Crop Tree Enhancement of Green Ash (*Fraxinus pennsylvanica*) in a West Tennessee Hardwood Bottom

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Wayne Clatterbuck, Major Professor

We have read this thesis and recommend its acceptance:

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Accepted for the Council:

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Vice Provost and Dean of the Graduate School

(Original signatures are on file with official student records.)
Crop Tree Enhancement of Green Ash (*Fraxinus pennsylvanica*) in a West Tennessee Hardwood Bottom

A Thesis Presented for the

Master of Science

Degree

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John Luke Bowers

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Abstract

Crop tree enhancement is a forest management technique undertaken to maintain, enhance, and improve the species composition, growth rate, and stem quality of stands so that management objectives may be better and more quickly accomplished. In 1996, a crop tree enhancement study involving green ash (*Fraxinus pennsylvanica*) in a 16-year-old, naturally regenerated, mixed-species, pole-sized, bottomland hardwood stand was initiated at Ames Plantation in West TN. Treatments included a crown-touching release, a crown-touching release plus one-time fertilizer application, and a control, applied in a randomized block design with five 25-crop tree repetitions of the three treatments. Initial crop tree diameters, heights, clear bole lengths, crown dimensions, and crown classes, as determined by the crown rating system for southern hardwoods (Meadows et al. 2001), were recorded at this time. Eighteen years later in 2014, measurements were again recorded. Additionally, competing species, determined with a 10F wedge prism, and the depth to mottled soil horizons for each crop tree were recorded. Growth in diameter, height, crown length, and crown spread over the 18-year study period were calculated. Analysis of variance tested for differences in treatment response. Relationships between the depth to mottled horizons, treatment response, and block layout were examined with chi-square analysis and correlation analysis. Release and release plus fertilize treatments generally did not differ in diameter, height, crown expansion, and crown class. However, both outperformed the control treatment. Release and release plus fertilize treatments maintained a greater percentage of upper canopy green ash crop trees than the control. Crop trees of different crown classes responded to release at varying degrees, with the largest increases in diameter and crown expansion occurring in the co-dominant class. Releasing dominant crop trees did not yield significantly greater growth, while some intermediate trees benefitted from release. The depth to mottled horizons fluctuated across the study area, but with little relationship to crop tree growth. Competing species composition differed at varying depths to mottled horizons. Crop tree enhancement appears to be a beneficial management strategy for
improving growth rates and maintaining the upper canopy status of green ash in mixed-species, bottomland hardwood stands.
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Chapter 1: Introduction

Crop tree enhancement (CTE) is a forest management technique undertaken to maintain, enhance, and improve the species composition, growth rate, and stem quality of stands so that management objectives may be better and more quickly accomplished. Traditionally, the primary economic focus of forestry has been the production of timber for wood and paper products. While monetary return remains one of the driving forces for forest management, increased emphasis is being directed upon the concepts of ecological sustainability and biodiversity. In response, the active management of mixed-species stands has grown rapidly in popularity.

Mixed-species stands, however, present unique management challenges. Every species in a stand grows at distinct rates and is influenced independently by shifts in resource availability on a temporal and spatial scale (Oliver and Larson 1996). As species richness increases, the more complex the patterns of stand development become. To accomplish management objectives, particularly objectives related to species composition and timber quality, it often becomes necessary to influence stand development patterns to favor certain trees over others.

Crop tree enhancement, although not necessarily a new concept, could provide unique opportunities in mixed-species stands, allowing forest managers to maintain biodiverse species mixtures, all while improving timber value by directing management attention, and concurrently growth, towards the most valuable individual trees within a stand. Essentially, the goal is to “enhance” a stand with a subset of trees of a more desirable species and quality that cater to specific objectives, while leaving the remaining components of the stand intact.

Enhancement is achieved through providing increased growing space to selected crop trees by reducing crown competition from adjacent trees. The removal of trees directly competing with a crop tree’s crown is called crop tree release (Miller et al. 2007). Other treatments that may favor the crop
tree, such as pruning and direct fertilization, can also be implemented within a crop tree enhancement regime.


However, most of the studies conducted on crop tree management have been on a short-term basis, and although their findings are promising, it is the long-term impact over the life of a stand that is of greatest importance. For timber production, the higher-value final product provides the justification for implementing any mid-rotation silvicultural operation. The impact following crop tree enhancement throughout a rotation has been much less established.

Additionally, crop tree enhancement's impact has not been investigated for the abundance of species and site conditions common in eastern hardwood stands (Houston et al. 1995). Consider mixed-species bottomland hardwood stands common across the southeastern US, where shifting water levels, rapid soil deposition, topographical micro-variations, and unique species mixtures make for complex management scenarios and require multifaceted approaches.

Green ash (*Fraxinus pennsylvanica*) is a commonly occurring species in hardwood bottoms that may present unique opportunities to investigate the effectiveness of crop tree enhancement. A highly sought-after commercial tree species, green ash on most sites is characterized by a clear, straight bole for about half of the total height at maturity. On productive, bottomland sites in the southern part of its range, green ash can reach heights up to 120 feet and diameters at breast height of 24 to 30 inches (Fitzgerald et al. 1975). Seeds are consumed by a number of game and nongame animals and birds. This
ability to meet multiple timber and wildlife related management objectives gives credence to green ash as a potential crop tree species.

In addition, green ash commonly fails to maintain its crown position in the canopy of mixed-species stands (Kennedy 1990). It remains underneath more rapidly growing associates, not attaining its potential in terms of volume and log grade. Crop tree enhancement could represent a possible tool to alleviate this problem, providing green ash with the increased growing space and additional resources needed to increase growth rates, maintain good stem form, and achieve dominant and co-dominant crown positions in the mature stand. Few, if any, studies have been conducted on the impacts of crop tree management on green ash in mixed-species hardwood bottomland forests.

The objective of this research is to evaluate the success of crop tree enhancement treatments applied to green ash in a 16-year-old, naturally regenerated, mixed-species, pole-sized, bottomland hardwood stand after 18 years following application. The success of crop tree enhancement will depend on the maintenance of green ash as an overstory component of the stand, its improvement of green ash growth rates, and its impacts on green ash stem quality. In addition, explanations of crop tree enhancement success or failure relating to crown characteristics and soil conditions will be developed.
Chapter 2: Review of the Literature

**Crop Tree Enhancement**

Crop tree enhancement is a versatile, management objective-driven approach to mid-rotation silviculture of particularly high-relevance in mixed-species hardwood forests. At its roots, crop tree enhancement is a combination of stand evaluation and silvicultural treatments designed to promote the development and growth of individual crop trees within a forest matrix that are well-suited to accomplishing management objectives. The process begins with a clear identification of these objectives, followed by an evaluation of stand potential, and ultimately by the selection and treatment of crop trees (Houston et al. 1995). In many ways, crop tree enhancement involves the same processes from the more common terminology, crop tree management, as described by Perkey et al. (1993). A crop tree is one that displays desirable characteristics, such as high timber value or wildlife benefit, that help meet management objectives and possesses the ability to respond to treatment and remain competitive for the rotation of the stand (Miller et. al 2007, Morrissey et al. 2011). Crop trees can be of species that are underrepresented in a given stand, with the objective being to simply maintain their presence. Typically, trees of desirable species with dominant and co-dominant crown classes should be targeted. Species selection is flexible, but limited by management objectives, stand potential, and local market conditions. The number of crop trees to manage per acre is also influenced by these factors, in addition to, a forester’s judgement on how many stems of high-quality it would require to make the operation economically viable. The additional benefits to revenue from crop tree enhancement must offset the costs to perform the operation for it to be economically feasible (Miller 1984). The end goal of crop tree enhancement is a mature stand composition enriched with competitive crop trees of high-quality and value contributing to the accomplishment of the stand’s management objectives (Miller 2000).
Silvicultural treatments incorporated into a crop tree enhancement regime typically include release and/or direct fertilization. Pruning is also a common technique to benefit crop tree development. This review focuses primarily on crop tree release and direct fertilization.

**Crop Tree Release**

Crop tree release is an intermediate silvicultural treatment undertaken to provide additional growing space to selected trees through the removal of crown competition from adjacent trees. Unlike traditional thinning approaches which seek to re-distribute site resources more or less equally across the residual stand, the goal of crop tree release is to target site resources towards only a small number of selected crop trees (Lamson et al. 1990, Mercker 2004, Miller et al. 2007). Typically, the goals of crop tree release are to improve species composition, accelerate growth rates, and promote better stem quality. A complete crown-touching release is a common recommendation (Perkey et al. 1993, Nyland 1997). Release involves cutting or deadening trees that touch or are within a specified distance of the crop tree’s crown, in order to reduce competition for light and other site resources (Figure 1). To conduct the practice correctly, only the trees competing with a crop tree should be removed. Trees not in direct competition should remain intact. After release, crop trees typically respond by extending their roots and branches, becoming more vigorous and competitive as they adapt to additional resources and expand into the vacated growing space (Oliver and Larson 1996).

Crop trees typically respond to release along four observable growth characteristics: height, diameter at breast height (DBH), crown size, and length of clear stem (Miller 1997). Research from the Fernow Experimental Forest showed a 10-year DBH growth response of 3.5 inches for yellow-poplar (*Liriodendron tulipifera*) and 2.8 inches for red oak (*Quercus rubra*) following crop tree release (Perkey et al. 1993). In a study conducted on an even-aged, pre-commercial stand of central Appalachian hardwoods in West Virginia, the three-year diameter growth of released trees was 0.2 to
Figure 1: Crop tree release involves removing adjacent competing tree crowns from selected crop trees (green). Pictured above is an example of a complete crown-touching release, as described by Miller et al. (2007), where competing trees on all sides of crop tree are removed.
0.4 inches greater than unreleased trees (Smith and Lamson 1983). Height growth increase was negligible over this time period. Stringer et al. (1988) reported that three-year diameter growth of released trees was accelerated over control trees in small-sawtimber sized white oak (*Quercus alba*) stands in Kentucky. Twillmann (2004) conveyed that crop tree release in upland oaks resulted in shorter times until financial maturity was reached. Ward (2007) reported increased diameter and volume growth of black birch (*Betula lenta*) over eight years, and in that study demonstrated the importance of proper timing of crop tree management procedures. In young stands, the canopy gaps created by crop tree release are more rapidly re-occupied by the crop tree and neighboring tree crowns, limiting epicormic branching on the bole of the crop tree. In older stands, canopy gaps are filled in more slowly after release, because gaps are larger from larger trees being removed and growth rates have somewhat declined with older trees. Released pole-sized stems of black walnut (*Juglans nigra*) displayed growth rates twice as fast as unreleased stems, and the release response was greatest for dominant and co-dominant stems (Clark 1967). Wood et al. (1996) showed a positive growth response in yellow birch in a naturally regenerated 20-year-old stand and also indicated a threshold exists between gap size following release and the response of the crop tree. Too much crown release may promote epicormic sprouting on the bole due to increased sunlight reaching the tree’s lower bole, while too little crown release didn’t provide adequate increases to growth.

Crop tree management has proven ineffective in some scenarios as well. The results of a study on the response of seven-year-old stems of yellow-poplar and black cherry (*Prunus serotina*) to crop tree release after five years indicate released stems showed little significant difference from unreleased stems in height, diameter, and crown position (Trimble 1973). This study was re-examined five years later, for a total of ten years after release, and the same conclusion that release did not significantly benefit tree growth was again reported (Smith 1979). The authors of both these studies suggested releasing crop trees should be delayed until the crown classes are more distinguishable, citing that age...
seven was likely too early to permanently improve the crown position of most the crop trees. Ellis (1979) revealed the impact of release on growth rates was minimal for black cherry and white ash (*Fraxinus americana*), but improved upon for sugar maple (*Acer saccharum*). Leak and Solomon (1997) reported one pre-commercial application of crop tree release did not result in appreciable increases in growth for white ash and yellow birch after five years.

Long term studies on crop tree management have been conducted much less frequently. In an 18-year-old study, Ward (2013) reported complete crown release of upland oak species increased 18-year diameter growth and the maintenance of oaks in the overstory. Another long term study involving diameter growth after release of paper birch (*Betula papyrifera*), sugar maple, yellow birch, American beech (*Fagus grandifolia*), red maple (*Acer rubrum*), and white ash demonstrated white ash did not significantly benefit from crop tree release, but the other species did respond positively to varying degrees (Leak and Solomon 1997).

Several studies indicate crop tree management can improve competitiveness and crown position. Pre-commercial crop tree release increased upper canopy persistence and diameter growth of oak saplings in Connecticut measured 24 years after crop tree release (Ward 2013). Working with northern red oak and black cherry in West Virginia, Schuler (2006) discovered the crown class distribution of released northern red oak had improved over a ten-year period compared to unreleased stems, in addition to, observed increases in crown expansion and diameter growth. Schuler’s results agreed with a separate study reporting released stems had greater survivability and less crown-class retrogression than unreleased stems in an 8 to 12-year-old stand of Appalachian hardwoods (Wendel and Lamson 1987). Generally, trees with released crowns tend to maintain their initial crown class better than unreleased trees (Marquis 1969, Trimble 1973, Miller 2000).
Crop Tree Fertilization

Fertilization of forest trees and stands has been of interest for a considerable period of time. Fertilization is one of the few components in the forester’s toolbox that actually can improve site productivity, rather than simply working within its constraints. Central to this line of thinking is the core principle that few forest soils provide an optimum supply of nutrients essential for the development and growth of trees (Smith et al. 1997). The three elements most likely to be deficient in forest soils, due to their significant roles in plant physiology, are nitrogen, phosphorous, and potassium. Increasing the supply of these elemental nutrients, particularly nitrogen, through fertilization generally improves the growth of forest trees. Miller (1981) describes the nutritional stages that occur within stand development that have implications for fertilization. Tree growth is very dependent on soil nutrient concentrations before canopy closure occurs, and response to fertilization can be expected during this time. However, fertilization is unlikely to produce a response after canopy closure has occurred, unless additional growing space becomes available. This suggests alleviating crown growing space after canopy closure through a crop tree release along with a well-timed fertilizer application could produce a positive growth response.

Fertilization has long been noted for accelerating growth in southern pine plantations, typically through the use of phosphorous on water-logged sites (Walker 1960, Fox et al. 2007). Results in hardwood plantations and natural forests are less firmly established, due to the wide range in species and site productivities. For hardwood trees, VanDerZanden (2000) states fertilization is typically targeted to the rooting zone of the tree (Figure 2). Some field trials with fertilizers in northern hardwoods have demonstrated success, while others show no additional growth response following fertilization (Lea and Brockway 1986). Pope et al. (1982) determined significant increases in volume growth for young black walnut plantations can be achieved through nitrogen fertilization at a rate of 100
Figure 2: Crop tree fertilization treatments should be targeted at root zone of crop trees. This image was obtained from VanDerZanden (2000).
lbs/acre. In a natural bottomland hardwood stand in north-central Louisiana, fertilization resulted in significant increases in 2-year diameter increment for red oak, white oak, and sweetgum (*Liquidambar styraciflua*) (Dunn et al. 1999). Devine et al. (2002) reported survival, height, and diameter for 17-year-old cherrybark oak and loblolly pine were not significantly affected by third-year fertilization.

Studies involving fertilization as a component of crop tree management have most often been conducted on a short-term basis. Ellis (1979) noted fertilization with nitrogenous fertilizer (ureaform) and triple superphosphate had no detectable effect on the 2-year diameter growth of sugar maple and white ash crop trees, but significantly improved growth for black cherry. In a study from Vermont, Hannah (1985) reported the use of fertilizers for accelerating pole-sized yellow birch and sugar maple crop trees in several trials failed to produce additional growth responses to the thinning alone. The lack of response was attributed to the relatively fertile soils in Vermont inherently containing adequate amounts of essential elements, yielding fertilizers incapable of producing an additional growth response in crop trees. In a separate case, fertilization with ammonium nitrate was shown to increase basal area for a three-year period for black walnut crop trees (Stringer and Wittwer 1985). Another study, conducted in Virginia, on the impacts of crop tree release and fertilization on white oaks in a mixed-hardwood stand indicated that fertilization provided additional benefit to diameter growth over crop tree release alone (Creighton 2014). The success of fertilizer application in hardwoods is closely linked to initial site quality, soil processes, the native fertility of the stand, and the type of tree species desired for management.

**Green Ash Silvics**

Green ash is a highly adaptable species, growing naturally on sites ranging from frequently flooded clay soils to sandy or silty soils with limited moisture (Kennedy 1990). The silvical characteristics of green ash are summarized in Table 1. The native range of green ash covers most of the eastern United
Table 1: Silvical characteristics of green ash (*Fraxinus pennsylvanica*). Adapted from Kennedy (1990) and Hodges (1997).

<table>
<thead>
<tr>
<th>Silvical Characteristic</th>
<th>Green Ash</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soils</td>
<td>Adaptable; Most commonly on alluvial soils along rivers, streams, and swamps; Grows best on fertile, well-drained soils.</td>
</tr>
<tr>
<td>Topography</td>
<td>Occurs on wide-range of sites; Natural stands confined to well-drained ridges and poorer drained clay flats in bottomlands; Component of the elm-ash-sugarberry forest type.</td>
</tr>
<tr>
<td>Reproduction</td>
<td>Dioecious; Flowering occurs in Spring; Fruit are winged, single-seeded samaras; Seed fall occurs from Fall into Winter; Seed is wind-disseminated. Germination may occur in following Spring or after a period of dormancy; Sapling and pole-sized stumps sprout readily.</td>
</tr>
<tr>
<td>Growth and Yield</td>
<td>On productive, bottomland sites, volume growth can exceed 39 to 65 ft³/acre annually. Heights of 120 ft. and diameters of 24 to 30 in. can be achieved.</td>
</tr>
<tr>
<td>Shade Tolerance</td>
<td>Classified as moderately tolerant to tolerant of shade when young. Seedlings respond well to release, behaving more intolerant of shade as age increases.</td>
</tr>
<tr>
<td>Flood Tolerance</td>
<td>Tolerant of flooding regimes of up to several months during dormant and early growing seasons.</td>
</tr>
<tr>
<td>Damaging Agents</td>
<td>Insect pests include the exotic, invasive emerald ash borer, oystershell scale, carpenterworm, and brownheaded ash sawfly. Diseases from Anthracnose (<em>Gloeosporium aridum</em>) and <em>Mycosphaerella fraxinola</em> can cause premature defoliation. <em>Phymatotrichum omnivorum</em> can cause root rot.</td>
</tr>
<tr>
<td>Wildlife Uses</td>
<td>Seed consumed by many game and nongame animals and birds.</td>
</tr>
<tr>
<td>Economic Uses</td>
<td>Wood valued for strength, hardness, high shock resistance, and excellent bending qualities. Used for commercial lumber, veneer, tool handles, and sometimes baseball bats (though not as desirable as white ash).</td>
</tr>
</tbody>
</table>
States, extending from Nova Scotia west to southeastern Alberta across the southern portion of Canada; south through central Montana, northeastern Wyoming, to southeastern Texas; and east to northwestern Florida and Georgia. Green ash grows best on fertile, moist, well-drained soils of alluvial origin. In pure, even-aged stands in Georgia, volume growth can exceed 39 to 65 cu. ft. per acre per year and attain heights of 120 feet or more in 50 years (Fitzgerald et. al 1975). More commonly, green ash is found growing in mixed-stands associated with species like boxelder (Acer negundo), American sycamore (Platanus occidentalis), eastern cottonwood (Populus deltoides), American elm (Ulmus americana), and various species of bottomland oaks, like cherrybark oak (Quercus pagoda) and swamp chestnut oak (Quercus michauxii).

The root systems of green ash are extensive. The root system is typically saucer-shaped with no distinct taproot and its roots penetrate about three to four feet into the soil. Green ash seedlings possess rooting habits that allow them to withstand temporary flooding, such as regenerating new secondary roots on the submerged stem, accelerating anaerobic respiration when oxygen is low, and oxidizing its rhizopheres. These adaptations likely enable green ash to withstand the flooding that occurs frequently on bottomland hardwood forests. In a separate study, green ash was determined to be very responsive to changes in moisture conditions (Broadfoot 1969).

Green ash is classified as shade tolerant when young. Seedlings have been shown to persist 15+ years in understory and still respond to overstory release. Sprouts can grow rapidly and will maintain their early dominance in thick stands. On Sharkey clay soils, dominant green ash sprouts achieved diameters at breast height of 1.5 inches and heights of 15 feet by age five (Johnson 1961). As green ash trees grow older, their shade tolerance becomes more intermediate (Kennedy 1990). The typical regeneration sequence for green ash in southern bottomland forests usually begins with advance reproduction in the understory of an established canopy. Current year seed-origin seedlings are rare
under high-shade conditions. Sapling and pole-sized stumps re-sprout vigorously, and seedlings can persist 15+ years in the understory. Seedlings and sprouts respond well to release when the overstory is removed.

There may be genetic differences in the growth habits between green ash from the more northerly portion of its range versus those from the more southerly portions. Trees from northern origins followed a more determinate pattern, completing height growth and terminal bud set by late June, and dropping their leaves in late September before the first frost. Trees from southern origins exhibited a more indeterminate growth habit and retained live green leaves into the later months of autumn, even after the first severe frost (Wright 1959).

Green ash is a highly sought-after commercial tree species. In fact, it is one of the most valuable commercial species occurring in southern bottomland hardwood forests, second only to cherrybark oak and swamp chestnut oak. The demand for green ash is driven by its qualities of strength, hardness, high shock resistance, and bending properties.

Green ash commonly fails to maintain its crown position in the canopy of mixed forests, particularly in the elm-ash-maple cover type (Wright 1959, Kennedy 1990). Oftentimes, it submerges in the stand underneath more rapidly growing associates, not attaining its potential in terms of volume and log grade. Crop tree management could represent a possible tool to alleviate this problem, providing green ash with the increased growing space and additional resources needed to increase growth rates, maintain good stem form, and achieve dominant and co-dominant crown positions.

Few, if any, studies have been conducted on the impacts of crop tree management on green ash in mixed-species hardwood bottomland forests.
Southern Bottomland Hardwood Forests

Bottomland hardwood forests occur naturally on floodplain sites along rivers and streams in the Atlantic and Gulf Coastal plains (Figure 3). They comprise approximately 32 M acres of forest land from Virginia to East Texas (McKnight and Johnson 1980). Bottomland hardwood forests occur to some extent along all major and minor streams east of the Great Plains, in addition to, other wetland areas such as inland muck swamps, coastal and estuarial swamps, bays, and hammocks (Hodges 1995). Flooding and inundation are key abiotic drivers in bottomland forests. Inherently high moisture levels contribute to these forests’ productivity, but too much water can also make a site less conducive to tree growth. Across the Southeast, bottomland hardwood forests support a wide variety of tree species, of which approximately 50 have commercial value (Kellison and Young 1997). Each displays its own characteristics for site preference, growth, development, and reproduction (Meadows and Stanturf 1997). The high variability of these forests can be attributed to their productivity, shifts in site quality from minute differences in moisture regime and elevation, and rates of deposition (Hodges 1997). Slight disparities in relief result in considerable differences in soil and drainage conditions. A difference of a few feet in elevation can lead to vastly different site conditions. This ultimately produces a wide-ranging species composition and successional patterns driven by both autogenic and allogenic forces. Bottomland hardwood forests are not only valued for timber production. They also have irreplaceable functions in water storage, enhancing water quality, nutrient cycling, and wildlife habitat to an expansive range of species.

Mixed-bottomland hardwoods are one of three generic type groups of southern bottomland hardwoods as described by Hodges (1995) and adapted from Putnam et al. (1960), with the other two being the cottonwood-willow and the bald cypress-tupelo type groups. The species composition of this diverse type group depends on site and successional stage. Ridges are typically occupied by cherrybark
Figure 3: Location of the Southern Bottomland Hardwood Region and the Brown Loam Bluffs Subregion (diagonal lines). Bottomland hardwoods occur across the Atlantic and Gulf Coastal Plain. Major stream bottoms are indicated by dark gray areas. Image obtained from Hodges (1994).
oak, sweetgum, and swamp chestnut oak, while flats and low ridges support ash, sweetgum and water oak. Low, poorly drained flats can contain overcup oak (*Quercus lyrata*), willow oak (*Quercus phellos*), green ash, and hickory (*Carya* spp.). Green ash is present and grows well on lower and middle slopes in the Brown Loam Bluffs region.

Mixed bottomland hardwoods are recommended to be managed under in even-aged systems, relying on natural regeneration following a complete clearcut (Hodges 1995). Even-aged systems provide the light conditions necessary to regenerate the most valuable bottomland hardwood species, such as the oaks, ash, sweetgum, and yellow-poplar. Uneven-aged systems can be considered, but group selection is typically recommended under this scenario, as single-tree selection tends to promote the regeneration of less-desirable shade-tolerant species. The most common forms of regeneration in mixed bottomland hardwood forests are from advance reproduction, followed by coppice regeneration. Light-seeding species can successfully regenerate from seed if mineral soil is exposed and moisture conditions are favorable.

The southern bottomland hardwood region has undergone major periods of change during the last 100 years. Much of the original forest was cut over and converted to row-crop agriculture between the 1950s and late 1970s, due to the land’s innate high productivity. Efforts to slow the loss of bottomland hardwoods and, in many cases, return cleared areas to forests have occurred since the late 1980s. Primarily through government-subsidized efforts, such as the Conservation Reserve Program, former forest land that was cleared for agriculture, but could no longer sustain row crop production because of frequent flooding, has been re-planted in hardwoods. The overwhelming majority of bottomland hardwood forests throughout the South are under private-ownership, with small family forest owners composing the largest percentage. Public ownership of bottomlands has increased
slightly over the past 25 years as a result of mitigation purchases by the federal government and the establishment of state and federal wildlife refuges (Hodges 1995).

The Brown Loam Bluffs are a recognized sub-section of the southern bottomland hardwood forest stretching alongside the eastern Mississippi River valley from Louisiana to southern Illinois, with the widest expanses occurring in Mississippi and Tennessee. The Brown Loam Bluffs are a strip of loess-covered, deeply dissected uplands with very rich, but erosive, soils (Hodges 1995). This sub-section of the southern bottomland hardwood forest is widely considered to be one of the most productive hardwood areas in the nation (Johnson 1958). Yields from well-stocked stands can be over 500 board feet per acre annually (Johnson 1991, Hodges 1995). The site of the study central to this thesis work is Ames Plantation in southwest TN, within the Brown Loam Bluff region.

**Soil Mottling and its Relationship with Tree Growth**

A distinguishing characteristic of bottomlands is that they are subject to frequent flooding and inundation. The relationship between fluctuating moisture levels, soil conditions, and tree growth is critically important to properly managing bottomland hardwood forests. Seasonally saturated soil conditions typically result in diagnosable profile characteristics, such as the presence of mottles (Diers and Anderson 1984).

Mottles are a product of soil redox processes, primarily the reduction and oxidization of Iron (Fe) and Manganese (Mn) oxides. When soil is saturated with water, bacteria begin depleting available free oxygen needed to digest the organic matter. When a sufficient amount of oxygen is depleted, anaerobic bacteria are enabled to begin utilizing oxygen from oxidized Fe and Mn oxides. These oxides become reduced as oxygen is removed, increasing their solubility and dissolvability. As the Fe and Mn oxides are dissolved, they are carried by water in the soil until encountering an oxygen-rich area, where they oxidize and precipitate from solution, producing deposits of reddish Fe oxide and/or black Mn.
oxides. The areas from which Fe and Mn oxides were removed become light grayish in color. This is commonly called a gleyed soil color. These mottles are formed due to saturated soil conditions, and as result, can be used to determine the depth of the potential seasonal high water table (Diers and Anderson 1984, Mercker et al. 2011).

Mottles, or the degree of mottling, are characterized by their abundance, size, and color. In the field, evaluation is conducted with the Munsell color chart, a soil diagnostic tool based upon the soil color’s hue, value, and chroma (Munsell Color 2000). The kind, amount, and location of mottles in the soil profile determine soil drainage class. The presence of high levels of gray mottles indicates poor soil drainage and frequent flooding and inundation. The depth to mottling, due to its direct relation to the seasonal high of the water table, likely has important implications for root growing space and the development of bottomland trees.

Depth to mottling has been used as a diagnostic indicator of soil saturation and, concurrently, species suitability in past research. Mercker et al. (2011) applied depth to mottling to determine site suitability for planting various red oak species by dividing the depths into three categories corresponding to drainage class: Poorly drained with 50% gray matrix at 0 – 9”, Somewhat poorly-drained at >9 – 18”, and Moderately well-drained at >18”. Depth to mottling was investigated again in another study involving soil to site index predictions in North Mississippi and West Tennessee, although it ultimately proved to be an unreliable variable in this case (McClurkin 1963). As part of an examination of the relation between tree growth and site factors, conducted at Ames Plantation in West Tennessee, depth to mottling was reported to be an influential variable for the site index of yellow-poplar and not influential for sweetgum, cherrybark oak, southern red oak, and white oak (Hebb 1962).

For green ash, only limited information regarding its specific relationship with depth to mottling is available. In a study by Robertson et al. (1978) on species importance values across various site
conditions, areas that frequently supported green ash were where the presence of mottling was close to
the surface, elevations were relatively low compared to other sites, prolonged flooding occurred, and
relative large amounts of sand and low amounts of clay were in the least permeable horizon.

The Emerald Ash Borer

Green ash as a species faces a relatively new and serious threat from the invasive wood boring
insect, the emerald ash borer (Agrilus planipennis). The emerald ash borer is a beetle native to eastern
Asia that has recently become an invasive, exotic insect pest in North America. Since its initial discovery
in June 2002, the emerald ash borer has rapidly emerged as the most serious threat to the North
American ash (Fraxinus spp.) resource (McCullough and Roberts 2002). In the short time this little beetle
has inhabited North America, it has killed millions upon millions of ash trees in forests and urban areas
alike. In fact, the problem is so extensive that entomologists now fear that the emerald ash borer could
wipe out a substantial portion, if not the majority, of ash trees. Susceptible North American ash species
include green ash, white ash, and black ash (Fraxinus nigra) (Cappaert et al. 2005).

The emerald ash borer has been positively identified in Arkansas, Colorado, Connecticut,
Georgia, Illinois, Indiana, Iowa, Kansas, Kentucky, Maryland, Massachusetts, Michigan, Minnesota,
Missouri, Nebraska, New Hampshire, New Jersey, New York, North Carolina, Ohio, Ontario,
Pennsylvania, Quebec, Tennessee, Texas, Virginia, West Virginia, and Wisconsin. Its range continues to
expand, seemingly able to go anywhere where ash species occur. In Tennessee, 47 out of 95 counties,
primarily in the eastern half of the state, have been placed under emerald ash borer quarantine as of
June 2016 (TN Department of Agriculture 2016).

While the threat of the loss of the ash resource in North America seems to impact the scientific
value of a silvicultural study of crop tree enhancement on green ash, this may not be the case. Green
ash remains a highly-valuable timber species that grows in importance as global wood markets become
more connected and coordinated. Research into meeting the expanding demand for diversified wood products will always be a worthy pursuit. Ultimately, the end game for the overall impact of emerald ash borer on the bottomland ash resource remains speculative and whether ash remains a significant forest tree in the United States or not, this research project may still be applicable and the results can be compared with other bottomland tree species. Another consideration is that this green ash study site could be a reference for the health and growth of green ash to measure the impact and perhaps spread of the emerald ash borer.

**Management Implications**

This thesis will contribute to the growing body of knowledge on crop tree management in eastern hardwood stands, but especially in bottomland hardwood stands. Unique to this project is the long term nature of the data this study provides. Given the extended period of time, 18 years, over which crop trees have responded to treatment, the growth and development of green ash crop trees, in relation to existing adjacent trees, can be evaluated. Insights and refinements into how green ash crowns develop under released and control conditions and how crown class at the time of treatment impacts eventual crop tree success are investigated. This knowledge can be applied to other mixed-species bottomland hardwood stands with green ash components in the species composition. Many of the findings from this work could be extended to other bottomland hardwood species, and give more credence to the effectiveness of crop tree enhancement of promoting high-value trees within a stand.

Another aspect of this thesis work will be an evaluation of the effectiveness of examining site quality for crop tree management in bottomland hardwoods from determining the depth to mottled horizons for each individual crop tree. This microsite, individual-crop-tree-scaled approach to site evaluation could prove an effective method of refining the crop tree selection process. Sites with increased mottling closer to the surface could be deemed unsuitable for crop tree management for
certain species due to the inherent water/moisture relationships of the sites. Evaluating depth to
mottling could be incorporated into the practice of crop tree enhancement in selecting suitable crop
tree species where it is practical in bottomland hardwoods.

If the objectives of the thesis are achieved, this evaluation of crop tree enhancement with green
ash in bottomland hardwood stands will offer many valuable insights into the applicability of this forest
management technique for bottomland conditions not frequently investigated up until this point.
Chapter 3: Study Objectives and Hypotheses

1) Compare the response of green ash crop trees to crop tree release, crop tree release plus one-time fertilization, and a no management control for diameter at breast height, total height, clear bole length, crown expansion, and crown class 18 years after treatment. The hypothesis is released crop trees will grow more in DBH and total height, expand further in crown size, and maintain crown class more effectively after 18 years than control crop trees. Little difference between green ash crop trees given release and release plus fertilization will be detected.

2) Determine how the distribution of crown classes of green ash crop trees were affected by crop tree release, crop tree release plus one-time fertilization, and a no management control 18 years after treatment. The hypothesis is crop trees given release and release plus fertilization treatments will maintain their crown classes better than control crop trees after 18 years.

3) Determine how the response of green ash crop trees to crop tree release, crop tree release plus fertilization, and a no management control differed between the dominant, co-dominant, intermediate, and suppressed crown classes 18 years after treatment. The hypothesis is the greatest gains to growth as a result of release and release plus fertilization treatments will be observed in the dominant and co-dominant crown classes.

4) Determine if and how the depth to mottled horizons changes across the study area. The hypothesis is depth to mottling horizons will change across the study area.

5) Determine if the treatment response of green ash crop trees for diameter at breast height and crown class 18 years after treatment is different on sites with mottled horizons occurring in the
first 12 inches of soil, 12 to 24 inches of soil, and beyond 24 inches of soil. The hypothesis is depth to mottled horizons will have little negative impact to crop tree growth on sites with better drainage and mottled horizons beyond 12 inches of soil, but negative impacts may occur on sites with poorer drainage and mottling in the first 12 inches of soil.

6) Determine the competition cluster tree species composition for crop trees on sites with mottled horizons occurring in the first 12 inches of soil, 12 to 24 inches of soil, and beyond 24 inches of soil. The hypothesis is the average competing tree species composition will alter with the depth to mottling horizons.
Chapter 4: Methods

Study Site

The study is located at Ames Plantation in Fayette and Hardeman counties in West Tennessee (Figure 4). Ames Plantation covers approximately 18,400 acres of land (Ames Plantation 2014). The plantation is located approximately 60 miles east of Memphis and 10 miles north of the Tennessee-Mississippi line near Grand Junction, Tennessee and has approximately 12,000 acres of forest, 2,000 acres of commodity row-crops, and maintains about 300 head of Angus beef cattle and 40 horses. The forested land is distributed between approximately 2,600 acres of bottomland hardwoods, 3,500 acres of pine plantation, and 8,500 acres of upland hardwoods. The plantation serves as the location of the National Field Trial for Bird Dogs. Ames Plantation is privately owned and operated by the Trustees of Hobart Ames Foundation (Ames Plantation 2014). Ames Plantation also functions as one of the University of Tennessee’s AgResearch and Education Centers. At any given time, research projects related to agriculture, forestry, and wildlife are ongoing on the property.

The study site is located within a mixed-species bottomland hardwood stand on Ames Plantation property called Henley Bottom (Figure 5). The site’s coordinates are 35°07’48.25” N, 89°14’16.06” W. The stand is even-aged and comprised of pole-sized hardwood stems of various species, including sweetgum, green ash, eastern cottonwood, American sycamore, cherrybark oak, American elm, boxelder, yellow-poplar, river birch (Betula nigra), and black willow (Salix nigra). The study site encompasses approximately 10.5 acres.

The Henley Bottom stand was completely harvested in 1980. The prior stand contained a large sweetgum component, with significant amounts of American sycamore, eastern cottonwood, and cherrybark oak. Seedling-sized green ash trees were observed in the understory. The stand naturally regenerated, primarily through coppice and advance regeneration, into an even-aged, mixed-species
Figure 4: The location of Ames Plantation within the state of Tennessee in relation to the University of Tennessee-Knoxville (Image courtesy of Google Earth).
Figure 5: Aerial image (4292 feet) of the Henley Bottom Stand at Ames Plantation in West Tennessee. The site’s coordinates are 35°07'48.25” N, 89°14'16.06” W. The green ash crop tree enhancement study site is located within the white outline (Image courtesy of Google Earth).
hardwood stand. Approximately 16 years after harvest in 1996, the Henley Bottom stand was selected for this crop tree enhancement study. Green ash was selected as the target crop tree species for this study because of its desirable timber qualities and presence throughout the stand.

Soils in Henley Bottom are of alluvial origin and are comprised of primarily Falaya silt loams, Waverly silt loams, and Lexington silt loams (NRCS 2014). Textures are primarily silty loams, with some sandy loams present in certain areas. Drainage ratings range from somewhat poorly drained to well drained. Soils are productive for tree growth, with site indices of 90 to 100 feet at base age 50 for green ash and cherrybark oak. The river system associated with this bottom is the North Fork of the Wolf River, which eventually feeds into the Mississippi River just north of Memphis. The study site is located within the greater Mississippi Alluvial Floodplain. Ames Plantation falls within the Brown Loam Bluffs sub-region of the southern bottomland hardwood forest region. Soils here developed from wind-deposited loess originating from retreating glaciers in more northern latitudes during the late Pleistocene epoch (Johnson 1958; 1991). During the past 25 years, areas of this stand have experienced considerable amounts of sand deposition.

The climate of this region is characterized as temperate, with warm summers and mild winters. The average annual high and low temperatures are 71.8°F and 48.6°F, respectively (US Climate Data 2016). Average annual precipitation is 56 inches.

**Study Establishment**

In the mid-1990s, several stands across Ames Plantation were selected to evaluate the impacts of crop tree enhancement on a variety of species and site conditions. These studies were initiated under the guidance of Dr. Allan Houston. The Henley Bottom stand was selected as the location for a study on the impacts of crop tree enhancement on green ash, in addition to a few other secondary species such as cherrybark oak and river birch, in mixed-species bottomland hardwood forests. The crop tree
management techniques to be evaluated consisted of crown release and fertilization. Together, this research was entitled “crop tree enhancement.” The overall goal of these treatments was to enhance the growth and development of selected individual trees, a subset that was projected to become an increasing component of the stand’s composition and value as it approached maturity.

In January 1996, the green ash crop tree enhancement study was established in the Henley Bottom stand. Before initiating the treatments, crop trees were first identified and marked. The selection of crop trees and implementation of treatments was conducted by Dr. Allan Houston and members of his work crew following the guidelines briefly summarized below.

Following a uniform process, crop tree cells were allocated equidistantly across Henley Bottom (Figure 6). Each crop tree cell had a diameter of 32 feet and contained one crop tree. To begin, a 175-foot baseline was established along the stand boundary. Starting from the bottom corner of the stand boundary, the marker moved 17.5 feet along the baseline. Turning 90 degrees and facing into the stand, the marker moved another 17.5 feet to establish the center of the 1st cell. This center point was marked with a brightly-flagged staff. The marker searched within a 17.5-foot radius from cell center for a potential crop tree of a desirable species. When a crop tree was identified, the tree was clearly marked at eye level with orange spray paint and a numbered tag. Cell 1 corresponded to crop tree 1 and so on. If a potential crop tree was not present in the cell, the tree was recorded as an unfilled cell. After marking the cell’s crop tree, the marker returned to the cell center. The marker then paced 35 feet parallel to the baseline to reach the cell center for cell 2, where another crop tree was identified and marked. This method was repeated to create a five cell by five cell block, approximately 0.7 acres in size. Fifteen adjacent blocks across Henley Bottom were created using this method, and the five repetitions of three treatments were randomly allocated across the blocks. The use of a repetition blocking system was
Figure 6: Schematic of the green ash crop tree enhancement study site in Henley Bottom at Ames Plantation in West TN. Three treatments, Release, Rel&Fert, and Control, were allocated randomly across five 25-crop-tree repetition blocks in a randomized block design.
grounded in the assumption that minor site differences across the Henley Bottom likely impacted
treatment response, particularly site differences relating to soil drainage and the depth to mottled soil
horizons. Each block consisted of 25 cells. The entire study area was approximately 10.5 acres. This
created a total of 375 crop tree cells, equally distributed across the five blocks of the three treatments.
Approximately 36 crop trees per acre were selected.

Green ash was the primary target species for crop tree selection. Green ash stems account for
approximately 70% of the crop trees in the study or 264 stems. In cells where a suitable green ash stem
could not be located, secondary target species were chosen. Secondary target species accounted for
25% of the crop trees or 93 stems. This included 27 cherrybark oak, 26 river birch, 11 American
sycamore, 10 sweetgum, 10 yellow-poplar, 4 black willow, 3 cottonwood, and 2 willow oak. A cell was
left unfilled in the event that no suitable crop tree of any preferable species could be located. Unfilled
cells accounted for the remaining 5% or approximately 18 cells.

The same criteria were used to select crop trees across all of the treatment blocks. Trees were
selected based on species, form, and likelihood to respond to release, a function of crown size, health,
and dominance relative to other trees in the cell. Primarily dominant and co-dominant stems with
minimal stem defects were chosen. Promising individuals from the intermediate class were chosen
when dominant and co-dominant stems could not be located in the cell.

Crop tree enhancement treatments were performed in January of 1996, when crop trees were
approximately 16 years old. In the summer of 2014, when re-measurement occurred, the stand was 35
years old and 18 years had passed since the study began.


**Treatments**

Three silvicultural treatments were used in this study: Release, Release & Fertilize, and Control. The treatments were applied in a complete, randomized block design with five repetitions of the three treatments. The 25 crop trees within a repetition were given the same treatment.

The release treatment was replicated on five blocks across the stand. The crowns of the crop trees were given a crown-touching release on all four sides. All stems with crowns touching the crowns of the crop trees were felled with a chainsaw. The release and fertilization treatment was performed on five blocks across the stand. The crowns of the crop trees in the release and fertilize treatments were given a crown-touching release on all four sides, in addition to, a one-time application of fertilizer (20 N-10 P-0 K) over the rooting area (two to three feet beyond crown radius) at a rate of 1 pound per inch of DBH. The control treatment involved five blocks across the stand. This treatment consisted of nothing more than measuring and labeling the crop trees.

**Data Collection**

Before the implementation of the treatments in 1996, initial data on individual crop trees were recorded. The species and crop tree number were recorded for each tree. Diameter at breast height (DBH) to the nearest 0.1 inch was measured using a logger’s tape (Figure 7). Total height and height to green crown were measured to the nearest foot using a clinometer. Number of 16-foot logs was determined. Crookedness of each 16-foot log was gauged manually on a 0 to 3 scale (0 - no crooks, 3 - very crooked). Mean crown spread was measured to the nearest foot using a cloth tape on the North/South and East/West azimuths. Crown class for each crop tree was evaluated using the crown rating system for southern hardwoods (Meadows et al. 2001) (Table 2). Trees marked for removal were recorded by species and height was estimated to the nearest 5-feet. Removal trees were clearly marked with fluorescent spray paint. The release, release and fertilize, and control regimes were then executed.
Figure 7: Measuring DBH of green ash crop trees in Henley Bottom at Ames Plantation in West TN in 2014, 18 years after the crop tree enhancement study was initiated.
Table 2: A numerical rating system for crown classes of southern hardwoods (Meadows et al. 2001) provides a more objective and orderly procedure for assessing crown classes on the basis of crown position in the canopy and crown characteristics.

<table>
<thead>
<tr>
<th>Crown Characteristic</th>
<th>Points</th>
</tr>
</thead>
<tbody>
<tr>
<td>Direct Sunlight from Above</td>
<td>0 - 10</td>
</tr>
<tr>
<td>Direct Sunlight from the Sides</td>
<td>0 - 10</td>
</tr>
<tr>
<td>Crown Balance</td>
<td>1 - 4</td>
</tr>
<tr>
<td>Relative Crown Size</td>
<td>1 - 4</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Crown Class</th>
<th>Total Rating (2 – 28)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dominant</td>
<td>24 – 28 points</td>
</tr>
<tr>
<td>Codominant</td>
<td>17 – 23 points</td>
</tr>
<tr>
<td>Intermediate</td>
<td>10 – 16 points</td>
</tr>
<tr>
<td>Suppressed</td>
<td>2 – 9 points</td>
</tr>
</tbody>
</table>
following initial data collection. Diameters of the crop trees were re-measured in the fall of 1996, 1997, and 1998.

In late summer 2014, data collection on the crop trees and their surrounding competitors was re-initiated. The crop trees were re-located and clearly marked with orange fluorescent spray paint. Some crop trees were not located (presumed dead), but most were located. The missing crop trees account for approximately 5% of the original 375 crop trees or 19 stems.

Each crop tree was recorded for its number and species. DBH was measured with a standard logger’s tape to the nearest 0.1 inch. Total height, height-to-green crown, and clear bole length were measured with a clinometer to the nearest foot. Crown length was obtained by subtracting height-to-green-crown from the total height for each crop tree. Mean crown spread was paced out and estimated to the nearest five-foot increment on the North/South azimuth and the East/West azimuth. Each crop tree was again evaluated for its amount of crook (0 to 3). Crown class was quantified for each crop tree using the crown rating system for southern hardwoods developed by Meadows et al. (2001). Basal area around the crop tree was measured using a 10-factor prism. For each “in” tree, species was recorded and DBH was estimated to the nearest two-inch diameter class. Total height was estimated to the nearest five-foot increment. The distance from the “in” tree to the crop tree was also paced and estimated to the nearest five-foot increment. Each “in” tree determined with the 10-factor prism and above four inches in DBH was considered to be a member of the crop tree’s “competition cluster” or surrounding competitor trees. As used in this study, a competition cluster refers to the surrounding neighborhood of trees competing with a crop tree and experiencing similar growing conditions.

Within each basal area sweep, one or two of strongest free-to-grow competitor(s) of each crop tree were selected for additional measurements. These competitors represent the most prominent members of each competition cluster. Their crown class was evaluated using the crown rating system
and their mean crown spread was estimated to the nearest five-foot increment. Crown spread measurements on the North/South and East/West azimuths were averaged to produce a mean crown spread.

In the late fall of 2014, the soil depth to mottling for each live crop tree was measured and recorded. Depth to mottling was assessed to determine the soil depth where tree root growth could potentially be inhibited by anaerobic conditions and the water table. Using a soil probe, a reading was taken five feet away from the crop tree at the point judged to be the highest elevation. This was done to maintain consistency in sampling. Every six inches of soil was examined for the presence of mottling and an in-the-field texture assessment. The soil probe was marked at six inch intervals for 30 inches. The six-inch interval in which mottling occurred was determined. The presence of mottles was assessed using the Munsell Soil Color Charts (Munsell Color 2000) (Figure 8). The soil color required for mottling were greys of chroma 2, value 6 or greater on pages 7.5YR and 10YR. Soil texture was evaluated using the textural classes and processes as described in the Tennessee State Land Judging Guide (Denton et al. 1996). The majority of soils in Henley Bottom are classified as silt loams according to the Web Soil Survey, and this texture was supported on the ground. Block five, containing crop trees 300 through 375, had noticeably higher amounts of sand deposition than the other blocks.

Growth in diameter, height, mean crown spread, crown length, and clear bole length after 18 years were calculated by subtracting 1996 values from 2014 values. Annual diameter growth for 1996, 1997, and 1998 was also calculated.

Crop trees were analyzed on a per-species basis. Sample size greatly limited statistical analysis in all species except green ash.

Within the green ash crop trees, sample sizes were further divided into groups by crown based on 1996 data. Crown classes of green ash crop trees in 1996, as determined by the crown rating system
Figure 8: Evaluating depth to mottling for green ash crop trees in Henley Bottom at Ames Plantation in West in 2014, 18 years after the crop tree enhancement study was initiated. The soil color required for mottling were greys of chroma 2, value 6 or greater on pages 7.5YR and 10YR in the Munsell Soil Color Charts (Munsell Color 2000).
developed by Meadows et al. (2001), were the criteria for sub-dividing the data. Four crown classes were represented amongst the crop trees in 1996, dominant, co-dominant, intermediate, and suppressed. Treatment impacts were then compared between and within crown classes.

Depth to mottled horizons was another criterion upon which the green ash crop tree data was sub-divided. The six 6-inch ranges where sufficient mottled horizons occurred (1 = 0-6”, 2 = 6-12”, 3 = 12-18”, 4 = 18-24”, 5 = 24-30”, 6 = 30+) were separated into three ranges to increase sample sizes and make comparisons between groups more feasible. The three depth to mottled horizon ranges (1 = 0-12”, 2 = 12-24”, 3 = 24+) were then utilized in compare treatment impacts and competing species compositions.

Data Analysis

Analysis of variance (ANOVA) was used to test for differences among green ash treatments for DBH, height, mean crown spread, crown length, clear bole length, crown class, and crown rating in 1996 and 2014. ANOVA also determined differences in growth and/or change of these response variables over 18 years from 1996 to 2014. DBH growth over 1996, 1997, and 1998 were examined to determine the initial impact of the treatments. Data were analyzed using PROC MIXED in SAS 9.4 (SAS Institute 2015). Least squares means were separated using Fisher’s protected least significant difference, with a significance level of P=0.05.

Crown class point score, as determined by the crown rating system for southern hardwoods, classified each crop tree’s crown into one of four categories: 1 for dominant, 2 for co-dominant, 3 for intermediate, and 4 for suppressed. The numeric breakdown and percentages of crop trees occurring in each crown class were then calculated for 1996 pre-treatment crop trees and the 2014 post-treatment crop trees. These two breakdowns were compared graphically to determine how the treatments and 18 years of growth post-treatment influenced crown class distribution.
Treatment differences within 1996 crown classes were also examined using PROC MIXED in SAS 9.4 and Fisher’s least significant differences (SAS Institute 2015) with a significance level of p=0.05.

Simple correlations in SAS 9.4 were used to investigate the presence and strength of relationships between green ash crop tree parameters and the three depth to mottled horizon ranges (1 = 0-12”, 2 = 12-24”, 3 = 24+”). Relationships between depth to mottled horizons and the following crop tree parameters were investigated: DBH in 2014, total height in 2014, DBH growth over 18 years, total height growth over 18 years, mean crown spread in 2014, and crown class score in 2014.

The three depth to mottled horizon ranges then allowed for comparisons of treatment impacts utilizing ANOVA in PROC MIXED in SAS 9.4 (SAS Institute 2015). Treatment impacts on DBH, 18-year DBH growth, and crown class across the three depths were determined. Least squares means were separated using Fisher’s protected least significant difference, with a significance level of p=0.05. Competition cluster species composition at each depth was also calculated.

Contingency tables and Pearson’s Chi-square analysis investigated the relationships between several discrete variables in the dataset, utilizing NCSS (NCSS 10 Statistical Software 2015). Repetition number, 1 to 5, and mottling rank, 1 to 3, were examined to construct how the soil conditions changed across the blocked study site, by determining the independence of the depth to mottled horizons and repetition. Mottling rank was then examined with crown class, 1 to 4, in 1996 and 2014, to give an indication if crown classes of green ash crop trees are independent from depth to mottled horizons. Crown class may be associated with overall crop tree performance and response to treatment.
Chapter 5: Results

Crop Tree Species Composition and Mortality

At study initiation, the stand was assigned 375 crop tree cells. The crop tree species distribution at study initiation in 1996 and 18 years after treatment by species and treatment is exhibited in Table 3. Of the 264 green ash crops trees in 1996, 84 were release, 89 were release plus fertilize, and 91 were control. Of the 233 green crop trees alive in 2014, 71 were release, 80 were release plus fertilize, and 82 were control.

Several green ash crop trees still alive in 2014 had been adversely impacted by factors deemed external to the experiment, such as vine suppression and weather damage, and were thus disqualified from analysis. Disqualified green ash crop trees included four release, one release plus fertilize, and one control.

Mortality of crop trees after 18 years was 11%. Most of the mortality was with green ash. Green ash mortality was evenly distributed across the three treatments: release with 10% mortality, release plus fertilize with 9%, and control with 9%.

Comparison of Treatment Impact on DBH, Height, Clear Bole Length, and Crown Expansion

Diameter at breast height (DBH) between R, RF, C green ash crop trees did not differ (p=0.4569) at the time of treatment in 1996. By 2014, R and RF crop trees were significantly larger in DBH than C crop trees (p=0.0041). DBH growth after 18 years was also significantly greater (p<0.0001) for R and RF than C crop trees (Table 4). No significant differences occurred between R and RF crop trees for 2014 DBH and 18-year DBH growth. Over the first three growing seasons following treatment, no significant differences between treatments occurred within a year, but overall DBH growth over the three-year period was significantly greater (p<0.0001) for R and RF crop trees than C crop trees (Table 5).
Table 3: Crop tree species composition at the time of study initiation in 1996 and 18 years later in 2014 are presented for the crop tree enhancement study at Ames Plantation in West TN. Green ash crop trees are further divided by treatment.

<table>
<thead>
<tr>
<th>Species</th>
<th>Treatments</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Release</td>
</tr>
<tr>
<td>Green ash</td>
<td>264</td>
</tr>
<tr>
<td>Cherrybark oak</td>
<td>27</td>
</tr>
<tr>
<td>River birch</td>
<td>26</td>
</tr>
<tr>
<td>A. sycamore</td>
<td>11</td>
</tr>
<tr>
<td>Sweetgum</td>
<td>10</td>
</tr>
<tr>
<td>Yellow-poplar</td>
<td>10</td>
</tr>
<tr>
<td>Black willow</td>
<td>4</td>
</tr>
<tr>
<td>E. cottonwood</td>
<td>3</td>
</tr>
<tr>
<td>Willow oak</td>
<td>2</td>
</tr>
<tr>
<td>Unfilled Cells</td>
<td>18</td>
</tr>
<tr>
<td>Total</td>
<td>375</td>
</tr>
</tbody>
</table>
Table 4: Mean diameters at breast height (inches) at study initiation in 1996 and 18 years later in 2014, 18-year DBH growth, standard errors, and letter groupings for green ash crop trees at study initiation are presented for the crop tree enhancement study at Ames Plantation in West TN.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>1996 DBH</th>
<th>2014 DBH</th>
<th>18-Year DBH Growth</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>SE</td>
<td>Group</td>
</tr>
<tr>
<td>Release</td>
<td>5.4</td>
<td>0.45</td>
<td>A(^a)</td>
</tr>
<tr>
<td>Rel + Fert</td>
<td>5.7</td>
<td>0.44</td>
<td>A</td>
</tr>
<tr>
<td>Control</td>
<td>5.6</td>
<td>0.44</td>
<td>A</td>
</tr>
</tbody>
</table>

\(^a\) Different letters within the same column indicate significant differences at the p=0.05 level.
Table 5: Mean DBH growth over the first three growing seasons following crop tree enhancement treatments, standard errors, and letter groupings for green ash crop trees are presented for the crop tree enhancement study at Ames Plantation in West TN.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Mean</th>
<th>Standard Error</th>
<th>Letter Group</th>
</tr>
</thead>
<tbody>
<tr>
<td>Release</td>
<td>1.08</td>
<td>0.07</td>
<td>A</td>
</tr>
<tr>
<td>Rel + Fert</td>
<td>1.13</td>
<td>0.07</td>
<td>A</td>
</tr>
<tr>
<td>Control</td>
<td>0.82</td>
<td>0.06</td>
<td>B</td>
</tr>
</tbody>
</table>

Different letters within the same column indicate significant differences at the p=0.05 level.
In 1996, no significant difference (p=0.4177) in crop tree total height was detected between the three treatments. By 2014, total heights of RF crop trees were significantly greater (p=0.0066) than C crop trees (Table 6). Total height was not different between the R crop trees and the C and RF crop trees. For height growth over 18 years, R and RF crop trees did not significantly differ from one another. However, both increased in height significantly more (p=0.0002) than C crop trees.

Mean crown spread between treatments in 1996 was not different (p=0.5451). In 2014, mean crown spreads of R crop trees were significantly greater (p=0.0227) than C crop trees (Table 7). Release plus fertilize crop trees did not significantly differ from R or C crop trees. A similar trend was observed in 18-year mean crown spread growth, where R crop trees were significantly larger (p=0.0031) than C crops, but no difference was detected between RF crop trees and the other two treatments.

Crown lengths of the three treatments did not significantly differ in 1996 (p=0.1187). By 2014, treatment differences were apparent, where the crown lengths R and RF crop trees were significantly larger (p=0.0006) than C crop trees by a margin of approximately five feet (Table 8). Crown length growth after 18 years was significantly different (p<0.0001) between all three treatments, where R crop trees were larger than both opposing treatments and RF crop trees were only larger than C crop trees.

In 1996, significant differences in clear bole length between treatments did not exist (p=0.2582). By 2014, there were still no significant differences (p=0.1538) between the R, RF, and C treatments (Table 9). However, differences did occur in clear bole length growth over the 18-year period between study initiation in 1996 and 2014. The clear bole lengths of RF crop trees grew significantly more (p=0.0195) over 18 years than R crop trees. Control crop trees did not differ in clear bole length growth from either opposing treatment.
Table 6: Mean total heights (feet) at study initiation in 1996 and 18 years later in 2014, 18-year total height growth, standard errors, and letter groupings for green ash crop trees are presented for the crop tree enhancement study at Ames Plantation in West TN.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>1996 Total Height</th>
<th>2014 Total Height</th>
<th>18-Year Total Height Growth</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>SE</td>
<td>Group</td>
</tr>
<tr>
<td>Release</td>
<td>49.0</td>
<td>2.50</td>
<td>A\textsuperscript{a}</td>
</tr>
<tr>
<td>Rel + Fert</td>
<td>50.0</td>
<td>2.50</td>
<td>A</td>
</tr>
<tr>
<td>Control</td>
<td>50.0</td>
<td>2.52</td>
<td>A</td>
</tr>
</tbody>
</table>

\textsuperscript{a} Different letters within the same column indicate significant differences at the p=0.05 level.
Table 7: Mean crown spreads (feet) at study initiation in 1996 and 18 years later in 2014, 18-year mean crown spread growth, standard errors, and letter groupings for green ash crop trees are presented for the crop tree enhancement study at Ames Plantation in West TN.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>SE</td>
<td>Group</td>
</tr>
<tr>
<td>Release</td>
<td>8.4</td>
<td>0.41</td>
<td>A^</td>
</tr>
<tr>
<td>Rel + Fert</td>
<td>8.6</td>
<td>0.42</td>
<td>A</td>
</tr>
<tr>
<td>Control</td>
<td>8.7</td>
<td>0.42</td>
<td>A</td>
</tr>
</tbody>
</table>

^ Different letters within the same column indicate significant differences at the p=0.05 level.
Table 8: Mean crown lengths (feet) at study initiation in 1996 and 18 years later in 2014, 18-year crown length growth, standard errors, and letter groupings for green ash crop trees are presented for the crop tree enhancement study at Ames Plantation in West TN.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>SE</td>
<td>Group</td>
</tr>
<tr>
<td>Release</td>
<td>18.6</td>
<td>1.40</td>
<td>B</td>
</tr>
<tr>
<td>Rel + Fert</td>
<td>20.1</td>
<td>1.39</td>
<td>A</td>
</tr>
<tr>
<td>Control</td>
<td>19.4</td>
<td>1.39</td>
<td>AB</td>
</tr>
</tbody>
</table>

* Different letters within the same column indicate significant differences at the p=0.05 level.
Table 9: Clear bole lengths (feet) at study initiation in 1996 and 18 years later in 2014, 18-year clear bole length growth, standard errors, and letter groupings for green ash crop trees are presented for the crop tree enhancement study at Ames Plantation in West TN.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>1996 Clear Bole Length</th>
<th>2014 Clear Bole Length</th>
<th>18-Year Clear Bole Length Growth</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>SE</td>
<td>Group</td>
</tr>
<tr>
<td>Release</td>
<td>19.0</td>
<td>1.11</td>
<td>A</td>
</tr>
<tr>
<td>Rel + Fert</td>
<td>17.0</td>
<td>1.09</td>
<td>A</td>
</tr>
<tr>
<td>Control</td>
<td>18.0</td>
<td>1.08</td>
<td>A</td>
</tr>
</tbody>
</table>

*a Different letters within the same column indicate significant differences at the p=0.05 level.
Comparison of Treatment Impact on Crown Class Distribution

Crown class scores, as determined by the crown rating system developed by Meadows et al. (2001), of the three treatments did not significantly differ ($p=0.3210$) in 1996. At this time, all three treatments averaged co-dominant crown classes. By 2014, R and RF crop trees had significantly greater ($p<0.0001$) crown class scores than C crop trees (Table 10). Release and RF crop trees did not differ in crown class score. After 18 years since treatments were implemented, R and RF crop trees had maintained co-dominant crown classes on average, while C crop trees had rescinded to intermediate crown classes on average.

Of the 71 green ash crop trees given the R treatment in 1996, 21 trees were assigned a crown class ranking of dominant (30%). Thirty-five trees ranked as co-dominant (49%). Twelve ranked as intermediate (17%), and three ranked as suppressed (4%). In 2014, R green ash crop trees had a crown class distribution of 13 dominant (18%), 39 co-dominant (55%), 12 intermediate (17%), and seven suppressed (10%).

The crown class distribution in 1996 of the 80 green ash crop trees given the RF treatment was 15 dominant (19%), 53 co-dominant (66%), 10 intermediate (12%), and two suppressed (3%). By 2014, the RF crown class distribution had shifted to 10 dominant (13%), 48 co-dominant (60%), 16 intermediate (20%), and six suppressed (7%).

The 1996 crown class of the 82 green ash crop trees given the C treatment was 18 dominant (22%), 54 co-dominant (66%), nine intermediate (11%), and one suppressed (1%). In 2014, the C crown class distribution was one dominant (1%), 33 co-dominant (40%), 27 intermediate (33%), and 21 suppressed (26%). Figure 9 is a depiction of treatments and crown class distribution for 1996 and 2014.
Table 10: Mean crown class scores according to the system developed by Meadows et al. (2001), standard errors, letter groupings, and ratings for green ash crop trees at study initiation in 1996 and 18 years later in 2014 are presented for the green ash crop tree enhancement study at Ames Plantation in West TN.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>1996 Crown Class Score</th>
<th>2014 Crown Class Score</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>SE</td>
</tr>
<tr>
<td>Release</td>
<td>19.5</td>
<td>0.72</td>
</tr>
<tr>
<td>Rel + Fert</td>
<td>20.0</td>
<td>0.70</td>
</tr>
<tr>
<td>Control</td>
<td>20.5</td>
<td>0.70</td>
</tr>
</tbody>
</table>

* Different letters within the same column indicate significant differences at the p=0.05 level.
Figure 9: Crown class distributions for green ash crop trees by treatment before crop tree enhancement treatments in 1996 and 18 years later in 2014. Upper canopy crown classes are colored green, while lower canopy crown classes are red. Release and Rel + Fert maintained higher percentages of upper canopy crop trees than control after 18 years.
The Impact of Crown Class on Treatment Response

Green ash crop trees assigned dominant crown classes in 1996 were composed of 21 R, 15 RF, and 18 C. No significant difference was observed in 1996 DBH (p=0.8974) (Table 11) and total height (p=0.5023) (Table 12). For these same measures in 2014, R, RF, and C crop trees in the dominant crown class showed no significant differences (p=0.9254; p=0.4992). No significant differences were observed between treatments in 18-year DBH and height growth (p=0.4992; p=0.7462). Mean crown spread in 1996 did not significantly differ for R, RF, C crop trees (p=0.7096) (Table 13). Mean crown spread and growth in 2014 also did not significantly differ between the three treatments (p=0.4748; p=0.4470). Crown length did not differ between the treatments in 1996 (p=0.0619). By 2014, R crop trees were significantly larger (p=0.0059) than C crop trees, but RF crop trees did not differ from either treatment (Table 14). Release crop trees expanded crown lengths significantly more so (p<0.0001) than RF and C crop trees over the 18-year period, while RF crop trees were only significantly greater in crown length growth than C crop trees. Crown class score in 2014 barely showed significant difference between treatments. Release trees had significantly greater crown class scores than C crop trees (p=0.0492) at a significance level of p=0.05 (Table 15). Release plus fertilize crop trees did not significantly differ from R or C crop trees.

The co-dominant crown class in 1996 was composed of 35 R, 53 RF, and 54 C. DBH and total height were not significantly different between the three treatments in 1996 (p=0.3341; p=0.6210). In 2014, R and RF crop trees showed no significant difference in DBH, 18-year DBH growth, total height, and 18-year height-growth. However, the control treatment was significantly less than R and RF crop trees for DBH (p<0.0001), 18-year DBH growth (p<0.0001), total height (P<0.0001), and 18-year height growth (p=0.0005). Mean crown spread in 1996 did not significantly differ for R, RF, C crop trees (p=0.9029). In 2014, mean crown spread was significantly different for all three treatments, with R crop
Table 11: The impact of crown class at the time of study initiation on diameter at breast height in 1996 and 18 years later in 2014, 18-year diameter at breast height growth, standard errors, and letter groupings for green ash crop trees is presented for the crop tree enhancement study at Ames Plantation in West TN. A small sample in the suppressed crown class limited statistical comparison.

<table>
<thead>
<tr>
<th>1996 Crown Class</th>
<th>Treatment</th>
<th>1996 DBH</th>
<th>2014 DBH</th>
<th>18-Year DBH Growth</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Mean</td>
<td>SE</td>
<td>Group</td>
</tr>
<tr>
<td>Dominant</td>
<td>Release</td>
<td>6.49</td>
<td>0.58</td>
<td>A&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td></td>
<td>Rel + Fert</td>
<td>6.50</td>
<td>0.61</td>
<td>A</td>
</tr>
<tr>
<td></td>
<td>Control</td>
<td>6.71</td>
<td>0.58</td>
<td>A</td>
</tr>
<tr>
<td>Co-Dominant</td>
<td>Release</td>
<td>5.64</td>
<td>0.37</td>
<td>A</td>
</tr>
<tr>
<td></td>
<td>Rel + Fert</td>
<td>5.70</td>
<td>0.35</td>
<td>A</td>
</tr>
<tr>
<td></td>
<td>Control</td>
<td>5.39</td>
<td>0.35</td>
<td>A</td>
</tr>
<tr>
<td>Intermediate</td>
<td>Release</td>
<td>3.34</td>
<td>0.36</td>
<td>B</td>
</tr>
<tr>
<td></td>
<td>Rel + Fert</td>
<td>4.95</td>
<td>0.37</td>
<td>A</td>
</tr>
<tr>
<td></td>
<td>Control</td>
<td>4.40</td>
<td>0.42</td>
<td>A</td>
</tr>
<tr>
<td>Suppressed</td>
<td>Release</td>
<td>2.91</td>
<td>0.05</td>
<td>*</td>
</tr>
<tr>
<td></td>
<td>Rel + Fert</td>
<td>3.30</td>
<td>0.06</td>
<td>*</td>
</tr>
<tr>
<td></td>
<td>Control</td>
<td>4.3</td>
<td>0.08</td>
<td>*</td>
</tr>
</tbody>
</table>

<sup>a</sup> Different letters within the same column indicate significant differences at the p=0.05 level.
Table 12: The impact of crown class at the time of study initiation on total height in 1996 and 18 years later in 2014, 18-year total height growth, standard errors, and letter groupings for green ash crop trees is presented for the crop tree enhancement study at Ames Plantation in West TN. A small sample in the suppressed crown class limited statistical comparison.

<table>
<thead>
<tr>
<th>1996 Crown Class</th>
<th>Treatment</th>
<th>1996 Total Height</th>
<th>2014 Total Height</th>
<th>18-Year Total Height Growth</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Mean</td>
<td>SE</td>
<td>Group</td>
</tr>
<tr>
<td>Dominant</td>
<td>Release</td>
<td>51.0</td>
<td>3.29</td>
<td>A(^a)</td>
</tr>
<tr>
<td></td>
<td>Rel + Fert</td>
<td>51.0</td>
<td>3.36</td>
<td>A</td>
</tr>
<tr>
<td></td>
<td>Control</td>
<td>53.0</td>
<td>3.30</td>
<td>A</td>
</tr>
<tr>
<td>Co-Dominant</td>
<td>Release</td>
<td>51.0</td>
<td>2.07</td>
<td>A</td>
</tr>
<tr>
<td></td>
<td>Rel + Fert</td>
<td>51.0</td>
<td>2.07</td>
<td>A</td>
</tr>
<tr>
<td></td>
<td>Control</td>
<td>50.0</td>
<td>1.99</td>
<td>A</td>
</tr>
<tr>
<td>Intermediate</td>
<td>Release</td>
<td>38.0</td>
<td>2.17</td>
<td>B</td>
</tr>
<tr>
<td></td>
<td>Rel + Fert</td>
<td>45.0</td>
<td>2.30</td>
<td>A</td>
</tr>
<tr>
<td></td>
<td>Control</td>
<td>43.0</td>
<td>2.17</td>
<td>AB</td>
</tr>
<tr>
<td>Suppressed</td>
<td>Release</td>
<td>36.0</td>
<td>1.08</td>
<td>*</td>
</tr>
<tr>
<td></td>
<td>Rel + Fert</td>
<td>37.0</td>
<td>1.32</td>
<td>*</td>
</tr>
<tr>
<td></td>
<td>Control</td>
<td>40.0</td>
<td>1.87</td>
<td>*</td>
</tr>
</tbody>
</table>

\(^a\) Different letters within the same column indicate significant differences at the p=0.05 level.
Table 13: The impact of crown class at the time of study initiation on mean crown spread in 1996 and 18 years later in 2014, 18-year mean crown spread growth, standard errors, and letter groupings for green ash crop trees is presented for the crop tree enhancement study at Ames Plantation in West TN. A small sample size in the suppressed crown class limited statistical comparison.

<table>
<thead>
<tr>
<th></th>
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<th></th>
<th></th>
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<tbody>
<tr>
<td></td>
<td></td>
<td>Mean</td>
<td>SE</td>
<td>Group</td>
</tr>
<tr>
<td>Dominant</td>
<td>Release</td>
<td>9.7</td>
<td>0.72</td>
<td>A</td>
</tr>
<tr>
<td></td>
<td>Rel + Fert</td>
<td>10.3</td>
<td>0.77</td>
<td>A</td>
</tr>
<tr>
<td></td>
<td>Control</td>
<td>9.7</td>
<td>0.71</td>
<td>A</td>
</tr>
<tr>
<td>Co-Dominant</td>
<td>Release</td>
<td>8.7</td>
<td>0.36</td>
<td>A</td>
</tr>
<tr>
<td></td>
<td>Rel + Fert</td>
<td>8.5</td>
<td>0.32</td>
<td>A</td>
</tr>
<tr>
<td></td>
<td>Control</td>
<td>8.7</td>
<td>0.32</td>
<td>A</td>
</tr>
<tr>
<td>Intermediate</td>
<td>Release</td>
<td>5.9</td>
<td>0.67</td>
<td>B</td>
</tr>
<tr>
<td></td>
<td>Rel + Fert</td>
<td>7.5</td>
<td>0.67</td>
<td>A</td>
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<td></td>
<td>Control</td>
<td>7.0</td>
<td>0.75</td>
<td>AB</td>
</tr>
<tr>
<td>Suppressed</td>
<td>Release</td>
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<td>1.11</td>
<td>*</td>
</tr>
<tr>
<td></td>
<td>Rel + Fert</td>
<td>6.3</td>
<td>1.11</td>
<td>*</td>
</tr>
<tr>
<td></td>
<td>Control</td>
<td>7.8</td>
<td>1.17</td>
<td>*</td>
</tr>
</tbody>
</table>

* Different letters within the same column indicate significant differences at the p=0.05 level.
Table 14: The impact of crown class at the time of study initiation on crown length in 1996 and 18 years later in 2014, 18-year crown length growth, standard errors, and letter groupings for green ash crop trees is presented for the crop tree enhancement study at Ames Plantation in West TN. A small sample size in the suppressed crown class limited statistical comparison.

<table>
<thead>
<tr>
<th></th>
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<tr>
<td></td>
<td></td>
<td>Mean</td>
<td>SE</td>
<td>Group</td>
</tr>
<tr>
<td></td>
<td>Release</td>
<td>20.0</td>
<td>1.90</td>
<td>A\textsuperscript{a}</td>
</tr>
<tr>
<td></td>
<td>Rel + Fert</td>
<td>20.9</td>
<td>1.95</td>
<td>A</td>
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<td></td>
<td>Control</td>
<td>23.2</td>
<td>1.90</td>
<td>A</td>
</tr>
<tr>
<td>Co-Dominant</td>
<td>Release</td>
<td>19.9</td>
<td>1.22</td>
<td>A</td>
</tr>
<tr>
<td></td>
<td>Rel + Fert</td>
<td>20.2</td>
<td>1.15</td>
<td>A</td>
</tr>
<tr>
<td></td>
<td>Control</td>
<td>18.8</td>
<td>1.14</td>
<td>A</td>
</tr>
<tr>
<td>Intermediate</td>
<td>Release</td>
<td>12.3</td>
<td>0.98</td>
<td>C</td>
</tr>
<tr>
<td></td>
<td>Rel + Fert</td>
<td>20.0</td>
<td>1.07</td>
<td>A</td>
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<tr>
<td></td>
<td>Control</td>
<td>15.8</td>
<td>1.13</td>
<td>B</td>
</tr>
<tr>
<td>Suppressed</td>
<td>Release</td>
<td>13.0</td>
<td>0.94</td>
<td>*</td>
</tr>
<tr>
<td></td>
<td>Rel + Fert</td>
<td>10.0</td>
<td>1.15</td>
<td>*</td>
</tr>
<tr>
<td></td>
<td>Control</td>
<td>14.0</td>
<td>1.63</td>
<td>*</td>
</tr>
</tbody>
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\textsuperscript{a} Different letters within the same column indicate significant differences at the p=0.05 level.
Table 15: The impact of crown class at the time of study initiation on crown class score as determined by Meadows et al. (2001) in 1996 and 18 years later in 2014, 18-year crown class score change, standard errors, and letter groupings for green ash crop trees is presented for the crop tree enhancement study at Ames Plantation in West TN. A small sample size in the suppressed crown class limited statistical comparison.

<table>
<thead>
<tr>
<th>1996 Crown Class</th>
<th>Treatment</th>
<th>1996 Crown Class Score</th>
<th>2014 Crown Class Score</th>
<th>18-Year Crown Class Score Change</th>
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<tr>
<td></td>
<td></td>
<td>Mean</td>
<td>SE</td>
<td>Group</td>
</tr>
<tr>
<td>Dominant</td>
<td>Release</td>
<td>24.7</td>
<td>0.19</td>
<td>A</td>
</tr>
<tr>
<td></td>
<td>Rel + Fert</td>
<td>24.5</td>
<td>0.22</td>
<td>A</td>
</tr>
<tr>
<td></td>
<td>Control</td>
<td>24.9</td>
<td>0.20</td>
<td>A</td>
</tr>
<tr>
<td>Co-Dominant</td>
<td>Release</td>
<td>20.2</td>
<td>0.32</td>
<td>A</td>
</tr>
<tr>
<td></td>
<td>Rel + Fert</td>
<td>20.5</td>
<td>0.27</td>
<td>A</td>
</tr>
<tr>
<td></td>
<td>Control</td>
<td>20.3</td>
<td>0.27</td>
<td>A</td>
</tr>
<tr>
<td>Intermediate</td>
<td>Release</td>
<td>12.8</td>
<td>0.62</td>
<td>A</td>
</tr>
<tr>
<td></td>
<td>Rel + Fert</td>
<td>14.0</td>
<td>0.63</td>
<td>A</td>
</tr>
<tr>
<td></td>
<td>Control</td>
<td>14.3</td>
<td>0.72</td>
<td>A</td>
</tr>
<tr>
<td>Suppressed</td>
<td>Release</td>
<td>8.3</td>
<td>0.36</td>
<td>*</td>
</tr>
<tr>
<td></td>
<td>Rel + Fert</td>
<td>8.5</td>
<td>0.44</td>
<td>*</td>
</tr>
<tr>
<td></td>
<td>Control</td>
<td>8.0</td>
<td>0.62</td>
<td>*</td>
</tr>
</tbody>
</table>

* Different letters within the same column indicate significant differences at the p=0.05 level.
trees having the largest mean crown spread, the C crop trees having the smallest mean crown spread, and the RF crop trees falling between R and C crop trees (p=0.0002). Growth in mean crown spread after 18 years followed a similar trend, where the largest increases in the R crop trees, the smallest increases in the C crop trees, and the RF crop trees falling in between R and C crop trees (p<0.0001). Crown lengths did not differ between treatments in 1996 (p=0.2000). In 2014, R and RF crop trees were significantly greater (p=0.0032) in crown length than C crop trees. Crown length growth after 18 years was significantly greater (p=0.0441) for R crop trees than RF and C crop trees, but RF crop trees did not differentiate significantly from either opposing treatment. Crown class score in 2014 did not differ for R and RF crop trees, but both were significantly larger than C crop trees (p<0.0001). Release and RF crown class scores equated to co-dominant crown classes, while C scores equated to intermediate crown classes.

The intermediate crown class in 1996 was composed of 12 R, 10 RF, and 9 C. For 1996 DBH, RF and C were not significantly different from one another, but both were significantly greater than R (p=0.0055). For 1996 total height, RF was significantly greater than R (p=0.0482). This difference is on the edge of statistical significance. Control crop trees did not show significant difference from R or RF. For 2014, RF crop trees were significantly larger in DBH than R and C (p=0.0068). For 18-year DBH growth, RF was significantly greater than R and C (p=0.0236). Release and C did not significantly differ in 18-year DBH growth. Release, RF, and C crop trees did not show significant difference in total height in 2014 (p=0.0547) and 18-year height growth (p=0.6410). Mean crown spread in 1996 and 2014 did not significantly differ for R, RF, C crop trees (p=0.0529; p=0.3128). Growth in mean crown spread after 18 years also did not differ between treatments (p=0.6411). Crown length in 1996 was significantly greater (p<0.0001) for the RF treatment than the R and C treatments, while C treatment was significantly greater than the R treatment. However, R, RF, and C crop trees did not significantly differ in 2014 crown length (p=0.1159) or 18-year crown length growth (p=0.1153). Crown class score in 2014 was
significantly larger for RF crop trees than R and C crop trees (p=0.0331). No difference was observed between R and C crop trees. Although, RF crop trees were significantly larger in crown class score than R and C crop trees, the scores of all three treatments equated to intermediate crown classes.

The suppressed crown class in 1996 consisted of three R, two RF, and one C. The small sample size limited the power of statistical comparisons between treatments, so only treatment means are reported.

The diameter distribution of release trees at the time of treatment on eventual crown class 18 years later in 2014 is presented for both the number and percentage of released green ash crop trees in Figures 10 and 11 and for control crop trees in Figures 12 and 13. A greater percentage of released and control crop trees of larger diameters were in the upper canopy crown classes (dominants and co-dominants) while more trees in the smaller diameter classes were in the intermediate or suppressed crown class. The 4-inch diameter class of released trees had a nearly equal proportion of overstory (dominant and co-dominant) and subordinate crown classes (intermediate and suppressed), despite release. The 8-inch diameter class of control trees had a nearly equal proportion of overstory and subordinate crown classes, even without release.

**Alterations in Depth to Mottled Horizons across the Study Site**

Results from the Pearson’s Chi-Square analysis and contingency table reveal that the depth to mottled horizons (1-3) and repetition number (1-5) are not independent of one another (p=0.00001). Plots of the three mottling depth ranges suggest that sites with depths to mottled horizons in the first 12 inches occurred more frequently in repetitions 2, 3, and 4, than in repetitions 1 and 5 (Figure 14). This corresponds to the much lower occurrence of crop tree sites with depths to mottled horizons in repetitions, 2, 3, and 4, and their higher occurrence in repetitions 1 and 5. Generally, depths to mottled horizons in the 12 to 24 inch were most common across all repetitions.
Figure 10: The relationship of DBH (inches) in 1996 at the time of treatment to eventual crown class 18 years later in 2014 for released green ash crop trees is presented as a number of total released green ash crop trees. Upper canopy crown classes are colored blue, while lower canopy crown classes are black.
Figure 11: The relationship of DBH (inches) in 1996 at the time of treatment to eventual crown class 18 years later in 2014 for released green ash crop trees is presented as a percentage of total released green ash crop trees. Upper canopy crown classes are colored blue, while lower canopy crown classes are black.
Figure 12: The relationship of DBH (inches) in 1996 at the time of treatment to eventual crown class 18 years later in 2014 for control green ash crop trees is presented as a number of total control green ash crop trees. Upper canopy crown classes are colored blue, while lower canopy crown classes are black.
Figure 13: The relationship of DBH (inches) in 1996 at the time of treatment on eventual crown class 18 years later in 2014 for control green ash crop trees is presented as a percentage of total control green ash crop trees. Upper canopy crown classes are colored blue, while lower canopy crown classes are black.
Figure 14: Chi-square and contingency table analysis between depth to mottled horizons rank (1-3) and treatment repetition (1-5) reveal a lack of independence (p<0.0001). Depth to mottled horizons in the first 12 inches (rank 1) occurred much more frequently in repetitions 2, 3, and 4 than expected, indicating these repetitions are the wettest on the green ash crop tree enhancement study. Image produced with NCSS 2015.
**The Relationship between Depth to Mottled Horizons and Crop Tree Crown Class**

Results from the Pearson’s Chi-Square analysis and contingency table indicate that crown class in 1996 (p=0.06913) and crown class in 2014 (p=0.08314), scaled 1 to 4, are both independent of depth to mottled horizons, scaled 1 to 3 (Figures 15 & 16). This implies a lack of relationship between depth to mottled horizons and crop tree performance. An observational result from this analysis is that the majority of co-dominant crown classes occurred on sites with depths to mottled horizons in 12 to 24-inch range.

**The Impact of Depth to Mottled Horizons on Treatment Response**

Green ash crop trees occurring on sites with the depth to mottled horizons occurring in the first 12 inches of soil, deemed Mottle Rank 1, were composed of 10 R, 17 RF, and 17 C. Sites with depths to mottled horizons in 12 to 24 inches of soil, deemed Mottle Rank 2, were comprised of 47 R, 54 RF, and 47 C green ash crop trees. Sites with mottled horizons at or beyond 24 inches, deemed Mottle Rank 3, were occupied by 14 R, 9 RF, and 18 C.

Where depth to mottled horizons occurred in the first 12 inches of soil, C crop trees, at 5.77 inches DBH in 1996, were significantly larger (p=0.0288) than R crop trees, at 4.36 inches DBH in 1996 (Table 16). Release plus fertilize crop trees, at 5.10 inches, did not differ from either opposing treatment. By 2014, RF crop trees, at 10.47 inches DBH, were significantly larger (p=0.0324) than R crop trees, at only 7.67 inches DBH. Control crop trees, at 9.28 inches, did not differ from R or RF crop trees in 2014. Over the 18-year period, a RF crop trees grew 5.46 inches in DBH, a significantly greater (p=0.0095) amount than R crop trees, at 3.39 inches, and C crop trees, at 3.49 inches. Release and C crop trees did not differ in 18-year DBH growth. A similar trend occurred in crown class point score on Mottle Rank 1 sites (Table 16). In 1996, C crop trees, with a crown class score of 21.0, were significantly greater (p=0.0059) than R crop trees, at only 15.3 points in crown class score. Release plus fertilize crop trees,
Figure 15: Chi-square and contingency table analysis between depth to mottled horizons rank (1-3) and 1996 crown class rating (1-4) as determined by the crown rating system by Meadows et al. (2001) reveal that these factors are independent and not strongly related in the green ash crop tree enhancement study. Image produced with NCSS 2015.
Figure 16: Chi-square and contingency table analysis between depth to mottled horizons rank (1-3) and 2014 crown class rating (1-4) as determined by the crown rating system by Meadows et al. (2001) reveal that these factors are independent and not strongly related in the green ash crop tree enhancement study. Image produced with NCSS 2015.
Table 16: The impact of depth to mottling rank (1-3) by treatment on mean DBH in 1996 and 2014, 18-year DBH growth, crown class score in 1996 and 2014, 18-year change in crown class score, standard errors, and letter groupings for green ash crop trees is presented for the crop tree enhancement study at Ames Plantation in West TN. Letter groupings are organized horizontally across rows.

<table>
<thead>
<tr>
<th>Mottling Rank</th>
<th>Crop Tree Variable</th>
<th>Treatment</th>
<th>Release</th>
<th>Rel+Fert</th>
<th>Control</th>
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</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Mean</td>
<td>SE</td>
<td>Group</td>
</tr>
<tr>
<td>1 (0 - 12&quot;)</td>
<td>DBH - 1996 (in.)</td>
<td>4.36</td>
<td>0.63</td>
<td>B(^a)</td>
<td>5.10</td>
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<td></td>
<td>DBH - 2014 (in.)</td>
<td>7.67</td>
<td>1.23</td>
<td>B</td>
<td>10.47</td>
</tr>
<tr>
<td></td>
<td>18-year DBH growth (in.)</td>
<td>3.39</td>
<td>0.71</td>
<td>B</td>
<td>5.46</td>
</tr>
<tr>
<td></td>
<td>Crown Class Score – 1996</td>
<td>15.3</td>
<td>1.56</td>
<td>Y(^a)</td>
<td>18.2</td>
</tr>
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<td></td>
<td>Crown Class Score – 2014</td>
<td>12.9</td>
<td>1.88</td>
<td>Y</td>
<td>17.8</td>
</tr>
<tr>
<td></td>
<td>Crown Class Score Change</td>
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<td>1.72</td>
<td>X</td>
<td>-0.3</td>
</tr>
<tr>
<td>2 (12 - 24&quot;)</td>
<td>DBH - 1996 (in.)</td>
<td>5.77</td>
<td>0.43</td>
<td>A</td>
<td>5.87</td>
</tr>
<tr>
<td></td>
<td>DBH - 2014 (in.)</td>
<td>11.21</td>
<td>0.77</td>
<td>A</td>
<td>11.07</td>
</tr>
<tr>
<td></td>
<td>18-year DBH growth (in.)</td>
<td>5.44</td>
<td>0.46</td>
<td>A</td>
<td>5.19</td>
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<td>Crown Class Score – 1996</td>
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<td>Crown Class Score – 2014</td>
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<td>X</td>
<td>18</td>
</tr>
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<td>Crown Class Score Change</td>
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<td>0.89</td>
<td>X</td>
<td>-2.4</td>
</tr>
<tr>
<td>3 (24&quot;+)</td>
<td>DBH - 1996 (in.)</td>
<td>5.44</td>
<td>0.69</td>
<td>A</td>
<td>6.12</td>
</tr>
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<td></td>
<td>DBH - 2014 (in.)</td>
<td>11.06</td>
<td>1.35</td>
<td>AB</td>
<td>12.62</td>
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<td>18-year DBH growth (in.)</td>
<td>5.57</td>
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<tr>
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<td>Crown Class Score – 2014</td>
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<td>1.88</td>
<td>XY</td>
<td>19.4</td>
</tr>
<tr>
<td></td>
<td>Crown Class Score Change</td>
<td>-3.0</td>
<td>1.54</td>
<td>X</td>
<td>-3.1</td>
</tr>
</tbody>
</table>

\(^a\) Different letters within the same row indicate significant differences at the p=0.05 level.
with a crown class score of 18.2, did not differ from the two other treatments. In 1996, RF and C crop trees ranked as co-dominant crown classes, while R crop trees ranked as intermediate crown classes. By 2014, RF crop trees, with a co-dominant crown class score of 17.8, were significantly larger (p=0.0144) than R and C crop trees, with intermediate crown class scores of 12.9 and 12.8 respectively. Although R crop trees did not differ from C crop trees in crown class point score where depth to mottling occurred in the first 12 inches of soil, R and RF crop trees, at -2.3 and -0.3 points respectively, declined in crown class point score significantly less (p=0.0003) than C crop trees, which lost an average of -8.3 points.

On Mottle Rank 2 sites, with the depth to mottling in the 12 to 24-inch range, results were more consistent. In 1996, the R, RF, and C treatments showed no difference in DBH, at 5.77 inches, 5.87 inches, and 5.67 inches respectively (p=0.7828). After 18 years in 2014, R and RF crop trees, with DBHs of 11.21 inches and 11.07 inches respectively, were significantly larger (p=0.0356) than C crop trees, with a DBH of 9.75 inches. At 5.44 inches and 5.19 inches, R and RF crop trees significantly outgrew (p=0.0031) C crop trees in DBH over 18 years. For crown class point score, no difference was detected between R, RF, and C crop trees, averaging 20.1, 20.4, and 20.4 points respectively. Crop trees from all treatments were ranked as co-dominants in 1996 on Mottling Rank 2 sites. However, by 2014, R and RF crop trees, with co-dominant crown class point scores of 19.0 and 18.0, were significantly greater (p<0.0001) than C crop trees, with an intermediate crown class point score of 14.3. Release and RF crop trees, with crown score changes of only -1.0 and -2.4 points respectively, maintained their crown rankings over 18 years significantly better (p<0.0001) than C crop trees, that declined an average of -6.2 points.

Mottle Rank 3 sites had depths to mottled horizons occurring at or beyond 24 inches in soil depth. In 1996, no difference was detected between the R, RF, and C treatments, each averaging 5.44 inches, 6.12 inches, and 5.23 inches respectively (p=0.2583). In 2014, RF crop trees, at 12.62 inches,
were significantly larger (p=0.0139) than C crop trees, at only 9.11 inches. Release crop trees averaged 11.06 inches in DBH in 2014 and did not differ from either opposing treatment. For 18-year DBH growth, R and RF crop trees, with 5.57 and 6.54 inches respectively, significantly outpaced (p=0.0042) C crop trees, with only 3.90 inches. All three treatments showed no difference (p=0.4203) in crown class point score and ranked as co-dominants at the time of treatment in 1996, with R crop trees averaging a score of 20.8 points, RF crop trees scoring 22.3 points, and C crop trees scoring 20.5 points. By 2014, RF crop trees averaged 19.4 points in crown class point score, which was significantly greater (p=0.0325) than C crop trees with a score of only 14.5 points. Even though R crop trees, with 18.3 points, did not differ from RF or C crop trees in crown class points scored, both R and RF crop trees ranked as co-dominants while C crop trees ranked as intermediates. The decline in crown class point score was significantly more pronounced in C crop trees, with -6.2 points, over the 18-year period than the decline in the R, with -3.0 points, and the RF, with -3.1 points.

**Correlations between Response Variables and Depth to Mottled Horizons**

Few significant relationships were observed between depth to mottled horizons and the main response variables in 2014. In general, inconsistent trends were observed across the R, RF, and C treatments.

For R green ash crop trees, depth to mottled horizons showed no significant relationships with DBH in 2014, total height in 2014, DBH growth over 18 years, mean crown spread in 2014, or crown class point score. However, depth to mottled horizons did have a moderate, positive 0.33706, 0.0040 correlation with total height growth over 18 years.

For RF green ash crop trees, depth to mottled horizons showed no significant relationships with total height in 2014, DBH growth over 18 years, total height growth over 18 years, mean crown spread
in 2014, and crown class point score in 2014. There was a significant, weak 0.24002, 0.0332 correlation with DBH in 2014.

For C green ash crop trees, depth to mottled horizons was not significantly related to DBH in 2014, DBH growth over 18 years, mean crown spread in 2014 and crown class score in 2014. However, depth to mottled horizons did display a weak, positive 0.29753, 0.0066 correlation with total height in 2014 and a weak, positive 0.22869, 0.0388 correlation with total height growth over 18 years.

**Competition Cluster Species Composition by Depth to Mottled Horizons**

A depth to mottling rank of 1 was given to 80 crop tree cells, meaning that the depth to mottled horizons was reached within the first 12 inches of soil. The average competition cluster species composition of the basal area for crop trees of rank 1 was 26% sweetgum, 15% river birch, 11% green ash, 10% cherrybark oak, 8% American sycamore, 7% black willow, 7% American elm, 6% boxelder, 5% eastern cottonwood, 3% yellow-poplar, 1% red maples, and 1% other species (Figure 17).

For depth to mottling rank 2, 194 cells were assigned. For these crop trees, the depth to mottled horizons occurred within 12 to 24 inches. The average competition cluster species composition for crop trees of rank 2 was 23% green ash, 21% sweetgum, 15% river birch, 9% American sycamore, 7% eastern cottonwood, 7% cherrybark oak, 5% boxelder, 5% American elm, 4% black willow, 1% yellow poplar, 1% red maple, and 1% other species (Figure 17).

For depth to mottling rank 3, 50 cells were assigned. This corresponds to a depth to mottled horizons of 24+ inches. The average competition cluster species composition was 34% green ash, 11% river birch, 10% sweetgum, 9% American sycamore, 7% other species, 6% American elm, 5% cherrybark oak, 5% eastern cottonwood, 2% boxelder, 1% black willow, and 1% red maple (Figure 17).
Figure 17: Competition cluster species compositions (%) for green ash crop trees on three depth to mottled horizons ranks. Mottling horizons occur in the first 12” of soil for MR1, 12 to 24” for MR2, and beyond 24” for MR3. Important species for observing trends are colored in yellow, purple, green, red, and black.
Chapter 6: Discussion

Treatment Impact on DBH, Height, Clear Bole Length, and Crown Expansion

The significant increases in diameter growth and crown expansion for released green ash crop trees over the controls indicate that the treatments were successful in improving upon the growth rate of green ash on this site. In response to the additional growing space provided from release, crop trees expand their crowns laterally to capture this vacated space and obtain more light. Crown expansion is associated with root growth into the surrounding soil. Once a crop tree’s crown has increased in leaf area and photosynthetic capacity, more growth can be dedicated to secondary growth and diameter expansion (Pallardy 2008, Oliver and Larson 1996). This positive impact on DBH growth has been observed in many crop tree release studies (Wendel and Lamson 1987, Stringer et al. 1988, Wood et al. 1996, Miller 1997, Miller 2000, Ward 2007, Ward 2009, Ward 2013).

Release (R) and release plus fertilization (RF) treatments resulted in larger crop tree DBHs after 18 years than control treatments. This same result was observed in 18-year DBH growth, with release and release plus fertilization outpacing the control by 1.2 and 1.5 inches respectively (Table 4). A typical green ash crop tree given the release treatment is displayed in Figure 18. No significant difference was uncovered between the release and release plus fertilization treatment, which suggests either the addition of a one-time fertilizer application at the time of release offered little benefit across all the green ash crop trees or that any additional growth impact from fertilization was short-term and has been masked after 18 years of growth between measurements. Ellis (1979) reported no significant additional growth response over controls from fertilization in white ash crop trees. The lack of additional response from the fertilizer application could be attributed to the inherent high fertility of the soils in Henley Bottom. On soil types with adequate amounts of essential elements, fertilizers may not provide an additional growth response (Hannah 1985).
Figure 18: A typical green ash crop tree 18 years after release in Henley Bottom at Ames Plantation in West TN. This 36-year-old crop tree has a diameter at breast height of 10.4 inches and a total height of 75 feet.
To streamline discussion of treatment impact, the R and RF will hereby be referred to as the released crop trees, unless explicitly stated otherwise. Although no difference was detected between release and release plus fertilization, the increase in DBH growth indicates the green ash crop trees responded positively to release by capturing the additional growing space and translating it successfully into secondary growth. The lack of significant difference between treatments during the first three growing seasons after treatment, from 1996 to 1998, indicates that any positive response in DBH growth to release did not occur immediately (Table 5). This postulation deviates from findings of a study on crop tree release in mixed Appalachian hardwoods, where DBH growth over the first three growing seasons for release trees exceeded that of control trees (Smith and Lamson 1983). For the first few growing seasons following release, crop trees are concentrated on building crown and capturing the vacated growing space in the canopy with primary growth, and a DBH response is delayed. As the larger crown is established, the rate of DBH growth subsequently increases (Oliver and Larson 1996). This explanation supports what probably occurred in the green ash study, where the DBH growth response was more gradual. By 2014, complete crown closure around the crop trees was observed, placing crop trees in a more competitive situation once again and likely inhibiting DBH growth.

A positive response also was observed in crown length and mean crown spread expansion for the 18-year study period. Released green ash trees gained approximately five additional feet of crown length and two to three feet of additional crown spread compared to the control (Tables 7 & 8). In a reviewed study, crown cross-sectional area increased considerably for black cherry and northern red oak crop trees after 10 years following release (Schuler 2006). Although the discernable margin in these crown characteristics has likely diminished over the 18-year period across the entire study, the discrepancies between treatments indicate that green ash crop trees were able to capture additional growing space provided by release and maintain larger crowns. Since the relationship between crown size and diameter is positively correlated, a tree’s capacity to grow and increase in volume depends on
the ability of the tree’s crown to continue to expand (Pallardy 2008, Oliver and Larson 1996). Once canopy closure occurs in mixed-hardwood stands, it appears that crop tree release allows green ash to continue to expand its crown, thus improving growth. Crown expansion is directly related to maintenance of crown position within the stand.

Total height growth was greater for release and release plus fertilization treatments than the control, by approximately four and six feet respectively, although total height in 2014 was only significantly greater for the release plus fertilization treatment (Table 6). These results are somewhat surprising, as several studies have shown that release has little significant effect on height growth (Trimble 1973, Lamson and Smith 1978, Wendel and Lamson 1987, Miller 2000) and can even negatively impact it (Allen and Marquis 1970). Trees are stimulated to increase in height so that they achieve canopy positions above competitors where light resources are most available. Which trees within a stand successfully attain heights placing their crowns above adjacent competitors is a function of species growth characteristics and genetic predisposition, microsite quality, stand age, stand development patterns, and the frequency and scale of disturbances (Oliver and Larson 1996). When the competition is removed through crop tree release, as a form of targeted man-made disturbance, and light becomes less limiting, height growth is weakened in favor of lateral crown expansion. In this case, green ash crop tree height growth appears to be improved following treatment. However, the difference between treatments was numerically small, although significant, at only five or so feet (Table 6), suggesting that the true benefit of crop tree enhancement for green ash does not occur in height growth. The discrepancy in height growth after 18 years could be due to control trees diminishing in crown class to intermediate and suppressed conditions, while released trees are better maintaining upper canopy crown positions. Ultimately, height growth in response to release is influenced by the degree of release. If the competition around a crop tree is thinned more heavily, height growth is more negatively impacted, as a considerable amount of energy instead goes towards re-occupying the released crown
space. If crown competition is thinned less heavily, height growth difference is less pronounced. In young stands, like Henley Bottom, trees have smaller crowns, thus smaller openings are left after removal that are re-occupied quickly, stimulating height growth to re-initiate.

Clear bole length is another factor impacted by degree of release. According to Miller (1997), as supported by his investigation of crop tree release on northern red oak, a heavy crown release can promote epicormic branching by allowing light to reach the lower bole of crop trees. Another finding from Miller’s 1997 study is that epicormic branching is influenced by the length of time until crown closure following release. In young stands, the vacated growing space following release is reoccupied relatively quickly by the crop tree and surrounding competitors, creating conditions where epicormic branching is less likely to occur. This trend was observed in the 16-year-old green ash crop trees in this study. Young trees at the stem exclusion stage of stand development have small crowns and smaller openings to close after release, limiting the sunlight to the lower bole and persistence of epicormic branches, especially after 18 years. This finding is supported with clear bole lengths being similar between released and control trees in this green ash study, with all treatments averaging approximately 33 to 35 feet of clear bole (Table 9). In all three treatments, green ash crop trees averaged approximately two 16-foot logs of branch-free timber. However, length of clear bole does not imply grade or value of the logs. Released trees had larger diameters, contained more volume, and had fewer stem defects. Other studies have shown that crop tree release promoted an increase in live limbs from crown expansion, an increase in dead lower limbs from natural pruning, and a decrease in epicormic branches for crop trees in a mixed, young hardwood stand (Sonderman 1987). Less epicormic branching could, in the long run, potentially contribute to an improved tree grade.
Treatment Impact on Crown Class Distribution

Released green ash crop trees maintained their crown position more successfully than controls over the study period. In 1996, all treatments averaged co-dominant crown classes (Table 10). By 2014, release and release plus fertilization treatments were still classified as co-dominants on average, while controls had regressed to the intermediate class. This finding demonstrates the ability of crop tree enhancement to maintain green ash as a component of the upper canopy, although there is little evidence to suggest crop tree enhancement can improve crown position. Several other studies have reached a similar conclusion. Ward (2013) concluded that crop tree release improved the upper canopy persistence of oak saplings after 24 years, highlighting a percentage difference of 30% between released and control stems at maintaining co-dominant crown classes. These results mirror the findings of Wendel and Lamson (1987). Crop tree release enhanced the competitiveness of northern red oak with co-dominant and intermediate trees growing in association with black cherry by maintaining or improving crown position (Schuler 2006).

A comparison of the green ash crown class distribution between 1996 and 2014 is a persuasive example of how crop tree enhancement is serving its purpose in retaining green ash in the overstory of the Henley Bottom stand. In 1996, all treatments had similar distributions of dominant, co-dominant, intermediate, and suppressed crown classes, averaging roughly 80 to 85% in upper canopy positions (Figure 9). By 2014, released green ash trees from both treatments maintained upper canopy positions at a rate of 73%, but controls had rescinded to only 41% of crowns in the upper canopy. Suppressed crop trees represented 26% of control crop trees. Without release, the green ash component is fading from the stand. This tendency of green ash in unmanaged settings to not maintain its crown position has been observed in prior works (Kennedy 1990), and crop tree enhancement may be an effective strategy to overcome this issue for green ash growing in mixed-species bottomland stands. Increasing the upper
canopy persistence of selected trees is perhaps the greatest potential benefit of precommercial crop tree enhancement (Ward 2013). When these selected trees are of high value relative to the stand’s management objectives, be it timber production or any other species-quality driven issue, the value of crop tree enhancement can truly be realized. By maintaining greater percentages of more-valuable green ash upper canopy, as observed in this study, the inherent timber value of the Henley Bottom is considerably improved compared to stands with greater proportions of less-valuable species, like American sycamore, eastern cottonwood, and sweetgum.

**The Impact of Crown Class on Treatment Response**

Investigating how treatment impact differed after 18 years within crown classes observed at the time of release is useful for refining the crop tree selection process. Smith (1977) and Ward (1995) state that the percent increase in DBH growth is inversely related to initial crown class. In a study on white ash and black cherry crop trees, the rate of growth response to release was determined largely by initial size (Ellis 1979). Existing crop tree management recommendations suggest that treatment response is greatest in the co-dominant and strong intermediate crown class, limited in the dominant crown class, and least impactful in the suppressed crown class (Miller et al. 2007). Strong intermediates possess larger crowns and receive more light than other intermediates, but are still generally below co-dominants in canopy position. They have a greater likelihood of maintaining or advancing in canopy position, due to their similarities with co-dominants. Stringer et al. (1988) recommended to only target crop trees for release if they are dominants or co-dominants. Hannah (1985) suggests selecting and releasing only large-crowned crop trees of good form. Other studies have documented diameter growth increases from crop tree release in the dominant and co-dominant crown classes, but dominants increased to a lesser degree relative to initial size (Wendel and Lamson 1987, Miller 2000, Ward 2009).
In Wendel and Lamson’s 1987 crop tree study, released trees with intermediate crown classes outgrew corresponding control trees.

For green ash crop trees with dominant crowns, no difference was detected in DBH, total height, or mean crown spread after 18 years (Tables 11, 12, & 13). Essentially, no apparent differences in growth were observed among dominant green ash crop trees despite treatment, suggesting that releasing green ash growing in dominant crown positions may not be as pertinent as releasing co-dominants and strong intermediates. Once green ash has obtained an upper canopy position, growing space is less limited, especially for crown expansion. Any additional growing space provided by release may not be necessary, because the green ash has already achieved dominance over nearby competitors and can continue to grow more or less uninhibited. Dominants have a stronger likelihood of maintaining their canopy position as the stand ages. Although most crop tree management guidelines recommend releasing trees with dominant crowns, this work gives evidence that this may not be necessary. This finding could be useful in refining the crop tree selection process and lowering its implementation costs.

The greatest positive impact on green ash crop tree growth was observed within the co-dominant crown class. After 18 years, released co-dominant green ash crop trees were roughly two inches larger in DBH, six feet taller in total height, three feet wider in mean crown spread, and five feet longer in crown length than control trees (Tables 11, 12, 13, & 14). Co-dominant crop trees appear to be in the best position to respond to crop tree enhancement. Co-dominants possess sufficient resources and large enough crowns to positively respond to release, but are somewhat limited in light availability from the side by their surrounding competitors. These trees could benefit from more crown space, and they are already at a fairly strong competitive status relative to other trees in the stand to capture the relinquished growing space following release. As observed with green ash in this study, Miller et al.
(2007) states that if released, co-dominant trees stand a much greater chance of maintaining their position in the canopy.

The response within the intermediate class was more variable than in the dominant and co-dominant classes. The release treatment alone appeared to offer no additional growth benefit over the control in terms of DBH, total height, or crown expansion (Tables 11, 12, 13, & 14). The release and fertilization treatment did display significantly larger DBHs in 2014 than the control and release treatment. The lack of positive response in the release treatment for trees in the intermediate crown class could be due to a significantly lower average DBH and smaller crown size at the time of treatment in 1996 (Tables 11 & 13). Less competitive green ash trees with intermediate crowns could have also occurred where the water-table and depth to mottling were closer to the soil surface, providing an inhibitor to root growth and negatively impacting site quality and subsequently growth. The positive difference in DBH for release plus fertilization crop trees may indicate that fertilization in more saturated soil conditions improved growth response and allows the vacated growing space to be better captured than just release alone. Generally, any positive impact of releasing intermediate green ash crop trees appears to be negligible by 18 years following release. The lack of positive response suggests that releasing intermediate green ash crop trees may not be effective in mixed-species bottomland stands. Many vigorous, fast-growing competitors growing in association with the green ash crop trees in Henley Bottom, such as American sycamore, sweetgum, and eastern cottonwood, are well-suited to capture relinquished crown space. Although treating intermediates does improve the likelihood that green ash will remain in the stand composition and survive after 18 years, stand value is hardly increased, as intermediates typically possess poorer form and a lack of appreciable size. By age 16 when the treatments were applied, the capacity of intermediates to capture the additional growing space from release is unlikely. The growing space was likely filled by more rapidly growing associates before the intermediate green ash could achieve a large enough size to be able to compete with adjacent trees.
successfully. In shade-intolerant species, crop trees with subordinate crown classes typically do not respond positively to crop tree release (Trimble 1973, Trimble 1974, Smith and Lamson 1983, Miller 2000). Response of intermediate crown class green ash was similar, although green ash is more intermediate in shade tolerance. Strong intermediates, those whose crown class point score (Meadows et al. 2001) runs from 13 to 16 points, may stand a stronger chance of maintaining or advancing in crown position and thus could be considered for potential crop trees.

Although the sample size within the suppressed crown class of green ash crop trees was too small to warrant statistical comparison, releasing these trees did not appear to offer any growth, development, or stand persistence benefits. Suppressed individuals typically possess lower crown vigor and higher stress levels from being relegated to the lower canopy. Even if released, trees in the suppressed crown class cannot respond adequately to capture growing space before the more vigorous adjacent competitors do.

**Depth to Mottled Horizons: Shifts across the Study Site**

The depth to mottled horizons follows a general trend across the Henley Bottom study site. The lack of independence from repetition block indicates that depth to mottled horizons does change across the study area. In general, the areas with the shallowest depths to mottling, or the wettest and most poorly-drained sites, are repetition blocks 2 and 3, followed closely by block 4. On these sites, the number of crop tree sites with mottled horizons in the first 12 inches of soil is much greater than repetition blocks 1 and 5 (Figure 14). Blocks 2, 3, and 4 also display lower counts of sites with mottled horizons beyond 24 inches. Blocks 1 and 5 have low counts for mottled horizons in the first 12 inches and higher counts for mottled horizons in the 24 inch plus range.

The area towards the middle of the study site, where repetition blocks 2, 3 and 4 occur, is one of the wetter areas on the study site. Observationally, several sloughs and drainages transect this portion
of the stand that will have some impact on crop tree growth and development. Root growth is potentially more limited in these blocks, because this area holds surface water for a longer portion of the year. When mottling occurs closer to the surface, root development is further inhibited due to decreased growing space above the anaerobic horizons. The differences in depths to mottled horizons across the study site validate the use of a randomized block study design for this experiment.

The minute differences in site quality related to drainage and the depth to mottling could potentially have an appreciable impact on green ash crop tree growth and development, but the degree of impact is difficult to determine.

Competing species composition also shifts as the depth to mottled horizons changes. Shifts in species composition is an important indicator of minute shifts in elevation and subsequently drainage in bottomland hardwood forests (Hodges 1995).

**Depth to Mottled Horizons: Relationships with Crop Tree Growth**

Chi-square analysis between mottling depth and crown class, correlation analysis between mottling depth and crop tree growth parameters, and an analysis of variance on treatment response at the three mottling depth levels, were used to investigate depth to mottled horizons and green ash crop tree performance.

The lack of association between depth to mottled horizons and green ash crop tree crown class in 1996 and 2014 suggests that green ash crown class distribution was not strongly impacted by either shallower or deeper depths to mottled horizons, at least at the level investigated in this study (Figures 15 & 16). This finding agrees with a separate study located at the northern edge of the southern floodplain forest in south Illinois, where green ash was reported to have wider tolerances for flooding and poor aeration than previously conveyed (Robertson et al. 1978). A more intensive evaluation of soil
mottling depth, in addition to other factors, such as drainage capacity, for individual crop trees could potentially reveal the absence or presence of relationships to crop tree growth.

Correlation analysis within each treatment between crop tree growth parameters, such as DBH in 2014, total height in 2014, DBH growth over 18 years, mean crown spread in 2014, crown class point score, and the depth to mottled horizons, did not reveal any relationships. Although more soil mottling closer to the surface was identified in some areas of the study site, losses to green ash growth response to crop tree enhancement were not detected across treatment blocks.

One weak, but positive correlation, uncovered in both the release and control treatments, was between depth to mottled horizons and total 18-year height growth (refer to Page 70). The control treatment displayed a weak, positive correlation with total height in 2014, indicating that as depth to mottled horizons increases, height growth is greater, and inversely, as depth to mottled horizons decreases, height growth is less. These relationships were not observed in the release plus fertilization treatment, suggesting that green ash crop trees with this treatment may have performed better on wetter sites. Fertilization at the time of release may have benefitted crop tree height growth on the sites with greater mottling and longer sustained wet periods. Several publications have reported that, under various conditions, fertilization on water-logged sites can be beneficial (Pritchett 1980, Fox et al. 2007). However, the relationship in this case is weak, and the lack of association between mottling and other crop tree growth variables suggests that mottling is not significantly impeding green ash crop tree growth. Broadfoot (1969) determined that depth to mottling in inches was not an important variable in site-index regression analysis for green ash growing in southern bottomlands, but depth to mottling was a significant predictor of site index for cherrybark oak and water oak. Generally, Broadfoot cites difficulties in relating soil to site index for southern hardwoods, particularly due to the wide range of soils and conditions under which many species grow.
Comparisons within each range of mottling depths were somewhat limited by sample size for the 0 to 12-inch range and the 24 inches plus range. The large majority of green ash crop trees occurred where the depth to mottling was in the 12 to 24-inch range. On microsites where the depth to mottled horizons occurred beyond the first 12 inches of soil, mottling ranges 2 and 3, green ash crop tree performance within each treatment group followed similar trends as the averages from the entire study population (Table 16). On these sites, where mottling and thereby drainage were less limiting, released green ash trees performed better than controls in DBH growth and crown class maintenance over 18 years, suggesting that green ash growth is not limited significantly when depths to mottling occur beyond the first foot of soil depth.

In contrast, on sites where mottling occurred in the first 12 inches, the release treatment alone did not perform better than the control treatment. The release plus fertilization treatment did, however, display greater DBH growth and crown maintenance on these sites. Two speculative reasons are offered for these differences. The first reason is, in 1996, the population of green ash crop trees on sites with mottling in the first 12 inches of soil was significantly less in DBH and crown class than the control and release plus fertilization treatments (Table 16). The released crop trees on average had intermediate crown classes in 1996, while other treatment groups had co-dominant crowns. Through happenstance alone, the green ash crop trees given the release treatment on the more water-logged sites, as indicated by greater mottling, started from a less competitive position than the green ash crop trees in the other two treatments. This likely has a large role in eventual crop tree success in 2014. As previously noted, the response to release is less in intermediate trees than in dominant and co-dominant trees at the time of crown closure. A second, more speculative reason is on these more water-logged sites, fertilization actually provided some initial benefit to the green ash crop trees, affording
them a boost in mineral nutrition, thereby increasing the crop tree’s resources enough to allow the relinquished growing space to be captured. The benefits of fertilization, particularly phosphorus fertilization, on water-logged sites in the southeast have long been established (Pritchett 1980, Fox et al. 2007). However, the small sample size of green ash crop trees with mottling in the first 12 inches of soil and the significantly smaller DBH at the time of release may influence the analysis of the release response of the intermediate crown class.

Considering the lower success rates of release where more mottling occurred, green ash may not be well-suited to compete on these sites. Green ash usually occurs on ridge bottoms and shallow depressions within these ridges, and may extend to more poorly drained areas (Robertson et al. 1978).

**Competition Cluster Species Composition in relation to the Depth to Mottled Horizons**

A common defining feature of mixed-hardwood bottomland forests is that minor fluctuations in elevation and drainage can produce widely altered species compositions (Hodges 1995). By analyzing how the species within a crop tree’s competition cluster, as a percentage of total basal area, changed at the three ranges for depth to mottling, site preferences for species occurring in Henley Bottom can be assessed, all while considering that species occurrence is driven by many more factors other than depth to mottling. This discussion will primarily focus on the competing species that made the largest shifts in occurrence as depth to mottled horizons changed. These species are sweetgum, green ash, cherrybark oak, river birch, and black willow.

Sweetgum is a widely-adaptable species that achieves its best growth rates on moist alluvial clays and loamy soils of river bottoms, but is also capable of growth on a wide range of sites (Kormanik 1990). In this study, the occurrence of sweetgum decreased as the depth to mottling increased (Figure 17). Sweetgum was the most significant competitor for crop trees growing on sites with mottling in the first 12 inches, composing 26% of the basal area. In contrast, sweetgum comprised only 10% of the basal
area on sites where mottling occurred beyond 24 inches. Sweetgum appears better suited to wetter sites in Henley Bottom than other competitors, but as the soil becomes more well-drained, sweetgum has a more difficult time competing with other species.

Green ash was the main crop tree species of interest in this study due to its wide-occurrence in Henley Bottom and its high timber value. Green ash was also a significant competitor of the crop trees. It tended to follow an opposite trend from sweetgum. Green ash was least common on sites where mottling occurred in the first 12 inches of soil, more prevalent on sites with mottling between 12 and 24 inches, and most common on sites where mottling occurred beyond 24 inches, where it accounted for 34% of the basal area (Figure 17). Green ash performs best on the more well-drained sites. This finding also explains why green ash crop tree performance, particularly in the release treatment, was less successful on sites with more shallow depths to mottling.

Cherrybark oak achieves its best development on loamy, well-drained soil, frequently along first bottom ridges, well-drained terraces, and hummocks. Form and quality of cherrybark oak suffer on sites with poor drainage, but good form is usually obtained on sites with good drainage (Krinard 1990). As a percentage of total competing species basal area, cherrybark oak was most prevalent on sites with mottling in the first twelve inches, and increasingly less common where depths to mottling were greater (Figure 17). Cherrybark oak seemingly occurred more frequently on less well-drained sites in Henley Bottom. Although this presence contrasts with favorable soil-site relationships of cherrybark oak, across all three mottling ranges, cherrybark oak accounted for less than ten percent of relative basal area. Henley Bottom as a whole did not contain many well-suited sites for cherrybark oak development. Sites where it occurred were likely on small ridges or slightly elevated hummocks, where roots had more room to grow unhampered by the water table fluctuation. Depth to mottling is considered to be an important variable in cherrybark oak occurrence (Broadfoot 1969).
River birch commonly occurs on alluvial soils and is tolerant of high soil moisture (Grelen 1990). One study even suggests river birch requires soils that maintain moisture levels near field capacity all year (Wolfe and Pittillo 1977). River birch is listed as being moderately tolerant of flooding, but is usually found of sites with higher moisture levels. In Henley Bottom, river birch accounted for 15% of the competing species basal area on sites with mottling in the first 24 inches (Figure 17). When mottling depth increased beyond 24 inches, river birch prevalence decreased to 11%. As the year-round soil moisture required to produce mottles decreases, river birch becomes less able to survive and grow than some of its associates.

Black willow is a wet-site species commonly found along river margins, swamp edges, and sloughs, where the water level is high, and is not appreciably damaged by flooding (Pitcher and McKnight 1990). This trend was observed in Henley Bottom, where black willow was most commonly found along drainage ditches and sloughs. Although black willow was not a significant crop tree competitor in the study area, it occurred more frequently on sites with shallower depths to mottling and less frequently where mottling occurred beyond 24 inches (Figure 17).

The other primary species of crop tree competitors, American sycamore, American elm, boxelder, eastern cottonwood, yellow-poplar, and red maple, generally maintained similar percentages of basal area across all three depth to mottling ranges.

**Management Implications: Crop Tree Enhancement with Green Ash**

Green ash growing in mixed-species bottomland hardwoods in the South can be managed with crop tree enhancement. The green ash crop tree enhancement study at Ames Plantation in West Tennessee provides evidence in conserving and sustaining the species in the overstory of southern hardwood bottomlands. Without the crop tree enhancement treatments, green ash diminishes. Green ash, a highly valuable timber species with additional wildlife benefits, achieved greater rates of diameter
growth and was successfully maintained as an overstory component following crop tree enhancement after 18 years. At stand age 34 years, green ash given crop tree enhancement treatments in the Henley Bottom stand are well-positioned with greater volumes, diameters, and heights than control green ash trees.

Crop tree enhancement is most assured when concentrating treatments on trees with co-dominant crown classes. The most positive growth response to crown release was seen amongst the green ash crop trees with co-dominant crowns. Although many established crop tree management guidelines advocate releasing trees with dominant crowns, this green ash study provides evidence that this may not be necessary. Both the released and control green ash crop trees with dominant crowns performed comparatively well. Crop trees with subordinate crown classes generally should not be released. The response of green ash crop trees with intermediate and suppressed crown classes was not sufficient enough to warrant the investment to release or fertilize. Strong intermediates, with crown classes point scores (Meadows et al. 2001), of 13 to 16 may respond positively to release and should potentially be considered for crop tree enhancement.

The co-dominant crown class should be targeted for crop tree release (Figure 9). The diameters of released crop trees associated with the co-dominant crown class designations are exhibited in Figures 10 and 11. Diameter may be an easier and more practical surrogate for landowners and inexperienced practitioners than crown class assessment for crop tree release than the crown point system by Meadows et al. (2001). Pre-release crop tree diameters of five to seven inches have the most successful growth responses to maintain upper canopy crown positions in green ash trees with crop tree release (Figures 10 and 11). A four-inch DBH or less should not be selected, because only an approximate 50% of green ash crop trees achieved an upper canopy position despite release. Approximately 90% of crop trees less than four inches in DBH had lower canopy positions after 18 years. If an insufficient number of
Crop trees can be located across a stand with good spacing and diameters of five or greater inches, crop trees can be selected from the four-inch class, realizing that their likelihood for a favorable growth response in attaining or maintaining an overstory position is much less than larger diameters.

Growth responses for the control treatment crop trees suggest that an eight-inch DBH should be the maximum crop tree size targeted (Figures 12 and 13). Even without release, 50% of green ash crop trees possessed upper canopy positions after eighteen years for trees that were eight inches at the time of treatment. All of the control green ash crop trees with DBHs greater than eight inches possessed upper canopy positions after 18 years, suggesting that these larger trees do not need to be released. Green ash crop trees within the range of diameters between five and eight inches at the time of treatment in 1996, when the stand was 16 years old, showed the greatest positive growth response to crop tree enhancement. The five to eight-inch range of the green ash crop tree diameter distribution is presented in Figure 19. These diameters should be targeted for crop tree enhancement based on the likelihood of possessing upper canopy crown positions after 18 years. This diameter range could be utilized in the other crop tree management applications, especially for pole-sized green ash growing in mixed-species bottomland stands. The range would likely expand or contract based on crop tree species, stand age, and site quality, but generally targeting the middle portion of the diameter distribution will likely produce the most positive results.

The timing of crop tree release and/or fertilization is critical in crop tree enhancement. Miller et al. (2007) recommends applying crop tree release early in stand development for even-aged stands. In this green ash study, crop tree enhancement procedures were performed at age 16. Crown closure had occurred by this time and trees were in competition for growing space, but the crown classes of potential crop trees were distinguishable. Alleviating growing space through crown release at this time, before crop trees suffered extensive negative impacts from a competition-driven lack of resources,
Figure 19: Diameter distribution for green ash crop trees in a 16-year-old, naturally regenerated, mixed-species bottomland hardwood stand in West TN at the time of treatment in 1996. The area beneath the curve shaded in gray represents the range of diameters that should be targeted for crop tree release based on the likelihood of possessing upper canopy crown classes 18 years later. Green ash crop trees with diameters greater than eight inches are likely to maintain upper canopy positions without release, but those with diameters less than five inches will probably have lower canopy positions whether or not release is performed.
enabled the pole-sized green ash to expand crown size and maintain crown position relative to other less-valuable species. If too much time passes under intensive stem exclusion conditions before crop trees are released, the expected growth response is much less, as indicated by the control treatment, where green ash crop trees are fading from the stand compared to the release treatment. Conducting crop tree enhancement when the stand is younger allows a greater potential pool of crop trees to be maintained in the overstory. Crop tree enhancement treatments for green ash should be implemented soon after crown closure and crown class differentiation, but before extensive negative impacts from competition have occurred. Waiting too long can influence crop tree response, especially growth rate and continued crown expansion. For green ash in even-aged, naturally regenerated, mixed-species bottomland hardwood stands, similar to the one encountered in this study, the proper age to initiate crop tree enhancement appears to be around age 15 to 20 years.

The Henley Bottom stand was 34 years old when follow-up measurements were taken. Eighteen years have passed since crop tree enhancement treatments were applied to green ash crop trees. Another release treatment could be beneficial to the green ash crop trees, particularly for crop trees with co-dominant crowns. Canopy closure has again occurred, and crop tree crowns are under highly stocked to overstocked growing conditions. Additional crown growing space could result in even-greater diameter growth rates. This treatment would of course need to be economically justified by an appreciable increase in growth and value of released crop trees. The larger size and greater marketability of removed material from a crop tree release treatment at this time would further offset costs.

Fertilization of green ash crop trees may not be warranted in bottomland hardwood stands. Little to no additional benefit from one-time fertilization at the time of release was observed amongst the green ash crop trees growing in Henley Bottom. This recommendation may be applicable to other
hardwood trees in mixed bottomland stands, where nutrients are generally not limiting. Funds directed towards fertilization of crop trees could instead be directed towards releasing a greater number of crop trees or a second round of release on the original crop trees as previously stated. If economically feasible, more continued fertilization applications may increase growth and volume.

Evaluating depth to mottled horizons for every crop tree may not be the most practical or effective method of determining site quality during the crop tree selection process. While it does allow for a manager to obtain a general understanding of a site’s hydrology, it may not improve the crop tree selection process and could over complicate it. Potential benefits from depth to mottling determinations would be that one could avoid selecting a crop tree of a particular species growing on a site where it may not be as competitive as some of its associates. This, in turn, would save money by not releasing a crop tree that will not respond well and be outgrown by a more site-suitable species. However, if a manager is sticking to the primary guideline of selecting crop trees from only overstory crown classes, the site is probably adequate enough for the growth of that particular species to respond to treatment. Mottling evaluations would offer much more benefit in an afforestation setting, where a manager seeks to establish a mixed-species hardwood planting on a site with no existing trees to offer clues on site-species suitability.

The numerical rating system for crown classes of southern hardwoods, developed by Meadows et al. (2001) was successfully demonstrated in this study as an effective method of evaluating crown class of green ash and predicting future success to crop tree enhancement treatments (Table 2). The rating system would likely work in field applications of crop tree enhancement when trying to identify potential crop trees prior to treatment. The system is relatively easy to apply and could even be taught to landowners to apply to their own stands. Meadows et al. (2001) states that the “reliable and consistent identification of crown classes is an important task that affects many silvicultural decisions in
everyday operations, such as timber cruising and marking.” Crop tree enhancement could be added to that list.

The economic feasibility of crop tree enhancement is closely tied to a persistence or maintenance of high-value species within the stand that contribute directly to management objectives. While improving growth rates is important, ensuring that the most-valuable species in relation to management objectives will be components of the mature stand is most critical. In a mixed-species stand, where timber value can vary widely between species competing for the same growing space, crop tree enhancement seeks to improve overall stand value by increasing the number of high-value individual trees. In this study, the persistence of released green ash crop trees as dominant and co-dominants after 18 years demonstrates that crop tree enhancement can be successful in mixed-species bottomland hardwood stands. The additional increases in diameter growth were also a significant benefit.

Conclusions

Three crop tree enhancement treatments were observed in this study: a complete crown-touching release, a complete crown-touching release plus one-time fertilizer application, and a control. These treatments were implemented on a 16-year-old, pole-sized, mixed-species bottomland hardwood stand. Green ash was the primary crop tree species of interest in this thesis.

Both crop tree enhancement treatments, release and release plus fertilization resulted in larger DBHs and greater rates of 18-year DBH growth than controls for green ash crop trees. For total height, release plus fertilization was greater than release and control treatments. However, release and release plus fertilization outpaced the control in 18-year total height growth. Released green ash crop trees displayed greater crown expansion, for both mean crown spread and crown length, after 18 years than controls. No appreciable differences in clear bole length were found between the treatments. Most
importantly, released green ash crop trees possessed co-dominant crown classes on average after 18 years, while the control crop trees averaged intermediate crown classes. For all variables, little difference was detected between the release and release plus fertilization treatments. Overall, crop tree enhancement improved the growth rates and overstory persistence of green ash (Objective 1).

Crop tree enhancement succeeded at maintaining green ash as an overstory component after 18 years. Released green ash crop trees had greater numbers of trees in the dominant and co-dominant crown classes than the control. The control treatment had more green ash crop trees with intermediate and suppressed crown classes than the release treatments. Without crop tree enhancement, green ash appears to be fading from the stand (Objective 2).

The response to crop tree enhancement was greatest in green ash crop trees with co-dominant crown classes at the time of treatment. The growth response was positive among crop trees with dominant crown classes, but dominants within the control treatment still performed comparatively well. Many crop tree management guidelines recommend targeting trees with dominant crowns for crop trees. This study gives evidence that this may not be necessary, at least for green ash. For the intermediate crown class, the growth response was more variable, indicating that performing crop tree enhancement on these trees may not provide additional benefit. Strong intermediates, with crown class point scores (Meadows et al. 2001) of 13 to 16 points, may benefit from crop tree enhancement. Suppressed green ash trees did not respond positively to treatment and should not be selected as crop trees. Overall, crop tree enhancement benefitted co-dominant green ash crop trees the most, indicating that these trees should primarily be targeted for crop trees (Objective 3).

Depth to mottled horizons did change across the study site (Objective 4). Three ranges were used to describe depth to mottled horizons: 0 to 12 inches, 12 to 24 inches, and 24 inches plus. Blocks 2 and 3 had the most crop tree cells with mottling in the 0 to 12-inch range, indicating that these areas
were the wettest and experienced the most water-logged conditions. Block 4 also displayed a comparable amount of crop tree cells with mottling in the first 12 inches. Blocks 1 and 5 were the drier areas in the study site.

Depth to mottled horizons had little impact on the success of crop tree enhancement at improving the growth and maintenance of green ash in the Henley Bottom stand (Objective 5). No significant impact on green ash DBH and crown class could be attributed to the depth to mottled horizons. While there might be important relationships between mottling, soil drainage, rooting depth, and crop tree success, they were not detected within the range of soil variables investigated in this study.

Competition cluster tree species composition did change slightly as the depth to mottled horizons changed. The five competing species that made the biggest shifts were sweetgum, green ash, cherrybark oak, river birch, and black willow. Sweetgum generally decreased in presence as the depth to mottling increased. Green ash became much more prevalent as the depth to mottling increased. Cherrybark oak occurred most on sites with mottling in the first twelve inches, and became increasingly less common where depths to mottling were greater. River birch generally occurred most on the wetter sites, where mottled horizons were closer to the soil surface. The same can be said for black willow, which was more common on sites with shallower mottling than sites with deeper mottling. Other competing species for the crop trees did not display any strong trends associated with mottling depth. Depth to mottled horizons did have an impact on competing species composition (Objective 6).

Crop tree enhancement of green ash in Henley Bottom on Ames Plantation property appears to have been successful after 18 years. Green ash trees given crop tree release treatments displayed increased diameter growth rates, higher crown classes, and maintained their canopy positions more effectively than green ash trees under control conditions. Although this thesis only discusses impacts of
crop tree enhancement on green ash in one stand, many of the other common bottomland hardwood species could be impacted in a similar fashion. Other highly valued bottomland species, such as cherrybark oak and swamp chestnut oak could benefit from crop tree enhancement studies. Oak species have been demonstrated in many instances to respond positively to crop tree enhancement techniques, although these studies are typically performed on upland sites. Because of the diverse species composition, greater site productivity, and generally non-limiting moisture levels, crop tree enhancement presents unique opportunities in bottomland hardwood stands. Through this technique, managers and landowners can improve stand value by increasing the proportion and growth of high-value species within the stand directly contributing to management objectives, all while maintaining the inherent structure and biodiversity of mixed-species stands.
References


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Vita


Forestry, as a discipline, was mostly foreign to John when he enrolled at Clemson University in Clemson, South Carolina in the fall of 2010. John chose to major in forestry mostly because he harbored a lifelong obsession with the great outdoors and wanted a career that allowed him to spend a lot of time outside. After a few years into his studies and a successful completion of Clemson Forestry Summer Camp, he realized that he had found the right field to be in. While at Clemson, John worked as undergraduate technician in the Clemson Silviculture and Ecology Lab, where he gained forest research experience and developed a desire to pursue a graduate education. He graduated from Clemson in May 2014.

In June of 2014, John accepted a position as a graduate teaching and research assistant within the Department of Forestry, Wildlife, and Fisheries at the University of Tennessee. While splitting his time working, taking classes, and assisting with silviculture labs at UT, he worked on a long term research project investigating the impacts of crop tree enhancement of green ash in a west TN hardwood bottom. His career goals include obtaining for forest management position in the public sector, potentially with a federal or state agency. Earning a PhD in forestry and natural resources may be another long term career goal.