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A MID-ROTATION BOTTOMLAND RED OAK STAND THREE YEARS AFTER THINNING AND FERTILIZATION

A Thesis

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TABLE OF CONTENTS

ABSTRACT

To determine the effects of intermediate silvicultural treatments on bottomland hardwoods, two types of thinning (crown thinning and low thinning) and one level of fertilizer (200 lb/ac N + 50 lb/ac P) were applied to a predominantly red oak stand in southeastern Texas. Treatments were applied in a 3 × 2 factorial arrangement as a randomized complete block design of 12 ac in size. Crop trees were selected prior to the treatments, and diameter at breast height measurements were taken pre-treatment and for three proceeding years to assess diameter growth response of all trees. Epicormic branching measurements were also taken for three years post-treatment to evaluate epicormic branching response of all crop trees to crown thinning, low thinning and fertilization. Furthermore, reproduction plots were established pre-treatment to evaluate reproduction height growth response to all intermediate treatments. First-year results showed no significant difference in current annual increment (CAI) of crop-tree diameter growth response; however, second-year results of CAI diameter growth showed that crop trees in thinned plots achieved significantly more growth than in unthinned plots. With third-year results of CAI diameter growth, crop trees in crow-thinned plots grew significantly better than in both low-thinned and unthinned plots, all regardless of fertilization. Epicormic branching was generally greater in crown-thinned and fertilized plots immediately following treatment, and reproduction height growth was generally greater in crown-thinned, and in some cases, fertilized plots.

INTRODUCTION

Bottomland hardwood forests occur mainly on floodplain sites of recent alluvium; however, other non-alluvial wet sites can support many of the same hardwood species (Hodges 1994). Alluvial floodplains themselves occur along most streams within the United States, but they are most common and most extensive in the Atlantic Coastal Plain, East Gulf Coastal Plain, Mississippi Alluvial Plain, and West Gulf Coastal Plain (Hodges 1997). Approximately 30 million acres of bottomland hardwood forests remained in the southeastern United States in 1994, which is less than one-half of such acreage present at the time of European settlement (Hodges 1994). According to Hodges (1994), much of this acreage reduction was a result of conversion to agricultural use within the Mississippi River Alluvial Plain. Currently there are 214 million acres of forested land in the Southeast (Wear and Greis 2002). Of that, more than 32 million acres are considered forested wetlands including bottomland hardwood forests (Wear and Greis 2002). Furthermore, according to Hodges and Switzer (1979), most bottomland areas are potentially very productive; however, they are growing below their potential due to the past practices of high grading and lack of effective management. This statement could be made about current hardwood forests as well (Allen et al. 2001, Devall et al. 2001, Stanturf et al. 2001).

Taylor et al. (1990) believed the conversion of bottomland forests to agricultural use resulted in a large number of functional changes in these ecosystems that have reduced the values derived from forested wetlands in general. Ecological functions include community dynamics, physio-chemical processes, surface water storage, ground water storage, and fish and wildlife habitat (Taylor et al. 1990). Valuable services to humans include biomass production, food chain support, erosion control, water quality protection, flood storage and control, low flow augmentation, and deep aquifer recharge (Taylor et al. 1990). The ecology of bottomland hardwoods is complicated even further by the exceptional diversity of species that occur over wide areas and wide ranges of sites (Hodges and Switzer 1979). According to Spencer (1981), the most extensive conversion of bottomland hardwood forests to agricultural use occurred between 1937 and 1977. This occurred in the Mississippi Alluvial Plain when soybeans became an important agricultural crop in the United States (Spencer 1981). During this conversion, the state with the greatest removal of bottomland acres was Arkansas having only 880,000 ac of its original 8 million bottomland acres remaining in 1985 (Lynch 1991). Although rates of forested wetland loss has declined since the 1970's (Greis 2002), conservation of bottomland hardwood forests for timber production and wildlife habitat will remain an important issue (Taylor et al. 1990).

Throughout the 1990's and up to the present day, afforestation and reforestation of bottomland acres has increased (Greis 2002). As evidence of public interest in bottomland hardwood reforestation, Allen and Kennedy (1989) published a booklet describing the need for bottomland forest restoration, especially in the Mississippi Alluvial Plain. This booklet is also a systematic instruction guide to any private landowner on how to reforest bottomlands. In another technical report written to landowners, Allen et al. (2001) described steps required in bottomland hardwood restoration from evaluating the initial site, up to intermediate treatments, and final harvest. Furthermore, Devall et al. (2001) stated restoration and reforestation of bottomland hardwood forests has gained widespread appeal because of potential historic renewal, benefit to wetland functions, benefit to wildlife habitat, recreational benefit, and financial benefit to landowners. Finally, Stanturf et al. (2001) stated that ecological and economic goals are not incompatible in bottomland forest restoration, and habitat improvement in bottomland hardwood forests often results from silvicultural treatments such as thinnings, which generate income as well as offset the costs of restoration.

One of the cornerstones of silviculture is thinning, which can be defined as any cutting made in an immature stand to stimulate the growth of residual trees as well as to redistribute stand growth by utilizing potential mortality (Hawley and Smith 1954). This research project is concerned with two types of thinning: crown thinning and low thinning. Crown thinning (also known as high thinning or thinning from above) involves removing trees from upper crown classes to favor development of the best trees of the same crown classes (Smith et al. 1997). Low thinning (also known as German thinning or thinning from below) is aimed at anticipating mortality and salvaging yield (Daniel et al. 1979). This method involves removing trees from the lower crown classes to speed up the natural process of self-thinning (Smith et al. 1997). The best-known proponent of this thinning philosophy was Georg Ludwig Hartig, who is named as one of the fathers of modern forestry (Fernow 1913). Starting around 1795, Hartig's views have greatly influenced forestry (Fernow 1913). Hartig, who became chief of the Prussian Forest Service in 1811, declared in no case should thinning break the canopy closure (Fernow 1913). After the development of the Kraft Method of Crown Classification in 1884, there was somewhat of a revolt against the philosophy of thinning from below (Assmann 1970). Foresters from France and Germany began to advocate crown thinning (also know as French thinning in France) due to its already proven practice in France (Zeide 2001). However, as implemented, crown thinning can come "perilously close to . . . destructive high-grading" (Zeide 2001). Smith et al. (1997) stated crown thinning should be implemented to achieve economic gain throughout the life of a stand and should be applied to pure stands of shade-tolerant species. Smith et al. (1997) also stated low thinning is best applied to stands where almost all trees are merchantable, and in relation to this, Meadows (1996) stated early pulpwood thinnings in bottomland hardwoods have recently become more economically attractive.

Langsaeter (1941) found increasing volume could only be attained by increasing the number of trees in a given stand; however, total volume in that stand can only increase if an added tree increases total volume. Therefore, total volume increases with the number of trees up to a certain density where increasing the number of trees will cause a reduction in total volume due to loss of growth (Langsaeter 1941). Curtis et al. (1997) attempted to identify the ends of the plateau in Langsaeter (1941), but they found total volume increment increases with stand density. Thinning also tends to increase growth of individual trees at the expense of their number as well as the volume growth of the entire stand (Curtis et al. 1997). Furthermore, according to Daniel et al. (1979), there is little a silviculturalist can do to increase total cubic-foot growth on a given site, because final basal area and height are determined by the rotation age. Maintaining adequate stocking and the desired species composition, however, requires much skill (Daniel et al. 1979). Beyond this, only two areas seem open to manipulation – the average stand diameter can be influenced by manipulating stand density and total yield can be increased by salvaging potential mortality (Daniel et al. 1979). Crown thinning seems to be the best choice for the former and low thinning for the latter.

Fertilization can often be a difficult tool to understand in forest management and is rarely used in hardwood silviculture. Sometimes fertilization will favor strong trees so that it will hasten suppression of weaker trees (Smith et al. 1997). There may even be cases of soil extremely deficient in nutrients where fertilization must be coupled with thinning to produce any effect (Smith et al. 1997). The following concentrations of nitrogen (N), phosphorous (P), and potassium (K) are considered adequate in most higher plants (gymnosperms and angiosperms): 15,000 mg/kg (N), 2000 mg/kg (P), and 10,000 mg/kg (K) in dry plant tissue (Salisbury and Ross 1992). However, Stone (1977) found growth in young even-aged stands is more limited by competition between trees than by availability of nitrogen, phosphorous, or potassium, on well-drained soils with site indices of 60 or better.

Soils in general are more commonly deficient in nitrogen than in any other element, and, second to nitrogen, phosphorous is most often the next limiting element (Salisbury and Ross 1992). Nitrogen is absorbed by plants in the form of either nitrate or ammonium ions and phosphorus in the form of phosphate ions (Salisbury and Ross 1992). Nitrogen is most important in the development of plant leaves and shoots, and phosphorous is most important in the development of roots and fruiting structures (Salisbury and Ross 1992). Although not used in this study, potassium is another important element in plant growth and development (Salisbury and Ross 1992). Because of the importance of nitrogen, phosphorous, and potassium together, commercial fertilizers are often labeled respectively by the percentages of compounds containing these three elements, such as 20-10-20 (Nelson 1998). This fertilizer would contain 20 percent urea [$CO(NH_2)_2$] yielding elemental N, 10 percent diammonium phosphate [$(NH_4)_2H_2PO_4$] yielding elemental P, and 20 percent potassium chloride [KCl] yielding elemental K (Nelson 1998). In relation to the crop-tree method of stand management, Houston et al. (1995) stated fertilizer is best applied in early March (in the Southeast) of the first and subsequent growing seasons following a thinning treatment.

Meadows and Hodges (1997) stated that intermediate management of bottomland hardwood forests has increased over the past twenty-five years, and there has become a renewed interest in thinnings and other partial cuttings. They also stated that the focus of thinnings has shifted from "stand-level prescriptions in uneven-aged stands to individual-tree-level prescriptions in even-aged stands" (Meadows and Hodges 1997). This study is concerned with crop-tree diameter growth in an even-aged bottomland hardwood stand, which corresponds directly to the shift in focus noted by Meadows and Hodges (1997). Meadows and Stanturf (1997) also reported that improvement cutting, commercial thinning, and partial cuttings involving some form of crop-tree release have become increasingly common in southern bottomland hardwood forests.

According to Stanturf (1997), the USDA Forest Service has developed a strategic plan for its research efforts. After a meeting of more than one hundred people in February 1997 at the Center for Bottomland Hardwood Research, responses and written comments were eventually organized into four categories (Stanturf 1997). The primary category in need of research by the USDA was the regeneration of bottomland hardwoods, followed by stand management in bottomland hardwoods, relations between forest management and wildlife and fisheries, and ecosystem processes and functions in forested wetlands (Stanturf 1997). Although most of the focus of Stanturf (1997) is on regeneration methods, little has been discovered about advance reproduction responses to the intermediate treatments of thinning and fertilization. Even though this study is not being done in the context of the shelterwood method of regeneration, data is being recorded to detect changes in stocking, growth, and vigor of reproduction in relation to the silvicultural methods applied. Due to past difficulties noted in regeneration of bottomland oaks (Clatterbuck and Meadows 1992, Hodges and Gardiner 1993, Stanturf 1997), further exploration is needed to capture any opportunities to enhance the development of advance oak reproduction.

In a publication intended to inform private landowners about bottomland forest management, the Louisiana Department of Agriculture and Forestry (LDAF) (1995) advocated low thinning to "leave the largest, most desirable trees to provide seeds . . . [and] eventually raise the quality of the whole forest." They may leave crown thinning out of their prescription because of the general landowner's temptation to high-grade during a crown thinning. In keeping with LDAF (1995), Allen et al. (2001) also proposed low thinning as the best intermediate bottomland hardwood thinning treatment. Allen et al. (2001) supported this statement by saying healthy trees generally require a live crown to total height ratio of 40 percent or greater, and trees below this proportion are most likely in subordinate crown positions. In a similar publication, intended for general hardwood management in Canada, Robertson et al. (1991) advocated crown thinning but specifically warned against high-grading of timber stands; they did not discuss low thinning as an option. It is clear there are differing philosophies related to thinning in general as well as thinning in hardwood forests.

RESEARCH OBJECTIVES AND HYPOTHESES

Objectives

The research objectives are to

1. determine the effects of thinning combined with fertilization on *crop-tree diameter growth* in a mid-rotation bottomland red oak stand;
2. determine the effects of thinning and fertilization on *epicormic branching* in a mid-rotation bottomland red oak stand; and
3. determine the effects of thinning and fertilization on *advance reproduction* in a mid-rotation bottomland red oak stand.

Hypotheses

Objective 1

The first objective of the study was to evaluate the effects of thinning and fertilization on crop-tree diameter growth in a mid-rotation bottomland red oak stand according to the following hypotheses.

Hypothesis 1.1

There will be a positive response in diameter growth of crop trees following both crown and low thinning.

Johnson (1968) found thinning significantly increased growth in sweetgum (*Liquidambar styraciflua* L.) stands. He reported thinning a stand to a residual basal area of approximately 70 square feet per acre (ft^2/ac) was the best method to effect volume growth. He also stated heavy thinning to 50-55 ft^2/ac residual basal area produced the best diameter growth per tree, but, in this case, volume growth per acre was lower.

Feduccia (1979) found cubic-foot volume growth (ft^3/ac) increased directly with residual basal area (ft^2/ac) in a thinned slash pine (*Pinus elliottii* Engelm.) plantation, and that diameter increment was related inversely to stand density. Furthermore, Feduccia and Mann (1976) stated that studies with heavy thinnings stimulating diameter growth, but reducing volume growth are not new. All are in keeping with Long (1985) who stated that forest management objectives often involve a compromise between two mutually exclusive goals: maximizing stand growth and maximizing individual tree growth.

Meadows and Goelz (1993) discovered when plots within a water oak (*Quercus nigra* L.) plantation were heavily thinned that trees in these plots exhibited substantially higher diameter growth rates than trees in lightly thinned or unthinned plots. Prior to thinning, the water oak plantation had an average basal area of 86 ft^2/ac; light thinning and heavy thinning reduced stands to 34 and 52 ft^2/ac, respectively. Meadows and Goelz (1993) also found heavy thinning substantially increased the diameter growth rate of individual trees to nearly double that of trees in the unthinned stand; however, they found no significant difference in stand-level basal area growth rates between the three treatments. Seven-year results of the same study found no significant difference in stand-level basal area growth; however, both thinning treatments ultimately showed an increase diameter growth of residual trees with no significant differences between the two levels of thinning (Meadows and Goelz 1999). Furthermore, Johnson and McKnight (1969) reported that thinning significantly increased growth rates in black willow (*Salix nigra* Marsh) stands. Average basal area was originally 130 ft^2/ac and was cut to 95, 75, and 55 ft^2/ac in different treatment plots. Growth per acre was best on plots thinned to 95 ft^2/ac in the 18-year-old stand and best on plots thinned to 55 ft^2/ac in the 24-year-old stand.

Hypothesis 1.2

There will be a greater positive response in diameter growth of crop trees after crown thinning than after low thinning.

Kelty et al. (1987) concluded removal of understory trees was not a useful method for influencing overstory growth rates especially in most oak-dominated hardwood stands in the northeastern United States; the soil types involved in this study were glacial till soils. Because both glacial till soils and bottomland alluvial soils are known to have abundant soil moisture and nutrients, a possible correlation can be drawn between these oak stands and bottomland red oak stands. Since Kelty et al. (1987) found understory tree removal did not affect overstory growth, crown thinning may prove to be better than low thinning in bottomland red oak stands. Johnson and McKnight (1969) also found that removal of larger (dominant or codominant) trees resulted in better stand growth rates than removal of smaller (suppressed) trees.

Lambert (1957) discovered in a water oak stand that volume growth of individual crop trees was much less correlated with basal area growth of the stand than with each competing tree's diameter growth. Lambert's (1957) findings seem to advocate crown thinning, which tends to focus on reducing the competition between crop trees of the upper crown classes. Therefore, stand-level basal area should not be the only guiding factor in a timber marker's mind. He should also focus on removing competing trees of upper crown classes while favoring the most vigorous trees in the stand.

However, if thinnings are extremely heavy, too much sunlight may enter the stand and promote epicormic branching on individual trees, lowering wood quality in some cases; to lessen the probability of epicormic branching, frequent but light thinnings are suggested (Meadows 1995). Kirkham and Carvell (1980) also discovered during selection thinning (dominant trees with large crowns and poor natural pruning removed) and crown thinning in mixed oak and cove hardwood stands that woody biomass, total biomass, and number of species significantly increased in the understory. In contrast, they found low thinning consistently showed smaller values in the same categories.

Accordingly, if thinnings are light, the forest canopy will close within 2 to 3 years preventing excessive understory growth as well as minimizing epicormic branching. Then, a relatively minor amount of overstory trees can be removed during each thinning. The volume of overstory trees removed will, of course, have to be enough to make it economically feasible to harvest. A proper balance between frequency and intensity of crown thinnings is, therefore, important. Conversely, while low thinnings are usually a safe alternative to no treatment, they may not always release a stand's greatest potential for diameter growth. In this case, total stand growth may have to be sacrificed to produce the best diameter growth and log quality among crop trees (Long 1985).

Stand stocking is a relationship of stand density to some value that is considered "normal," and the use of stand stocking guides for hardwoods may be helpful in making decisions on when to apply silvicultural treatments as well as what types of treatments are needed. The first attempt at stocking guides for southern bottomland hardwoods was completed by Putnam et al. (1960). Through years of field experience, Putnam et al. (1960) suggested "hypothetical" stand stocking tables for bottomland hardwoods. Later, Gingrich (1967) developed stand stocking graphs for upland oaks using stand density related to what was considered an adequate level of stand stocking. Gingrich (1967) developed A, B, and C levels of stocking: stands above these levels were overstocked, fully stocked, and understocked, respectively. Then, Goelz (1990) further explored Gingrich (1967) by preparing stocking guides based on predicted growth; he did this using growth and yield models for southern Appalachian hardwood forests developed by Bowling et al. (1989). Next, Goelz (1995a,b) developed hardwood stocking guides using similar statistical modeling; however, he adapted the Gingrich (1967) B-line to be the suggested residual stocking of Putnam et al. (1960) rather than the minimum full stocking of Gingrich (1967). Finally, Goelz (1997) used all the previous interpretations to develop C-10, 15, 20, and 25 lines, which represent the respective amount of years required to reach his suggested B-line of residual stocking.

Hypothesis 1.3

There will be a greater positive response in diameter growth of crop trees in thinned and fertilized plots than in plots thinned alone.

A study performed on red (*Quercus rubra* L. and *Quercus velutina* Lam.) and white (*Quercus alba* L.) oaks in the Boston Mountains of Arkansas found 2-yr diameter growth response to fertilization regardless of thinning (Graney and Pope 1978). In this study, basal area around each crop tree was reduced to about 70 ft^2/ac, and crop trees were individually fertilized with two different concentrations of fertilizer (200 pounds per acres (lb/ac) N + 45 lb/ac P and 400 lb/ac N + 45 lb/ac P) (Graney and Pope 1978). Two-year results found diameter growth response for thinned red oaks increased by 52 percent in the 200-lb treatment and by 97 percent in the 400-lb treatment (Graney and Pope 1978). Ten-year results of the same study found sample trees had an immediate positive response to thinning and fertilization that increased throughout the duration of the study (Graney 1987). Graney (1987) also found fertilization significantly increased diameter growth response and was probably influenced synergistically by the thinning treatment. Maximum response to fertilization occurred during the first two years following treatment; however, it was generally greater than unfertilized trees through the ninth and tenth years of the study (Graney 1987).

In western conifer stands, Miller et al. (1988) found fertilization with N (200 lb/ac) can increase wood production in about 70 percent of thinned and unthinned Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) stands in southwestern Oregon. Cochran (1991) also found that a single application of 200 lb/ac N + 33 lb/ac sulphur increased periodic annual increments of basal area and volume by 1.7 $ft^2·ac^{-1}·yr^{-1}$ and 43 to 68 $ft^3·ac^{-1}·yr^{-1}$, respectively, over 4- to 5-year periods. Miller and Reukema (1977) found fertilizing with nitrogen on Site V Douglas-fir in southwest Washington increased diameter and height growth of concurrently released dominant trees by about 85 percent. They also recommend fertilizing shortly before or after thinning on nitrogen deficient sites to accelerate response to release (Miller and Reukema 1977). Similarly, Cochran (1979) warned against fertilization without thinning in ponderosa pine (*Pinus ponderosa* Dougl. ex Laws.) stands since much of the increased growth may be by trees that never reach marketable size. Furthermore, Harrington and Wierman (1985) found that fertilization with nitrogen, applied as either urea or ammonium nitrate, increased both height and diameter growth of western redcedar (*Thuja plicata* Donn ex D. Don) by 40 percent in thinned plots regardless of the source of nitrogen.

Scott et al. (2001) found fertilizer responses can depend on site and land use history. Fertilization of young sweetgum stands with N at 56 kilograms per hectare (kg/ha) and 112 kg/ha showed better response on a poorly drained pine cutover site than on a well-drained former agricultural field (Scott et al. 2001). Additionally, Kennedy (1993) concluded spacing had no effect on foliar nutrient composition, but position within the crown did significantly affect some nutrient concentrations in bottomland hardwood stands. Tissue concentrations of N, calcium (Ca), and magnesium (Mg) were affected the most with P and K showing little practical differences (Kennedy 1993). Concentrations of N were significantly higher in the upper tree crowns where new foliage and tissue were being formed, and concentrations of Ca and Mg, which are not as readily translocated as N, were significantly higher in the lower portions of tree crowns (Kennedy 1993).

Furthermore, Stringer and Wittwer (1985) discovered that individual tree fertilization with N (ammonium nitrate) at 4.5 kg/tree yielded a 31 percent increase in basal area growth in natural black walnut (*Juglans nigra* L.) stands. Fertilizer was applied in this study by punching holes to a depth of 30 cm with a 2.5-cm metal bar within an area defined by the crown spread of each crop tree. This coincides with Houston et al. (1995) who recommended that commercial fertilizers be applied within the rooting zone of each crop tree. Schaertl et al. (1997) also conducted a study where bole diameter responses to fertilization and release of crop trees were evaluated in a pole-sized white oak stand. Schaertl et al. (1997) applied broadcast fertilizer to plots at a rate of 150 lbs of nitrogen and 35 lbs of phosphorous per acre in Spring 1993 and 1995 and released dominant or codominant crop trees by removing competing trees around them in Spring 1993. In third-year results, he found that pooled mean diameter of released and fertilized plots was significantly greater than plots released alone, fertilized alone, or untreated

(Schaertl et al. 1997). With the above results in mind, fertilization in combination with thinning could add a long-term increase in crop-tree growth.

Objective 2

The second objective of the study was to determine the effects of thinning and fertilization on epicormic branching in a mid-rotation bottomland red oak stand according to the following hypothesis.

Hypothesis 2

Thinning and fertilization of the bottomland red oak stand will decrease the occurrence of epicormic branching on tree boles.

An epicormic branch is "a shoot arising from an adventitious or dormant bud on a stem or branch of a woody plant" (Harlow et al. 1996). American foresters first became interested in epicormic branching in the early 1900's when virgin hardwood forests became more scarce and second-growth forests became the primary source of lumber (Brown and Kormanik 1970). Furthermore, epicormic branching and thinning can be closely related (Meadows and Burkhardt 2001). Johnson (1968) noted heavy thinnings in sweetgum stands caused considerable epicormic branching. Meadows (1996) also reported that the two disadvantages associated with partial cuttings in hardwood stands are excessive logging damage to residual trees and production of epicormic branches on the boles of residual stems. As outlined by Meadows (1995), there are three important factors that affect production of epicormic branches in hardwoods (which appear to be controlled by a complex interaction); they are species (genotype), stress, and sunlight.

Osmond et al. (1987) defined biological stress as any factor causing a plant's growth and reproduction to fall below a value normal for that given species.

Furthermore, Chapin (1991) stated that all plants respond to stress in basically the same way: by a decline in growth rate as well as a decline in the acquisition of all resources. However, Levitt (1980) defined biological stress as any change in environmental conditions that may reduce *or* adversely change a plant's growth or development. Levitt (1980) also distinguished between avoidance and tolerance of stress; during avoidance, the plant responds by attempting to reduce the impact of the stress factor (sometimes by growth), and during tolerance, the plant simply endures and survives the stress factor. Biological stress due to competition for nutrients and sunlight may be a cause of avoidance in the form of epicormic branching. Biological stress is further complicated by nutrient availability in the soil as it relates to nutrient demand by the plant (Clarkson 1985). Under conditions of high nitrogen availability, plants have a low potential to absorb nitrogen; this illustrates that nitrogen demand by the plant has more effect on nitrogen uptake than availability of nitrogen in the soil (Clarkson 1985).

Epicormic branches also clearly affect log grade. Kenna (1981) asserted adventitious twig diameter of 0.375 inches is a defect in logs under 14 inches diameter inside bark (DIB); on logs > 14 inches DIB, only every other such epicormic branch is considered a defect. Meadows and Burkhardt (2001) found epicormic branching had a detrimental effect on log grade of individual trees, caused by as few a five epicormic branches evenly distributed on a 16-ft log. Log defects will then directly affect lumber grade. Meadows and Burkhardt (2001) also found epicormic branches have a serious effect on lumber grade with over 50 percent of the lumber that would have been graded as either First and Seconds or Select without epicormic branches was downgraded to No. 1 Common or below due to epicormic branching defects. Furthermore, Meadows and

Burkhardt (2001) found defects caused by epicormic branches resulted in a 13 percent reduction in lumber value produced in the final harvest. Miller (1996) found 11 percent of trees had reduced butt log quality due to deferment cutting in central Appalachian hardwoods. He also found trees producing epicormic branches showed no significant improvement in butt log grade from year 2 until year 10 of the study (Miller 1996). Meadows (1995) showed a table of hardwood species and their propensity to epicormic branching. He listed the following species (favored as crop trees in this study) and their propensity toward epicormic branching in his assessment:

1) sweetgum (high);
2) willow oak (*Quercus phellos* L.) (high);
3) water oak (high);
4) cherrybark oak (*Quercus pagoda* Raf.) (medium); and
5) green ash (*Fraxinus pennsylvanica* Marsh) (low).

Meadows and Goelz (2001) applied three levels of thinning to a bottomland red oak and sweetgum stand located in a minor creek bottom in west-central Alabama; those levels were lightly thinned to 70-75 percent residual stocking, heavily thinned to 50-55 percent residual stocking, and thinned to the B-line as recommended by Goelz (1995a). Meadows and Goelz (2001) showed thinning had little effect on epicormic branching in red oaks but greatly increased the production of epicormic branches in sweetgum. Meadows and Goelz (2001) also reported heavy thinning caused a minimal increase in epicormic branching, especially among red oak crop trees; however, both B-line and light thinning retained significant numbers of lower-crown-class trees increasing the risk of epicormic branching.

Objective 3

The third objective of the study was to determine the effects of thinning and fertilization on advance reproduction in a mid-rotation bottomland red oak stand in relation to the following hypothesis.

Hypothesis 3

Thinning and fertilization of the bottomland red oak stand will increase relative stocking and height growth of advance reproduction.

Advance reproduction is reproduction already in place before the existing, mature stand of trees is removed (Smith et al. 1997). Much early research has evaluated the proper amount of advance oak reproduction required prior to final harvest in upland hardwood stands. Sander et al. (1976) developed an elaborate tally system to evaluate adequacy of advance oak reproduction and stump sprouting in black oak. Sander et al. (1984) developed a similar system for evaluation of advance oak reproduction in the Ozark Mountain Region of Missouri. Marquis and Bjorkbom (1982) also developed a reproduction tally sheet to evaluate hardwood stands most likely to regenerate successfully after clearcutting in Allegheny hardwoods. Furthermore, Loftis (1990) developed a model to predict post-harvest performance of red oak reproduction, and Dey et al. (1996) developed a regeneration simulator designed to assess adequate oak reproduction in the Ozark Mountain Region.

In southern bottomland hardwoods, Johnson (1980) found that generally the taller an understory tree is before release, the faster it will grow after release. He also found hardwoods reproduce naturally through stump and root sprouts of cut trees and through seedlings that germinate in new openings (Johnson 1980). Additionally, understory reproduction is likely of shade-tolerant species with slow early growth rates, and all sprouts achieve their most rapid growth in the first five years (Johnson 1980). The tally system developed by Johnson (1980) was created from years of field experience in hardwood reproduction evaluations and is based upon a point system similar to previous methods. Likewise, Clatterbuck and Meadows (1992) stated bottomland oaks depend on advance reproduction and stump sprouting for successful natural regeneration, and most regeneration failures have been attributed to a lack of advance oak reproduction as well as a lack of cut trees with the potential to coppice. Furthermore, Simms and Loftis (1988) recommended midstory herbicide treatments to enhance the development of advance oak reproduction prior to shelterwood cutting, deferment cutting, or clearcutting.

Hart et al. (1995) modified Johnson's (1980) reproduction evaluation system by weighing ash seedlings > 1 ft tall more heavily and weighing oak and ash seedlings < 1 ft tall less heavily than Johnson (1980). The method recommended by Hart et al. (1995) via Johnson (1980) (with local forest management or research adaptations) is now a common hardwood reproduction inventory used within the USDA Forest Service and the USDI Fish and Wildlife Service. Furthermore, Belli et al. (1999) found that larger seedlings and stump sprouts have a competitive advantage over smaller seedlings (< 1 ft tall) if released and free to grow. The ability to distinguish between resprouted or low vigor seedlings (< 1 ft and > 1 yr old) and newly germinated seedlings (< 1 ft and < 1 yr old) is also needed to determine potential to grow if released, because older seedlings with established root systems (especially among oak species) have a better chance of surviving when released (Merz and Boyce 1956). However, Johnson and Krinard (1989) found, if left alone, the majority of new understory oak seedlings will die within 5 years of germination. All of the above guides are based on stocking, size, species, and age of advance reproduction. Nonetheless, Bowling and Kellison (1983) contend advance oak reproduction is not needed on the majority of bottomland sites for oak to become a significant component in sites allowed to naturally regenerate, if there is adequate potential for stump sprouting.

Furthermore, Hodges and Gardiner (1993) asserted that adequate oak reproduction in hardwood stands is a problem complicated by the lack of understanding of oak physiology. Gardiner et al. (2001) attempted to address this problem by measuring photosynthesis of Nuttall oak (*Quercus nuttallii* Palm.) seedlings planted beneath a canopy of eastern cottonwood (*Populus deltoids* Bartr. ex Marsh.). Gardiner et al. (2001) found these seedlings developed with a carbon assimilation capacity similar to open-grown plants. This generates management implications of interplanting oak species with other early successional species, and may promote underplanting of oaks in shelterwood situations where they receive more light than typical thinnings. Likewise, Goelz and Meadows (1994) found more extreme overstory removals promoted the best regeneration establishment after harvest using an uneven-aged management regime in the Loessial Bluff Region of Mississippi.

MATERIALS AND METHODS

Geographic Location, Soil Type, and Site Index

The bottomland red oak stand in this study is located in Angelina County, Texas. It is situated in eastern Texas in the Western Gulf Section of Coastal Plains and Flatwoods within the Outer Costal Plain Mixed Forest Province (Keys et al. 1995). The major forest type of this area is southern pine with mixed hardwoods. The study area is located on both sides of the Shawnee Creek floodplain, which drains into the Neches River. Shawnee creek can be described as a minor bottom according to the definition of Hodges and Switzer (1979). The closest incorporated town to the study area is Zavalla, Texas. The land is currently owned by Temple-Inland Corporation of Diboll, Texas, and is leased to Wolf Creek Hunting Club of Zavalla, Texas.

Soils found on the study site are of the Pophers Series, which are classified as fine-silty, siliceous, acid, thermic Aeric Fluvaquents (Dolezel 1988). These soils are somewhat poorly drained and slowly permeable (Dolezel 1988). Due to a slope of less than 1 percent, runoff is slow (Dolezel 1988). This soil overflows 2 to 3 times per year in most years, and flooding lasts for several days (Dolezel 1988). The water table is at or near the surface during the cool season, and due to frequent flooding and extended wetness, pine seedlings should not be planted on this type of soil (Dolezel 1988). Pophers soil is used almost entirely as woodland, and is well suited for production of quality hardwoods, such as water oak, willow oak, and swamp chestnut oak (*Quercus michauxii* Nutt.) (Dolezel 1988). This was proven by estimating site index (base age 50 years) to be 90-95 for cherrybark oak, water oak, and willow oak, using the method suggested by Baker and Broadfoot (1979). A map of the study area is shown in Figure 1.

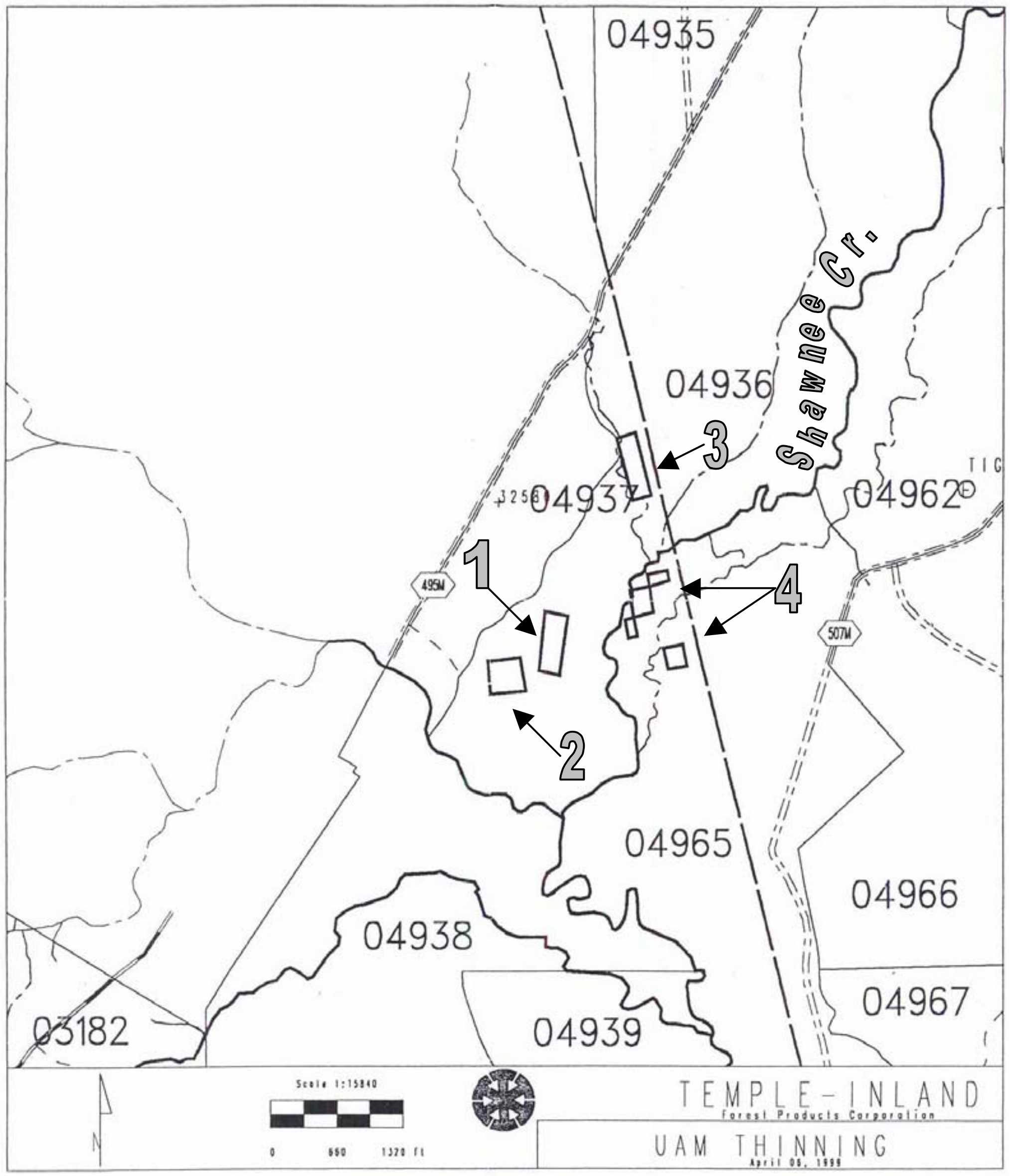

Figure 1. A map of the study area showing Blocks 1, 2, 3, and 4.

History, Climate, and Forest Cover Type

The site was originally intended for regeneration of a loblolly pine (*Pinus taeda* L.) plantation (pers. comm. Matthew Lowe, Research Forester, Temple-Inland Forest Products Corporation, PO Drawer N, Diboll, Texas 75941). It was mechanically prepared by shearing, and herbicides were not used. However, soon after the seedlings were planted, c. 1970, flooding resulted in high seedling mortality. A decision was then made to allow the area to naturally revert to an even-aged bottomland red oak stand.

Historic records of climate data show the growing season in Angelina County averages 244 days with the last freeze in the spring occurring around March 14 and the first freeze in the fall occurring around November 13 (Griffiths et al. 1987). Winters tend to be mild with about 35 days where the temperature falls below 32° F, and summers tend to be hot and humid with about 103 days where temperature rises above 90° F (Griffiths et al. 1987). The average annual daily maximum and minimum temperatures are 78° F and 56° F, respectively, and the mean annual precipitation is 41.5 inches, including about 65 days with 0.1 inches or more of precipitation (Griffiths et al. 1987).

The period of time required to grow a stand of trees to an optimum size or age of either economic or natural maturity is called the rotation (Smith et al. 1997). Rotation can also be defined as the age at which annual growth rate falls below some acceptable level in either physical or economic terms, usually no less than 5 percent (Daniel et al. 1979). The rotation age for the bottomland red oak stand in this study is approximately 60 years (pers. comm. Matthew Lowe). Therefore, it is at mid-rotation and is now 32 years old. The entire stand covers an area of approximately 80 ac., and the primary species now occupying the site are willow oak, water oak, cherrybark oak, and sweetgum. The study site is located on a flat in a minor creek bottom according to the definition of Hodges (1997). Briscoe (1955) reports that these sites have the potential to achieve growth rates of 4.7, 4.2, 3.4, and 2.1 inches in diameter per decade for cherrybark oak, swamp chestnut oak, water oak, and green ash, respectively.

According to Eyre (1980) the majority of this stand can be classified as the willow oak – water oak – diamond leaf (laurel) oak (88) forest cover type, which is commonly described as a "pin oak flat." Like Eyre (1980), Little (1979) does not recognize a difference between diamond leaf oak and laurel oak. In the past, diamond leaf oak has been given the status of a separate species (*Quercus obtusata* Ashe.) (Sargent 1965). Furthermore, laurel oak (*Quercus laurifolia* Michx.) is sometimes called swamp laurel oak to distinguish it from laurel oak (*Quercus hemisphaerica* Bartr. ex Willd.), which is also called Darlington oak (Harlow et al. 1996). All three species have been noted to occupy the same range (Harlow et al. 1996) (Sargent 1965). This may indicate only clinal variation within the same species. For the purpose of this study, the description of Eyre (1980) will suffice. Another important forest cover type that forms a component of the stand is the swamp chestnut oak – cherrybark oak (91) cover type (Eyre 1980). This is important to note because the statistical block design was applied in relation to where these specific forest cover types occurred on the landscape.

Experimental Design and Treatment Application

The study area includes four replications (blocks). Each block is approximately 3 ac in size. Within each 3-ac block, there are six 0.5-ac, rectangular treatment plots. Within each 0.5-ac treatment plot there is a 0.25-ac, rectangular measurement plot surrounded by a 15-ft buffer strip. The 15-ft buffer strip was installed to limit the spread of fertilizer between measurement plots. Inside each 0.25-ac measurement plot, there are two 0.01-ac, circular subplots, which were established to assess reproduction effects resulting from each of the six treatments. The factorial arrangement of treatments for each of the 0.5-ac treatment plots is listed as follows:

1) crown-thinned – fertilized,

2) crown-thinned – unfertilized,

3) low-thinned – fertilized,

4) low-thinned – unfertilized,

5) unthinned – fertilized, and

6) unthinned – unfertilized (control).

All were assigned randomly to each of the six treatment plots within each of the four blocks. The study was established in 1998 and pre-treatment measurements were taken. The study has now undergone its fourth year of measurements following the third growing season after the treatments were applied.

The selection of crop trees was accomplished using crown size, stem position, and crown classification. The crop-tree method was chosen because there is a need to place more attention on individual trees within bottomland hardwood stands. Smith and Long (2001) stated that culmination of stand-level production invariably precedes, sometimes by decades, culmination of individual tree production. Furthermore, according to Stringer et al. (1988), the crop-tree approach concentrates treatment benefits from intermediate treatments on trees with the highest potential to increase in value; in area-wide thinnings, trees are more likely to be removed without considering benefits to the residual stand.

When using the crop-tree method, Houston et al. (1995) stated that a list of acceptable tree species and stem quality classes must first be created. The tree class system suggested in Meadows (1996) was used in selecting crop trees for the study, and the Kraft Crown Classification Method lists four crown positions: dominant, codominant, intermediate, and overtopped (suppressed). Crop-tree selection was limited to trees of the codominant or dominant crown classes in relation to spacing. Meadows et al. (2001) stated that the four factors ultimately contributing to crown classification are amount of direct sunlight received from above, amount of direct sunlight received from the sides, crown balance, and relative crown size. When the trees were marked in February 1999, ideas relating to the development of Meadows et al. (2001) were well known and used in the selection of crop trees. All red oak trees that exhibited healthy crowns, exhibited or had the potential to develop a grade 1 butt log (Kenna 1981), had few to no epicormic branches on the butt log, and were free of disease were considered suitable crop trees. Other species were selected as crop trees when no suitable red oak species existed; this was done to uphold the thinning method applied and to maintain proper spacing.

Species favored for crop-tree selection were ranked as follows: 1) cherrybark oak, 2) water oak, 3) willow oak, 4) green ash, and 5) sweetgum. Crop trees were selected in the control plots as well as the treated plots. As previously defined, crown thinning consisted of removing trees from the dominant and codominant crown classes while leaving all trees within the intermediate and suppressed classes. During low thinning, only trees from the intermediate and suppressed crown classes were removed. When marking the stand for harvest, trees within the buffer strip were considered competition and recognized as pseudo-crop trees even though they were not measured as part of this study. This was done so that the observations in each measurement plot would not be biased and would be in keeping with the applied silvicultural treatments of crown and low thinning which were applied in early March 1999. During thinning treatments, trees were felled by chainsaw and left in place because of wet soil conditions.

Following the thinning treatments, a single application of granulated fertilizer yielding both nitrogen and phosphorous nutrients was applied to each of the plots randomly selected to receive fertilizer. The fertilization treatment was based on standard fertilization practices used in loblolly pine silviculture (Jokela and Stearns-Smith 1993), and is similar to fertilizer treatments used in upland hardwoods by Graney and Pope (1978). Nitrogen was applied at the rate of 200 lb/ac and phosphorus was applied at the rate of 50 lb/ac as ammonium nitrate (34-0-0) and diammonium phosphate (18-46-0) respectively. Hand-spreaders were used to apply the fertilizer in late June 1999, later than originally planned, due to early-spring flooding at the study site.

Measurements

Prior to harvest, all trees within each 0.25-ac measurement plot were described as follows:

1) species;
2) DBH (diameter at breast height, 4.5 ft above ground) of all trees > 3.5 inches (to the nearest tenth inch);
3) distance in feet from each tree center to plot center (recorded in tenths of feet);
4) azimuth of each tree in relation to plot center; and
5) crown classification.

Pre-treatment measurements were taken in the winter of 1998-1999. First-year measurements (after treatment) of tree DBH were collected in December 1999. Second-year measurements of tree DBH were taken in December 2000. Third-year measurements of tree DBH were taken in December 2001. Any changes in crown class will be expected to be minimal across the 3 years of the study. All DBH measurements were recorded in centimeters from the 2000 growing season onward. Initial and first-year measurements were recorded in inches.

All the following advance reproduction measurements were recorded in the dormant season pre-treatment and for each of the three years after treatment. After the 2000 growing season, all woody species within each 0.01-ac reproduction plot were assessed in two ways:

1) a dot tally count to measure height by size class; and
2) detailed measurements of each oak and green ash ≥ 1 ft tall.

Advance reproduction recorded by dot tally was separated by woody species and fell into six categories:

1) height < 1 ft and age < 1 year old;
2) height < 1 ft and age > 1 year old;
3) height between 1 and 3 ft;
4) height > 3 ft but < 0.5 inches DBH;
5) 0.6 – 3.5 inches DBH; and
6) > 3.5 inches DBH.

After the dot tally was complete, detailed tree measurements of all oak and ash advance reproduction included

1) height of all trees ≥ 1 ft tall and ≤ 0.5 inches DBH;
2) DBH of all trees ≥ 0.6 inches DBH;
3) tree growth (extension of apical meristem) within that year;

4) distance to plot center (recorded in tenths of feet);

5) azimuth in relation to plot center; and

6) a vigor rating of good, medium, or poor.

All the above advance reproduction measurements were taken after the 2000 growing season. Initially, during preharvest data collection (winter 1998-1999), detailed measurements were taken on all woody species within each reproduction plot. These measurements were repeated for the 1999 growing season. However, this method was abandoned in favor of taking detailed measurements of oak and ash species only.

Epicormic branching was also measured on each crop tree within each of the 24 measurement plots. It was measured from zero to 17.5 ft high on the tree bole to assess butt log quality. All epicormic branches were categorized as < 1 ft or > 1 ft in length to assess the importance of log defect. This takes into account the fact that older, more established branches are a greater threat to log quality. All branches were tallied by length within each 1-ft height increment separately; they were also broken into two categories within each 1-ft, height increment: > 1 ft (old) and < 1 ft (new). First-year epicormic data was collected to assess the 1999 growing season, second-year measurements were taken to assess the 2000 growing season, and third-year measurements were taken to assess the 2001 growing season. However, pre-harvest measurements of epicormic branching were not recorded.

Analyses

All statistical analyses were done with SAS Version 8 (SAS Institute 2000). The measurement unit was each tree, the experimental unit was each plot, and the sampling unit was the stand itself. Furthermore, this study was analyzed using a randomized complete block design (RCBD). This was done appropriately through analysis of variance (ANOVA) with 3 degrees of freedom for blocking, 5 degrees for freedom for treatments, and 15 degrees of freedom for error, which makes 23 degrees of freedom total. Significant differences were reported through ANOVA when $p \leq 0.1$ in the initial F-test. Comparison between each of the separate treatments was analyzed using the Least Significant Difference (LSD) multiple pairwise comparison method. The linear model for a RCBD design is

$Y_{ij} = \mu + \alpha_i + \beta_j + \varepsilon_{ij}$,

where

Y_{ij} = each observation within each treatment (i) and each block (j);

μ = the grand mean;

α_i = the effect of treatment i (i = 1, 2, 3, 4, 5, 6);

β_j = the effect of block j (j = 1, 2, 3, 4);

ε_{ij} = random error associated with the response of treatment i upon block j; and

$\varepsilon_{ij} \sim N(0, \sigma^2)$.

The assumptions of the model are that

1) the populations have normal distributions;

2) the population variances are equal but unknown;

3) the data are independent random samples from the populations; and

4) the treatment effects are additive and linear.

Specifically, average DBH and trees per acre (trees/ac) in 2001 of both crop trees and all trees was calculated according to treatment as a precursor to the calculation of relative stocking levels using the method suggested by Goelz (1995a). Then, tree species composition was calculated both pre-treatment and post-treatment as trees/ac by species class and as a percentage of total basal area per acre by species class. The species classes used were willow oak, water oak, cherrybark oak, sweetgum, miscellaneous, elm, ash, other oaks, and hickory. Other oak species in the stand included swamp chestnut oak, overcup oak (*Quercus lyrata* Walt.), post oak (*Quercus stellata* Wangenh.), and Shumard oak (*Quercus shumardii* Buckl.). Hickory species found included shagbark hickory (*Carya ovata* (Mill.) K. Koch), pignut hickory (*Carya glabra* (Mill.) Sweet), and bitternut hickory (*Carya cordiformis* (Wangenh.) K. Koch). Elm species found included American elm (*Ulmus americana* L.), slippery elm (*Ulmus rubra* Mühl.), and winged elm (*Ulmus alata* Michx.). Miscellaneous species found in the stand included boxelder (*Acer negundo* L.), red maple (*Acer rubrum* L.), American hornbeam (*Carpinus caroliniana* Walt.), sugarberry (*Celtis laevigata* Willd.), hawthorn (*Crataegus* spp. L.), persimmon (*Diospyros virginiana* L.), honeylocust (*Gleditsia triacanthos* L.), blackgum (*Nyssa sylvatica* Marsh.), loblolly pine, American sycamore (*Platanus occidentalis* L.), and black cherry (*Prunus serotina* Ehrh.). Finally, stand level stocking was calculated using the following multiple linear regression equation suggested by Goelz (1995a):

$$S = 0.01373N + 0.00960N + 0.00378ND^2,$$

where

S = percent relative stocking;

N = trees/ac;

D = quadratic mean diameter (in inches);

$D^2 = (BA / N) / 0.005454$; and

BA = basal area/ac (ft^2).

Next, periodic annual increment (PAI) of mean diameter growth in 1999, 2000, and 2001 was evaluated through ANOVA to show the progression of cumulative growth according to treatment. For example, PAI in 2001 was calculated by taking each tree's diameter measurement in 2001 (x_3), subtracting each tree's pre-treatment diameter measurement (x_{pre}), and then dividing that quantity by 3 to represent the period (third-year) that the measurement was taken: $(x_3 - x_{\text{pre}}) / 3$. For the final step in figuring PAI, the value for each tree was then totaled to calculate the periodic mean growth. Then, current annual increment (CAI) of mean diameter growth was evaluated each year using a repeated-measures ANOVA. This was essentially mean growth within each of the three years of 1999, 2000, and 2001, showing the contribution of each year's growth toward PAI. For example, CAI in 2001 was calculated by taking each tree's diameter measurement in 2001 (x_3) and subtracting each tree's diameter measurement in 2000 (x_2): $x_3 - x_2$. For the final step in figuring CAI, the value for each tree was then totaled to calculate the current year's mean growth. Epicormic branching values were also calculated by summing the mean number of epicormic branches by individual crop tree, block, plot, and branching category (<1 ft or >1 ft in length). Means were then compared by treatment and branching category using ANOVA.

Advance reproduction composition was evaluated by placing stems into size and species classes. Advance reproduction species classes used were ash, elm, hickory, miscellaneous, oak, shrub, sugarberry, and sweetgum. Elm species included American, slippery, and winged elm. Hickory species included bitternut, pignut, and shagbark hickories. Miscellaneous species included red maple, American hornbeam, western catalpa (*Catalpa speciosa* Warder ex Engelm.), persimmon, honeylocust, chinaberry

(*Melia azedarach* L.), red mulberry (*Morus rubra* L.), blackgum, eastern hophornbeam (*Ostrya virginiana* (Mill.) K. Koch), slash pine, loblolly pine, and Chinese tallowtree (*Sapium sebiferum* (L.) Roxb.). Oak species included willow, water, cherrybark, swamp chestnut, white, and overcup oaks. Shrubs included fringetree (*Chionanthus virginicus* L.), hawthorn, swamp-privet (*Forestiera acuminata* (Michx.) Poir.), possumhaw (*Ilex decidua* Walt.), American holly (*Ilex opaca* Ait.), yaupon (*Ilex vomitoria* Ait.), downy serviceberry (*Amelanchier arborea* (Mich. f.) Fern.), and American elder (*Sambucus canandensis* L.). Size classes were previously discussed and are labeled as follows for pre-treatment and 1999:

1) Class A = stem height < 1 ft;
2) Class B = stem height between 1 ft and 3 ft;
3) Class C = stem height > 3 ft but < 0.5 inches DBH; and
4) Class D = stem DBH 0.6 – 3.5 inches.

Size classes are labeled as follows for 2000 and 2001:

1) Class A1 = stem height < 1 ft and age < 1 year old;
2) Class A2 = stem height < 1 ft and age > 1 year old;
3) Class B = stem height between 1 ft and 3 ft;
4) Class C = stem height > 3 ft but < 0.5 inches DBH;
5) Class D = stem DBH 0.6 – 3.5 inches; and
6) Class E = stem DBH > 3.5 inches.

Advance reproduction stocking was also calculated using the point system suggested by Hart et al. (1995). This system records all oak and ash from seedlings < 1 ft in height to mature poletimber of 15 inches DBH. All seedlings < 1 ft in height are only given one-half a point due to a lower potential to grow if released. All ash seedlings > 1 ft in height are given higher point values than oak seedlings due to their better potential to grow if released. Furthermore, ash saplings from 2 to 5 inches DBH are given 3 more points than oak saplings of the same size for the same reason. All plots totaling 12 or more points are considered fully stocked, and ≥ 60 percent of all plots sampled on a site must be stocked for adequate reproduction. An example of the tally sheet for Hart et al. (1995) is shown in Figure 2.

Species	Height (feet)						DBH (inches)						Total
	<1		1-3		>3		2-5		6-10		11-15		
Oaks	Pt.	#	Pt.	#	Pt.	#	Pt.	#	Pt.	#	Pt.	#	
	0.5		2		3		3		2		1		
	0.5		2		3		3		2		1		
	0.5		2		3		3		2		1		
	0.5		2		3		3		2		1		
	0.5		2		3		3		2		1		
	0.5		2		3		3		2		1		
Ash													
	0.5		6		6		6		2		1		
	0.5		6		6		6		2		1		
	0.5		6		6		6		2		1		
	0.5		6		6		6		2		1		
	0.5		6		6		6		2		1		
	0.5		6		6		6		2		1		

Stocked = 12 points or more
Total points for plot ______

Figure 2. The tally sheet suggested by Hart et al. (1995) adapted from Johnson (1980).

To conclude all analyses, advance reproduction growth response was calculated using the detailed measurements of oak and ash seedlings. First, PAI of advance reproduction height growth was calculated using the same method described for tree diameter growth. Then, all treatment means were compared using ANOVA to determine statistically significant differences. Next, CAI of advance reproduction height growth was calculated using the same method described for tree diameter growth except that reproduction height growth was directly measured each year, so there was no need to subtract the previous year's height measurement. Calculation of CAI explained height growth within each year of the study and showed the contribution of each year's height growth toward the amount of cumulative height growth. Then, ANOVA was used to show significant differences in advance reproduction height growth between treatments.

RESULTS AND DISCUSSION

Tree Species Composition

The primary species found on the site were willow oak, water oak, cherrybark oak, and sweetgum (Figure 3), and the number of trees/ac of all species was 342 pre-treatment and 231 post-treatment. It appears that the presence of willow oak was reduced the greatest during thinning where trees/ac decreased from 162 to 112; however, willow oak continued to dominate the site. Due to thinning, water oak decreased from 59 to 41 trees/ac, sweetgum from 31 to 20 trees/ac, and cherrybark oak from 29 to 21 trees/ac.

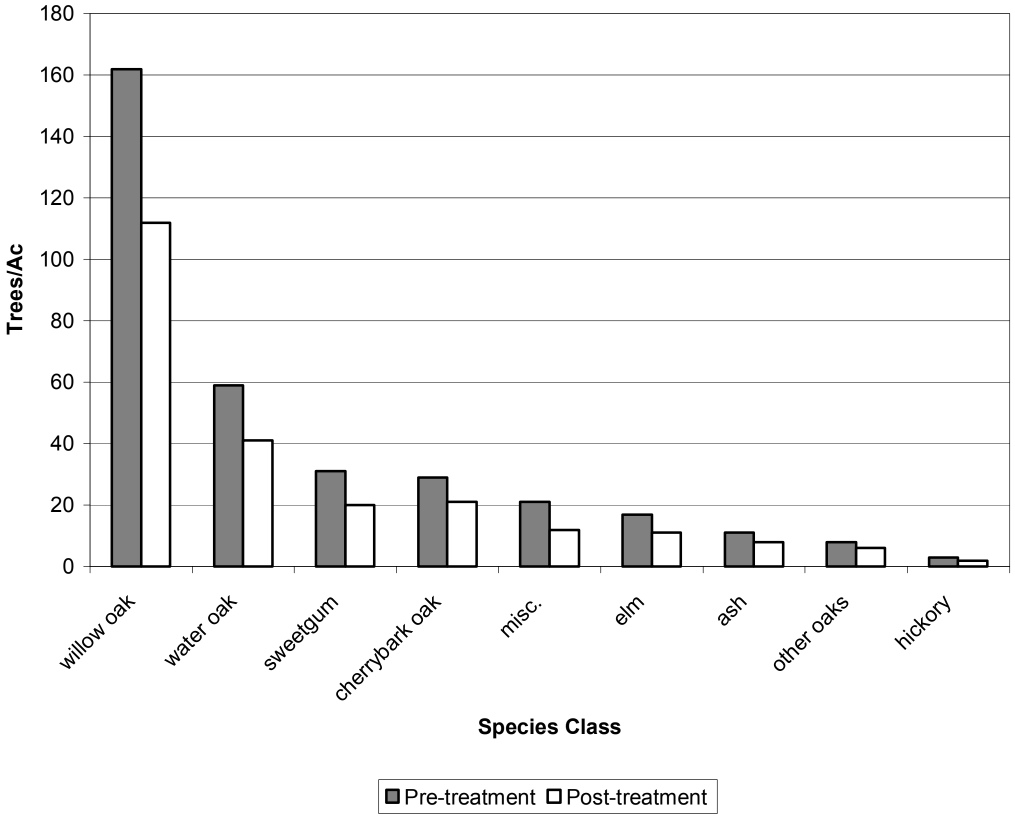

Figure 3. Pre-treatment and post-treatment tree species composition shown as number of trees/ac and grouped by species class.

Total basal area pre-treatment was 129 ft^2/ac, and total basal area post-treatment was 102 ft^2/ac regardless of thinning treatment. Tree species composition (Figure 4) shown as a percentage of total basal area per acre better reinforces the species dominance of willow oak (50), water oak (18), and cherrybark oak (10) pre-treatment; and willow oak (51), water oak (18), and cherrybark oak (11) post-treatment. When shown as a percentage of total basal area, in no case does the occurrence of sweetgum in the stand surpass the occurrence of cherrybark oak, which was preferred to sweetgum in the selection of crop trees.

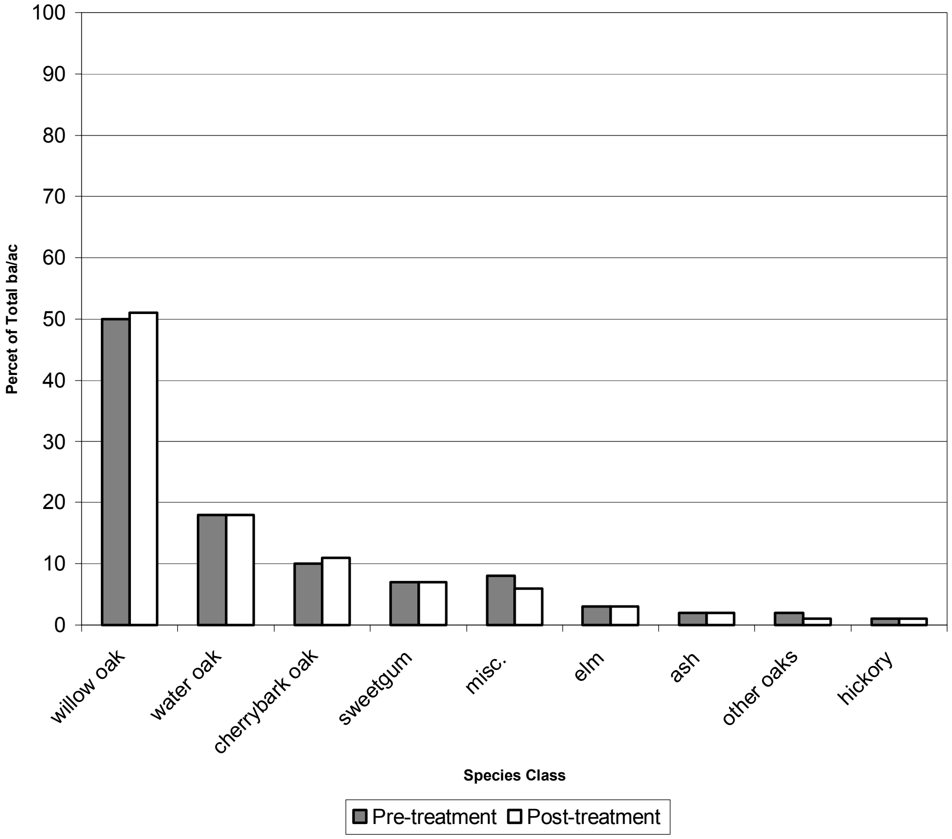

Figure 4. Pre-treatment and post-treatment tree species composition shown as a percentage of total basal area per acre and grouped by species class.

Current Mean Tree Diameter

To show the average size of trees currently occupying the stand, mean diameter of all trees and crop trees in 2001 was calculated by treatment (Table 1). The mean diameter of all trees in the stand was 9.12 (0.09) inches and the mean diameter of all crop trees in the stand was 12.55 (0.15) inches (numbers in parentheses represent standard error). Mean diameter of all trees in low-thinned plots (10.56) was significantly greater than in both crown-thinned (8.47) and unthinned (8.70) plots most likely due to the greater number of dominant and codominant trees left in the stand after low thinning. However, the mean diameter of all trees in low-thinned plots (10.56) does not exceed the mean diameter of crop trees in any treatment.

Table 1. Mean diameter of all trees and crop trees by treatment in 2001 where values in parentheses represent standard error and means with the same letter are not significantly different.

Trees	Treatments	Mean Diameter
		inches
All Trees	Crown	8.47 (0.16) b
	Low	10.56 (0.16) a
	No	8.70 (0.13) b
Pr > F		< 0.0001
All Trees	Fertilized	9.23 (0.13)
	Unfertilized	9.01 (0.12)
Pr > F		0.40
Crop Trees	Crown	12.72 (0.23)
	Low	12.72 (0.25)
	No	12.13 (0.28)
Pr > F		0.82
Crop Trees	Fertilized	12.92 (0.22)
	Unfertilized	12.24 (0.20)
Pr > F		0.82

Tree Stocking Levels Related to Stand Density

The first measurement in calculating stand density is trees per acre (Figure 5). A steep decline in trees per acre was shown between pre-treatment (1998) and 1999 due to the thinning treatments. The trees per acre values then decreased respectively with the treatments of no thinning, crown thinning and low thinning. A slight decline in trees per acre was noted due to a 3 percent decrease in stems per acre throughout the study from mortality related to self-thinning.

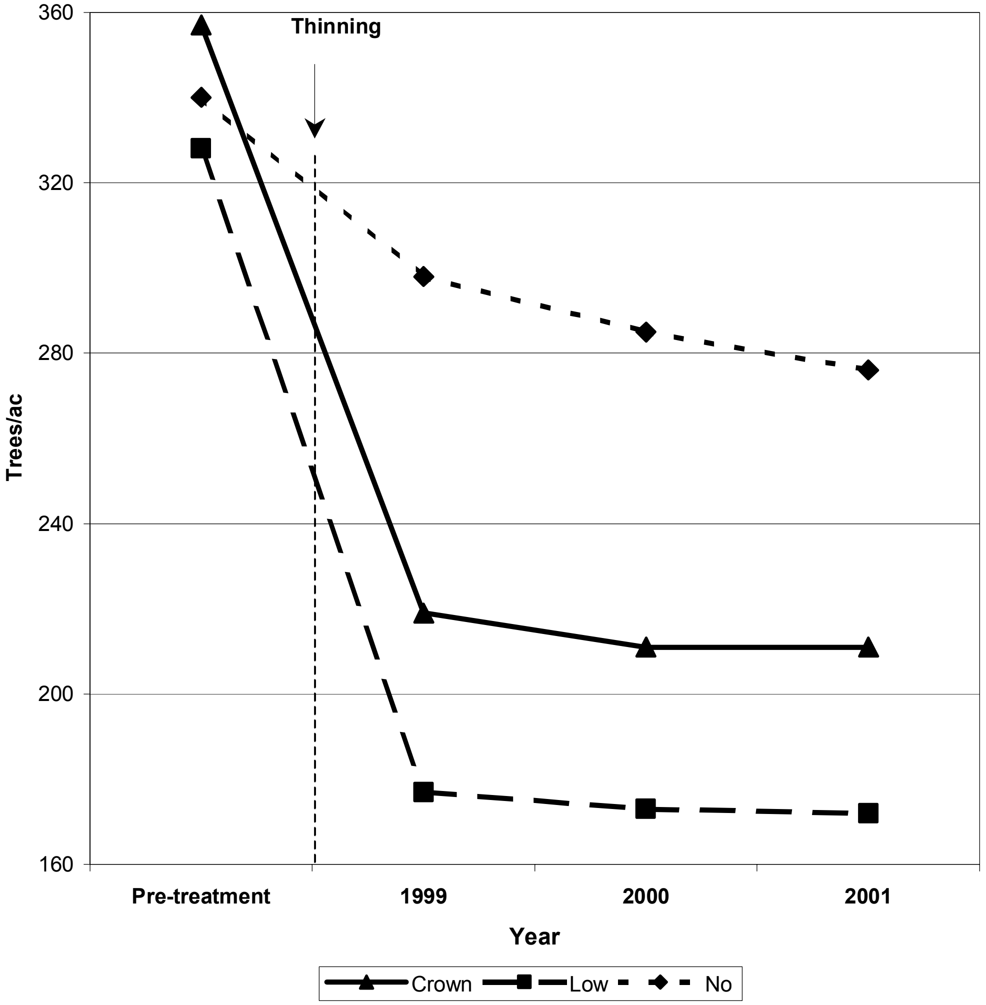

Figure 5. Total number of trees/ac by thinning treatment and year with a dashed vertical line representing when the thinning treatments were applied.

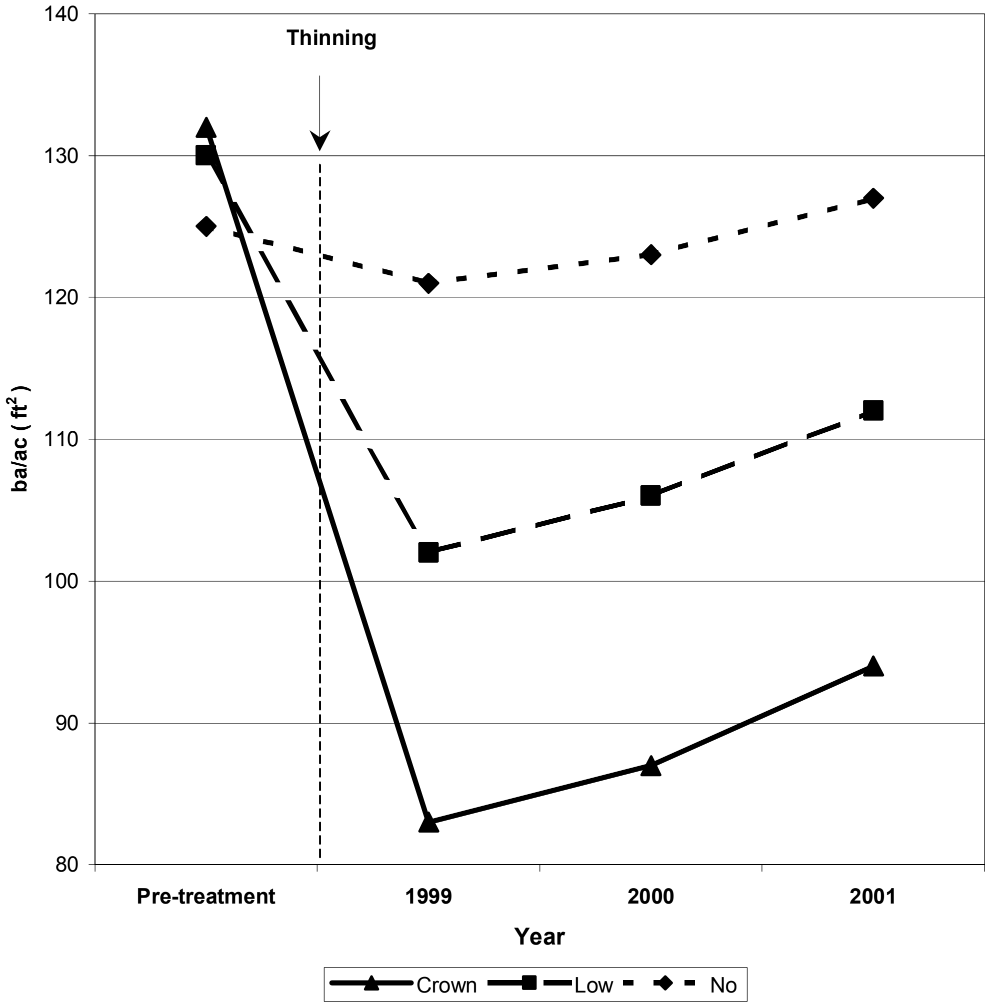

Figure 6. Total stand-level basal area by thinning treatment and year with a dashed vertical line representing when the thinning treatments were applied.

The second important measurement used in calculating stand density is basal area (Figure 6). Again, a steep decline was shown between pre-treatment and 1999 because of the thinning treatments. The basal area values increased respectively with the treatments of no thinning, low thinning, and crown thinning. Note that basal area removed in crown thinning was greater than that removed during low thinning; however, trees/ac removed in low thinning was greater than that removed during crown thinning. The reason for this was that during crown thinning some dominant and codominant trees (larger diameter trees) were removed to hasten the development of trees in the same crown classes, and during low thinning all trees of intermediate and suppressed crown classes were removed (smaller diameter trees) to hasten the process of self-thinning.

Stand stocking is a relationship of stand density to some value that is considered “normal” — in this case, for bottomland hardwood stands. Percent of stand level stocking was significantly different in relation to all thinning treatments for all three years post-treatment with no significant differences in stocking due to fertilization treatment (Table 2). Post-treatment stocking in unthinned plots was always greater than stocking in low-thinned plots, which was in turn greater than stocking in crown-thinned plots. Furthermore, stocking in unthinned plots was always > 100 percent, and 2001 stocking in low-thinned plots approached 100 percent at 98 percent stocking. Levels of stocking related to all treatments had quadratic mean diameters above 7 inches but below 11 inches, which was well below the manage-or-regenerate threshold of 16 inches suggested by Goelz and Meadows (1997).

Table 2. Percent of stand-level stocking by treatment and year where values in parentheses represent standard error (all < 1 percent), and percentages with the same letter are not significantly different.

Treatments	Pre-treatment	1999	2000	2001
Crown	123 (0.11)	77 (0.12) c	79 (0.13) c	85 (0.14) c
Low	120 (0.12)	90 (0.12) b	93 (0.13) b	98 (0.14) b
No	117 (0.11)	111 (0.11) a	112 (0.12) a	115 (0.12) a
Pr > F	0.44	< 0.0001	< 0.0001	< 0.0001
Fertilized	123 (0.07)	93 (0.08)	96 (0.08)	100 (0.09)
Unfertilized	117 (0.08)	92 (0.08)	94 (0.09)	98 (0.09)
Pr > F	0.12	0.39	0.32	0.25

Crop Tree Diameter Growth Response

Among all trees, PAI of diameter growth in 1999 and 2000 was significantly greater in unthinned plots than in thinned plots. This was most likely due to the removal of trees in thinned plots, since there were always less trees/ac in thinned plots than in unthinned plots (Figure 5). No difference in PAI of crop trees was noted until 2000 and 2001 when crop trees in thinned plots achieved significantly greater diameter growth than crop trees in unthinned plots. The growth of all trees preceding the growth of crop trees may be a case of stand level growth preceding individual tree level growth (Feduccia 1979, Feduccia and Mann 1976, Long 1985, Smith and Long 2001).

Table 3. PAI diameter growth of all trees and crop trees by treatment and year, where values in parentheses represent standard error, and means with the same letter are not significantly different.

Trees	Treatments	1999 PAI	2000 PAI	2001 PAI
			inches	
All Trees	Crown	0.10 (<0.01) b	0.12 (0.01) b	0.15 (0.01)
	Low	0.12 (0.01) b	0.13 (0.01) b	0.13 (0.01)
	No	0.14 (0.01) a	0.14 (0.01) a	0.14 (0.01)
Pr > F		0.01	0.03	0.37
Crop Trees	Crown	0.30 (0.02)	0.38 (0.02) a	0.44 (0.02) a
	Low	0.32 (0.03)	0.39 (0.05) a	0.38 (0.03) a
	No	0.29 (0.01)	0.30 (0.01) b	0.32 (0.01) b
Pr > F		0.13	0.06	0.01
All Trees	Fertilized	0.12 (0.01)	0.13 (0.01)	0.14 (0.01)
	Unfertilized	0.12 (0.01)	0.13 (<0.01)	0.14 (<0.01)
Pr > F		0.67	0.48	0.26
Crop Trees	Fertilized	0.28 (0.02)	0.34 (0.02)	0.38 (0.02)
	Unfertilized	0.33 (0.02)	0.37 (0.03)	0.38 (0.03)
Pr > F		0.13	0.33	0.78

Furthermore, results of CAI showed that diameter growth of all trees in 1999 was better in unthinned plots than in thinned plots (Table 4), which may be caused by greater basal area per acre in unthinned plots than in thinned plots (Figure 6). In 2000, CAI diameter growth of crop trees in thinned plots was significantly greater than CAI diameter growth of crop trees in unthinned plots. Most importantly, 2001 CAI diameter growth of crop trees in crown-thinned plots was greater than CAI diameter growth of crop trees in either low-thinned or unthinned plots. The diameter growth responses to thinning found in this study are typical of many studies (Feduccia 1979, Graney 1987, Graney and Pope 1978, Johnson 1968, Johnson and McKnight 1969, Lambert 1957, Langsaeter 1941, Meadows and Goelz 1993, Meadows and Goelz 1999, Meadows and Goelz 2001, Schaertl et al. 1997, Scott et al. 2001, Stone 1977, Stringer and Wittwer 1985, Stringer et al. 1988), but no study was found that specifically compared crown thinning and low thinning in bottomland hardwoods.

Table 4. CAI diameter growth of all trees and crop trees by treatment and year where values in parentheses represent standard error and means with the same letter are not significantly different.

Trees	Treatments	1999 CAI	2000 CAI	2001 CAI
			inches	
All Trees	Crown	0.10 (<0.01) b	0.15 (0.01)	0.20 (0.02)
	Low	0.12 (0.01) b	0.15 (0.01)	0.15 (0.02)
	No	0.14 (0.01) a	0.15 (0.01)	0.17 (0.02)
Pr > F		< 0.01	0.26	0.14
Crop Trees	Crown	0.30 (0.02)	0.47 (0.02) a	0.55 (0.05) a
	Low	0.32 (0.03)	0.45 (0.06) a	0.38 (0.04) b
	No	0.29 (0.01)	0.31 (0.02) b	0.36 (0.03) b
Pr > F		0.13	0.02	< 0.01
All Trees	Fertilized	0.12 (0.01)	0.15 (0.01)	0.18 (0.02)
	Unfertilized	0.12 (0.01)	0.15 (0.01)	0.16 (0.02)
Pr > F		0.67	0.26	0.47
Crop Trees	Fertilized	0.28 (0.02)	0.40 (0.03)	0.45 (0.03)
	Unfertilized	0.33 (0.02)	0.42 (0.05)	0.42 (0.05)
Pr > F		0.13	0.67	0.43

Epicormic Branching Response of Crop Trees

Mean number of all epicormic branches regardless of length only showed a difference in 2000 where crop trees in crown-thinned plots had more epicormic branches than crop trees in unthinned plots (Figure 7). This is most likely due to a greater amount of sunlight reaching tree boles in crown-thinned plots (Meadows 1995). In 2000, the same occurred except that crop trees in fertilized plots had significantly more epicormic branches than crop trees in unfertilized plots (Figure 8).

Next, mean number of epicormic branches according to branch length showed a difference in 2000 and 2001 where more epicormic branches >1 ft were found on crop trees in crown-thinned plots than in unthinned plots (Figure 9). Furthermore, in 1999, 2000, and 2001, more branches >1 ft occurred on crop trees in fertilized plots (Figure 10). In respect to thinning, these findings tend to contradict those of Meadows and Goelz (2001) who found that heavier thinning caused a minimal increase in epicormic branching among crop trees. They stated that retaining significant amounts of lower-crown-class trees increases the risk of epicormic branching. However, findings in the study at hand upheld the findings of Chapin (1991) and Osmond et al. (1987) who said that plants usually respond to an increase in stress by exhibiting a decrease in growth. Over all, there was a great decline in epicormic branches < 1 ft in 2000 and 2001, which tends to indicate most new epicormic branches formed directly after thinning. Figures 7 and 8 also show a decline in total number of epicormic branches throughout the study. Therefore, relatively few new branches have formed in 2000 and 2001, and those that formed after thinning are slowly dying back due to canopy closure.

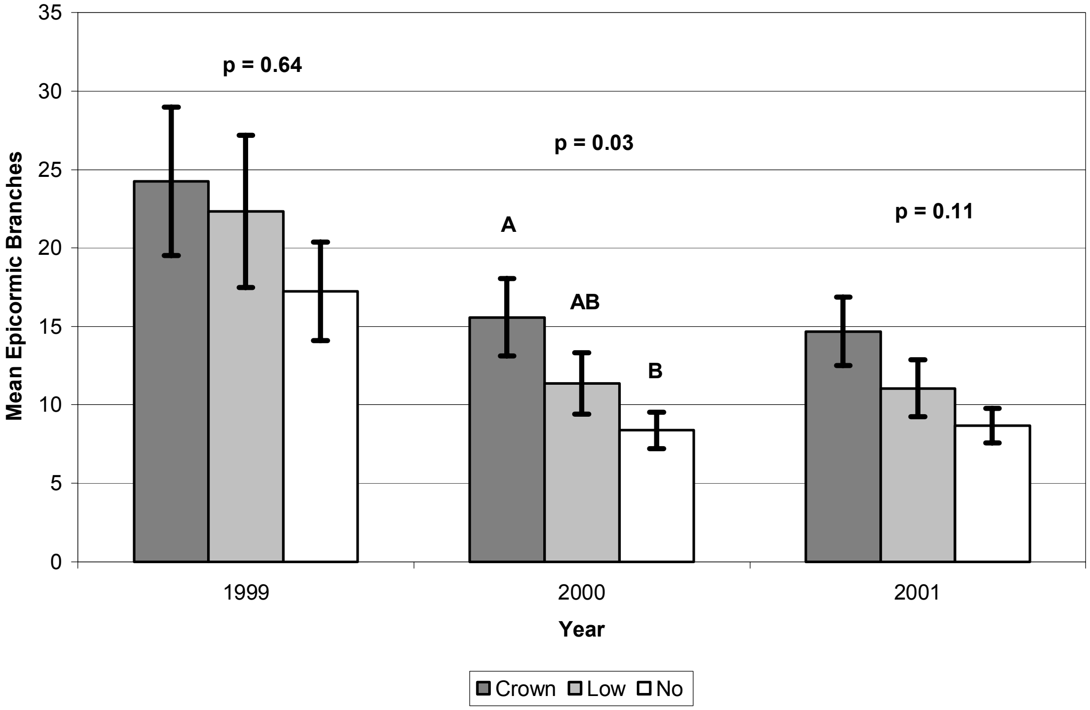

Figure 7. Mean number of all epicormic branches by thinning treatment and year where means with the same letter are not significantly different and vertical bars represent standard error.

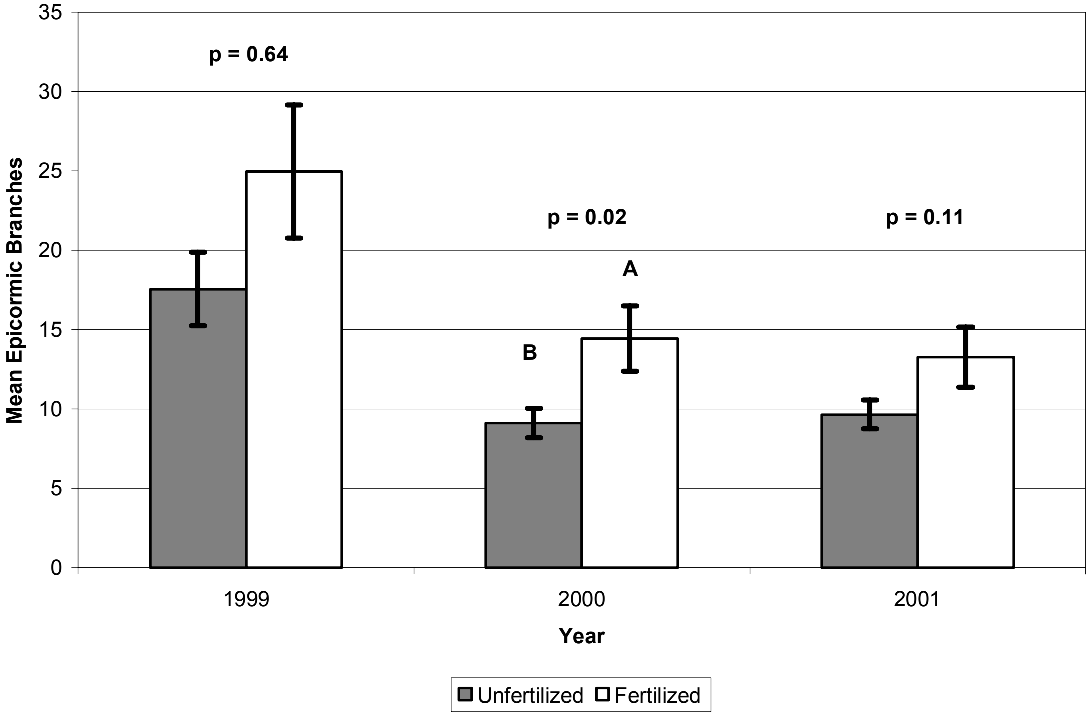

Figure 8. Mean number of all epicormic branches by fertilization treatment and year where means with the same letter are not significantly different and vertical bars represent standard error.

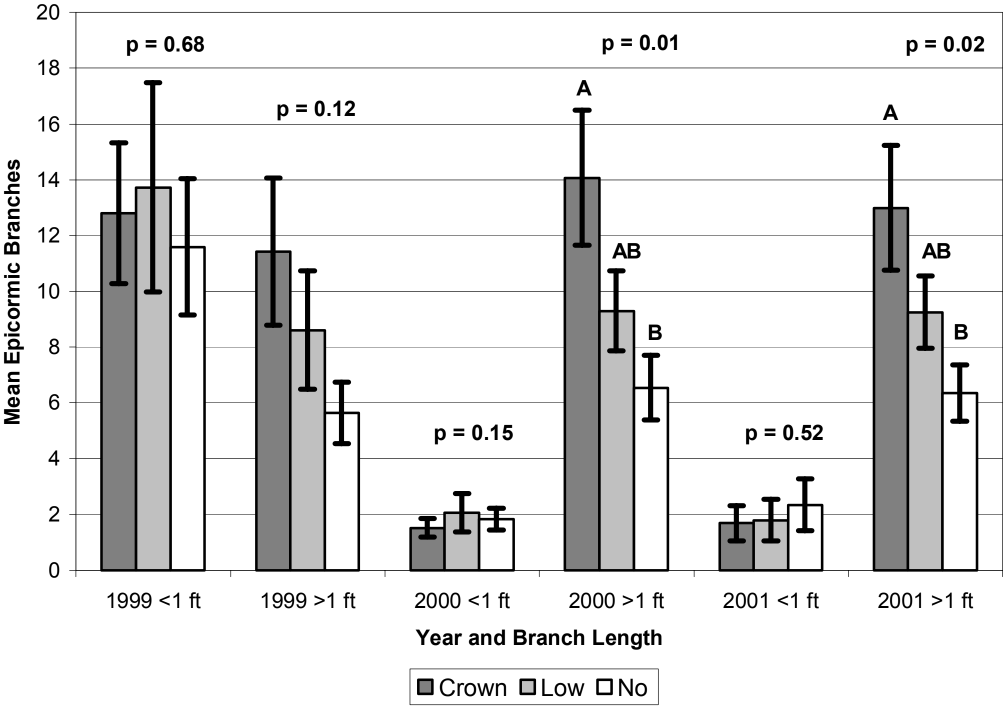

Figure 9. Mean number of epicormic branches by thinning treatment, year, and branch length where means with the same letter are not significantly different and vertical bars represent standard error.

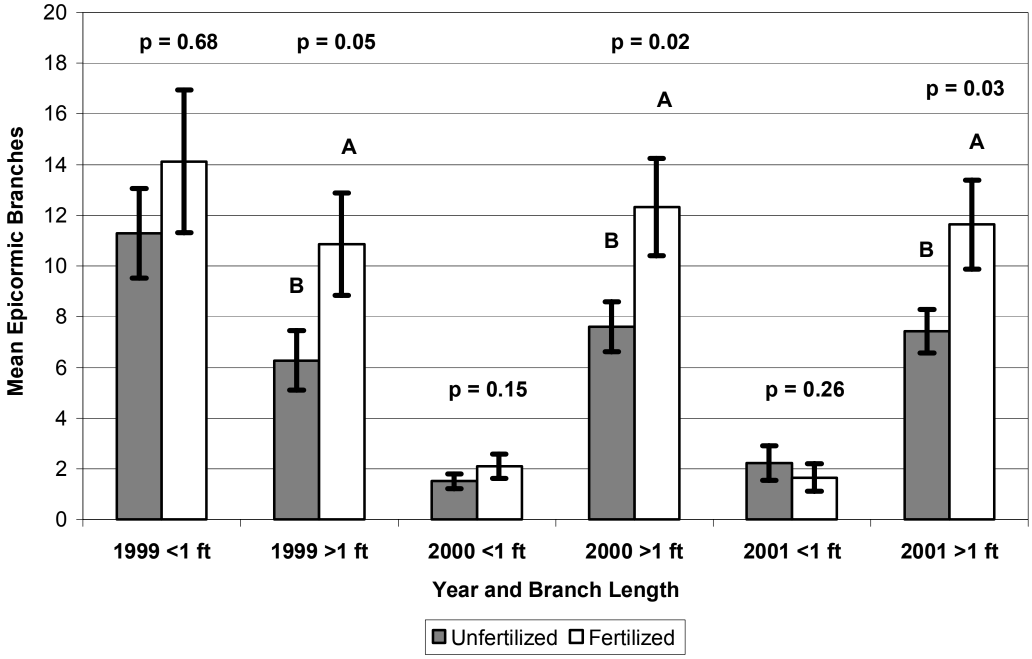

Figure 10. Mean number of epicormic branches by fertilization treatment, year, and branch length where means with the same letter are not significantly different and vertical bars represent standard error.

Reproduction Composition

Reproduction was divided into size and species classes for an assessment of composition as trees/ac (Figures 11 – 14). In 1998, oak in classes A (2302) and B (169) dominated with a relatively high amount of sugarberry (150), ash (142), and elm (110) in class A compared to proceeding years. In 1999, oak in classes A (1098) and B (260) remained high and shrubs remained constant. In 2000 and 2001, oak in classes A1, A2, and B continued to remain relatively high as shrubs remained relatively constant across all four years. The large amount of oak seedlings in classes < 1 ft in height and 1 to 3 feet in height can be attributed to the dominance of oak as an overstory species. However, oak and ash seedlings < 1 ft in height only received one-half a point apiece when stocking was figured according to Hart et al. (1995) as opposed to ash 1 to 3 feet in height and ash > 3 ft in height which both received 6 points apiece. Hart et al. (1995) concluded that seedlings < 1 ft in height have much less of a chance to grow if released.

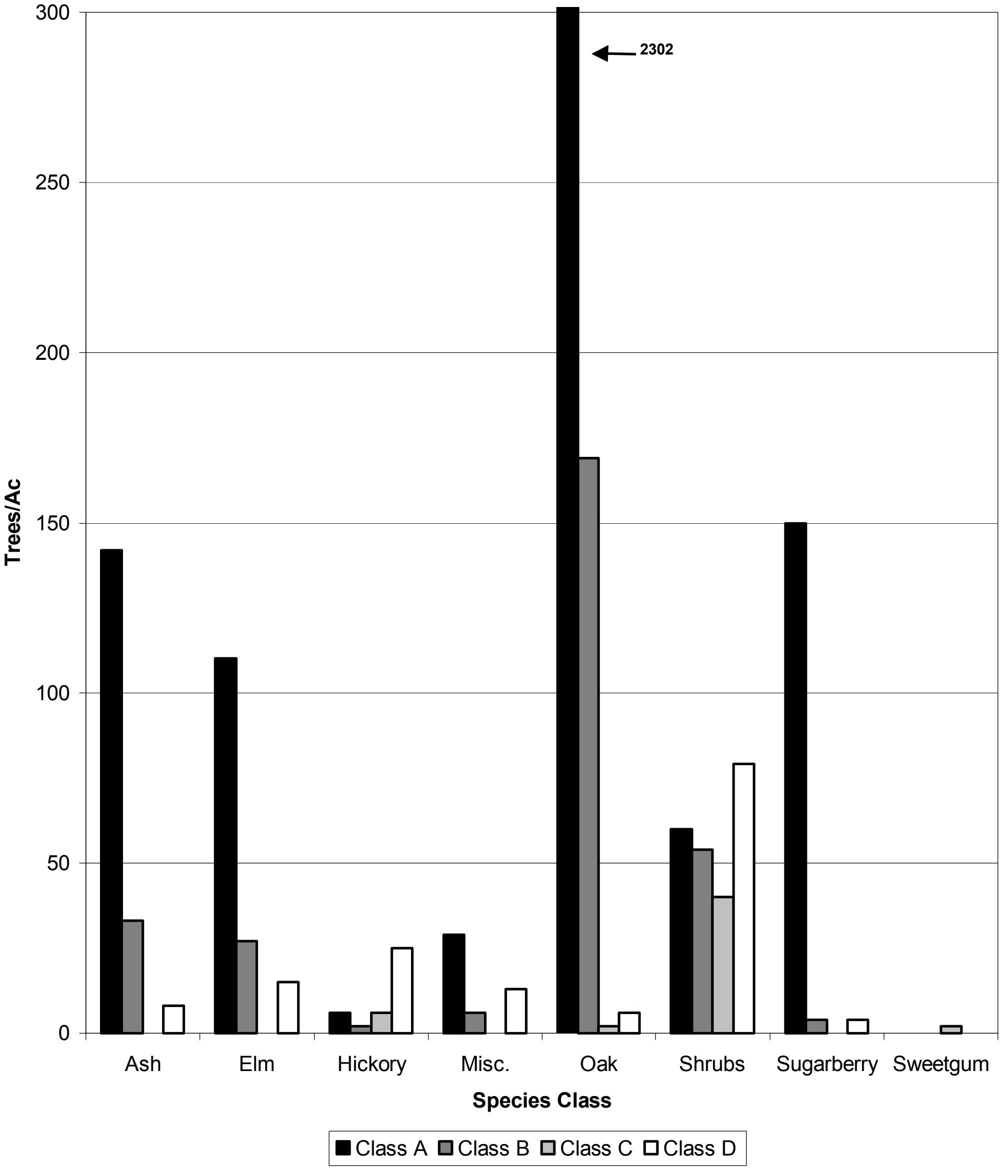

Figure 11. Pre-treatment reproduction composition (trees/ac) by size and species class where size classes A, B, C, and D are height < 1 ft, height between 1 ft and 3 ft, height > 3 ft but < 0.5 inches DBH, and DBH 0.6 to 3.5 inches respectively.

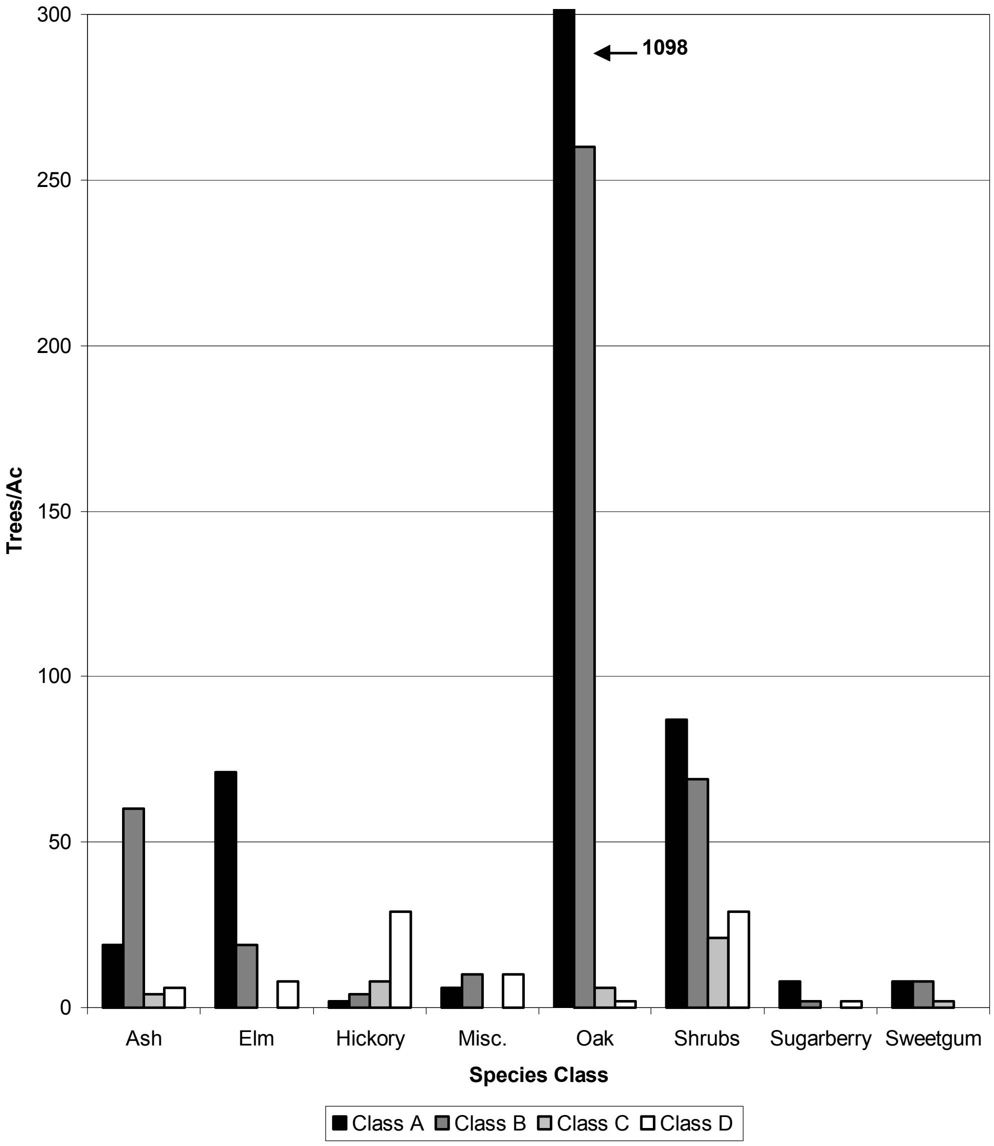

Figure 12. 1999 reproduction composition (trees/ac) by size and species class where size classes A, B, C, and D are height < 1 ft, height between 1 ft and 3 ft, height > 3 ft but < 0.5 inches DBH, and DBH 0.6 to 3.5 inches respectively.

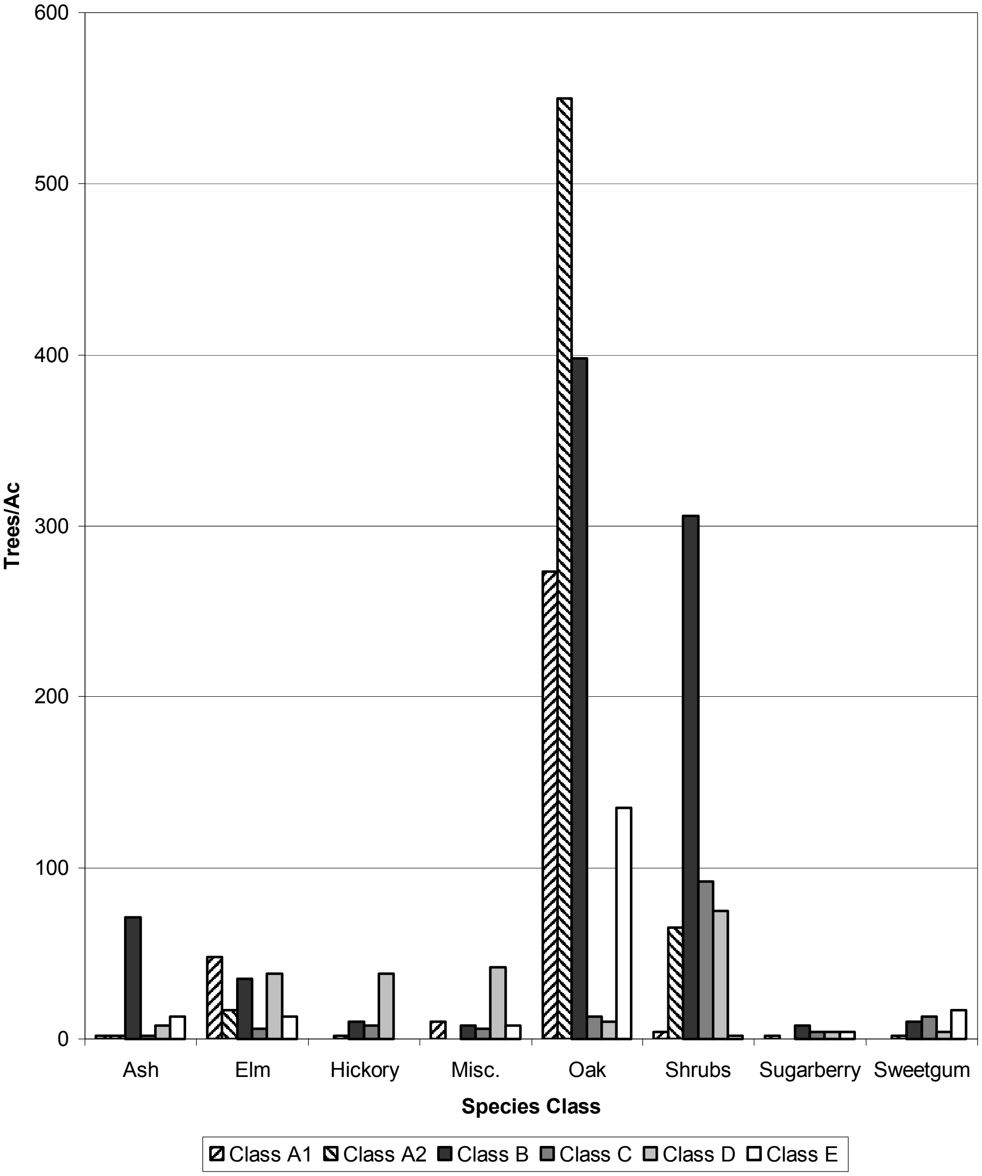

Figure 13. 2000 reproduction composition (trees/ac) by size and species class where size classes A1, A2, B, C, D, and E are height < 1 ft and age < 1 year old, height < 1 ft and age > 1 year old, height between 1 ft and 3 ft, height > 3 ft but < 0.5 inches DBH, 0.6 to 3.5 inches DBH, and > 3.5 inches DBH respectively.

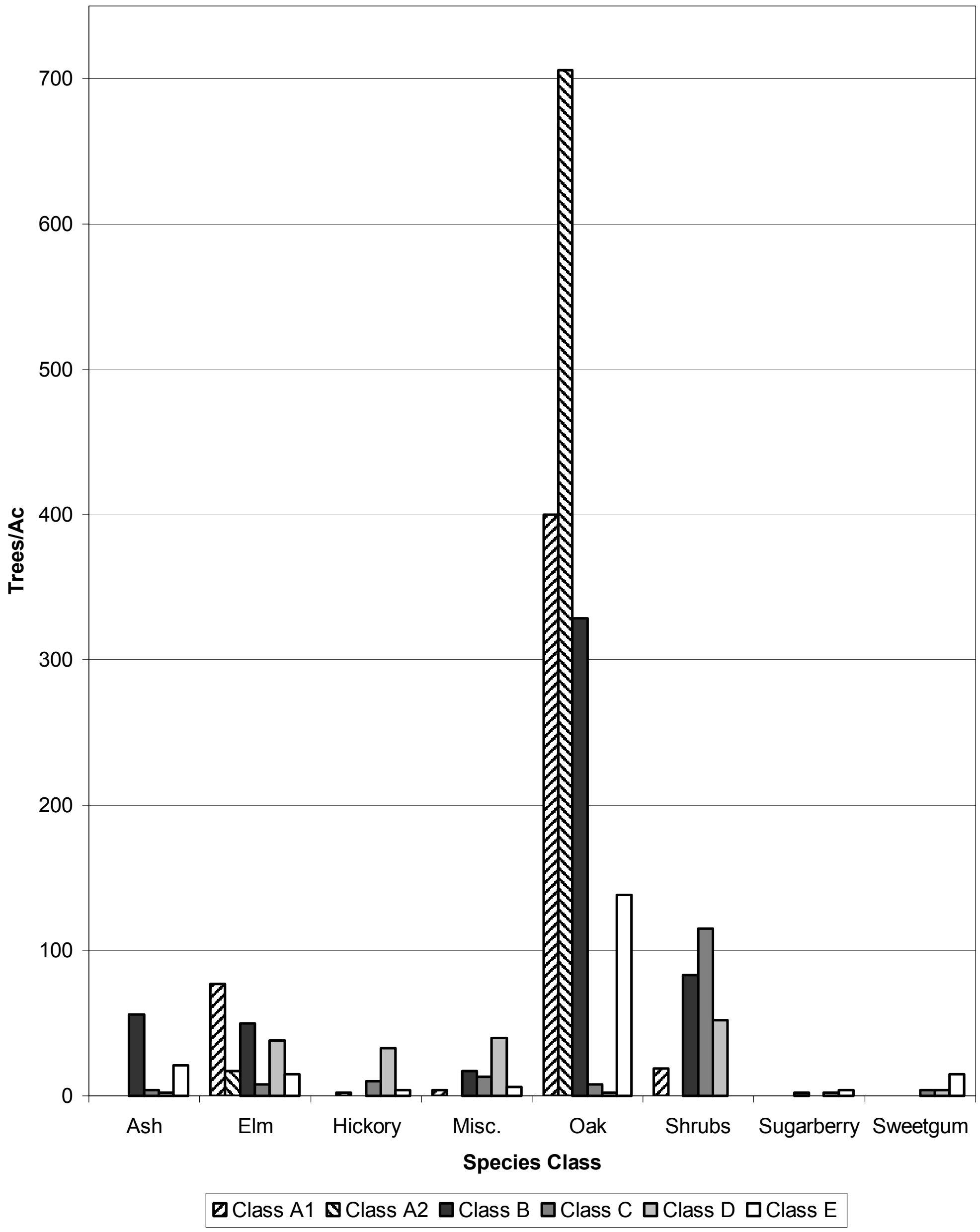

Figure 14. 2001 reproduction composition (trees/ac) by size and species class where size classes A1, A2, B, C, D, and E are height < 1 ft and age < 1 year old, height < 1 ft and age > 1 year old, height between 1 ft and 3 ft, height > 3 ft but < 0.5 inches DBH, 0.6 to 3.5 inches DBH, and > 3.5 inches DBH respectively.

Reproduction Stocking Levels

No differences were found in reproduction stocking due to stand level treatments (Table 5). Furthermore, in 1998, 1999, and 2001 the percent of stocked plots in the stand was < 60 percent (25, 33, and 50 percent respectively). Sixty percent is mentioned by Hart et al. (1995) as the minimum adequate percentage of stocked plots needed for regeneration of the stand. Only 2000 stocking was adequate where 63 percent of plots were stocked.

Table 5. Percent of stocked reproduction plots by treatment and year where values in parentheses represent standard error.

Treatments	Pre-treatment	1999	2000	2001
Crown	4 (2)	8 (4)	29 (2)	25 (<1)
Low	8 (<1)	8 (<1)	17 (<1)	13 (2)
No	13 (2)	17 (4)	17 (4)	13 (2)
Fertilized	17 (1)	25 (2)	38 (2)	25 (2)
Unfertilized	8 (1)	8 (1)	25 (2)	25 (2)
Pr > F	0.24	0.35	0.26	0.35

Reproduction Growth Response

Significant Differences in PAI of reproduction height growth were noted in 2000 and 2001. In 2000, crown-thinned plots showed greater PAI height growth than both low-thinned and untreated plots (Table 6). In 2001, crown-thinned plots showed greater PAI height growth than low-thinned plots, which in turn showed greater height growth than unthinned plots. These differences were most likely due to a greater amount of sunlight penetrating the forest canopy in thinned plots than in unthinned plots, which follows the recommendations of Simms and Loftis (1988). They suggested allowing greater amounts of sunlight to reach the forest floor for better responses to all types of reproduction treatments.

Table 6. PAI of reproduction height growth by treatment and year where values in parentheses represent standard error and means with the same letter are not significantly different.

Treatments	1999 PAI	2000 PAI	2001 PAI
		inches	
Crown	2.83 (0.49)	4.65 (0.75) a	3.59 (0.44) a
Low	3.11 (0.91)	3.03 (0.88) b	2.17 (0.56) b
No	3.11 (1.28)	2.24 (0.73) b	1.05 (0.41) c
Pr > F	0.96	0.04	< 0.01
Fertilized	3.07 (0.81)	3.90 (0.74)	2.55 (0.49)
Unfertilized	2.97 (0.70)	2.71 (0.60)	2.00 (0.48)
Pr > F	0.96	0.11	0.23

In 2001 and 2001, CAI reproduction height growth in crown-thinned plots was greater than both low-thinned and unthinned plots (Table 7). This was most likely due to a greater amount of sunlight reaching the forest floor in crown-thinned plots as noted in PAI reproduction height growth. Furthermore, 2000 CAI reproduction height growth was greater in fertilized plots than in unfertilized plots.

Table 7. CAI of reproduction height growth by treatment and year where values in parentheses represent standard error and means with the same letter are not significantly different.

Treatments	1998 CAI	1999 CAI	2000 CAI	2001 CAI
			inches	
Crown	0.89 (0.21)	1.39 (0.40)	3.82 (1.08) a	3.17 (0.53) a
Low	0.63 (0.23)	1.09 (0.26)	2.14 (0.74) b	1.66 (0.43) b
No	1.17 (0.25)	1.06 (0.32)	1.59 (0.42) b	0.85 (0.34) b
Pr > F	0.87	0.69	0.06	< 0.01
Fertilized	0.86 (0.19)	1.17 (0.26)	3.18 (0.82) a	1.91 (0.34)
Unfertilized	0.93 (0.19)	1.19 (0.28)	1.86 (0.47) b	1.88 (0.55)
Pr > F	0.87	0.69	0.09	0.93

CONCLUSIONS AND RECOMMENDATIONS

Crop Tree Diameter Growth

Hypothesis 1.1 suggested a positive response in radial growth of crop trees following both crown and low thinning. This proved to be true when crop trees in thinned plots showed higher PAI diameter growth than unthinned plots in 2000 and 2001. Most notably, crown-thinned plots showed a higher CAI diameter growth rate than both low-thinned and unthinned plots in 2001. Hypothesis 1.2 suggested a greater positive response in radial growth of crop trees after crown thinning than after low thinning. This was only the case during 2001 measurements of CAI diameter growth. Furthermore, hypothesis 1.3 suggested a greater positive response in radial growth of crop trees in thinned and fertilized plots than in plots thinned alone. There was no diameter growth response of crop trees to fertilization treatment, which may be due to the current fertility of the soil. Under conditions of high mineral nutrient availability in soils, plants have a low potential to absorb mineral nutrients; therefore, nutrient demand by the plant has more effect on nutrient uptake than nutrient availability in the soil (Clarkson 1985). In other words, the crop trees in the study at hand could have already had enough nutrients when the fertilizer was applied.

Epicormic Branching

Hypothesis 2 suggested thinning and fertilization would decrease the occurrence of epicormic branching on tree boles. Drawing conclusions regarding epicormic branching measurements was difficult due to the absence of pre-treatment measurements. However, data from second and third-year results suggested a need for further research in this area. Crop trees in crown-thinned plots showed a significantly greater number of epicormic branches > 1 ft in 2000 and 2001. Furthermore, crop trees in fertilized plots also showed a significantly greater number of epicormic branches > 1 ft in 1999, 2000, and 2001 measurements. However, there was a great decline in epicormic branches < 1 ft in 2000 and 2001, which indicated most new epicormic branches formed directly after thinning. There was also a decline in total number of epicormic branches throughout the study, which indicated that branches formed after thinning have begun to die back.

Reproduction Growth and Stocking

Hypothesis 3 suggested thinning and fertilization would increase the height growth and stocking of advance reproduction. Thinning did increase the mean height growth of individual stems; however, reproduction stocking levels were not affected by the thinning treatments. PAI reproduction height growth in crown-thinned plots was greater than growth in unthinned plots in 2000 and 2001. Furthermore, CAI reproduction height growth in 2000 and 2001 shows crown-thinned plots achieved significantly greater height growth than both low-thinned and untreated plots. Finally, 2000 CAI reproduction height growth was greater in fertilized plots than in unfertilized plots.

Stand Management Decisions

Due to the greater than adequate level of relative stocking, it is recommended that this stand be thinned again prior to harvest and sometime within the next 10 years due to the current age of the stand (32 years old). Low-thinned plots need to be reduced to at least 70 ft^2 BA/ac and 120 trees/ac, and crown-thinned plots need to be reduced to at least 55 ft^2 BA/ac and 150 trees/ac. Residing just below the B-line of stocking suggested by Goelz (1995a), the trees will then be allowed 10 years after a second thinning to approach full stocking. At this time, a reproduction evaluation will be done to determine if adequate reproduction stocking exists prior to final harvest. Since the most logical alternative for future species composition in this stand is red oak, steps should be taken to insure adequate red oak reproduction on the site. If stocked reproduction plots fall below 60 percent (Hart et al. 1995), when final harvest is eminent, it may be necessary to re-evaluate reproduction stocking in the fall of the next year in which a sufficient acorn crop is produced. When this is not an option, the cost of underplanting oaks after a shelterwood cut and midstory herbicide treatment may need to be evaluated.

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VITA

Alexander Michalek is originally from Cabot, Lonoke County, Arkansas. Cabot, bordering on Arkansas's Ouachita Mountain Range and Mississippi River Alluvial Valley, was once a small, quiet community of less than 3000 people. However, it has grown exceptionally in the past 10 years due to its 40-mile proximity to downtown Little Rock, Arkansas. From a young age, Alexander has been interested in trees, forested land use, and the wild outdoors in general, so when he graduated from Cabot High School on May 22, 1992, he went on to study forestry at Louisiana Tech University in Ruston, Louisiana. During his years in Ruston, Alexander also worked for Willamette Industries, Inc., Ruston Forestry Division as a Forestry Technician. After graduating from Louisiana Tech University on March 6, 1999, he went to work for the USDA Forest Service at the Calcasieu Ranger District in Gardner, Louisiana, as a Timber Marker and Firefighter. His interest in silviculture of bottomland hardwood forests and an opportunity to continue his education in forestry prompted him to enroll in a Master of Science program at Louisiana State University and Agricultural and Mechanical College in Baton Rouge, Louisiana, where he is scheduled to receive his degree on May 23, 2003. Alexander is currently employed with the USDA Forest Service, National Forests in Mississippi at the Delta Ranger District in Rolling Fork, Mississippi, as a Professional Forester.