season, but increased in August relative to other treatments. This response corresponded to a 6 cm August water deficit. At the Duke site, thinning lowered the proportion of early season growth compared to non-thinned treatments. For both sites, most of the annual growth was completed by the end of June.
- Weeding prolonged leaf retention at the Hill site an additional 6 days compared to non-weeded stems, whereas thinning increased leaf retention 8 days over non-thinned stems at the Duke site.
- Vector analyses illustrate the nutrient content and foliar biomass responses to each treatment. Vectors for nitrogen and phosphorus show deficiencies ameliorated or at least lessened by almost all treatments. Potassium did not appear deficient in association with thinning + weeding treatments. In addition, each of the weeding, fertilization and thinning treatments resulted in increased foliar biomass, suggesting leaf area per stem was restricted.
- Of the physical leaf characteristics, leaf number and leaf size were best correlated with yellow-poplar growth at the Hill forest site. Leaf duration was best correlated

with yellow-poplar growth at the Duke site. Foliar nutrient concentrations were not well correlated with growth.

- Results suggest that growth resources are not being acquired and/or allocated in a way that maximizes growth of individual stems. The thinning + weeding treatments demonstrate that maximum growth rates are achievable from inherent site resources that are focused on individual stems. Without thinning and weeding, the response to fertilization treatments suggests that inherent site resources are not suitable to maximize growth.

The final chapter focused on the idea that regeneration can be managed post-harvest by imposing weeding, fertilization and thinning treatments. As I noted in previous chapters, yellow-polar is a very responsive species, and a major competitor to more economically desirable species (*e.g.*, white oak). The three-year growth response and survival probabilities for black cherry, dogwood, pine spp., red maple, white oak and yellow-poplar were compared at the Hill Forest site to assess each species response to the treatments, as well as the performance of each relative to yellow-poplar based on initial size. Even though this study was limited to 3 years, the data indicate that there may be potential to alter natural stand dynamics and growth rates by using relatively simple to apply silvicultural manipulations of site resources.

- Three-year growth rates based on initial size were highest for yellow-poplar in every treatment. However, the ranking of the other species did change by treatment. Black cherry compared favorably with yellow-poplar on fertilized plots. By contrast, white oak was competitive with yellow-poplar on control plots, but became less so on weeded and/or fertilized plots. In fact, white oak was the least responsive (growth-wise) of the six species to the weeding and fertilization treatments.

- Survival probabilities through year 3 converged toward 1.0 beginning around 60 cm for initial height for yellow-poplar. Non-fertilized and non-weeded red maple tended to reach near maximum survival probabilities at smaller sizes than yellow-poplar, while dogwood and black cherry had much lower survival throughout the range of initial sizes. Black cherry, red maple and white oak on fertilized plots, and white oak and red maple on weeded plots demonstrated greater survival than yellow-poplar for smaller initial sized stems.