ABSTRACT

NEWTON, LESLIE PHELPS. Thinning and Fertilizing Young Coastal Plain Hardwoods. (Under the direction of Daniel J. Robison.)

A thinning and fertilization study was installed on a 7-year-old naturally regenerated hardwood stand on somewhat poorly drained soils in the Atlantic Coastal Plain of North Carolina (Northampton County). Dominant species were sweetgum (*Liquidambar styraciflua* L.) and red maple (*Acer rubrum* L.). Treatments were thinning (to 3000 stems per hectare in February 1997) and fertilization (238 kg/ha N and 58 kg/ha P hand broadcast in May 1998 as urea and diamonium phosphate), applied separately and in combination. Trees were measured for diameter and height in 1997 and again during the dormant season in 2000/2001. Other measured variables included canopy, specific leaf area, foliar nutrients, competition (woody and herbaceous), soil properties and nutrients, and depth to the water table. Fertilization had a significant positive impact on diameter, height, basal area and volume growth, stem densities, foliar N, leaf area, and leaf area duration. In addition, fertilization appeared to limit the growth and development of woody shrubs and coppiced stems, and accelerate natural self-thinning. Thinning had little to no significant impact on tree growth or nutrient levels, and appeared to allow for increased levels of competing vegetation. The canopy on the thinned-only treatment was less dense than any other treatment and there were more shrubs (predominantly wax myrtle [*Myrica cerifera* L.]) and vines (predominantly poison ivy [*Toxicodendron radicans* L.]) on the thinned-only treatment. The combined thinning and fertilization treatment resulted in the highest levels of incremental growth between 1997 and 2001, but only the fertilization effect was significant. Based on the results from foliar and soil analyses, the site does not appear to be phosphorus-deficient, and the strong fertilization effect may be the result of ameliorating a nitrogen deficiency.

Both sweetgum and red maple responded well to fertilization. Given the lack of significant block effect noted for red maple throughout the study, red maple appears to be the more elastic of the two species. Trees observed in this study would most likely benefit from another application of nitrogen, as would most forest stands on similar sites. This study has shown that it is highly unlikely that stand development at this age can be accelerated through thinning alone, although growth benefits gained from thinning may become more evident as the stand ages. Fertilization alone, or in combination with thinning, not only accelerates stand development, but may also increase long-term productivity.

THINNING AND FERTILIZING YOUNG COASTAL PLAIN HARDWOODS

by

LESLIE PHELPS NEWTON

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

FORESTRY

RALEIGH

2003

APPROVED BY:

_____	_____
H. Lee Allen	Barry Goldfarb
_____	_____
Theodore H. Shear	Daniel J. Robison Chair of Advisory Committee

BIOGRAPHY

Leslie Carol Phelps was born in Asheville, North Carolina, the middle of five children. Her formative years were spent roaming the woods of Penland, the cornfields of Winterville, and the beaches of Nags Head every summer. She met and married her high school sweetheart (thus adding "Newton" to her name) while living in Winterville and spent the next eighteen years building a life with her husband, Jim, and their sons Chris and Jimmy. During that time the family migrated to Raleigh, her husband's hometown. When the younger son was in high school, Leslie decided the time was ripe for pursuing a formal education, so she quit her job with the Medical Board and began taking classes at North Carolina State University. After two years as an academic gypsy, she took a course in dendrology and learned of the discipline of Forestry. Struck with the extreme practicality of caring for the woods while growing trees for timber production, and touched by the camaraderie she observed within the Department, she applied and was accepted into the undergraduate program of Forest Management. While still an undergraduate, she began working as a technician for the NC State Hardwood Research Cooperative and, upon receiving her Bachelor of Science degree in 2000, was accepted as a Master's student in the Hardwood Research Cooperative. She completed her Master of Science in Forestry in the Spring of 2003 and was accepted as a PhD student in Forest Entomology at NC State. She will work under the direction of Fred Hain and research issues relating to Fraser fir and the balsam woolly adelgid.

ACKNOWLEDGEMENTS

It takes a village (as the saying goes) to raise a child and so, too, a Master's student. There are many people that I would like to acknowledge for their assistance with this project, beginning with my committee. I would like to thank Dan Robison, committee Chair and my major professor, for giving me the opportunity to pursue this research and for providing the financial and technical support of the Hardwood Research Cooperative during the completion of the project. I am grateful for his guidance, direction and friendship throughout this process, and will remember him always as the very embodiment of graciousness and courtesy. I thank Lee Allen, my first silvicultural 'guru,' for his enthusiasm, inspiration and encouragement, and for the excellent example that he sets. Barry Goldfarb shared with me his practical wisdom and extensive knowledge (he knows everything, as his students will insist), and was always available to listen to me ramble (coherently or otherwise) about statistics. I appreciate his belief in me and look forward to having him on my PhD committee. I thank Ted Shear for his honesty and his constructive criticism.

I thank Gerald Hansen for designing and installing the project in 1997 and for his willingness to share early measurements and his thoughts on the project, and International Paper Company for partially funding the research and for allowing us to wander around their lands for many months.

If not for the assistance of David Gadd and Jim Bridges, technicians for the Hardwood Research Cooperative, I would still be digging wells and sorting out leaves from the litterfall study. They dragged in the power auger and dug the wells for me, helped measure trees, collect (and sort, dry and weigh) litter, measure water levels, collect soil, and other tasks too numerous to detail. Their dedication and attention to detail, despite extreme tedium and the assault of seed ticks, was a thing of beauty and I appreciate their good attitudes throughout it all. Karen Hess and Britt Hart helped with leaf sorting and weighing, and I thank them for it. Brad Harris assisted with foliage collections

during the worst two days of my graduate school experience—a spider-, tick- and chigger-filled hardwood sapling stand in the humidity and oppressive heat of the Coastal Plain in August is not a good time—and I will always appreciate his making available to our little group his grandparents' cottage on Lake Gaston. Without that respite, we may never have returned to the study site. Ever. P.K. Munishi assisted with litter collections and well measurements, and regaled me with stories of his little village on the slopes of Mount Kilimanjaro, and I am a better person for having known him. Peter Birks, Jamie Schuler and Robert Jetton provided practical advice and encouragement, and I thank them for it. I am grateful to Denise Pauliac, Lab Manager for the Forest Nutrition Cooperative, for her assistance with the laboratory analyses and for her good advice, patience, and sense of humor. I thank Robin Hughes for her many kindnesses and for keeping track of receipts and funding matters. Dan Kelting provided invaluable assistance with the soil analyses and interpretation of results, and Tom Wentworth gave advice relating to the competing vegetation measurements. I appreciate it tremendously. I thank Marcia Gumpertz and Kathleen Kiernan for their assistance with the statistical analyses.

My son, Jimmy, served as a 'sometime' technician—paid and unpaid—throughout the project and I am grateful to him for it. My sisters—especially Cathie—served as sounding boards and were welcome diversions and sources of encouragement. Lastly, I acknowledge the rest of my own little tribe—my husband, Jim, our elder son, Chris—and Jimmy too, for their constancy, love, and belief in me. Thanks, Fig. Thanks, boys.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

INTRODUCTION

Hardwood forests are an important resource and provide a broad range of benefits including watershed protection, wildlife habitat, timber production, carbon sequestration, and recreation areas. Hardwoods have traditionally been harvested for lumber, veneer, plywood, pulpwood and poles. The short fibers of hardwoods are ideal for producing high quality paper, and improvements in technology have allowed for more low-value hardwoods to be used for paper production and engineered wood-products (*e.g.*, oriented strand board) (Luppold *et al.* 2002). There are over 81 million hectares of timberland throughout the South and 55 million hectares (68%) are in hardwoods (including oak/pine types). More than half of these are in small trees—15.7 million hectares are seedling/sapling size, 13.7 million hectares are pole size—and of these about 20% are young trees—11.2 million hectares are under 19 years old (Smith *et al.* 2001). Virtually all of these hardwoods are in naturally regenerated stands.

Young hardwood forests are particularly effective in producing fiber for the paper industry and fixing carbon to offset carbon emissions (Hagenstein 1996). Harvests of Southern hardwood roundwood for pulp as opposed to sawtimber have risen steadily since the 1960s (Luppold *et al.* 2002). Hardwood timber production in the South is projected to increase by 47 percent between 1995 and 2040, and hardwood inventory to peak in 2025 and then begin to decline between 2025 and 2040 (Wear and Greis 2002). The projected decline is a result of the lack of technology to increase growth in hardwood stands given predicted harvest volumes (Prestemon and Abt 2002). While most removals come from natural stands, short rotation hardwood plantations may be a viable alternative (Robison *et al.* 1998). Many hardwood forests in the South have been degraded by past logging practices, such as highgrading (Kellison *et al.* 1988) and some types are becoming lost altogether, such as nonriverine wet hardwood forests (Schafale 1999) and mesic hardwood forests on the Coastal Plain (Phillips 1994). Oak regeneration is a recognized problem throughout the Eastern

states for multiple reasons, some unknown (McGee and Loftis 1992). In the mid-Atlantic states, many of the oak-hickory forests owe their status to the loss of the American chestnut (*Castanea dentata* [Marsh.] Borkh.) (Abrams 1992) and, although the conditions that led to their dominance no longer exist, this forest type is nonetheless important for wildlife and timber (particularly northern red oak [*Quercus rubra* L.]) and is aesthetically pleasing. After harvest, these stands often regenerate to a less desirable timber species composition (Hix and Lorimer 1991, Loftis 1990, O'Hara 1986, McGee 1982). Given the above, coupled with the prediction of harvests that will eventually exceed growth and inventory, it seems prudent to manage natural hardwood stands carefully. More intensive management could be required in some stands to increase productivity so that timber demands can be met, with more extensive management called for in other stands so that desired forest types can be studied and preserved.

Studies in natural hardwoods have long demonstrated that reducing stem density (thinning) can have many positive benefits in production forestry, provided damage to the residual stand and soils are prevented. Thinning adjusts growing space for individual trees by removing neighboring competitors and allowing for an increase in the allocation of resources to residual trees (Smith *et al.* 1997). Thinning can also capture mortality (Drew and Flewelling 1979, Resovsky 1984) and result in improved species composition. Most natural hardwood thinning studies and practices have focused on pole-sized stands 20 to 30 years of age or older, and have been done in Appalachian and northern hardwood stands. During the first 20 years of a rotation, young even-aged hardwood stands undergo a period of intense competition and self-thinning, and relatively little volume is accumulated in stems that will persist until rotation age. Some thinning studies have been done in sapling-sized natural hardwoods and favorable results have been observed. Increases in diameter growth following precommercial thinnings have been observed in young (10 to 14 years) Appalachian hardwoods (*e.g.*, Downs 1946, Della-Bianca 1975, Lamson and Smith 1978, Resovsky 1984, Lamson *et al.* 1990). Coastal Plain and Piedmont sapling stands are less predictable in their

responses and precommercial thinning studies have not always yielded positive results (Kellison *et al.* 1981), yet some studies have shown that repeated cleanings in young bottomland hardwood stands increase productivity and value (Kellison *et al.* 1988). Recent studies conducted in Piedmont clearcuts suggest that even very young stands (2 to 4 years) respond favorably to manipulations including competition control and fertilization (Romagosa and Robison 2002, Schuler and Robison 2001).

Fertilization ameliorates nutrient limitations (Smith *et al.* 1997) and can hasten stand development, in particular by increasing canopy area and/or duration. The production of wood produced by a plant is linearly related to the amount of light energy intercepted by the forest canopy (Cannell 1989). The amount of light intercepted is a function of, in part, canopy reflectance, canopy development over a rotation and persistence of the foliage during each season, and overall canopy size and structure (Landsberg and Gower 1997). Research has shown that an increase in leaf area will result in an increase in productivity (Vose 1994, Albaugh *et al.* 1997, Landsberg and Gower 1997, Allen 2000), and the rate of growth in leaf area is linearly related to the nitrogen (N) supply to the roots (Ingestad 1982, Ågren 1985, Cannell 1989) and positively correlated with foliar N (Mewborne 1997). Ameliorating nitrogen deficiencies, which are common in many forests, not only increases leaf area, but may also increase the production of palisade tissue leading to higher rates of photosynthesis per unit of leaf area (Kozlowski and Pallardy 1997). Phosphorus (P) is often immobilized in soil microbes or adsorbed by aluminum and iron (Havlin *et al.* 1999). It has long been known that soils in the poorly drained Coastal Plains of the Southeast are often P-deficient and P fertilization can increase growth dramatically (Gent *et al.* 1986) and recent studies have revealed that many well-drained sites can benefit from P fertilization (Allen and Colbert 1998). In fact, the benefits obtained by adding phosphorus to a severely P-deficient site can last through the rotation and increase the expected site index (for pines, base age 25) by as much as four meters (Gent *et al.* 1996).

Studies in forest fertilization have been taking place in the United States since the late 1800s, but many were one-time applications of several elements with no replications (Binkley *et al.* 1995). Auchmoody and Filip (1973) reported on the status of hardwood forest fertilization studies in the eastern United States from 1936 to the early 1970s, and reported favorable results obtained from applications of N, P and potassium (K) on seedling, sapling, and pole-sized natural stands, primarily in the Northeastern states. Lea *et al.* (1979) observed increases in growth in mature Allegheny hardwood stands from N fertilization. Increased growth responses have been found in studies conducted in the South as well (Broadfoot 1966, Farmer 1970, Dunn *et al.* 1999). It should be noted, however, that the increased resources from mineral fertilization are not only available for the growing crop trees, but also can be utilized by herbaceous and woody vegetation, including sprouts arising from the tree stumps cut during the thinning process (Kellison *et al.* 1981, Goelz and Meadows 1999), all of which can be competition for the crop trees.

The current thinning and fertilization study of young naturally regenerated Coastal Plain hardwoods was developed by Dr. Gerald Hansen of International Paper Company in 1997 and installed by International Paper Company and the NC State University Hardwood Research Cooperative. The initial objective of this study was to determine the effects of precommercial thinning and fertilization, separately and in combination, on the stand-level growth of sapling-sized trees (≥ 3.8 cm dbh) and other vegetation in a 7-year-old naturally regenerated mixed hardwood stand in the Atlantic Coastal Plain of North Carolina. Additional objectives were to:

- conduct a litterfall collection to determine treatment differences after four growing seasons and to examine litterfall patterns;
- conduct a nutrient analysis of foliage from the dominant tree species and from a representative woody competitor; and
- conduct soil analyses to determine if treatment differences existed.

LITERATURE REVIEW

Stem density management in developing stands is discussed and a review of thinning and fertilization studies in young, developing natural hardwood stands given. Silvics of the dominant woody species on the study site are discussed. These species include sweetgum (*Liquidambar styraciflua* L.), red maple (*Acer rubrum* L.), oaks from the red oak group (southern red oak [*Quercus falcata* Michx.], water oak [*Q. nigra* L.], willow oak [*Q. phellos* L.]), and the shrub wax myrtle (*Myrica cerifera* L.) as the largest species of competing vegetation.

Early Stand Development and Density Management

Stand initiation begins after a major disturbance and new plants arise from seeds, sprouts, or advance regeneration to fill the growing space made available by the removal of the original stand. The new plants compete for resources (space, light, water, nutrients) and those with the most competitive advantages (*e.g.*, existing seed bank, well developed root system and the ability to regenerate through stump or root sprouts, rapid growth, allelopathic capabilities) can quickly occupy the available growing space and can dominate the site for decades or even centuries. Prior to crown closure, the site can contain many different species (including trees, shrubs, herbs and various other vegetative types) and until the growing space is fully occupied, each plant's growth is relatively unhampered by other competing individuals (Oliver and Larson 1996).

Once the growing space is fully occupied, competition, both inter- and intraspecific, intensifies. The beginning of the stem exclusion stage, called the "brushy stage" (Gingrich 1971), is the time when the trees (and, presumably, large shrubs) are within the same canopy layer and foliage has closed in to prevent any further species invasion. Eventually this foliage layer rises, a canopy is formed, and the shade intolerant leaves and plants underneath are not able to receive adequate sunlight and either die or are suppressed. Below ground competition can also exclude many plants.

As trees expand their crowns horizontally, they compete with neighboring trees for sunlight and either dominate (the neighbor is suppressed and eventually killed) or are dominated (suppressed and killed) by the neighboring tree(s) (Oliver and Larson 1996). In a single-species stand of intolerants, this death by suppression is called "natural" or "self-thinning" (Peet and Christensen 1987). Perala *et al.* (1999) identify three categories of self-thinning: time-density, size-density, and density-size. The time-density relation (or "Sukatchev effect" [Gause 1934, Harper 1977]) says that self-thinning will begin to occur earlier on a good site than on a poor site. In a mixed-species stand, the same pattern can occur between multiple species with similar growth habits and requirements. However, in a mixed-species stand, there are generally shade tolerant species (*e.g.*, red maple) that can inhabit a lower stratum within the vertical architecture of the stand and survive for decades (Oliver and Larson 1996).

In size-density relations, as trees grow they require more growing space and, thus, competition with adjacent plants increases. Density-size relations can be used to predict the maximum number of individuals that can occupy a site based on the size of individuals (also known as the "-3/2 power law of self-thinning"), and management diagrams based on the -3/2 power law have been developed to aid forest managers in assessing stand development (Drew and Flewelling 1979, Oliver and Larson 1996). Forest managers can anticipate when the stand is approaching this "zone of imminent competition-mortality" (Jack and Long 1996) based on a species-specific maximum density diagram, and thin the stands prior to reaching maximum density, thus utilizing suppressed trees (capturing mortality) and encouraging the growth of residual trees. Most management diagrams are for older stands and studies are currently being conducted to develop density management tools for very young stands (Schuler and Robison 2003).

Young naturally regenerated Southern hardwood stands under the age of 19 have been described as a jungle of desired and undesired species, vines, briars and annuals (Kellison *et al.* 1988). Stem densities in unmanaged stands on the Coastal Plain have been observed at 35000 stems

per hectare (SPH) at age 2 (Kellison 1971) and 22500 at age 7 (this study). In the Piedmont, densities have been observed at 32500 and 33750 SPH at ages 1 and 2, respectively (Romagosa and Robison 1999), 163000 at ages 3 and 4 (Schuler and Robison 2001), 20700 SPH to 23000 SPH at age 4 (Steinbeck and Kuers 1996); 19400 SPH to 20700 SPH at age 6 (Waldrop 1997); 19300 SPH to 25200 SPH at age 7 (Steinbeck and Kuers 1996); and 6425 SPH (Zahner and Meyers 1982) to 20000 SPH at age 10 (Steinbeck and Kuers 1996).

From a timber-producing perspective, stand density is important because mean tree diameter and volume increase as stem density decreases (Jack and Long 1996). Stand basal areas in young Piedmont hardwood stands have been observed at 3.45 m^2/ha (19300 SPH) to 3.7 m^2/ha (25200 SPH) at age 7, and 6.02 m^2/ha (16400 SPH) to 6.24 m2/ha (20000 SPH) at age 10 (Steinbeck and Kuers 1996). A stand basal area of 10.33 m^2/ha (6425 SPH) was observed in a Piedmont mixed oak stand of sprout origin at age 10 (Zahner and Meyers 1982).

Precommercial Thinning, Release, and Cleaning

Results from density manipulation studies vary by site, species composition, stand age and stand development. Increases in diameter growth have been observed in response to precommercial thinning in many sapling size Appalachian hardwood stands between the ages of 10 and 14 (Downs 1946, Trimble 1974, Della-Bianca 1975, Lamson and Smith 1978 and 1989, Lamson 1983 and 1988, Smith and Lamson 1983, Resovsky 1984, Lamson *et al.* 1990), although some studies have shown no diameter response (Trimble 1973, Beck 1977, Resovsky 1984). Thinning has been shown to capture mortality (Della-Bianca 1975). In the above studies, height growth has been either impaired or unaffected by thinning, and Trimble (1974) found that 7-year-old red maple and northern red oak responded differently to thinning during the first five years post treatment. The treated red maple exhibited greater height growth than the control during the first two years post treatment and the northern red oak exhibited greater height growth during the 3rd to 5th year post treatment. Total

growth over the five years did not differ among treatments. Unfavorable responses in the above studies include decreases in clear bole length in northern red oak and yellow poplar (*Liriodendron tulipifera* L.) as compared to the control (Lamson and Smith 1978 and 1989), retardation of stem pruning (Trimble 1973 and 1974), and an increase in grapevine (*Vitis* spp.) damage (Trimble 1973, Lamson and Smith 1978). Central hardwood sapling stands have responded to thinning treatments similarly, with diameter increases (Church 1955, Allen and Marquis 1970, Sonderman 1985), indifferent responses in height (Allen and Marquis 1970), and increases in stem defects (Sonderman 1985, Hilt and Dale 1980). Many researchers have observed that regular thinnings beginning at an early age can result in increased merchantable volume growth over the life of the stand (*e.g.*, Gingrich 1971, Kellison 1988, Smith *et al.* 1997, Walker and Oswald 2000).

Coastal Plain and Piedmont bottomland sapling stands are less predictable in their responses and, while some northern hardwood stands can be sapling size at ages 4 to 7, it can take longer for low quality Coastal Plain stands to reach that point in development. Kellison *et al.* (1981) conducted growth and yield studies of very young (less than 6 years), sapling-size (10 years) and precommercial (20 to 25 years) natural hardwood stands in the South and found that thinning very young stands, either by severing, strip-disking or fertilization, met with unfavorable results. Severing unwanted stems resulted in coppiced sprouts that competed with and even dominated crop trees within one to two years; strip-disking reduced stocking too much and also encouraged the growth of Japanese honeysuckle (*Lonicera japonica* Thunb.), and fertilization simply failed to produce positive results. Thinning sapling-sized stands produced "indifferent" results and was not economically justified. Thinning at 20 to 25 years of age produced positive results and was recommended with caution for high value crops, particularly in regard to logging damage. In later studies, Kellison *et al.* (1988) found that repeated cleanings (removal of undesirable [as defined by the land owner] species) beginning at age 3 and continuing to age 22 increased the productivity and value of bottomland hardwoods.

Resovsky (1984) conducted an intensive study of precommercial thinning in young naturally regenerated Southern hardwood stands across several stand types in North Carolina, South Carolina, Alabama, Florida, and Georgia, including oaks, sycamore (*Platanus occidentalis* L.), green ash (*Fraxinus pennsylvanica* Marsh.), sweetgum, black gum (*Nyssa sylvatica* Marsh.), yellow poplar, red maple, and miscellaneous other hardwoods. In the Resovsky study, five-year old sweetgum on a Coastal Plain wet flat did not grow in height (the only variable measured) as well as the control after a precommercial thin. Mixed species stands and stands (individually) dominated by green ash, black gum and sycamore in the Coastal Plains and Piedmont bottomlands, ranging in age from 10- to 17-years-old had positive diameter, basal area and volume growth only when density was reduced to less than 1000 SPH.

Precommercial thinning and cleaning of 4-year-old water tupelo stands in the Mobile-Tensaw River Delta, after three growing seasons, produced a favorable response only in productive stands with high density (Goelz and Meadows 1999). Recent studies conducted in Piedmont clearcuts suggest that individual trees in very young stands (2 to 4 years) respond favorably to manipulations including density control (Schuler and Robison 2001).

Forest Fertilization

Studies in forest fertilization have been taking place since the late 1800's, but many of the early studies were one-time applications of several elements with no replications (Binkley *et al.* 1995). Auchmoody and Filip (1973) reported on the status of hardwood forest fertilization studies in the eastern United States from 1936 to the early 1970's and presented the following. Favorable results have been obtained from applications of N, P and/or K on seedling, sapling and pole sized natural stands, primarily in the Northeastern states (species include pin oak (*Q. palustris* Muenchh.), white ash (*Fraxinus americana* L.), honey locust (*Gleditsia triacanthos* L.), black locust (*Robinia pseudoacacia* L.), red oak, hybrid poplar (*Populus* cv. Charkoweinsis x *P.* cv. Caudina, *P.* cv.

Generosa), and yellow poplar). Hardwoods are recognized as being more nutrient-demanding than conifers and are likely to respond vigorously to fertilization. Response is dependent upon the supply of available nutrients in the soil and whether nutrient limitations exist. Nitrogen is often the most limiting nutrient in hardwood forests and P becomes limiting once the N limitation has been ameliorated. Response to N is greatest in the second year following fertilization. Nitrogen increases leaf area (including leaf size, mass and number), delays leaf fall in the winter, and may increase photosynthetic efficiency. The amount and length of response varies. Nitrogen is often lost through leaching (as NO_3^-) or volatilization (as NH_3) and P is immobilized in the soil.

Broadfoot (1966) found significant increases in the diameter and height growth of a 20-year-old (sapling-size) Louisiana sweetgum-oak stand with five annual applications of N-P-K fertilizer. Foliar N content was greater in the fertilized trees as well. Farmer *et al.* (1970) conducted a fertilization study (300 kg/ha N or 300 kg/ha N and 66 kg/ha P) of pole- and small sawlog-sized pine (*Pinus* spp.) and mixed hardwoods on 37 sites across the Tennessee Valley. After five growing seasons, they found that hardwoods responded better to fertilization than pines (48 to 55% increase in stand basal area for hardwoods versus 29 to 45% increase for pines). The effects of fertilization, for the most part, were greatest during the second and third year following application for both pines and hardwoods. Yellow poplar responded well to fertilization, as did white oak (*Quercus alba* L.) and hickory (*Carya* spp.) (although not as well as yellow poplar), and red oak did not respond well to fertilization. Foliar N and P content increased with fertilization in yellow poplar and loblolly pine (*Pinus taeda* L.), and foliar N increased with fertilization in white oak.

Auchmoody (1982) conducted fertilization experiments with young Allegheny hardwoods in Pennsylvania and found that N and N+P resulted in significant height, diameter and basal area growth in seedling and sapling sized black cherry (*Prunus serotina* Ehrh.), with the increased growth responses lasting four to five years. Additionally, he found that fertilization increased leaf weight and foliar N, P and K over the control in black cherry seedlings and saplings.

Dunn *et al.* (1999) observed a 70% gain in diameter growth of pole-sized sweetgum and oak species in a Louisiana bottomland with 168 kg/ha N and 56 kg/ha P after two growing seasons. Cramer *et al.* (2000) found that fertilization of two young (pole-sized) Northern hardwood stands in New Hampshire significantly increased foliar N concentrations in pin cherry (*Prunus pennsylvanica* L.), paper and yellow birch (*Betula papyrifera* Marsh. and *B. alleghaniensis* Britton), sugar and striped maple (*Acer saccharum* Marsh. and *A. pensylvanicum* L.), and American beech (*Fagus grandifolia* Ehrh.), but not in red maple.

Fertilization and Thinning Combined

Stone (1977) conducted thinning and N, P, and K fertilization studies in six pole-sized Northern hardwood stands in Michigan and Wisconsin. Fertilization did not produce any significant gains in diameter growth after three years. Thinning was effective in every case, with diameter growth gains ranging from 39 to 80%. However, Graney and Pope (1978) found that thinning and fertilization (200 kg/ha N and 45 kg/ha P or 400 kg/ha N and 45 kg/ha P) of pole-sized red and white oaks resulted in positive diameter growth (gains ranging from 48 to 97%) after two years, more as a response to fertilization than thinning.

In two fertilizer studies involving release and fertilization (various combinations of N, P, K, Ca, and lime) of pole-size yellow birch and sugar maple trees on four forest sites in Vermont, Hannah (1985) found that the fertilization treatments coupled with thinning did not result in any significant growth differences over the control, after five to fourteen years. The author advises that, rather than fertilization, "the money can be better spent" in a precommercial thinning that releases good-quality crop trees with large crowns.

Johnson *et al.* (1997) released and fertilized (200 kg/ha N, 260 kg/ha P, 217 kg/ha K) (release and fertilization applied separately and in combination) two 10-year-old yellow poplar stands (ridge and slope) in southwest Virginia. After three growing seasons, only a small diameter

response to release was observed and the treatments (with the exception of additional P and K) were repeated. After seven years, diameter growth on the released treatments had increased significantly, but there were no differences between the control and the fertilized treatments. Height growth was less than the control for the first five years after release, but after five years the released treatments outgrew the control (although the difference was not significant). The authors suggest that the trees initially responded to release by expanding their crowns laterally, rather than putting on height growth. Height growth was significantly greater in the combined release + fertilization treatment.

Schuler and Robison (2001) conducted a thinning, fertilization (N+P) and weed competition control study in two very young (ages 1 to 4) hardwood stands in the North Carolina Piedmont. One and a half years post treatment, both the fertilization-only and the full treatment (thin + fert + weed) significantly increased height growth of yellow poplar in both stands.

Silvics of Key Species

Sweetgum is a moderate to rapidly growing hardwood that grows throughout the South from bottomlands to uplands. Sweetgum is an important source for hardwood fiber, is used in the manufacture of utility and decorative plywood panels, and its seed is eaten by birds and small animals (Harlow *et al.* 1996). It grows on a range of soils, but best on moist alluvial clays and the loamy soils of river bottoms (Kormanik 1990). Sweetgum is moderately shade-intolerant and can be found in almost pure stands in the Coastal Plains, coming in as a pioneer on old-field sites or after commercial clearcuts. It is short- to medium-lived (< 150 years). Common associates include red maple, box elder (*Acer negundo*), river birch (*Betula nigra*), hickory (*Carya* spp.), sugarberry (*Celtis laevigata*), and pine (*Pinus* spp.). Understory associates often include dogwood (*Cornus florida*), alder (*Alnus* spp.) and eastern redbud (*Cercis canadensis*). Sweetgum is a prolific stump- and root-sprouter. Forty or more sprouts have been observed to reach sapling size from one root; the height of the sprouts is directly correlated with the lateral diameter of root from which the sprout originated

(Kormanik 1990). This species is a particularly good competitor with other tree species, provided it gets enough light and its crown regeneration potential has not been reduced.

Red maple, like sweetgum, is a ubiquitous species that can thrive on a wide range of elevation, soil types, pH, and moisture regimes, and is distributed across many landscapes throughout the southern and eastern United States. Red maple is a good fiber source, and it is important as browse for elk and deer. Trees are short- to medium-lived (< 150 years) and reach sexual maturity as early as age 4. Seeds are produced every year and have few germination requirements. Red maple is a prolific stumpsprouter and the sprouts grow faster than seedlings in height and leaf area (Walters and Yawney 1990). In the past, red maple has been a subclimax species that occupies space in the understory, but its dominance in the overstory is increasing and it is predicted to replace many of the historically dominant trees throughout forests in the eastern United States during the 21st Century (Abrams 1998, Tift and Fajvan 1999). Its status as the quintessential 'super-generalist' is due partly to its low resource requirements and its ability to function as both an early and late successional species, but its increasing dominance is not easily explained. Red maple is shade tolerant but it grows well in full sun. Its light saturation and light compensation points are lower than most early successional trees, and its leaf structural characteristics are modest (*e.g.*, small guard cells, low values for leaf area and thickness, low stomatal density), which contribute to lower rates of photosynthesis in both sun and shade. Clues to its survival and increasing dominance are intertwined in its ability to survive in the understory and utilize sunflecks well, its rapid response to release, its low mortality rates—particularly under droughty conditions—and the loss of oak and pine dominance taking place in eastern United States forests (Abrams 1998).

Oak is often considered the most important genus on the North American continent for native hardwood timber (Harlow *et al.* 1996). The most valuable sawtimber species are northern red oak and cherrybark oak, neither of which are common on the current study site. The most dominant

oaks on the current study site are willow oak, water oak, and southern red oak. Willow oak is a medium to large oak found primarily on silty or loamy bottomlands. Timber is used for lumber and fiber, and acorns are important for wildlife. Seed production begins at around 20 years of age and acorns are produced every year. Willow oak sprouts prolifically from stumps of small trees and is shade intolerant (Schlaegel 1990). Water oak is a medium-sized tree found in bottoms and lowlands on silty clays and loamy soils, but can also be found on uplands. Wood is valuable for fiber and fuel, and the acorns important for wildlife. Seed production begins at around 20 years. Water oak is capable of stumpsprouting. It is shade intolerant and does not compete well under crowed conditions. Southern red oak is a common upland species of medium size. Wood is used for lumber, fiber and fuel. Seed production begins around 25 years of age and the seeds germinate the first year. Southern red oak sprouts vigorously from stumps, particularly young stems. This species is intermediate in shade tolerance (Krinard 1990).

Wax myrtle is an evergreen shrub or small tree common on low-elevation sites throughout the South, particularly in the Coastal Plain and peninsular Florida. It can reach 12 m in height and 32 cm in diameter (Van Deelen 1991). It is an early successional species and can form dense thickets known as "hell nests" (Loveless 1959). Wax myrtle is a nodule-forming nonleguminous species and fixes atmospheric nitrogen through its association with actinomycetes of the genus *Frankia* at a rate of ~ 10 kg/ha/year (Permar and Fisher 1983). The presence of wax myrtle may improve site quality over time by enhancing soil nitrogen levels, but it can be competitive with tree species (Tolliver *et al.* 1995).

METHODS

Site Description

The study is located on International Paper Company land (formerly a Union Camp Corporation site) in northeastern North Carolina, approximately ten miles east of Weldon in

Northampton County. It is within the Middle Coastal Plain soil region (NCSU 1999) and lies along a gently sloping gradient, between agricultural fields at a higher elevation and a bottomland hardwood forest. Soils are mapped as somewhat poorly drained Lenoir silt loams (USDA Soil Conservation Service 1994). These soils exhibit a slow infiltration rate, low to moderate shrink-swell potential, a tendency toward ponding and wetness from December to April, and are generally low in fertility. This region receives average annual precipitation of 117 cm, has a mean annual temperature of 16°C (SERCC 2003), and has a growing season of 198 frost-free days (NCSU 1996). The forest stand consists of naturally regenerated hardwoods with scattered pines, which grew following a commercial clearcut in 1990. The current dominant species are sweetgum, red maple and oaks from the red oak group (Southern red oak, water oak, willow oak). Stem density at the beginning of the study (1997), including all trees ≥ 0.1 cm diameter at breast height (dbh), was approximately 21,000 SPH. Multiple sprouts originating from one stump were counted individually.

Experimental Design

The study was a randomized, complete block with a 2 x 2 factorial arrangement of treatments (thinning and fertilization as main effects) with three blocks. The blocks exhibited notable site differences, particularly Block 1 (slightly higher elevation by a few centimeters) from Blocks 2 and 3. Treatments are control (*Control*), fertilization only (*Fert*), thinning only (*Thin*), and thinning plus fertilization (*Thin* + *Fert*). Each of the 12 treatment plots (4 treatments and 3 blocks) measures 50.6 m x 50.6 m. Within each plot are 13 uniformly spaced circular 14.3 m^2 subplots used to assess tree and ground cover vegetation, placed in a serpentine pattern throughout the plot, at least 10 m from the edge of each treatment plot. Other parameters measured were not confined to these subplots, but all were at least 10 m from plot edges.

There is evidence of some shallow (less than 25 cm) agricultural ditching in Blocks 2 and 3 as remnants of prior land use (more than 60 years ago). These ditches no longer appear effective, although some very local surface drainage may occur because of them.

Treatments

Thinning was done in February 1997 with a brushcutter, using spacing and desirable species as a guide. Stem density (including all trees > 0.1 cm dbh) was reduced by approximately 64% (from ~ 21,000 SPH to ~ 7650 SPH). Workers were instructed to leave about 1 to 2 m between uncut (residual) trees, secondarily to favor the largest stems of oaks, and to leave intact stump sprout clumps of desired species. Fertilizer was hand broadcast in May and June 1998 as 238 kilograms per hectare (kg/ha) N (in urea and diammonium phosphate [DAP]) and 58 kg/ha P (in DAP).

Stem Density and Tree Size

Trees were measured in May 1997—soon after thinning treatments had been imposed, but before fertilization—and again in January 2001, representing four growing seasons of treatment response for the thinning treatment and three growing seasons for the fertilization treatments. Within each subplot, trees were identified by species and each tree ≥ 3.8 cm dbh (sapling) was measured for dbh and height (ht). Trees < 3.8 cm dbh were dot tallied in three diameter classes (0.1-1.2 cm, 1.3-2.5 cm, 2.6-3.8 cm). Trees and sprouts < 1.4 m tall were dot tallied. Dbh was measured with a diameter tape to the nearest 0.2 cm in 1997 and nearest 0.1 cm in 2001. Heights were measured with a telescopic height pole (± .2 m). A volume index (volume $trees_I$ or VT_I) was calculated for saplings with the formula [$VT_I = (\pi \times radius^2 \times height)/3$], based on the volume of a cone. Basal area (BA) for saplings was obtained by calculating BA for each tree, summing subplot data, and applying an expansion factor for total BA per hectare for each treatment plot. Basal area was estimated for the very small trees (< 3.8 cm dbh) by calculating BA for the midpoint dbh for each of the small stem

classes and multiplying the midpoint tree BA by the number of stems in each class. Subplot data were summed and expanded to estimate total BA per hectare of trees < 3.8 cm dbh in each treatment plot.

Leaf Area

Two methods were utilized to estimate the tree canopy. Percent canopy cover was measured in September 2000 with a spherical densiometer. Measurements were taken at approximately 4.3 m intervals diagonally across each treatment plot (ten per treatment plot) and the results averaged per plot. Litterfall collections were made from October 2000 through September 2001. Six (54 x 36 x 26 cm) baskets were placed diagonally across each treatment plot, approximately 7.3 m apart, but not directly under any trees greater than 11.4 cm dbh. The contents of each basket were collected regularly during the period (weekly during October and November 2000, and once each in December 2000, January 2001, February 2001, July 2001, and September 2001). Collected leaves were separated by species and other litterfall items grouped, dried to a constant weight at 67° C, and weighed (± 0.1 g). Data from each of the six baskets per treatment plot were summed and pooled (total area of 1.16 m^2) to represent one measurement per species per treatment plot per sample date.

Litter collections were tallied by month, and plotted by month and treatment to examine litterfall patterns.

Foliar Nutrients and Specific Leaf Area

In August 2000, leaves from sweetgum, red maple, willow oak and wax myrtle were sampled for foliar nutrients. Six healthy dominant or codominant trees or shrubs were chosen in each treatment plot to represent each species. From each individual, a mid-crown, south-facing branch was cut and fully expanded leaves (20 each from sweetgum and red maple, 30 from willow oak, and 40 from wax myrtle) collected from the tips of the branches to approximately the 5^{th} node.

Foliage was placed in plastic bags on ice in the field, and then transported to the laboratory where one half of the samples were transferred to paper bags and immediately dried to a constant weight at 67°C for tissue analysis. The other half were kept cool and measured for leaf area (± .1 cm^2) (ΔT Area Meter™) within 48 hours, after which time the samples were transferred to paper bags and dried to a constant weight at 67°C. After recording leaf area and weight, foliage from willow oak and wax myrtle were added back to those being dried for tissue analysis, so that foliar analyses were based on 10 leaves each for sweetgum and red maple, 30 for willow oak and 40 from wax myrtle from each treatment plot. Leaf samples were ground—sweetgum and red maple by abrasion in a cyclone mill; willow oak and wax myrtle by hand in a mortar and pestle (covered in saran wrap)—and a composite sample made (total of 3.0 g from 0.5 g from each of the six trees) for each species for each treatment plot.

The ground foliage (0.8 g per sample) was processed by wet digestion (HNO_3 and 30% H_2O_2) (Westerman 1990), and phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), sulfur (S), boron (B), manganese (Mn), copper (Cu), and zinc (Zn) determined by inductively coupled plasma optical emission spectroscopy (ICP-OES). Total nitrogen (N) was determined by gas chromatography.

Competing Vegetation

Competing vegetation was identified to type (shrub, stump sprout, vine, grass, forb, lichen/moss) and, in many cases, species. In mid-July 2000, area coverage and mean height measurements were obtained for each species/type of competition within each of the 13 subplots per treatment plot. Area coverage was estimated by the shadow projection method (*i.e.*, the area of ground completely covered by plant foliage if the sun were directly above it). Mean height of competition per species/type was estimated (± 10 cm). A competition volume index was estimated

for each competition type per subplot by calculating cubic meter volume (area x height) and dividing by 1000.

Soil Analysis

In January 2001, 13 soil samples were taken with a soil probe (2.54 cm diameter), from the top 20 cm of mineral soil of each treatment subplot and a composite sample per treatment plot (n = 12) made in the field. In the laboratory the samples were air dried, passed through a 2 mm sieve, and analyzed for moisture content, texture (by hydrometer method [Klute 1986]), pH (electrometric measurements in water [1:2 ratio of soil:water] with a pH meter), exchangeable acidity (exchangeable aluminum [Al] extracted in 1 M potassium chloride [KCl] by direct titration [Page 1982] and analyzed by an autotitrator), percent base saturation (exchangeable base cations—calcium [Ca], potassium [K], magnesium [Mg], sodium [Na]—extracted in 1 M ammonium chloride [NH_4Cl] (Robarge 1986) and analyzed by inductively coupled plasma atomic emission spectrometry [ICP-AES]), cation exchange capacity (CEC), and mineral nutrients (boron [B], copper [Cu], manganese [Mn], phosphorus [P], sulfur [S], and zinc [Zn] were extracted in Mehlich 3 solution [Mehlich 1984] and analyzed via ICP-AES; total N and total carbon [C] determined by gas chromatography).

Depth to Water Table

One shallow groundwater well was installed near the center of each of the 12 treatment plots. Holes were dug with a 15 cm diameter power auger to a depth of about 1.1 m. A PVC pipe (5.5 cm diameter and ~ 2 m long) with many vertical slits (~ 1 mm wide) was capped at each end, covered with a well sock and inserted into the hole. The hole was back-filled with fine sand to ground level and the well depth to water with respect to the forest floor was recorded approximately once a month from September 2000 through June 2002.

Statistical Analyses

A two-way analysis of variance (ANOVA) was performed to determine treatment differences for each of the tallied and measured variables. Data from each of the 13 subplots per treatment plot were pooled with one measurement for each variable representing each of the 12 treatment plots (ANOVA N = 12, each treatment n = 3). One subplot in the *Block 1 Thin* plot was excluded from all data analyses due to the presence of an unusually large tree, apparently a residual from the previous stand. For this treatment plot, data were pooled from 12 subplots. The difference in area was taken into account when applying an expansion factor and, where appropriate (*e.g.*, stem density, basal area, volumes), plot data were expanded to hectare scale prior to running the ANOVAs. The ANOVAs included block, treatment main effects, and interactive effects. Because block differences were visibly apparent, two ANOVAs were performed for each measured variable with a reduced (*y = Block + Thin + Fert + Thin x Fert*) and a full (*y = Block + Thin + Fert + Block x Thin + Block x Fert + Thin x Fert*) model. The ANOVAs were performed using SAS Institute's ADX-Interface and SAS/STATS programs (SAS 1999). The ADX-Interface utilizes Box-Cox power transformations. Any data transformations required were determined through ADX-Interface and applied prior to the ANOVA. Results present details from the ANOVA tables from the reduced model and, where appropriate, note significant findings from the full model. When significant (at the level $p \leq .10$) treatment effects were found, the 'lsmeans' procedure was applied with least squared means adjusted for multiple comparisons via Tukey's procedure (SAS 1999). However, because this study is only a two-factor experiment and these analyses are looking at treatment effects (main effects or interactions) rather than ranking individual treatments, the results from the means separations are presented in only a few isolated cases where it seems relevant to rank the individual treatments.

Simple linear regressions were calculated using SAS/Insight (SAS 1999), to examine the relationship between sapling volume (VT_I) and competing vegetation volume (VC_I). These

regressions were performed and plotted for all treatments combined and for each treatment separately using subplot data (Control n=39, Fert n=38, Thin n=37, Thin+Fert n=38). Competition data were missing for three subplots and one subplot was already removed from the entire study, so these subplots were not included in the regressions. Where appropriate, data were transformed prior to regression analyses.

RESULTS

Species Composition

Species consisted of sweetgum, red maple and oaks from the red oak complex. Averaging across all blocks, treatments and diameter classes and measured as stems per hectare, the stand was comprised of 54% red maple, 41% sweetgum, and 4% oak. The sapling diameter class (trees ≥ 3.8 cm dbh) consisted of 79% sweetgum, 14% red maple, and 6% oak. The smaller class (< 3.8 cm dbh) consisted of 58% red maple, 38% sweetgum, and 3% oak.

Data Presentation – Tree Categories

Results for tree density, size and changes are presented for (1) 1997 at the start of the study immediately after the thinning treatment was installed but before fertilization was conducted (results in Tables 1-2 and 8-9 indicate "*Pre-Fert*" as a dummy variable to account for the impending *Fert* treatment and any pretreatment differences in these plots), (2) 2001 after four years of stand response to thinning and three years of stand response to fertilization, and (3) the incremental changes in these factors between 1997 and 2001. Results for tree density, size and changes are divided into tree size categories as follows:

· all trees ≥ 1.4 m tall ("all trees" or "all stems")

· trees ≥1.4 m tall and < 3.8 cm dbh ("small trees" or "smaller class")

· trees ≥ 1.4 m tall and ≥ 3.8 cm dbh ("saplings" or "sapling class")

· trees < 1.4 m tall ("very small stems")

Density of All Stems > 1.4 m Tall

In 1997, immediately after thinning treatments were imposed and for all species combined, there were approximately 21000 stems per hectare (SPH) in the nonthinned treatments and 7600 SPH in the thinned treatments, reflecting a strong thinning effect (Table 1). By treatment, there were approximately 22500 SPH in the *Control* plots (50% sweetgum, 44% red maple, 4% oak); 19300 SPH in the *Fert* plots (71% red maple, 25% sweetgum, 3% oak); 8000 SPH in the *Thin* plots (49% sweetgum, 45% red maple, 5% oak); and 7300 SPH in the *Thin+Fert* plots (49% sweetgum, 49% red maple, 2% oak). By species, a significant thinning effect on density was found for red maple and oaks, but not for sweetgum. A significant block effect was found for all species combined, and for sweetgum and red maple separately. There were significantly more red maples on the *Fert* plots, reflecting a pre-fertilization difference in red maple stem densities.

In 1997, the majority (95%) of trees > 1.4 m tall were also < 3.8 cm dbh ("smaller class"), for all species and treatments (Table 2). Within the smaller class, there were approximately the same number of sweetgum and red maple in the *Control*, *Thin* and *Thin+Fert*, and more red maple than sweetgum in *Fert* plots. For all species combined (within the smaller class), the average density of the nonthinned treatments (~ 19700 SPH) was significantly greater than the thinned treatments (~ 6300 SPH) (Table 2). Blocking was significant for these small trees for all species combined and for sweetgum and red maple, but not for oaks.

For trees ≥ 3.8 cm dbh ("saplings" or "sapling class"), sweetgum was the dominant species in each treatment (Table 2), comprising over 75% of each treatment plot. There were no significant differences in sapling density between thinned and nonthinned treatments (overall mean of approximately 1300 SPH). Analyses of individual species showed no treatment differences in

sweetgum or red maple density in the sapling class (Table 2). The significant thinning effect seen for oak saplings (Table 2) was a reflection of no oak saplings present in the *Thin+Fert* plots.

In 2001, after four growing seasons for the thinning treatments and three for the fertilization treatments, for all species combined and including all trees > 1.4 m tall, there were approximately 23600 SPH in the *Control* (incremental increase of ~ 1100 trees), 18900 SPH in *Fert* (incremental loss of ~ 400 trees), 12800 SPH in *Thin* (incremental increase of ~ 4800 trees) and 9500 SPH in *Thin+Fert* (incremental increase of ~ 2100 trees) (Table 3). There were a few minor changes in species percent representation among the treatments in 2001. For all trees, the nonthinned treatments were comprised of relatively the same percentages of sweetgum, red maple and oak as in 1997, but red maple had gained overall dominance over sweetgum in the thinned treatments. There were significantly fewer trees in 2001 on the thinned treatments, for all species combined and for red maple and oaks separately, than in 1997. No treatment differences were found for sweetgum in 2001. A *Thin x Fert* interaction was found for red maple (Table 3).

In 2001 there remained a significant thinning effect on density in the smaller diameter class (< 3.8 cm dbh) for all species combined, and for red maple and oak separately (Table 4). No density differences among treatments were found for sweetgum. A *Thin x Fert* interaction was observed for red maple, and a fertilization effect for oak. There were no treatment differences in sweetgum or oak density for trees ≥ 3.8 cm dbh in 2001. For red maple, however, a significant fertilization effect was observed.

Between 1997 and 2001, there were significant increases in stem densities in the thinned treatments for all species combined, and for sweetgum and red maple separately (Table 5). Blocking was significant for all species combined, and also for sweetgum and red maple separately. For all species combined, a significant thinning and fertilization effect was observed in density of small trees (< 3.8 cm dbh) (Table 6). The thinned treatments—particularly *Thin*—had significantly increased in density, and the nonthinned treatments—particularly *Fert*—had significantly decreased

in density. This was also observed for sweetgum and red maple individually. Within the sapling class (≥ 3.8 cm dbh), a fertilization effect was observed in changes in stem density for all species combined, and for red maple.

Stem Density of Very Small Stems < 1.4 m Tall

In 1997, there were approximately 6800 stems per hectare < 1.4 m tall on the *Control*, 5400 SPH on *Fert*, 3500 SPH on *Thin* and 1800 SPH on *Thin+Fert*. A significant thinning effect was found for these sprouts and small stems in 1997 (Table 7). A means (lsd) separation (Tukey's test) showed that there were significantly fewer of these small stems on the *Thin+Fert* treatment, for all species combined and for red maple separately, than on the other treatments (data not shown in tables). Red maple was the dominant species within these small stems, comprising 59% of the *Control*, 84% of *Fert*, 70% of *Thin*, and 60% of *Thin+Fert*. Sweetgum composition ranged from 11 to 34%, and oaks comprised < 4% of every treatment. There was a significant blocking effect for all species combined, and for sweetgum and red maple separately.

In 2001, four years after the thinning treatments and three years after fertilization, the density of small stems and sprouts on the nonthinned treatments had decreased by 17% on the *Control* and 75% on *Fert*, but increased on the thinned treatments by 458% on *Thin* and 887% on *Thin+Fert*. Red maple remained the dominant species in all treatments except the *Control*, comprising 37% of the *Control*, 87% of *Fert*, 69% of *Thin*, and 91% of *Thin+Fert*. Sweetgum composition ranged from 8% in the thinned treatments to 51% of the *Control*. There was a significant thinning effect for all species combined and for sweetgum and red maple individually. Sweetgum exhibited significant blocking and fertilization effects and a *Thin x Fert* interaction (Table 7).

Incremental change in density of these small stems between 1997 and 2001 showed a significant thinning effect for all species combined and for red maple separately (Table 7). There

was a density change of -1154 SPH in the *Control*, -4600 SPH in *Fert*, +16000 in *Thin*, and +15600 in *Thin+Fert*.

Basal Area of Trees > 1.4 m Tall

In 1997, for all species combined, there were no statistical differences in basal area (BA) among the four treatments, averaging 5.5 m^2/ha (Table 8). Sweetgum comprised 69% of the total BA, red maple 26% and oaks (all species combined) 5%. There were no differences in overall BA for sweetgum among treatments, with sweetgum BA averaging 3.9 m^2/ha in the nonthinned treatments and 3.7 m^2/ha in the thinned treatments. A thinning effect was shown for red maple, with an average BA of 1.9 m^2/ha in the nonthinned treatments and 0.95 m^2/ha in the thinned treatments. For the oaks, significant blocking, thinning and fertilization effects were found.

By diameter class, for all species combined, analysis of stand BA in 1997 revealed a significant thinning effect for trees < 3.8 cm dbh, but no differences for trees ≥ 3.8 cm dbh (Table 9). The smaller diameter class (< 3.8 cm dbh) comprised 55% of the total BA on the nonthinned treatments and 31% of the total BA on the thinned treatments. Within this smaller diameter class, sweetgum comprised 47% of the total BA in the nonthinned treatments (3.4 m^2/ha) and 55% of the total BA in the thinned treatments (1.5 m^2/ha). There was a thinning effect for sweetgum trees < 3.8 cm dbh. Red maple comprised 45% of the BA for trees in the nonthinned treatments, which was significantly more than the 20% of BA of red maple in the thinned treatments. Oaks comprised 6% of BA for trees in the nonthinned treatments and 3% of BA in the thinned treatments. A significant thinning effect was noted in BA of oak trees < 3.8 cm dbh. Within the sapling class (trees ≥ 3.8 cm dbh), sweetgum comprised 84%, red maple 11% and oaks 8% of the total BA (mean 3.03 m^2/ha), but there were no statistical differences among treatments for these individual species or for all species combined (Table 9).

In 2001, data for stand BA showed a significant fertilization effect for all species combined and individually, and thinning was significant for all species combined, red maple and oaks, but not for sweetgum (Table 10). There were no significant *Thin x Fert* interactions, and blocking was generally significant among the tree species. Trees in the smaller diameter class (< 3.8 cm dbh) comprised 36% of total BA on the *Control* plots, 23% on the *Fert* plots, 20% on the *Thin* plots and 8% on the *Thin+Fert* plots (Table 11). For all species combined, the nonthinned treatments contained over 2.5 times the BA for these small trees than those of the thinned treatments (Table 11). Analysis of each dominant species showed the same pattern. The *Control* contained approximately the same percentage of sweetgum as red maple, but the other three treatments contained more of the small red maples. Thinning as a BA main effect on small trees was significant for sweetgum, red maple, and oaks. Fertilization was a significant main effect for red maple and oaks; and a *Thin x Fert* interaction was observed for red maple. Trees within the sapling class (≥3.8 cm dbh) comprised 64% of the *Control* BA, 77% of *Fert*, 80% of *Thin*, and 92% of *Thin+Fert*. The 2001 data revealed a strong fertilization effect, for all species combined, and for sweetgum and red maple separately (Table 11). There were insufficient oaks in the sapling class to conduct a statistical analysis. The *Fert* treatment had an overall BA 46% greater than the *Control* and 65% greater than *Thin*, and the *Thin+Fert* treatment had a BA 69% greater than the *Control* and 90% greater than *Thin*.

Incremental growth in total BA, for all trees > 1.4 m tall and all species combined, was enhanced by fertilization (Table 12). Basal area in the fertilized treatments was 49% greater than the *Control* and 91% greater than *Thin*. Sweetgum and red maple followed this general trend, but there were no differences in incremental BA growth for oaks. There was a significant block effect for all species combined and for sweetgum separately.

Because there were fewer small trees in the fertilized plots, there was significantly less BA in the fertilized sweetgum and red maple (Table 13). Fertilization had a significant positive effect on trees in the sapling diameter class (≥ 3.8 cm dbh), for all species combined and for sweetgum and red

maple separately (Table 13). Within the sapling class, for all species combined, *Fert* BA growth was enhanced by 69% over the *Control* and 94% over *Thin*. *Thin+Fert* sapling BA growth was enhanced by 82% over the *Control* and 109% over *Thin*. Incremental BA growth on the *Control* was greater by 15% than *Thin*. For sweetgum saplings, BA growth on the *Thin+Fert* treatment was enhanced by 135% over the *Control*, 142% over *Thin*, and 28% over *Fert*. Red maple sapling BA on the *Fert* treatment increased by more than 250% over that of the *Control* and 127% over that of *Thin*. Red maple on the *Thin+Fert* treatments responded similarly (Table 13). There was a significant block effect for all species combined and for sweetgum, but not for red maple.

Diameter, Height, & Stand Volume Index (VT_I) for Trees in the Sapling Class (≥ 3.8 cm Dbh)

In 1997, immediately after treatments were imposed, no differences were found among treatments in mean individual stem diameter (5.3 cm), height (5.5 m), or stand volume index (volume or VT_I) (6.7 m^3) for saplings, for all tree species combined or for sweetgum, red maple, or the oaks separately (Table 14). Sweetgum trees were larger in diameter (5.4 cm v. 4.8 cm) and in VT_I (5.7 m^3 v. 0.7m^3) than red maples. There was a significant block effect for diameter of all species combined and sweetgum.

In 2001, a significant positive fertilization effect was observed in diameter, height and VT_I for all species combined and sweetgum (Table 15). A positive fertilization effect was observed in height and VT_I of red maple. A significant *Thin x Fert* interaction was observed in VT_I for all species combined. A significant block effect was indicated for diameter, height and VT_I for all species combined and for sweetgum.

Fertilization enhanced incremental growth between 1997 and 2001 in individual tree diameter and height and stand VT_I, for all species combined and sweetgum (Table 16). Incremental growth in height and VT_I of red maple was enhanced by fertilization. The effect of thinning was not significant and there were no *Thin x Fert* interactions for incremental growth in diameter, height or

stand volume (Table 16). There was a significant block effect for all species combined and for sweetgum. Fertilization enhanced diameter growth by 72% for all species combined and by 87% for sweetgum. Fertilization enhanced height growth by 37% for all species combined, 43% for sweetgum, and 67% for red maple, and more than doubled the stand volume growth for all species combined (105% increase), sweetgum (132% increase), and red maple (160% increase).

Percent Canopy Cover

In September 2000, during the fourth growing season after the thinning treatment and third growing season after the fertilization treatment, percent canopy cover reflected significant treatment differences (Table 17). In addition to significant thinning, fertilization and block effects, there was a significant *Thin x Fert* interaction. A means separation (Tukey's test) showed that percent canopy cover in the *Thin* treatment was significantly lower than that of the other three (analysis not shown in Table 17). The *Fert* treatment had the most dense canopy, 53% greater than that of the *Thin* treatment and 11% greater than the *Control*, but only 4% more dense than the canopy in the *Thin+Fert* treatment.

Litterfall Collection

During the course of a 12-month period—October 2000 through September 2001—trees in the fertilized treatments dropped significantly more litter than in the nonfertilized treatments (Table 18). All litter types combined averaged 5689 kg/ha/year on the fertilized treatments and 3667 kg/ha/year on the nonfertilized treatments. Across all treatments, sweetgum contributed the most foliage, followed by red maple, oaks, then shrubs and vines combined. There was no impact of thinning or block effects in litterfall except for oak species. The pattern of litterfall production by month (Figure 1) showed that during peak litterfall (October and November), fertilized sweetgum

dropped significantly (P = .0003) more leaves in November than in October (ANOVA results not shown).

Foliar Nutrient Concentrations

Sweetgum foliage from the fertilized treatments had significantly higher percentage of N (1.47%) than the nonfertilized treatments (1.04%) (Table 19). There were significantly lower foliar P concentrations in the fertilized treatments than in the nonfertilized treatments (0.19 versus 0.22%). There were no significant differences in foliar concentrations of K (0.70%), Ca (0.85%), or Mg (0.35%) among treatments. Foliage from the fertilized trees contained more S than the nonfertilized trees (0.16 versus 0.13%). Among micronutrients, there were no treatment differences in foliar Mn (1146 ppm), B (26.6 ppm), or Zn (51.68 ppm) concentrations, but thinning and fertilization were significant as main effects for foliar Cu concentrations (5.4 ppm in fertilized treatments; 4.6 ppm in nonfertilized treatments; 5.32 ppm in thinned treatments; 4.61 ppm in nonthinned treatments).

Red maple foliage on the fertilized treatments had significantly higher percent N concentrations (1.6%) than foliage from the nonfertilized treatments (1.2%) (Table 20). Significant differences were observed for foliar Ca (1.3% fertilized; 1.1% nonfertilized; 1.1% thinned; 1.4% nonthinned), Mg (0.3% fertilized; 0.25% nonfertilized) and S (0.15% fertilized; 0.13% nonfertilized) concentrations. There were no treatment differences in foliar P (0.21%), K (0.64%), S (0.14%) concentrations, or the concentrations of micronutrients Mn (1100 ppm), B (30.6 ppm), or Cu (ppm). Foliar Zn concentrations were significantly higher in red maple foliage on the fertilized treatments (38.7 ppm) than the nonfertilized treatments (30.4 ppm).

Willow oak foliage showed a significant fertilization effect for N concentrations (2% fertilized; 1.7% nonfertilized) (Table 21). There were no treatment differences in foliar P (0.13%), K (0.67%), Ca (1%), Mg (0.21%), S (0.15%) concentrations, or the micronutrients Mn (1824 ppm) or B (36.7 ppm).

Wax myrtle foliage showed significant fertilization effects for N (2.25% fertilized; 2.11% nonfertilized); P (0.085% fertilized; 0.075% nonfertilized); K (0.8% fertilized; 0.06% nonfertilized); Ca (1.55% fertilized; 1.3% nonfertilized); Mg (0.45% fertilized; 0.35% nonfertilized); and S (0.26% fertilized; 0.21% nonfertilized) concentrations (Table 22). A thinning effect was found for foliar N concentrations (2.3% thinned; 2.1% nonthinned) and Ca (1.3% thinned; 1.6% nonthinned). Among the micronutrients, only foliar B concentrations showed a significant fertilization effect (46.0 ppm fertilized; 29.8 ppm nonfertilized). The mean concentration for foliar Mn was 279.3 ppm; Cu 3.3 ppm and Zn 32.1ppm.

Specific Leaf Area

Significant thinning and fertilization effects were found in specific leaf area (SLA) for sweetgum (Table 23). There were no treatment differences in SLA for red maple (averaging 149.2 cm^2/g). For willow oak there was a significant SLA fertilization effect and *Thin x Fert* interaction. Wax myrtle SLA exhibited a significant *Thin x Fert* interaction and there was a significant block effect for sweetgum, red maple and willow oak.

Competing Vegetation

Competing vegetation (VC_I) was classified into six different types: shrubs, sprouts (trees < 1 m tall), vines, grasses, forbs and mosses/lichens. Shrubs included wax myrtle (> 93% of shrubs on all treatments), *Vaccinium* spp., *Rhus* spp., St. John's wort (*Hypericum* sp.), and other minor species. Sprouts consisted of sweetgum (dominant on the *Control* at 48%) and red maple (dominant on the other treatments, at 37% of sprouts on *Fert*, 65% on *Thin* and 52% on *Thin+Fert*), with American holly (*Ilex opaca* Ait.), black cherry, and black gum present in smaller quantities. Vines consisted of poison ivy (*Toxicodendron radicans* L.) (the dominant vine on all treatments, at 98% of all vines on the *Control*, 97% on *Fert*, 81% on *Thin*, and 98% on *Thin+Fert*), grape, Japanese honeysuckle and

trumpet creeper (*Campsis radicans* L.). Grasses were a small component consisting of various grasses and rushes (unidentified). Forbs included partridge berry (*Mitchella repens* L.), *Lespedeza* spp., running cedar (*Lycopodium digitatum*), and various ferns (unidentified). Mosses/lichens (unidentified) were present in very small amounts and, as no statistical differences were found in the ANOVAs, are not presented separately in the tables.

Fertilization appeared to limit growth of competing vegetation, for all competition types combined and separately (Table 24). There were significantly less shrubs on the fertilized treatments, more vines on the thinned treatments, less grasses on the fertilized treatments, and no differences among treatments in VC_I for forbs. Competing vegetation on the *Control* was comprised of 81% shrubs, 2% sprouts, 12% vines, 5% grasses, and < 1% forbs. Competition on *Fert* consisted of 86% shrubs, 2% sprouts, 9% vines, 1% grasses, and < 1% forbs. Competition on *Thin* consisted of 62% shrubs, 5% sprouts, 20% vines, 12% grasses, and < 1% forbs. Competing vegetation on *Thin+Fert* was comprised of 18% shrubs, 31% sprouts, 44% vines, 4% grasses, and < 1% forbs.

A linear regression of subplot tree (≥ 3.8 cm dbh) volume (VT_I per subplot) on subplot competition volume (VC_I per subplot), by treatment, indicated a significant (albeit weak) inverse relationship between sapling volumes and all competition and shrubs in the *Control*; sprouts and grasses in the *Fert* treatment plots; and all competition, shrubs and vines in the *Thin* treatment plots (Table 25). There were no significant linear relationships found between tree volume and competition volume in the *Thin+Fert* plots (Table 25).

Soil Analysis

There were no treatment differences in the percent of sand (75%) or clay (6.9%), but a significant thinning effect and *Thin x Fert* interaction was found for silt (Table 26). There were no block effects on soil texture in the top 20 cm of soil.

Soil pH ranged from 4.2 to 4.6 across the treatment plots (Table 27). There were no differences among treatments in exchangeable acidity (1.4 meq/100g) or CEC (1.98 meq/100g). A significant fertilization effect was shown for soil Ca (123.5 ppm on fertilized treatments and 81.9 ppm on the nonfertilized treatments). There were no treatment differences found for the other soil nutrients and properties (Mg = 5.2 ppm, K = 16 ppm, Na = 6.2 ppm, B = 4.2 ppm, Cu = 0.4 ppm, Mn = 0.87 ppm, Zn = 4.8 ppm, S = 4.6 ppm, and P = 71.8 ppm; N and organic C averaged .05 and 1% dry weight, respectively). A significant fertilization effect was observed for percent base saturation (34% on fertilized treatments and 26.5% on nonfertilized treatments), and a significant *Thin x Fert* interaction for soil total N and C (Table 27). There were significant block effects for exchangeable acidity, CEC, base saturation, Cu, Mn, S, P, N and C.

Depth to Water Table

Depth to the water table (DWT) was measured approximately monthly from September 2000 to June 2002. Over all dates, DWT averaged 70 cm on the *Control*, 80 cm on *Fert*, and 68 cm on *Thin* and *Thin+Fert*. There were no significant treatment differences in these means. A block effect was found, but no *Block x Treatment* interactions were found in the full ANOVA model (data not shown).

Analysis of DWT on each collection date showed some significant differences in DWT among months, treatments, and blocks. There were no significant treatment differences in DWT from September 2000 to November 2000 (Figure 2). In January 2001, DWT on *Fert* (90 cm) was significantly greater than DWT on *Thin* (50 cm). In February 2001, DWT was greater on *Fert* (40 cm) than the other three treatments (17 cm). There were no treatment differences in DWT from May 2001 to October 2001. In November 2001, DWT was greater on *Fert* (66 cm) than on *Thin+Fert* (50 cm). There were no treatment differences in DWT in February 2002 (56 cm). In March 2002, DWT on *Fert* was greater (48 cm) than on *Thin+Fert* (23 cm). There were no treatment differences in

DWT from April 2002 to June 2002. Significant block effects were observed for six collection dates (Figure 3, significant block effect noted with an asterisk), but no *Block x Treatment* interactions were found in the full ANOVA model (data not shown).

DISCUSSION

Fertilization had a significant positive impact on diameter, height and volume growth of sapling sized trees (Table 16), total stand basal area growth (Tables 12-13), leaf area (Tables 17-18), foliar N concentrations (Tables 19-22), and leaf area duration (Figure 1). It also appeared to limit the growth and development of non-tree vegetative competition and tree stems < 1 m tall (Table 24). Thinning had little to no significant impact, either positive or negative, on tree growth (Tables 12-13, 16-22), although thinning did result in nonsignificant increases in mean stem diameter and height growth. Thinning also increased stem densities in small (Table 6) and very small (Table 7) trees. The combined *Thin+Fert* treatment did appear to improve sapling growth in diameter, height, volume, and basal area. However, there were relatively few *Thin x Fert* interactions and the only one that appeared to be biologically significant was the interaction observed for percent canopy cover (Table 17).

The positive growth in basal area was produced by the saplings (Table 13). The *Control* grew in basal area 6.0 m^2/ha in the four years, a growth rate of 1.5 m^2/ha/year. The *Fert* treatment grew 10.3 m^2/ha during the four-year study period, only the last three of which included fertilization effects. If the *Fert* treatment grew at the same rate as the *Control* during the first year (before fertilization had been applied), this treatment would have grown 8.8 m^2/ha during the three years following fertilization, a growth rate of 2.93 m^2/ha/yr, and almost twice that of the *Control*. It would take 14 years for a stand of similar characteristics growing at the same rate as the *Control* to reach the 10.3 m^2/ha basal area, rather than 10 years. This supports the idea that young natural stand

fertilization can accelerate stand development, and produce more wood faster. The two dominant species, sweetgum and red maple, responded very well to fertilization. Sweetgum diameter and volume growth on fertilized treatments was twice that of the *Control*, and red maple diameter, height and volume growth more than doubled following fertilization (Table 16).

The positive growth response resulting from fertilization was evident as noted above in the acceleration in growth and development, and also in the results from the foliar nutrient analysis for the dominant species, for foliar N concentrations in particular (Tables 19-21). Foliar N concentrations observed in the current study are relatively low when compared to results from other studies, *e.g.*, observed sweetgum N concentrations (% dry weight) in the *Control* at 1.01 (Table 19), while other researchers have seen nitrogen concentrations (% dry weight) in nonfertilized sweetgum of 1.1 (Nelson *et al.* 1995), 1.18 (Kennedy 1993), 1.51 (Broadfoot 1966), and 1.64% (Mewborn 1997). Nitrogen concentrations in the fertilized sweetgum in this study were lower (averaging 1.42% across the *Fert* and *Thin+Fert* treatments) than the range of 1.5 to 2.02% reported in sweetgum horticultural plantings (Mills and Jones 1996) and the post-fertilization concentrations of 1.69% in a natural stand (Broadfoot 1966) and 2.13% in a plantation (Mewborn 1997). Sweetgum foliar P (0.22% on the nonfertilized treatments, 0.19% on the fertilized treatments) was well within the expected range of 0.13 to 0.35% in sweetgum horticultural plantings (Mills and Jones 1996) and above the target value of 0.14% reported by the NC State Forest Nutrition Cooperative (unpublished data). This suggests that P was less limiting in the current study than N, however, the study design does not allow separation of the effects of N versus P. The observed N:P ratio from this study was 4.5 on the *Control* and averaged 7.75 with fertilization, which is within the range observed in low-N sweetgum plantations (North Carolina State University Hardwood Research Cooperative 2000). The soil analysis from this study shows high P levels across all treatments (Table 26). Other foliar macro- and micronutrients were within the expected ranges for sweetgum.

The observed red maple foliar N concentrations of 1.22% in the *Control* (Table 20) were somewhat lower than levels found in other studies of nonfertilized red maple (*e.g.*, 1.32% by Cramer *et al.* 2000, and ranging from 1.48-2.01% in Mitchell and Chandler 1939). The average N concentration in fertilized red maple foliage in this study was 1.58%, a value within the expected range of observed means (0.90 to 2.68%) in red maple horticultural plantings (Mills and Jones 1996). In fact, all foliar nutrients observed in red maple were within the published observed means (Mills and Jones 1996), except for Mn, which was somewhat higher than the published range of 20 to 765 ppm. Most foliar macronutrient concentrations in willow oak on the control were within the published observed range (Mills and Jones 1996), although N and P were on the low ends of the ranges (1.66 to 2.6% and 0.13 to 0.17%, respectively). Potassium concentrations in willow oak foliage were slightly lower than the expected range, and micronutrient concentrations in willow oak foliage on the control were higher than published means (Mills and Jones 1996). Willow oak foliage on the fertilized treatments contained more N (2%) than the nonfertilized (1.7%) treatments (Table 21). Wax myrtle foliage contained more N, but notably less P, Mn and Cu in its foliage than the deciduous trees studied (sweetgum, red maple, willow oak) on all of the treatments (Table 22). Concentrations of macro- and micronutrients in wax myrtle foliage were within the observed published ranges (Mills and Jones 1996), although Ca and Mg were slightly higher than the published ranges. Fertilization effects on wax myrtle foliage were significant for N, P, K, Ca, Mg, S, and B, all of which were observed in greater concentrations on the fertilized treatments. Wax myrtle is one of the few nodule-forming nonlegumes and has the capability to fix its own nitrogen through association with actinomycetes of the genus *Frankia* (Brady and Weil 1996), which surely influenced its foliar N concentrations.

In the current study, the positive growth responses obtained from fertilization in tree diameter and height, and stand basal area and volume, which are similar to those found in other studies of young hardwoods in natural stands (Farmer *et al.* 1970, Auchmoody 1982, Dunn *et al.*

1999), can be partially explained by considering the relationship between leaf area and wood production, as described earlier. Productivity can be estimated from leaf area, either for individual trees or for the canopy as a whole, and it is generally accepted that an increase in leaf area will result in an increase in productivity (Allen 2000, Landsberg and Gower 1997, Albaugh *et al.* 1997, Vose 1994).

After four years post-thinning and three years post-fertilization, the canopy of the thinned-only treatment was visibly and measurably less dense than the other treatments (Table 17). It is worth noting that the canopies of the *Fert* and the *Thin+Fert* treatments were nearly identical, but the combined treatment contained only half the total number of stems > 1.4 m tall as the fertilized-only treatment. Dramatic increases in leaf area can result from nitrogen fertilization on N-deficient sites (Vose *et al.* 1994) and are also observed when stands with open canopies are fertilized (Albrektson *et al.* 1977, Colbert *et al.* 1990). The above responses are indicative of the ability to accelerate stand development through fertilization (Vose *et al.* 1994). Differences in observed specific leaf areas (SLA) (Table 23) may have been influenced by the differences in canopy coverage. The higher SLAs of sweetgum, red maple and willow oak in the *Fert* treatment (Table 23) could be indicative of greater number of shade leaves in the mid-level canopy of the stand—from whence the foliage samples were taken—and, conversely, the lower SLA found in foliage from the *Thin* treatment could be the result of more sun leaves being produced in an open habitat with < 60% canopy coverage. Shade leaves are thinner than sun leaves and generally have less chlorophyll per unit of leaf area; they are better at capturing available incoming radiation at low light intensities but their light compensation and light saturation points are lower (Kozlowski and Pallardy 1997). Sun leaves, which generally have lower SLA than shade leaves, consistently exhibit higher photosynthetic capacity than shade leaves when grown in the full sun (McMillen and McClendon 1983). Low nitrogen concentrations in a leaf generally equate to low photosynthetic capabilities (Kozlowski and

Pallardy 1997), but in the current study the leaves on the *Fert* treatment consistently had greater N concentrations that the leaves on the *Thin* treatment, despite the higher SLA.

The month-by-month analysis of litterfall patterns (Figure 1) revealed that sweetgum on both fertilized treatments held onto its foliage longer into the autumn than the nonfertilized treatments, which supports other studies suggesting that N fertilization may increase leaf retention/duration (Miller and Miller 1976, Linder and Rook 1984, Nelson *et al.* 1995, Porter 1997). Photosynthesis rates in many deciduous trees accelerate in the spring as the trees refoliate, remain high during peak leaf area in the summer, then decrease as leaves senesce before abscising (Kozlowski and Pallardy 1997). Nitrogen fertilization results in greater proportion of late-formed leaves in sweetgum (Brown 1971) and these leaves abscise later in the season (Nelson *et al.* 1995). Thus, fertilization had the effect of building a larger and longer-held canopy, while thinning on a stand basis had the effect of pruning, which removed this same potential canopy.

The *Fert* treatment appeared to help limit the growth and development of non-tree vegetative competition (*e.g.*, shrubs, vines, grasses), relative to the volume indices of these competition types in the *Control* and *Thin* treatments (Table 24). Hardwoods are nutrient demanding (Auchmoody and Filip 1973) and can utilize additional resources more efficiently than pines (Allen and Albaugh 2000). They respond well to competition control (*e.g.*, sweetgum and water oak increased in basal area 70 and 58%, respectively, following control of herbaceous competition [Glover and Quicke 1999]; very young mixed hardwoods responded dramatically to vegetative control [Romagosa and Robison 2003]). In a study of red pine, red maple and black locust, the response of hardwoods to herbaceous control far exceeded that of the pines (Frederickson *et al.* 1993). In the current study, the *Thin* treatment contained the greatest volume of competing vegetation (Table 24). Thinning a stand of trees removes arborescent competition, but the site can quickly become occupied by vegetation such as grapevines in the mountains (Trimble 1973, Lamson and Smith 1978), coppiced sprouts and Japanese honeysuckle in the Piedmont (Kellison *et al.* 1981), and wax myrtle and poison ivy in the

Coastal Plains. The combined *Thin+Fert* treatment contains elevated volumes of vines and sprouts (stems < 1 m tall) (Table 24) as compared with the *Fert* treatment. The elevated volume of these vines and sprouts on the *Thin+Fert* treatment may be due, in part, to growth during the first year after the thinning treatment (February 1997) but before fertilization (May 1998) (variables not measured). The *Thin+Fert* treatment responded rapidly to fertilization, as measured by canopy cover (Table 17), litterfall (Table 18) and stem growth (Tables 12-13, 16-21). Based on the positive growth responses observed in this study, the trees receiving the combined treatment appear to have overcome any negative effects from the competing vegetation.

The linear regressions of sapling volumes on competing vegetation volumes, which are based on subplot data, showed relative differences in the relationships between sapling volumes and specific types of competition among the individual treatments (Table 25). This suggests that as different treatments limit or foster growth of competitors, so too does tree growth vary depending upon the type and relative abundance of the competitor. The relationship between tree volume and competition volume is rarely linear, depending upon the type and abundance of the competitor (Glover and Quicke 1999).

Block differences were apparent throughout the study (Tables 1-15, 17-24, 27, Figures 2-3) and the block effect in the ANOVA model accounted for this variability. Details from the full ANOVA model did not reveal any *Block x Treatment* interactions in regard to the well data, and although there were a few *Block x Treatment* interactions found in the full ANOVAs for a few of the measured variables (*e.g.*, all species dbh 2001, red maple volume 2001), they were not consistent and remain unexplained. Wells installed in the center of each treatment plot tracked the depth to the water table from August 2000 to June 2002 and the data illustrate the block effect (Figures 2-3). In Blocks 2 and 3, the water table was within 30 cm of ground surface in January 2001 and again in March and April of 2002. The greater elevation of the water table in Blocks 2 and 3 relative to Block 1 early in the growing season may have contributed to shorter effective growing seasons due

to restricted root conditions. Blocks 2 and 3 appeared to exhibit retarded growth and development such as delayed self-thinning and delayed leaf flush in the spring (personal observation). Stem density was higher on these lower blocks in 1997 and 2001, and individual stems were smaller than on Block 1 (data not shown), as possible evidence of this impact on growth and development.

Analysis of the top 20 cm of mineral soil revealed few differences among treatments in soil texture, although there was a significant thinning effect and a *Thin x Fert* interaction noted for silt concentrations. Given that changes in soil properties generally take many years, it is more likely that the differences observed are due merely to chance and inherent variability rather than treatment, although silt deposition during flooding may be important (Rapp *et al.* 2001). There were no treatment differences in pH ranges (Table 27), and the mean pH of 4.4, although strongly acid, falls within the expected range of forest Ultisols in warm humid regions (Brady and Weil 1996). There were no treatment differences noted in exchangeable soil acidity or effective cation exchange capacity (CEC), and the observed means for both (Table 26) fall within the expected range for soils in the Coastal Plain (*Dan Kelting, NCSU Forest Nutrition Cooperative,Raleigh, NC, personal communication)*. The fertilized treatments had significantly higher percent base saturation (34%) than the nonfertilized treatments (26.5%). Over all, base saturation was fairly low, indicating that most of the CEC (in this study, 66% on the fertilized treatments and 73.5% on the nonfertilized treatments) would be occupied by exchangeable acidity, which is commonly measured in acid soils by determining the levels of exchangeable aluminum ions in the soil solution (Brady and Weil 1996).

There were no significant treatment differences noted for soil nutrient concentrations, except that there was significantly more Ca on the fertilized treatments. Soil B and P concentrations were much higher than would be expected for this region, by a magnitude of approximately ten (Jin *et al.* 1988, Singh and Sinha 1976, Shuman *et al.* 1992, Harding and Jokela 1994), but this remains unexplained. A *Thin x Fert* effect was found for total soil N and also for total soil C. The percentages of both total N and total C were lower in the *Fert* and *Thin* treatments than the *Control*,

but were greater than the *Control* in the combined *Thin+Fert* treatment. The C:N ratio of 22 to 23 (from Table 27) is just under the threshold (C:N ≈ 24), above which soil microbes will scavenge the soil for N and deplete the supply of soluble nitrogen (Brady and Weil 1996), so it is likely that some N is being immobilized in the soil. Although no measures were made of available soil N (NH_4^+ or NO_3^-), it may be implied from measuring foliar N concentrations, which, as mentioned above, were higher in the fertilized treatments.

CONCLUSIONS

The primary objective of this study was to determine the effects of precommercial thinning and fertilization, separately and in combination, on the stand-level growth of sapling sized trees (dbh ≥ 3.8 cm) and other vegetation in a 7-year-old naturally regenerated mixed hardwood stand in the North Carolina Coastal Plain. Fertilization had a significant positive impact on diameter, height and volume growth of sapling sized trees, total stand basal area growth, foliar N concentrations, leaf area, and leaf area duration. The positive responses from fertilization are likely due to the amelioration of nitrogen deficiency, based on the obvious acceleration in growth and development and upon the low levels of nitrogen (even after fertilization) in the foliage of sweetgum and red maple, the dominant species on the site. Fertilization also appeared to limit the growth and development of non-tree vegetative competition and tree stems < 1 m tall under thinned overstories, and to accelerate natural self-thinning.

Thinning alone had little to no impact on tree growth, and instead appeared to increase stem densities in small (< 3.8 cm dbh) and very small (< 1.4 m tall) stems and to foster the growth of shrubs and vines rather than stem growth of desired trees. However, the slight increases noted in diameter and height growth following thinning, although not significant now, may become more significant with time.

Both sweetgum and red maple responded well to fertilization. Given the lack of significant block effect noted for red maple throughout the study, red maple appears to be the more elastic of the two species. Trees observed in this study would most likely benefit from another application of nitrogen, as would most forest stands on similar sites. This study has shown that it is highly unlikely that stand development at this age can be accelerated through thinning alone, although growth benefits gained from thinning may become more evident as the stand ages. Fertilization alone, or in combination with thinning, not only accelerates stand development, but may also increase long-term productivity.

LITERATURE CITED

Abrams, M.D. 1998. The red maple paradox: what explains the widespread expansion of red maple in the eastern forest? BioScience 48(5): 355-364.

Abrams, M.D. 1992. Fire and the development of oak forests. BioScience 42(5): 346-353.

Ågren, G.I. 1985. Theory for growth of plants derived from the nitrogen productivity concept. *Physiologia Plantarum* 64: 17-28.

Albaugh, T.J., H.L. Allen, P.M. Dougherty, L.W. Kress and J.S. King. 1998. Leaf area and above- and belowground growth responses of loblolly pine to nutrient and water additions. Forest Science 44(2): 317-328.

Albrektson, A., A. Aronsson, and C.O. Tamm. 1977. The effect of forest fertilization on primary production and nutrient cycling in the forest ecosystem. Silv. Fenn. 11: 233-239.

Allen, H.L. and T.J. Albaugh. 2000. Understanding the interactions between vegetation control and fertilization in young plantations: southern pine plantations in the southeast USA. In: Proceedings—II Seminário sobre Manejo de Plantas Infestantes em Áreas Florestais, Oct 18-19, 2000, Departamento de Ciências Florestais da ESALQ/USP, Brazil.

Allen, H.L. 2000. Silvicultural treatments to enhance productivity. In: J. Evans and L.A. Morris (eds). The Forests Handbook, Volume II. Oxford, UK: Blackwell Science Ltd. p. 129-139.

Allen, H.L. and S.R. Colbert. 1998. Nutritional management of southeast USA pine plantations: practice and opportunity. In: Proceedings X Silvotena-IUFRO Conference on Site Productivity Improvement, Concepcion, Chile. June 1998.

Allen, R.H. Jr. and D.A. Marquis. 1970. Effect of thinning on height and diameter growth of oak and yellow-poplar saplings. Research Paper NE-173. Upper Darby, PA: USDA Forest Service, Northeastern Forest Experiment Station. 11 p.

Assmann, E. 1970. The Principles of Forest Yield Study. New York: Pergamon Press. 606 p.

Attiwill, P.M. and G.W. Leeper. 1987. Cycles of nutrients in forests. In: Forest Soils and Nutrient Cycles. Victoria, Australia: Melbourne University Press. p. 128-183.

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

Auchmoody, L.R. and S.M. Filip. 1973. Forest fertilization in the eastern United States: hardwoods. In: Forest Fertilization Symposium Proceedings. General Technical Report NE-3. Upper Darby, PA: USDA Forest Service, Northeastern Forest Experiment Station. p. 211-222.

Beck, D.E. and R.M. Hooper. 1986. Development of a Southern Appalachian hardwood stand after clearcutting. Southern Journal of Applied Forestry 10: 168-172.

Beck, D.E. 1977. Growth and development of thinned versus unthinned yellow poplar sprout clumps. Research Paper SE-173. Asheville, NC: USDA Forest Service, Southeastern Forest Experiment Station. 11 p.

Binkley, D., R. Carter, and H.L. Allen. 1995. Nitrogen fertilization practices in forestry. In: (Peter Edward Bacon, ed.) Nitrogen Fertilization in the Environment. New York: Marcel Dekker, Inc. p. 421-441.

Brady, N.C. and R.R. Weil. 1996. The Nature and Properties of Soils (11th ed.). New Jersey: Prentice Hall. 740 p.

Broadfoot, W.M. 1966. Five years of nitrogen fertilization in a sweetgum-oak stand. Research Note SO-34. New Orleans, LA: USDA Forest Service, Southern Forest Experiment Station. 3 p.

Brown, C.L. 1971. Primary growth. In: Trees: Structure and Function. M.H. Zimmerman and C.L. Brown (eds.). New York: Springer-Verlag. p. 1-66.

Cannell, M.G.R. 1989. Physiological basis of wood production: a review. Scandinavian Journal of Forest Research 4: 459-490.

Church, T.W. Jr. 1955. Weeding—an effective treatment for stimulating growth of northern hardwoods. Journal of Forestry 53: 717-719.

Colbert, S.R., E.J. Jokela, and D.G. Neary. 1990. Effects of annual fertilization and sustained weed control on dry matter partitioning, leaf area, and growth efficiency of juvenile loblolly and slash pine. Forest Science 36: 995-1014.

Cramer, J., T. Fahey and J. Battles. 2000. Patterns of leaf mass, area and nitrogen in young northern hardwood forests. American Midland Naturalist 144: 253-264.

Daniel, T.W., J.A. Helms and F.S. Baker. 1979. Principles of Silviculture, 2nd ed. McGraw-Hill. 500 p.

Della-Bianca, L. 1975. An intensive cleaning of mixed hardwood saplings—10-year results from the Southern Appalachians. Journal of Forestry 73: 25-28.

Downs, A.A. 1946. Response to release of sugar maple, white oak, and yellow poplar. Journal of Forestry 44: 22-27.

Drew, T.J. and J.W. Flewelling. 1979. Stand density management: an alternative approach and its application to Douglas-fir plantations. Forest Science 25(3): 518-532.

Dunn, M.A., K.W. Farrish and J.C. Adams. 1999. Fertilization response in a natural bottomland hardwood stand in north-central Louisiana. Forest Ecology and Management 114: 261-264.

Farmer, R.E. Jr., G.W. Bengtson, and J.W. Curlin. 1970. Response of pine and mixed hardwood stands in the Tennessee Valley to nitrogen and phosphorus fertilization. Forest Science 16(2): 131-136.

Fisher, R.A. and D. Binkley. 2000. Ecology and Management of Forest Soils. New York: John Wiley & Sons. 489 p.

Fredricksen, T.S., S.M. Zedaker, D.W. Smith, J.R. Seiler and R.E. Kreh. 1993. Interference interactions in experimental pine-hardwood stands. Canadian Journal of Forest Research 23: 2032-2043.

Gause, G.F. 1934. The Struggle for Existence. New York: Hafner. 163 p.

Gent, J.A., H.L. Allen, R.G. Campbell, and C.G. Wells. 1986. Magnitude, duration, and economic analysis of loblolly pine growth response following bedding and phosphorus fertilization. Southern Journal of Applied Forestry 10: 124-128.

Gingrich, S.F. 1971. Management of young and intermediate stands of upland hardwoods. Research Paper NE-195. Upper Darby, PA: USDA Forest Service, Northeastern Forest Experiment Station. 26 p.

Glover, G. and H. Quicke. 1999. Growth response of loblolly pine, sweetgum, and water oak in a pine-hardwood study. Canadian Journal of Forest Research 29: 968-978.

Gobran, G.R. and S. Clegg. 1996. A conceptual model for nutrient availability in the mineral soil-root system. Canadian Journal of Soil Science 76: 125-131.

Goelz, J.C.G. and J.S. Meadows. 1999. Precommercial thinning of water tupelo stands on the Mobile-Tensaw River Delta: third-year results. Research Paper SRS-17. Asheville, NC: USDA Forest Service, Southern Research Station. 6 p.

Graney, D.L. and P.E. Pope. 1978. Fertilization increases growth of thinned and nonthinned upland oak stands in the Boston mountains of Arkansas. Research Note SO-243. New Orleans, LA: USDA Forest Service, Southern Forest Experiment Station. 4 p.

Hannah, P.R. 1985. Responses of yellow birch and sugar maple to release and fertilizer. Northern Journal of Applied Forestry 2: 108-110.

Harlow, W.M., E.S. Harrar, J.W. Hardin, and F.M. White. 1996. Textbook of Dendrology, 8th ed. New York: McGraw-Hill, Inc. 534 p.

Harper, J. 1977. Plant Population Biology. New York, NY: Academic Press. 892 p.

Havlin, J.L., J.D. Beaton, S.L. Tisdale, and W.L. Nelson. 1999. Soil Fertility and Fertilizers: An Introduction to Nutrient Management, 6th ed. New Jersey: Prentice Hall. 499 p.

Hilt, D.E. and M.E. Dale. 1980. Effects of repeated precommercial thinnings in central hardwood sapling stands. Southern Journal of Applied Forestry 6(1): 53-58.

Hix, D.M. and C.G. Lorimer. 1991. Early stand development on former oak sites in southwestern Wisconsin. Forest Ecology and Management 42: 169-193.

Hurst, G.A. and T.R. Bourland. 1980. Hardwood density and species composition in bottomland areas treated for regeneration. Southern Journal of Applied Forestry 4(3): 122-127.

Ingestad, T. 1982. Relative addition rate and external concentration: driving variables used in plant nutrition research. Plant, Cell and Environment 5: 443-453.

Jack, S.B. and J.N. Long. 1996. Linkages between silviculture and ecology: an analysis of density management diagrams. Forest Ecology and Management 86: 205-220.

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

Kellison, R.C., J.P. Martin, G. Hansen and R. Lea. 1988. Regenerating and managing natural stands of bottomland hardwoods. APA 88-A-6. Washington, D.C.: American Pulpwood Association Inc. 26 p.

Kellison, R.C., D.J. Frederick, and W.E. Gardner. 1981. A guide for regenerating and managing natural stands of Southern hardwoods. Bulletin 463. North Carolina Agricultural Service, Hardwood Research Program, School of Forest Resources, North Carolina State University, Raleigh, NC. 23 p.

Kellison, R.C. 1977. Changing the philosophies of hardwood management. In: USDA Forest Service, State and Private Forestry, Southeastern Area. Proceedings—Second Symposium on Southeastern Hardwoods, Dothan, Alabama, April 20-22, 1977. p. 107-113.

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

Kennedy, H.E. Jr. 1993. Effects of crown position and initial spacing on foliar nutrient composition of seven bottomland hardwoods. Research Note SO-371. New Orleans, LA: USDA Forest Service, Southern Forest Experiment Station. 6 p.

Kimmons, J.P. 1987. Biochemistry: cycling of nutrients in ecosystems. In: Forest Ecology. New York: Macmillan. p. 68-129.

Klute, A. (ed.) 1986. Methods of Soil Analysis: Part 1. Physical and Mineralogical Methods. Agronomy Monograph No. 9, 2nd ed. American Society of Agronomy, Inc., Soil Science Society of America, Inc., Madison, WI. p. 404-408.

Kormanik, P.P. 1990. Sweetgum. In: R.M. Burns and B.H. Honkala (Eds.) Silvics of North America. 2: Hardwoods. Agriculture Handbook 654. Washington, DC: USDA Forest Service, [Online]. Available: http://www.na.fs.fed.us/spfo/pubs/silvics_manual_table_of_contents.htm.

Kozlowski, T.T. and S.G. Pallardy. 1997. Physiology of Woody Plants, 2nd ed. Academic Press, CA, p. 120-121.

Kraft, G. 1884. Zur Lehre von den Durch Forstungen. Schlagstellungen und Lichtungseieben, Hannover (cited by Assmann 1970).

Krinard, R.M. 1990. Southern red oak. In: R.M. Burns and B.H. Honkala (eds.) Silvics of North America. 2: Hardwoods. Agriculture Handbook 654. Washington, DC: USDA Forest Service, [Online]. Available: http://www.na.fs.fed.us/spfo/pubs/silvics_manual_table_of_contents.htm.

Lamson, N.I., H.C. Smith, A.W. Perkey, and S.M. Brock. 1990. Crown release increases growth of crop trees. Research Paper NE-635. Radnor, PA: USDA Forest Service, Northeastern Forest Experiment Station. 8 p.

Lamson, N.I. and H.C. Smith. 1989. Crop-tree release increases growth of 12-year-old yellow-poplar and black cherry. Research Paper NE-622. Broomhall, PA: Northeastern Forest Experiment Station. 7 p.

Lamson, N.I. 1988. Precommercial thinning and pruning of Appalachian stump sprouts—10-year results. Southern Journal of Applied Forestry 12(1): 23-27.

Lamson, N.I. 1983. Precommercial thinning increases diameter growth of Appalachian hardwood stump sprouts. Southern Journal of Applied Forestry 7(2): 93-97.

Lamson, N.I. and H.C. Smith. 1978. Response to crop-tree release: sugar maple, red oak, black cherry, and yellow-poplar saplings in a 9-year-old stand. Broomhall, PA: Research Paper NE-394. USDA Forest Service, Northeastern Forest Experiment Station. 8 p.

Leak, W.B. 1983. Stocking, growth, and habit relations in New Hampshire hardwoods. Research Paper NE-523. Broomhall, PA: USDA Forest Service, Northeastern Forest Experiment Station. 11 p.

Linder, S. and D.A. Rook. 1984. Effects of mineral nutrition on carbon dioxide exchange and partitioning of carbon in trees. In: G.D. Bowen and E.K.S. Nambiar (eds.) Nutrition of Plantation Forests. London: Academic Press. p. 221-236.

Loftis, D. 1990. Predicting post-harvest performance of advance red oak reproduction in the Southern Appalachians. Forest Science 36(4): 908-916.

Loveless, C.M. 1959. A study of the vegetation in the Florida Everglades. Ecology 40(1): 1-9.

Luppold W., J. Prestemon and A. Schuler. 2002. The changing markets for hardwood roundwood. In: D. Zhang (ed.) Proceedings of the 2001 Southern Forest Economics Workshop, March 28-29, 2001, Atlanta, Georgia, School of Forestry and Wildlife Sciences, Auburn University. p. 96-100.

McCauley, O.D. and D.A. Marquis. 1972. Investment in precommercial thinning of northern hardwoods. Research Paper NE-245. Upper Darby, PA: USDA Forest Service, Northeastern Forest Experiment Station. 13 p.

McGee, C.E. and D.L. Loftis. 1992. Oak regeneration: a summary. In: D.L. Loftis and C.E. McGee (eds.) Oak Regeneration: Serious Problems, Practical Recommendations. Symposium Proceedings, September 8-10, 1992, Knoxville, Tennessee. p. 316-319.

McGee, C.E. 1982. Low-quality hardwood stands: opportunities for management in the interior uplands. General Technical Report SO-40. New Orleans, LA: USDA Forest Service, Southern Forest Experiment Station. 22 p.

McGee, C.E. and R.M. Hooper. 1970. Regeneration after clearcutting in the Southern Appalachians. Research Paper SE-70. Asheville, NC: USDA Forest Service, Southeastern Forest Experiment Station. 11 p.

McMillen, G.G. and J.H. McClendon. 1983. Dependence of photosynthetic rates on leaf density thickness in deciduous woody plants grown in sun and shade. Plant Physiology 72: 674-678.

Mehlich, A. 1984. Mehlich 3 soil extractant: a modification of Mehlich 2 extractant. Communications in Soil Science and Plant Analysis 15: 1409-1416.

Mewborn, B.M. 1997. Productivity, leaf area, and nutritional relationships in mid-rotation sweetgum and sycamore plantations. Master's Thesis. Department of Forestry, North Carolina State University, Raleigh, NC. 77 p.

Miller, G.W. 1984. Releasing young hardwood crop trees—use of a chain saw costs less than herbicides. Research Paper NE-550. Broomhall, PA: USDA Forest Service, Northeast Forest Experiment Station. 5 p.

Miller, H.G. and J.D. Miller. 1976. Effect of nitrogen supply on net primary production in Corsican pine. Journal of Applied Ecology 13: 249-256.

Miller, J.H., B.R. Zutter, S.M. Sedaker, M.B. Edwards, J.D. Haywood, and R.A. Newbold. 1991. A regional study on the influence of woody and herbaceous competition on early pine growth. Southern Journal of Applied Forestry 15(4): 169-179.

Mills, H.A. and J.B. Jones, Jr. 1996. Plant Analysis Handbook II: A Practical Sampling, Preparation, Analysis, and Interpretation Guide. Athens, GA: Micromacro Publishing. 422 p.

Nelson, L.E., M.G. Shelton, and G.L. Switzer. 1995. The influence of nitrogen application on the resorption of foliar nutrients in sweetgum. Canadian Journal of Forest Research 25: 298-306.

Newton, L.P. and D.J. Robison. 2001. Fertilization and thinning in a 7-year-old natural hardwood stand in eastern North Carolina. In: Proceedings of the Eleventh Biennial Southern Silvicultural Research Conference, Knoxville, TN, March 20-22, 2001. p. 190-192.

North Carolina State University. 1996. Average Growing Season for Selected North Carolina Locations—Jackson, Northampton County, NC. NCSU Horticulture Information Leaflet. North Carolina Cooperative Extension Service.

North Carolina State University Hardwood Research Cooperative. 2001. Thirty-seventh Annual Report. Raleigh, NC. 54 p.

O'Hara, K.L. 1986. Developmental patterns of residual oaks and oak and yellow poplar regeneration after release in upland hardwood stands. Southern Journal of Applied Forestry (10): 244-248.

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

Page, L.A., R.H. Miller and D.R. Keeney. 1982. Methods of Soil Analysis: Part 2. Chemical and Microbiological Properties. Madison, WI: American Society of Agronomy, Inc., Soil Science Society of America, Inc. 1159 p.

Peet, R.K. and N.L. Christensen. 1987. Competition and tree death. BioScience 37(8): 586-595.

Perala, D.A., R.A. Leary and C.J. Cieszewski. 1999. Self-thinning and stockability of the circumboreal aspens (*Populus tremuloides* Michx., and *P. tremula* L.). Research Paper NC-335. St. Paul, MN: USDA Forest Service, North Central Research Station. 16 p.

Permar, T.A. and R.F. Fisher. 1983. Nitrogen fixation and accretion by wax myrtle (*Myrica cerifera*) in a slash pine (*Pinus elliotti*) plantations. Forest Ecology and Management 5: 39-46.

Phillips, J.D. 1994. Forgotten hardwood forests of the Coastal Plain. Geographical Review 84(2): 162-171.

Porter, K.A. 1997. Productivity and leaf area relationships in Southeastern hardwood plantations. Master's Thesis. Department of Forestry, North Carolina State University, Raleigh, NC. 37 p.

Rapp, J., T. Shear, and D. Robison. 2001. Soil, groundwater, and floristics of a southeastern United States blackwater swamp 8 years after clearcutting with a helicopter and skidder extraction of the timber. Forest Ecology and Management 149: 241-252.

Resovsky, R.R. 1984. Growth response of naturally regenerated southern hardwoods to precommercial thinning with some basic economic implications. Master's Thesis. Department of Forestry, North Carolina State University, Raleigh, NC. 81 p.

Richardson, J.L. and M.J. Vepraskas. 2001. Wetland Soils: Genesis, Hydrology, Landscapes, and Classification. Boca Raton, Florida: Lewis Publishers. 417 p.

Robarge, W.P. and I. Fernandez. 1986. Standard operating procedure for measurement of exchangeable bases in 1 N NH_4Cl. In: Quality Assurance Methods Manual for Laboratory Analytical Techniques. United States Environmental Protection Agency and USDA Forest Service: Corvallis Environmental Research Laboratory, Corvallis, OR. p. 136-141.

Robison, D.J., B. Goldfarb and B. Li. 1998. Advancing hardwood production forestry. PaperAge. May: 22-24.

SAS Institute, Inc., SAS OnlineDoc®, Version 8, Cary, NC: SAS Institute, Inc., 1999.

Schafale, M.P. 1999. Nonriverine wet hardwood forests in North Carolina: status and trends. Raleigh, NC: North Carolina Natural Heritage Program, Division of Parks and Recreation (unpublished division report). 8 p.

Schlaegel, B.E. 1990. Willow oak. In: R.M. Burns and B.H. Honkala (Eds.) Silvics of North America. 2: Hardwoods. Agriculture Handbook 654. Washington, DC: USDA Forest Service, [Online]. Available: http://www.na.fs.fed.us/spfo/pubs/silvics_manual_table_of_contents.htm.

Schuler, J.L. and D.J. Robison. 2003. Identifying acceptable stocking levels in young, mixed hardwood stands in the Piedmont. In: Proceedings of the Twelfth Biennial Southern Silvicultural Research Conference, Biloxi, MS, February 24-28, 2003. (*in press*)

Schuler, J.L. and D.J. Robison. 2001. Response of 1- to 4-year-old upland hardwood stands to stocking and site manipulations. In: Proceedings of the Eleventh Biennial Southern Silvicultural Research Conference, Knoxville, TN, March 20-22, 2001. p. 266-269.

Scott, D.A., D.J. Kaczmarek, J.A. Burger and M.B. Kane. 2001. Sweetgum response to nitrogen fertilization on sites of different quality and land use history. In: Proceedings of the Eleventh Biennial Southern Silvicultural Research Conference, Knoxville, TN, March 20-22, 2001. p. 223-228.

Smith, D.M., B.C. Larson, M.J. Kelty and P.M.S. Ashton. 1997. The Practice of Silviculture: Applied Forest Ecology, 9th ed. New York: John Wiley & Sons, Inc. 537 p.

Smith, H.C. and N.I. Lamson. 1983. Precommercial crop-tree release increases diameter growth of Appalachian hardwood saplings. Research Paper NE-534. Broomhall, PA: USDA Forest Service, Northeastern Forest Experiment Station. 7 p.

Smith, H.C. and R.E. McCay. 1979. Estimating time required to cut grapevines in young, even-aged hardwood stands. Southern Journal of Applied Forestry 3(3): 125-127.

Smith, W.B., J.S. Vissage, D.R. Darr and R.M. Sheffield. 2001. Forest resources of the United States, 1997. General Technical Report NC-219. St. Paul, MN: USDA Forest Service, North Central Research Station. 190 p.

Sonderman, D.L. 1985. Stand density—a factor affecting stem quality of young hardwoods. Research Paper NE-561. Broomhall, PA: USDA Forest Service, Northeastern Forest Experiment Station. 8 p.

Southeast Regional Climate Center. 2003. Roanoke Rapids, North Carolina—Period of Record General Climate Summary, Year 1972 to Year 2000. http://cirrus.dnr.state.sc.us/cgi_bin/sercc/cliMAIN.pl?nc7319.

Steinbeck, K. and K. Kuers. 1996. Development of pine-hardwood mixtures following clearcutting on two upland sites in the Georgia Piedmont: 10 year results. Southern Journal of Applied Forestry 20(4): 203-208.

Stone, D.M. 1977. Fertilizing and thinning northern hardwoods in the lake states. Research Paper NC-141. St. Paul, MN: USDA Forest Service, North Central Forest Experiment Station. 7 p.

Tift, B.D. and M.A. Fajvan. 1999. Red maple dynamics in Appalachian hardwood stands in West Virginia. Canadian Journal of Forest Research 29: 157-165.

Tolliver, K.S., D.M. Colley, and D.R. Young. 1995. Inhibitory effects of *Myrica cerifera* on *Pinus taeda*. American Midland Naturalist 133: 256-263.

Trimble, G.R. Jr. 1974. Response to crop-tree release by 7-year-old stems of red maple stump sprouts and northern red oak advance reproduction. Research Paper NC-303. St. Paul, MN: USDA Forest Service, North Central Forest Experiment Station. 6 p.

Trimble, G.R. Jr. 1973. Response to crop-tree release by 7-year-old stems of yellow-poplar and black cherry. Research Paper NE-253. Upper Darby, PA: USDA Forest Service, Northeastern Forest Experiment Station. 10 p.

Van Deelen, T.R. 1991. *Myrica cerifera.* In: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Fire Sciences Laboratory (2003, April). Fire Effects Information System, [Online]. Available: http://www.fs.fed.us/database/feis/plants/tree/myrcer/all.html.

Vose, J.M., P.M. Dougherty, J.N. Long, F.W. Smith, H.L. Gholz and P.J. Curran. 1994. Factors influencing the amount and distribution of leaf area of pine stands. Ecological Bulletins 43: 102-114.

Vozzo, J.A. 1990. Water oak. In: R.M. Burns and B.H. Honkala (eds.) Silvics of North America. 2: Hardwoods. Agriculture Handbook 654. Washington, DC: USDA Forest Service, [Online]. Available: http://www.na.fs.fed.us/spfo/pubs/silvics_manual_table_of_contents.htm.

Waldrop, T.A. 1997. Four site-preparation techniques for regenerating pine-hardwood mixtures in the Piedmont. Southern Journal of Applied Forestry 21(3): 116-122.

Walker, L.C. and B.P. Oswald. 2000. The Southern Forest: Geography, Ecology, and Silviculture. Boca Raton, FL: CRC Press. 332 p.

Walters, R.S. and H.W. Yawney. 1990. Red maple. In: R.M. Burns and B.H. Honkala (eds.) Silvics of North America. 2: Hardwoods. Agriculture Handbook 654. Washington, DC: USDA Forest Service, [Online]. Available: http://www.na.fs.fed.us/spfo/pubs/silvics_manual_table_of_contents.htm.

Wear, D.N. and J.G. Greis. 2002. The Southern Forest Resource Assessment: Summary Report. General Technical Report SRS-54. Asheville, NC: USDA Forest Service, Southern Research Station. 103 p.

Wendel, G.W. and G.R. Trimble, Jr. 1968. Early reproduction after seed-tree harvest cuttings in Appalachian hardwoods. Research Paper NE-99. Upper Darby, PA: USDA Forest Service, Northeastern Forest Experiment Station. 16 p.

Westerman, R.L. 1990. Soil Testing and Plant Analysis, 3rd ed. Madison, WI: Soil Science Society of America. p. 406.

Wood, T. and F.H. Bormann. 1984. Phosphorus cycling in a northern hardwood forest: biological and chemical control. Science 223: 391-393.

Zahner, R. and R.K. Myers. 1984. Productivity of young Piedmont oak stands of sprout origin. Southern Journal of Applied Forestry 8(2): 102-108.

Table 1. Number of stems per hectare (Mean ± S.E.) for all trees > 1.4 m ht in 1997, immediately after thinning treatments were imposed.

Treatment (n = 3)	All tree species	Sweetgum	Red maple	Oaks (combined)
CONTROL	22339 ± 7370	11295 ± 6868	9807 ± 1166	950 ± 207
PRE-FERT*	19130 ± 467	4769 ± 1103	13662 ± 1446	574 ± 202
THIN	8053 ± 1566	3961 ± 1510	3675 ± 960	417 ± 136
THIN+PRE-FERT	7261 ± 1238	3532 ± 659	3586 ± 1029	125 ± 100
ANOVA (df 5, 6) P values				
Block	.0620[a]	.0726[a]	.0033	.1169
Thin	.0007	.1093	<.0001	.0109
Pre-Fert	.6399	.3778	.0109	.0484
Thin x Pre-Fert	.9102	.3928	.0089	.7634
F values	10.18	2.73	61.30	5.13

* "*Pre-Fert"* indicates measurements taken prior to installation of the *Fert* treatment on these plots.
[a]ANOVA for this variable based on $\log_{10}$ transformation.

Table 2. Number of stems per hectare (Mean ± S.E.) by diameter class (< 3.8 cm dbh and ≥ 3.8 cm dbh) for all trees > 1.4 m ht in 1997, immediately after thinning treatments were imposed.

	All tree species		Sweetgum		Red maple		Oaks (combined)	
Treatment (n = 3)	**< 3.8**	**≥ 3.8**	**< 3.8**	**≥ 3.8**	**< 3.8**	**≥ 3.8**	**< 3.8**	**≥ 3.8**
CONTROL	21138 ± 7420	1201 ± 221	10381 ± 6823	914 ± 204	9664 ± 1228	143 ± 65	807 ± 173	143 ± 36
PRE-FERT*	17947 ± 516	1183 ± 285	3873 ± 956	896 ± 311	13465 ± 1449	197 ± 36	484 ± 135	90 ± 89
THIN	6941 ± 1837	1111 ± 428	3070 ± 1864	890 ± 368	3526 ± 953	149 ± 52	345 ± 126	72 ± 47
THIN+PRE-FERT	5683 ± 1236	1558 ± 202	2169 ± 502	1363 ± 171	3371 ± 1042	215 ± 31	125 ± 31	0 ± 0
ANOVA (df 5, 6) P values								
Block	.0403[a]	.3635	.0444[a]	.3511	.0029	.4895	.3141	.0499
Thin	.0006	.6183	.0433	.4392	<.0001	.8154	.0194	.0760
Pre-Fert	.5329	.4692	.3845	.4276	.0123	.2684	.0813	.1469
Thin x Pre-Fert	.7324	.4361	.4069	.3941	.0086	.9069	.7046	.8199
F values	11.23	0.80	3.83	0.95	62.32	0.63	3.48	3.54

***** "*Pre-fert*" indicates measurements taken prior to installation of the *Fert* treatment on these plots.

[a] ANOVA for this variable based on $\log_{10}$ transformation.

Table 3. Number of stems per hectare (Mean ± S.E.) for all trees > 1.4 m ht in 2001, 4 years after the thinning treatments and 3 years after fertilization treatments were imposed.

Treatment (n = 3)	All tree species	Sweetgum	Red maple	Oaks (combined)
CONTROL	23433 ± 8490	11116 ± 7313	10704 ± 1395	1111 ± 225
FERT	18736 ± 2069	4195 ± 915	13716 ± 2484	663 ± 147
THIN	12901 ± 4533	4874 ± 2352	7264 ± 2125	512 ± 94
THIN+FERT	9395 ± 2166	4249 ± 1007	4984 ± 1225	161 ± 107
ANOVA (df 5, 6) P values				
Block	.0063[a]	.0452[a]	.0003[b]	.1769[b]
Thin	.0029	.4013	<.0001	.0041
Fert	.2215	.4171	.8856	.0141
Thin x Fert	.6222	.3831	.0053	.5488
F values	10.38	2.66	41.61	7.41

[a] ANOVA for this variable based on $\log_{10}$ transformation.
[b] ANOVA for this variable based on square root transformation.

Table 4. Number of stems per hectare (Mean ± S.E.) by diameter class (< 3.8 cm dbh and ≥ 3.8 cm dbh) of trees > 1.4 m ht in 2001, 4 years after thinning treatments and 3 years after fertilization treatments were imposed.

	All tree species		Sweetgum		Red maple		Oaks (combined)	
Treatment (n = 3)	**< 3.8**	**≥ 3.8**	**< 3.8**	**≥ 3.8**	**< 3.8**	**≥ 3.8**	**< 3.8**	**≥ 3.8**
CONTROL	20672 ± 8236	2761 ± 282	9341 ± 6831	1775 ± 544	10291 ± 1569	412 ± 190	681 ± 47	430 ± 269
FERT	15240 ± 2707	3496 ± 358	2295 ± 421	1900 ± 529	12497 ± 2494	1219 ± 289	412 ± 65	251 ± 125
THIN	10602 ± 4780	2299 ± 337	3326 ± 2345	1548 ± 52	6675 ± 2465	589 ± 355	350 ± 47	163 ± 61
THIN+FERT	6042 ± 1878	3353 ± 289	1972 ± 756	2277 ± 251	3980 ± 1211	1004 ± 47	90 ± 36	72 ± 72
ANOVA (df 5, 6) P values								
Block	.0050[a]	.6614	.0278[a]	.0277	.0009	.2170	.6629	.0987
Thin	.0024	.4112	.1469	.8407	.0002	.9339	.0009	.1173
Fert	.1117	.0401	.2221	.2752	.7465	.0345	.0026	.3108
Thin x Fert	.4476	.6587	.3958	.4290	.0148	.4167	.9361	.7307
F values	11.68	1.74	3.86	1.27	27.54	2.40	12.50	2.34

[a] ANOVA for this variable based on $\log_{10}$ transformation.

Table 5. Incremental change in number of stems per hectare (Mean ± S.E.) for all trees > 1.4 m ht between 1997 and 2001.

Treatment (n = 3)	All tree species	Sweetgum	Red maple	Oaks (combined)
CONTROL	1094 ± 1121	-179 ± 446	896 ± 442	161 ± 54
FERT	-394 ± 2116	-574 ± 289	54 ± 1813	90 ± 72
THIN	4848 ± 3332	913 ± 926	3589 ± 2385	96 ± 70
THIN+FERT	2133 ± 994	717 ± 521	1398 ± 567	36 ± 18
ANOVA (df 5, 6) P values				
Block	.0115	.0749	.0247	.4051
Thin	.0350	.0368	.0802	.3373
Fert	.1196	.5322	.1653	.2951
Thin x Fert	.6155	.8309	.5091	.9204
F values	6.30	3.18	4.40	0.90

Table 6. Incremental change by diameter class (< 3.8 cm dbh and ≥ 3.8 cm dbh) in number of stems per hectare (Mean ± S.E.) of all trees > 1.4 m ht between 1997 and 2001.

	All tree species		Sweetgum		Red maple		Oaks (combined)	
Treatment (n = 3)	**< 3.8**	**≥ 3.8**	**< 3.8**	**≥ 3.8**	**< 3.8**	**≥ 3.8**	**< 3.8**	**≥ 3.8**
CONTROL	- 466 ± 830	1160 ± 315	-1040 ± 18	861 ± 441	627 ± 574	269 ± 135	-126 ± 211	286 ± 233
FERT	-2707 ± 2138	2313 ± 173	-1578 ± 559	1004 ± 421	- 968 ± 2024	1022 ± 315	-72 ± 109	161 ± 54
THIN	3661 ± 3102	1188 ± 434	255 ± 545	657 ± 385	3149 ± 2610	439 ± 308	4 ± 97	91 ± 64
THIN+FERT	359 ± 863	1775 ± 296	- 197 ± 335	914 ± 189	609 ± 583	789 ± 65	-36 ± 65	72 ± 72
ANOVA (df 5, 6) P values								
Block	.0150	.4661	.3592	.0565	.0222	.2188	.1171	.3316
Thin	.0192	.2092	.0178	.6025	.0965	.8854	.4677	.2931
Fert	.0501	.0837	.2763	.4809	.0942	.0385	.9519	.5798
Thin x Fert	.6563	.8062	.9214	.8383	.6661	.3712	.6754	.6834
F values	6.92	1.61	2.87	2.11	4.68	2.38	1.41	0.90

Table 7. Number of very small stems < 1.4 m ht per hectare (Mean ± S.E.) in 1997, immediately after thinning treatments were imposed ; in 2001, after 4 years of thinning and 3 years of fertilization effect; and incremental change in density from 1997 to 2001.

	1997			2001			Period 'growth' 1997-2001		
Treatment (n = 3)	**All species**	**SG**	**RM**	**All species**	**SG**	**RM**	**All species**	**SG**	**RM**
CONTROL	6796 ± 3367	2008 ± 1158	4016 ± 1782	5648 ± 2697	2869 ± 1665	2079 ± 945	-1147 ± 1959	860 ± 861	-1936 ± 1104
FERT	5397 ± 2011	610 ± 323	4518 ± 1585	1363 ± 147	108 ± 31	1183 ± 135	-4034 ± 2134	-502 ± 293	-3335 ± 1698
THIN	3326 ± 1458	563 ± 368	2491 ± 917	19640 ± 9189	5153 ± 3664	13707 ± 5192	16314 ± 7795	4590 ± 3300	11216 ± 4428
THIN+FERT	1757 ± 881	592 ± 285	1058 ± 566	17248 ± 7620	1327 ± 389	15724 ± 7338	15491 ± 6780	735 ± 289	14666 ± 6793
ANOVA (df 5, 6) P values									
Block	.0084[a]	.0862[b]	.0141	.3691[a]	.0452[a]	.3958[a]	.6368	.3372	.7389
Thin	.0128	.1763	.0153	.0221	.0105	.0158	.0182	.1841	.0146
Fert	.1751	.3228	.5541	.2252	.0052	.5773	.7578	.1659	.8305
Thin x Fert	.4979	.3358	.2406	.5169	.0756	.9729	.8634	.4799	.6162
F values	7.73	2.44	6.43	2.81	9.43	2.72	2.29	1.59	2.50

[a] ANOVA for this variable based on square root transformation.
[b] ANOVA for this variable based on $\log_{10}$ transformation.

Table 8. Basal area (m^2/ha) of all trees > 1.4 m ht (Mean ± S.E.) in 1997, immediately after thinning treatments were imposed.

Treatment (n = 3)	All tree species	Sweetgum	Red maple	Oaks (combined)
CONTROL	6.5 ± 1.0	4.4 ± 1.2	1.5 ± 0.3	0.5 ± 0.2
PRE-FERT	5.8 ± 1.1	3.2 ± 0.9	2.3 ± 0.3	0.3 ± 0.2
THIN	4.2 ± 1.0	3.0 ± 0.6	1.0 ± 0.3	0.2 ± 0.1
THIN+PRE-FERT	5.3 ± 0.7	4.2 ± 0.7	1.0 ± 0.1	0.03 ± 0.02
ANOVA (df 5, 6) P values				
Block	.4627	.3955	.1300	.0016
Thin	.2047	.8591	.0135	.0096
Pre-Fert	.8387	.9763	.1915	.0623
Thin x Pre-Fert	.4254	.2344	.2180	.9133
F values	0.91	0.79	4.37	7.95

* *"Pre-fert"* indicates measurements taken prior to installation of the *Fert* treatment on these plots.

Table 9. Basal area (m^2/ha) of all trees by diameter class (< 3.8 cm dbh and ≥ 3.8 cm dbh) (Mean ± S.E.) in 1997, immediately after thinning treatments were imposed.

	All tree species		Sweetgum		Red maple		Oaks (combined)	
Treatment (n = 3)	**< 3.8**	**≥3.8**	**< 3.8**	**≥ 3.8**	**< 3.8**	**≥ 3.8**	**< 3.8**	**≥ 3.8**
CONTROL	3.6 ± 0.9	2.9 ± 0.6	2.1 ± 1.1	2.3 ± 0.5	1.2 ± 0.2	0.3 ± 0.2	0.25 ± 0.1	0.29 ± 0.1
PRE-FERT	3.2 ± 0.3	2.7 ± 0.8	1.0 ± 0.2	2.2 ± 0.8	1.9 ± 0.4	0.3 ± 0.1	0.18 ± 0.03	0.15 ± 0.1
THIN	1.5 ± 0.1	2.7 ± 1.1	0.8 ± 0.3	2.3 ± 1.0	0.7 ± 0.3	0.3 ± 0.1	0.07 ± 0.02	0.15 ± 0.1
THIN+PRE-FERT	1.4 ± 0.3	3.9 ± 0.7	0.8 ± 0.1	3.5 ± 0.6	0.6 ± 0.1	0.4 ± 0.1	0.03 ± 0.03	0.0 ± 0.0
ANOVA (df 5, 6) P values								
Block	.5258[a]	.1475	.0848[a]	.1263	.0814	.2244	.1772	----
Thin	.0015	.4889	.0887	.3417	.0041	.8710	.0313	----
Pre-Fert	.5854	.5168	.6582	.4110	.1754	.4927	.4349	----
Thin x Pre-Fert	.9838	.3655	.2838	.3472	.0890	.6011	.8015	----
F values	6.41	1.47	2.68	1.77	6.93	0.95	2.66	----

* *"Pre-fert"* indicates measurements taken prior to installation of the *Fert* treatment on these plots.

[a] ANOVA for this variable based on $\log_{10}$ transformation.

Table 10. Basal area (m^2/ha) of all trees > 1.4m ht (Mean ± S.E.) in 2001, 4 years after thinning treatments and 3 years after fertilization treatments were imposed.

Treatment (n = 3)	All tree species	Sweetgum	Red maple	Oaks (combined)
CONTROL	13.8 ± 1.3	8.4 ± 2.3	3.1 ± 0.6	1.8 ± 1.0
FERT	16.8 ± 2.2	9.8 ± 3.1	5.7 ± 0.9	1.0 ± 0.5
THIN	10.2 ± 2.2	6.7 ± 1.4	2.5 ± 0.9	0.9 ± 0.1
THIN+FERT	16.2 ± 1.0	12.6 ± 1.1	3.5 ± 0.1	0.2 ± 0.2
ANOVA (df 5, 6) P values				
Block	.0366	.0490	.2006	.0161[a]
Thin	.1183	.7305	.0622	.0211
Fert	.0083	.0511	.0273	.0141
Thin x Fert	.2376	.1722	.2148	.3441
F values	6.42	3.77	3.96	8.02

[a] ANOVA for this variable based on square root transformation.

Table 11. Basal area (m^2/ha) by diameter class (< 3.8 cm dbh and ≥ 3.8 cm dbh) of all trees > 1.4 m ht (Mean ± S.E.) in 2001, 4 years after thinning treatments and 3 years after fertilization treatments were imposed.

	All tree species		Sweetgum		Red maple		Oaks (combined)	
Treatment (n = 3)	**< 3.8**	**≥3.8**	**< 3.8**	**≥ 3.8**	**< 3.8**	**≥ 3.8**	**< 3.8**	**≥ 3.8**
CONTROL	5.0 ± 1.4	8.9 ± 1.3	2.5 ± 1.5	5.9 ± 1.5	2.1 ± 0.3	1.0 ± 0.6	0.25 ± 0.02	1.6 ± 1.0
FERT	3.9 ± 0.3	12.9 ± 2.4	0.8 ± 0.1	8.9 ± 2.9	3.0 ± 0.4	2.8 ± 0.6	0.11 ± 0.02	0.8 ± 0.5
THIN	2.0 ± 0.4	8.1 ± 2.6	0.7 ± 0.4	6.0 ± 1.8	1.2 ± 0.3	1.4 ± 0.9	0.11 ± 0.02	0.8 ± 0.1
THIN+FERT	1.3 ± 0.2	14.9 ± 1.2	0.4 ± 0.1	12.2 ± 1.1	0.9 ± 0.2	2.6 ± 0.1	0.01 ± 0.02	0.2 ± 0.2
ANOVA (df 5, 6) P values								
Block	.0561[a]	.0021	.0390[a]	.0084	.0021	.2145	.9865	----
Thin	.0004	.4791	.0201	.0042	<.0001	.8456	.0013	----
Fert	.0854	.0006	.1851	.0042	.0626	.0326	.0013	----
Thin x Fert	.4178	.1465	.3733	.1743	.0037	.6435	.3996	----
F values	12.87	17.44	4.94	9.66	41.37	2.39	13.04	----

[a] ANOVA for this variable based on $\log_{10}$ transformation.

Table 12. Incremental growth in basal area (m^2/ha) for all trees > 1.4 m ht (Mean ± S.E.) between 1997 and 2001.

Treatment (n = 3)	All tree species	Sweetgum	Red maple	Oaks (combined)
CONTROL	7.4 ± 0.3	4.1 ± 1.1	1.6 ± 0.3	1.3 ± 0.8
FERT	11.0 ± 1.5	6.5 ± 2.3	3.5 ± 0.6	0.6 ± 0.3
THIN	6.0 ± 1.6	3.6 ± 1.2	1.6 ± 0.5	0.7 ± 0.1
THIN+FERT	11.0 ± 1.0	8.3 ± 0.9	2.5 ± 0.2	0.2 ± 0.1
ANOVA (df 5, 6) P values				
Block	.0553	.0325	.3445	.1376
Thin	.4447	.4969	.3080	.2032
Fert	.0028	.0102	.0192	.1587
Thin x Fert	.4666	.2931	.3091	.8653
F values	6.94	5.66	3.02	2.06

Table 13. Incremental basal area (m^2/ha) growth by diameter class (< 3.8 cm dbh and ≥ 3.8 cm dbh) in basal area for trees > 1.4 m ht (Mean ± S.E.) between 1997 and 2001.

	All tree species		Sweetgum		Red maple		Oaks (combined)	
Treatment (n = 3)	**< 3.8**	**≥3.8**	**< 3.8**	**≥ 3.8**	**< 3.8**	**≥ 3.8**	**< 3.8**	**≥ 3.8**
CONTROL	1.3 ± 0.6	6.0 ± 0.6	0.4 ± 0.5	3.7 ± 1.0	0.9 ± 0.3	0.7 ± 0.4	0.1 ± 0.1	1.3
FERT	0.7 ± 0.5	10.3 ± 1.9	-0.2 ± 0.1	6.8 ± 2.4	1.0 ± 0.4	2.4 ± 0.6	-0.1 ± 0.05	0.7
THIN	0.5 ± 0.3	5.5 ± 2.0	-0.1 ± 0.1	3.7 ± 1.1	0.5 ± 0.3	1.1 ± 0.7	.05 ± 0.02	0.6
THIN+FERT	-0.1 ± 0.2	11.1 ± 1.0	-0.3 ± 0.1	8.7 ± 0.9	0.3 ± 0.2	2.2 ± 0.1	-.02 ± 0.03	----
ANOVA (df 5, 6) P values								
Block	.0514	.0106	.3301	.0213	.0503	.2300	.1995	----
Thin	.0366	.8999	.2719	.3252	.0440	.8554	.4564	----
Fert	.0996	.0009	.0976	.0046	.9156	.0271	.3090	----
Thin x Fert	.9936	.4246	.4893	.3428	.4842	.5398	.9603	----
F values	4.22	11.93	1.71	7.44	3.46	2.54	1.23	----

Table 14. Individual tree diameter, height and stand volume index (VT_I) for trees ≥ 3.81 cm dbh (Mean ± S.E.) in 1997, immediately after thinning treatments were imposed.

Treatment (n = 3)	All tree species			Sweetgum			Red maple		
	dbh (cm)	ht (m)	VT_I (m^3/ha)	dbh (cm)	ht (m)	VT_I (m^3/ha)	dbh (cm)	ht (m)	VT_I (m^3/ha)
CONTROL	5.4 ± 0.1	5.6 ± 0.1	5.6 ± 1.3	5.5 ± 0.2	5.8 ± 0.1	4.5 ± 1.1	5.0 ± 0.4	5.8 ± 0.5	0.6 ± 0.4
FERT	5.2 ± 0.2	5.5 ± 0.1	5.0 ± 1.5	5.4 ± 0.3	5.5 ± 0.1	4.1 ± 1.6	4.6 ± 0.1	5.6 ± 0.01	0.6 ± 0.1
THIN	5.2 ± 0.3	5.3 ± 0.3	5.1 ± 2.2	5.3 ± 0.3	5.3 ± 0.3	4.4 ± 2.0	4.6 ± 0.2	5.2 ± 0.5	0.5 ± 0.2
THIN+FERT	5.4 ± 0.3	5.7 ± 0.2	7.7 ± 1.7	5.5 ± 0.3	5.7 ± 0.2	6.9 ± 1.5	4.8 ± 0.2	5.7 ± 0.2	0.7 ± 0.1
ANOVA (df 5, 6) P values									
Block	.0453	.1428	.1174	.0652	.2123	.1063	.1722	.3795	.1728
Thin	.8141	.5843	.4544	.9808	.3900	.3240	.6635	.5093	.9691
Fert	.9952	.5265	.5111	.9970	.8406	.4085	.4931	.7439	.6185
Thin x Fert	.3093	.2201	.306	.4974	.1536	.2868	.2254	.3865	.4988
F values	2.42	1.63	1.73	1.89	1.53	1.99	1.47	0.77	1.11

Table 15. Individual tree diameter, height and stand volume index (VT_I) for trees ≥ 3.81 cm dbh (Mean ± S.E.) in 2001, 4 growing seasons after the thinning treatments and 3 years after fertilization.

Treatment (n = 3)	All tree species			Sweetgum			Red maple		
	dbh (cm)	ht (m)	VT_I (m^3/ha)	dbh (cm)	ht (m)	VT_I (m^3/ha)	dbh (cm)	ht (m)	VT_I (m^3/ha)
CONTROL	6.2 ± 0.5	6.9 ± 0.5	22.5 ± 4.9	6.5 ± 0.7	7.2 ± 0.5	15.5 ± 4.8	5.2 ± 0.4	6.4 ± 0.3	2.4 ± 1.5
FERT	6.4 ± 0.2	7.3 ± 0.3	35.5 ± 8.3	7.3 ± 0.3	7.7 ± 0.3	25.9 ± 9.3	5.3 ± 0.2	6.9 ± 0.1	6.7 ± 1.4
THIN	6.2 ± 0.6	6.7 ± 0.6	20.9 ± 8.1	6.6 ± 0.9	6.9 ± 0.7	15.5 ± 5.8	5.2 ± 0.1	6.1 ± 0.5	3.2 ± 2.1
THIN+FERT	7.2 ± 0.5	7.5 ± 0.3	41.9 ± 6.0	7.9 ± 0.7	7.8 ± 0.3	35.1 ± 5.5	5.6 ± 0.2	6.9 ± 0.2	6.5 ± 0.6
ANOVA (df 5, 6) P values									
Block	.0099	.0067	.0002	.0032	.0038	.0019	.2530	.1273	.1694
Thin	.1941	.9421	.2598	.2418	.7704	.1351	.5685	.6599	.8355
Fert	.0699	.0341	.0001	.0145	.0158	.0014	.3673	.0634	.0289
Thin x Fert	.2345	.3373	.0791	.4225	.3385	.1364	.5281	.6185	.7303
F values	6.13	6.88	37.18	9.71	8.93	15.88	1.05	2.32	2.64

Table 16. Incremental growth in individual tree diameter and height, and stand volume index (VT_I) for trees ≥ 3.81 cm dbh (Mean ± S.E.) between 1997 and 2001, after 4 growing seasons for the thinning treatments and 3 growing seasons for the fertilization treatments.

Treatment (n = 3)	All tree species			Sweetgum			Red maple		
	dbh (cm)	ht (m)	VT_I (m^3/ha)	dbh (cm)	ht (m)	VT_I (m^3/ha)	dbh (cm)	ht (m)	VT_I (m^3/ha)
CONTROL	0.8 ± 0.4	1.3 ± 0.4	16.8 ± 3.7	1.0 ± 0.5	1.4 ± 0.5	11.0 ± 3.7	0.2 ± 0.2	0.6 ± 0.3	1.8 ± 1.2
FERT	1.3 ± 0.3	1.8 ± 0.2	30.5 ± 7.1	1.9 ± 0.1	2.1 ± 0.2	21.7 ± 8.2	0.7 ± 0.02	1.3± 0.1	6.1 ± 1.5
THIN	1.0 ± 0.3	1.4 ± 0.2	15.6 ± 6.5	1.3 ± 0.6	1.6 ± 0.3	11.1 ± 4.3	0.6 ± 0.03	0.9 ± 0.1	2.7 ± 1.9
THIN+FERT	1.8 ± 0.3	1.9 ± 0.1	34.2 ± 5.1	2.4 ± 0.5	2.2 ± 0.2	28.2 ± 4.6	0.8 ± 0.05	1.2 ± 0.2	5.7 ± 0.6
ANOVA (df 5, 6) P values									
Block	.1017	.0013[a]	.0003	.0062	.0012[a]	.0058[b]	.9911	.7823	.1888
Thin	.2080	.4747	.4933	.1232	.6726	.3063	.2908	.6437	.8258
Fert	.0528	.0038	<.0001	.0036	.0017	.0016	.1119	.0705	.0231
Thin x Fert	.5769	.7402	.2039	.6509	.8882	.2598	.5509	.4472	.6226
F values	3.0	14.2	34.13	10.29	15.79	11.96	1.04	1.25	2.79

[a] ANOVA for this variable based on square transformation.
[b] ANOVA for this variable based on $\log_{10}$ transformation.

Table 17. Percent canopy cover (Mean ± S.E.) in 2000.

Treatment (n = 3)	**Percent Canopy Cover**
CONTROL	77.5 ± 4.8
FERT	86.2 ± 1.5
THIN	56.2 ± 10.3
THIN+FERT	82.9 ± 1.9
ANOVA (df 5, 6) **P values**	
Block	.0887
Thin	.0344
Fert	.0076
Thin x Fert	.0929
F values	6.88

Table 18. Litterfall collection (kg/ha) (Mean ± S.E.) over one year (October 2000 through September 2001).

Treatment (n = 3)	All species	Sweetgum	Red maple	Oak spp.	Other Trees	Shrubs/Vines	Twigs, Seeds, Bark (all species)
CONTROL	4088 ± 181	1614 ± 314	966 ± 229	767 ± 389	139 ± 131	283 ± 80	141 ± 28
FERT	5745 ± 233	2930 ± 308	1618 ± 281	535 ± 235	27 ± 22	87 ± 29	208 ± 61
THIN	3247 ± 489	1485 ± 348	973 ± 263	409 ± 183	10 ± 4	205 ± 32	34 ± 9
THIN+FERT	5633 ± 117	3115 ± 587	1625 ± 457	174 ± 164	141 ± 136	110 ± 42	114 ± 84
ANOVA (df 5, 6) P values							
Block	.3322	.2321	.4946	.0028[a]	.5928	.5647	.1305[b]
Thin	.1405	.9416	.9834	.0106	.9453	.6128	.0129
Fert	.0004	.0070	.0941	.0411	.9292	.0323	.2109
Thin x Fert	.2410	.6839	.9998	.9998	.2726	.3747	.6494
F values	11.85	4.01	1.11	11.51	0.52	2.03	4.05

[a] ANOVA for this variable based on square transformation.
[b] ANOVA for this variable based on $\log_{10}$ transformation.

Table 19. Sweetgum foliar nutrient concentrations (Mean ± S.E.) (collected August 2000, age 10).

Treatment (n = 3)	N	P	K	Ca	Mg	S	Mn	B	Cu	Zn
	% dry weight						ppm			
CONTROL	1.01 ± .09	0.22 ± .02	0.68 ± .05	0.85 ± .11	0.33 ± .03	0.13 ± .01	1225 ± 561	27 ± 1.4	4.2 ± .3	47 ± 1.9
FERT	1.42 ± .04	0.18 ± .01	0.77 ± .06	0.78 ± .05	0.37 ± .04	0.15 ± .01	1037 ± 42	27 ± 1.7	5.0 ± .1	54 ± 5.6
THIN	1.07 ± .07	0.22 ± .02	0.73 ± .06	0.97 ± .07	0.35 ± .03	0.13 ± .01	1007 ± 123	27 ± 0.6	4.8 ± .6	50 ± 2.9
THIN+FERT	1.52 ± .06	0.20 ± .02	0.62 ± .12	0.79 ± .05	0.35 ± .01	0.17 ± .01	1315 ± 293	26 ± 3.7	5.9 ± .2	55 ± 5.9
ANOVA (df 5, 6) P values										
Block	.1550	.0346	.0299	.5184	.0102	.5325	.1568	.2390	.3375	.3250
Thin	.2272	.4640	.3274	.4342	.9930	.1835	.9165	.9461	.0667	.6823
Fert	.0003	.0366	.7958	.1480	.3227	.0088	.8339	.6901	.0271	.2341
Thin x Fert	.7481	.4810	.1114	.4623	.1976	.3782	.4003	.6767	.6339	.8680
F values	12.04	4.15	3.61	1.11	4.99	3.82	1.20	0.81	3.26	0.94

Table 20. Red maple foliar nutrient concentrations (Mean ± S.E.) (collected August 2000, age 10).

Treatment (n = 3)	N	P	K	Ca	Mg	S	Mn	B	Cu	Zn
	% dry weight						ppm			
CONTROL	1.22 ± .03	0.21 ± .03	0.62 ± .08	1.28 ± .09	0.26 ± .01	0.13 ± .01	1359 ± 473	30 ± 2.8	8.5 ± 1.9	31 ± 1.4
FERT	1.62 ± .07	0.20 ± .01	0.65 ± .03	1.43 ± .16	0.29 ± .02	0.15 ± .02	1123 ± 96	31 ± 2.5	7.9 ± 0.3	36 ± 1.7
THIN	1.27 ± .09	0.21 ± .02	0.68 ± .05	1.01 ± .16	0.27 ± .01	0.13 ± .00	749 ± 102	29 ± 1.7	6.9 ± 0.8	30 ± 0.6
THIN+FERT	1.54 ± .06	0.21 ± .01	0.62 ± .04	1.24 ± .02	0.31 ± .02	0.16 ± .02	1170 ± 154	32 ± 1.5	9.8 ± 1.4	41 ± 1.9
ANOVA (df 5, 6) P values										
Block	.7170	.3128	.0305	.0813	.1784	.1171[a]	.5023	.8075	.8638	.9548
Thin	.8510	.7076	.6363	.0453	.2796	.5572	.3457	.9400	.9045	.1956
Fert	.0047	.6908	.6484	.0810	.0139	.0363	.7490	.3932	.4533	.0026
Thin x Fert	.3850	.8311	.1752	.7021	.8117	.9880	.2781	.7540	.2569	.1373
F values	4.16	0.64	3.21	3.75	3.58	2.77	0.83	0.28	0.51	5.89

[a] ANOVA for this variable based on $\log_{10}$ transformation.

Table 21. Willow oak foliar nutrient concentrations (Mean ± S.E.) (collected August 2000, age 10).

Treatment (n = 3)	N	P	K	Ca	Mg	S	Mn	B	Cu	Zn
	% dry weight						ppm			
CONTROL	1.69 ± .06	0.13 ± .01	0.65 ± .15	1.01 ± .15	0.19 ± .03	0.15 ± .00	2868 ± 1252	37 ± 1.9	6.2 ± .2	44 ± 5.0
FERT	2.04 ± .04	0.14 ± .01	0.75 ± .09	0.95 ± .05	0.24 ± .03	0.17 ± .01	1557 ± 264	38 ± 0.6	6.9 ± .1	42 ± 4.7
THIN	1.71 ± .03	0.14 ± .01	0.65 ± .06	1.14 ± .09	0.20 ± .01	0.14 ± .01	1695 ± 430	38 ± 1.7	5.4 ± .5	52 ± 2.1
THIN+FERT	1.88 ± .07	0.13 ± .01	0.62 ± .11	0.90 ± .06	0.22 ± .01	0.15 ± .01	1175 ± 177	33 ± 1.9	6.2 ± .3	46 ± 5.1
ANOVA (df 5, 6) P values										
Block	.4654	.1256	.0017	.3229	.2688[a]	.9350	.2801	.1701	.0152[a]	.0222
Thin	.2560	.5504	.1588	.6565	.7880	.3667	.2675	.1860	.0068	.0779
Fert	.0035	.9701	.4948	.1664	.1247	.3905	.1998	.2353	.0062	.2018
Thin x Fert	.1576	.1629	.1949	.3917	.6378	.5388	.5566	.1161	.9577	.6215
F values	5.53	1.78	9.96	1.26	1.36	0.47	1.43	2.43	10.30	4.44

[a] ANOVA for this variable based on square transformation.

Table 22. Wax myrtle foliar nutrient concentrations (Mean ± S.E.) (collected August 2000).

Treatment (n = 3)	N	P	K	Ca	Mg	S	Mn	B	Cu	Zn
	% dry weight						ppm			
CONTROL	2.05 ± .03	0.07 ± .003	0.62 ± .05	1.47 ± .07	0.36 ± .01	0.22 ± .01	327 ± 93	31 ± 3.7	2.8 ± .2	34 ± 3.3
FERT	2.15 ± .07	0.08 ± .003	0.84 ± .09	1.64 ± .18	0.43 ± .04	0.27 ± .02	355 ± 119	50 ± 7.3	3.8 ± .5	38 ± 1.3
THIN	2.17 ± .07	0.08 ± .009	0.64 ± .05	1.16 ± .16	0.35 ± .02	0.21 ± .01	152 ± 49	29 ± 5.9	3.3 ± .4	27 ± 0.9
THIN+FERT	2.36 ± .02	0.09 ± .002	0.76 ± .07	1.47 ± .02	0.47 ± .03	0.25 ± .01	283 ± 22	42 0.9	3.4 ± .2	29 ± 2.8
ANOVA (df 5, 6) P values										
Block	.7976	.3933	.0003[a]	.1479	.8776	.5805[a]	.3006	.1925	.2375	.6757
Thin	.0272	.1160	.3070	.0649	.5995	.2528	.1565	.2604	.9306	.0163
Fert	.0434	.0294	.0002	.0643	.0237	.0161	.3350	.0111	.1160	.2987
Thin x Fert	.5250	.9348	.1012	.530	.5662	.9298	.5216	.5287	.2317	.6780
F values	3.17	2.73	31.22	3.20	2.0	2.76	1.43	3.90	1.77	2.65

[a] ANOVA for this variable based on $\log_{10}$ transformation.

Table 23. Specific leaf area (cm^2/g) (Mean ± S.E.) for sweetgum, red maple, willow oak and wax myrtle. (foliage collected August 16, 2000).

Treatment (n = 3)	Sweetgum	Red maple	Willow oak	Wax myrtle
CONTROL	144 ± 5	150 ± 5	128 ± 11	203 ± 40
FERT	166 ± 13	157 ± 12	146 ± 9	178 ± 22
THIN	132 ± 17	146 ± 7	136 ± 15	150 ± 14
THIN+FERT	138 ± 12	144 ± 15	133 ± 12	225 ± 11
ANOVA (df 5, 6) P values				
Block	.0143	.0190	.0008	.4452
Thin	.0305	.2595	.5668	.9167
Fert	.0871	.7393	.0994	.3380
Thin x Fert	.3060	.5106	.0434	.0887
F values	6.41	3.73	13.98	1.41

Table 24. Competing vegetation (all non-tree vegetation and stems < 1 m ht) volume index (m^3 per hectare/1000) (Mean ± S.E.) (measured July 2000).

Treatment (n = 3)	All types	Shrubs	Sprouts	Vines	Grasses	Forbs
CONTROL	5.5 ± 2.7	4.5 ± 2.3	0.10 ± .04	0.7 ± 0.5	0.20 ± 0.20	0.0200 ± .0200
FERT	1.1 ± 0.2	0.9 ± 0.2	0.02 ± .01	0.1 ± 0.1	0.01 ± 0.01	0.0005 ± .0003
THIN	6.9 ± 1.2	4.3 ± 1.0	0.30 ± .15	1.4 ± 0.3	0.80 ± 0.20	0.0060 ± .0040
THIN+FERT	2.3 ± 0.7	0.4 ± 0.1	0.70 ± .34	1.0 ± 0.4	0.10 ± 0.06	0.0050 ± .0030
ANOVA (df 5, 6) P values						
Block	.5240	.4411[a]	.0460[a]	.1061[a]	.1497[b]	.1584
Thin	.4495	.6783	.0011	.0133	.0190	.5773
Fert	.0307	.0112	.1460	.0547	.0115	.2040
Thin x Fert	.9455	.2376	.0173	.2119	.3028	.2964
F values	2.00	3.37	11.67	5.27	5.91	1.75

[a] ANOVA for this variable based on $\log_{10}$ transformation.
[b] ANOVA for this variable based on square root transformation.

Table 25. Correlation coefficients (R) and P-values from linear regressions of sapling volume on competition volume index for each treatment.

Treatment	N	All types		Shrubs		Sprouts		Vines		Grasses	
		R	P-value	R	P-value	R	P-value	R	P-value	R	P-value
CONTROL	39	- .39	.0151	- .37	.0218	.22	.1785	- .20	.2111	- .20	.2388
FERT	38	.22	.1815	.26	.1130	- .29	.0754	- .17	.2943	- .31	.0586
THIN	37	- .37	.0256	- .36	.0290	- .14	.4400	- .37	.0220	.23	.1779
THIN + FERT	38	- .05	.7703	- .19	.2781	- .04	.8146	- .03	.8422	- .04	.8060

Table 26. Soil physical properties in 0-20 cm mineral soil depth (Mean ± S.E.) (January 2001).

Treatments (n = 3)	% Sand	% Silt	% Clay
CONTROL	76.0 ± 3.1	16.3 ± 0.8	7.7 ± 2.5
FERT	78.3 ± 1.7	14.8 ± 1.4	6.8 ± 0.8
THIN	76.0 ± 2.1	18.0 ± 2.0	6.0 ± 0.8
THIN+FERT	68.7 ± 4.3	24.4 ± 3.9	6.9 ± 0.9
ANOVA (df 5, 6) P values			
Block	.4745	.2057[a]	.1400[b]
Thin	.1613	.0261	.7286
Fert	.4403	.3664	.5717
Thin x Fert	.1613	.0874	.6749
F values	1.5	3.58	1.25

[a] ANOVA for this variable based on $\log_{10}$ transformation.
[b] ANOVA for this variable based on 1/y transformation.

Table 27. Soil Chemical Properties in 0-20 cm mineral soil depth (Mean ± S.E.) (January 2001).

Trmt (n = 3)	pH	Ex Acidity	CEC	Bases					Micronutrients				Other Macronutrients			C
				Ca	Mg	K	Na	BS	B	Cu	Mn	Zn	S	P	N (total)	(total)
	range	--- meq/100g ---		ppm[a]				%	ppm						% dry weight	
Control	4.2-4.6	1.5 ± 0.2	1.9 ± 0.2	79.2 ± 13.2	4.6 ± 1.5	4.4 ± 0.7	6.3 ± 0.6	25 ± 2.9	4.8 ± 0.4	0.3 ± 0.08	0.7 ± 0.4	4.8 ± 0.4	4.0 ± 0.9	56.8 ± 8.6	0.05 ± .004	1.1 ± .09
Fert	4.4	1.4 ± 0.1	2.1 ± 0.1	113.1 ± 14.6	5.9 ± 1.0	18.1 ± 0.3	6.0 ± 0.7	32 ± 2.4	4.1 ± 0.7	0.3 ± 0.05	0.6 ± 0.5	4.3 ± 0.4	3.3 ± 1.4	78.5 ± 5.8	0.04 ± .002	0.9 ± .05
Thin	4.3-4.5	1.3 ± 0.1	1.8 ± .05	84.5 ± 14.7	4.8 ± 2.1	14.6 ± 0.8	6.4 ± 0.1	28 ± 4.7	3.6 ± 0.5	0.4 ± 0.10	0.7 ± 0.6	4.6 ± 0.1	4.0 ± 1.9	62.9 ± 15.4	0.04 ± .003	0.9 ± .03
Thin+Fert	4.4-4.6	1.4 ± 0.2	2.1 ± 0.2	133.8 ± 13.4	5.5 ± 1.6	17.0 ± 0.5	6.1 ± 0.1	36 ± 5.2	4.5 ± 0.9	0.5 ± 0.20	1.5 ± 1.3	5.6 ± 0.9	6.9 ± 3.7	88.8 ± 37.1	0.05 ± .010	1.1 ± .20
ANOVA (df 5, 6) P values																
Block	---	.0074	.0747	.9373	.5037	.4500	.1283	.0970	.7763	.0388[a]	.0034[a]	.2592	.0081[a]	.0394[a]	.0572[a]	.0750[b]
Thin	---	.3566	.8979	.4465	.8129	.8907	.7755	.2786	.5919	.4304	.8463	.3269	.3425	.9348	.6445	.6381
Fert	---	.8908	.1336	.0408	.1188	.1504	.3825	.0478	.9087	.5457	.6174	.5786	.5927	.1293	.3667	.8654
ThinxFert	---	.5156	.5072	.6467	.6986	.6872	.9889	.8310	.3093	.8310	.5074	.2002	.1161	.7804	.0342	.0352
F values	---	5.25	2.35	1.55	1.02	0.95	1.37	2.94	0.42	2.58	6.98	1.39	5.73	2.96	3.64	3.17

[a] ANOVA based on $\log_{10}$ transformation.
[b] ANOVA based on 1/y transformation.

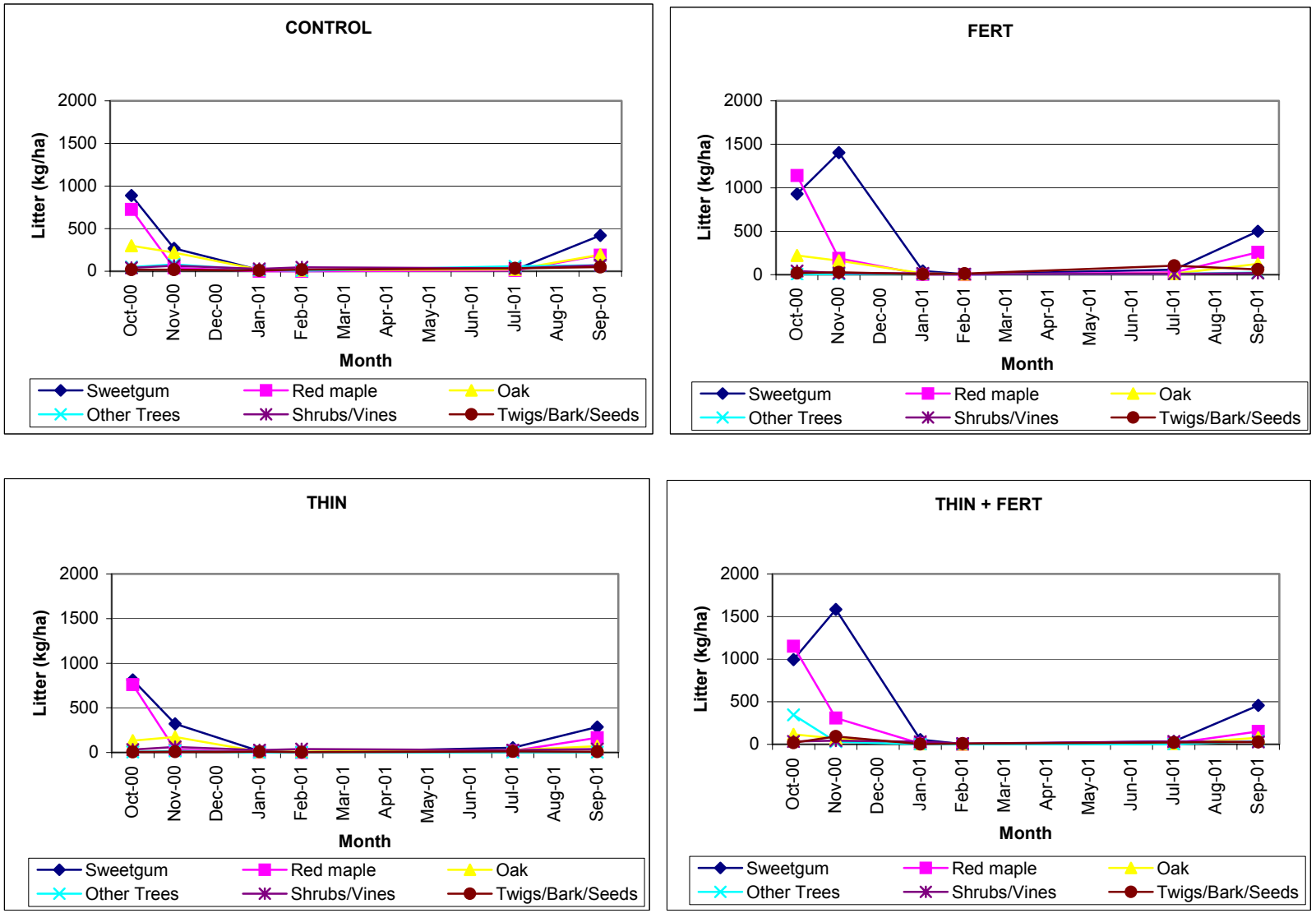

Figure 1. Annual production of litterfall (October 2001 to September 2002) by treatment and litter type (n = 3).

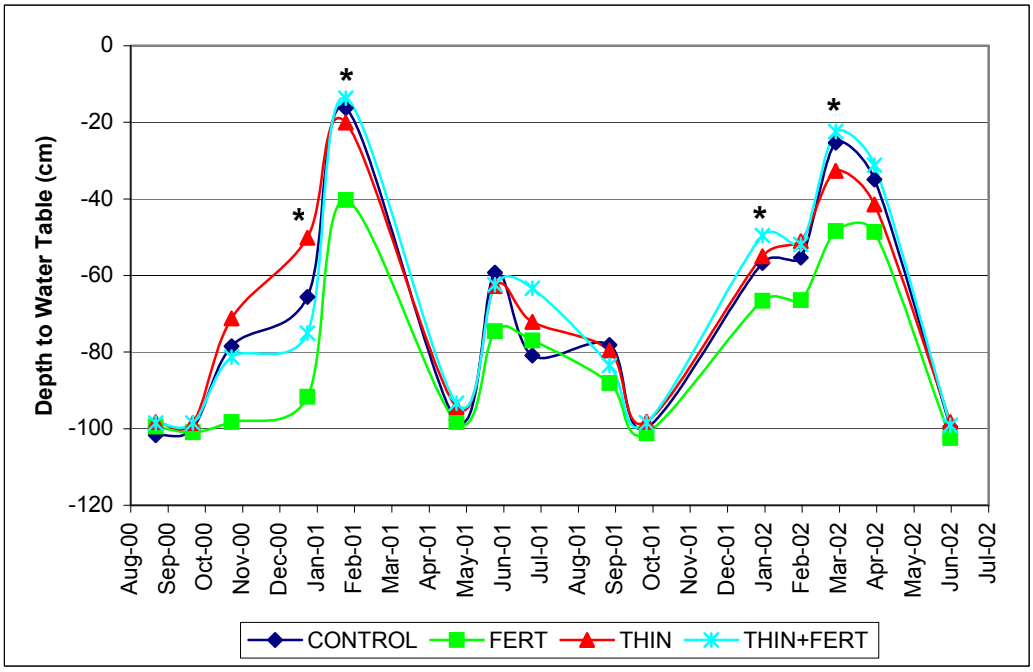

Figure 2. Mean depth to water table from ground surface (y-value of 0) by treatment (n = 3).
*** Indicates significant treatment differences by date at P < .1.**

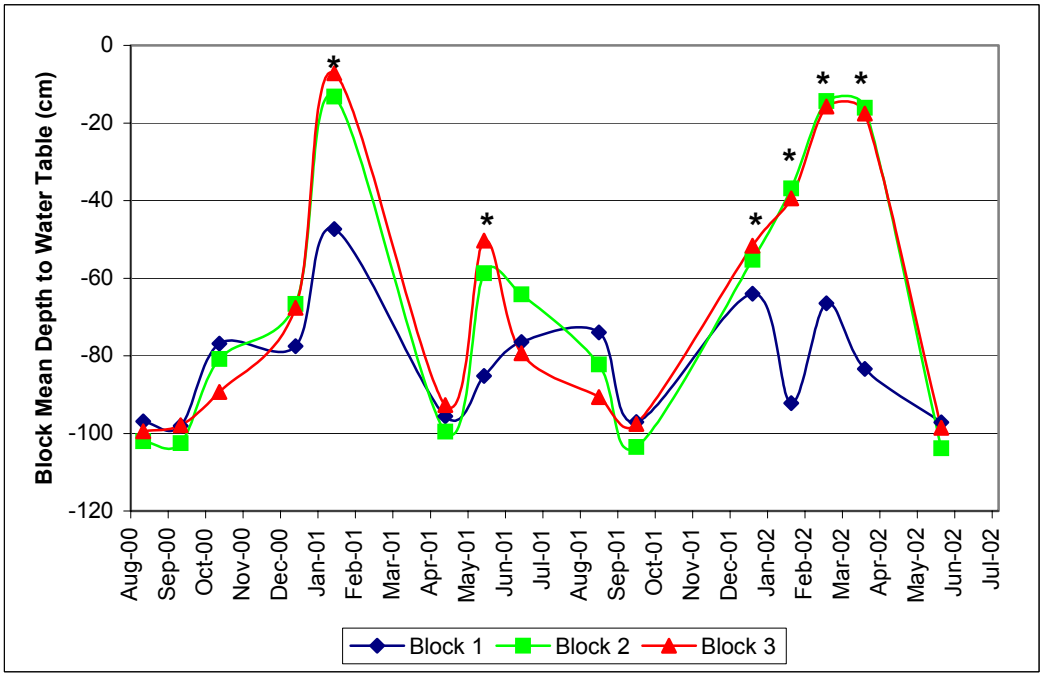

Figure 3. Mean depth to water table from ground surface (y-value of 0) by block (n = 3).
*** Indicates significant block differences by date at P < .1.**