



Crop Tree Management Improved Growth and Crown Class Maintenance of Green Ash: 18-Year Results

A. E. Houston¹ · W. K. Clatterbuck¹ · J. L. Bowers^{1,2}

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Abstract

A crop tree management study targeting green ash (*Fraxinus pennsylvanica* Marsh.) was established in a 16-year-old, naturally regenerated, mixed-species, bottomland hardwood stand in southwest Tennessee. The goal was to maintain or improve ascendance of green ash into the overstory of a developing stand that otherwise might not occur. Three treatments were examined: a complete crown-touching release; the same release treatment along with a one-time, fertilizer application; and a control. Initial diameters, heights and crown size parameters were measured in 1996 and 18 years later. The two release treatments did not differ significantly in diameter and height growth response, but statistically outperformed the control treatment. Similarly, crown class scores did not differ between the two release treatments, but were significantly improved from the control. Both release treatments displayed a greater percentage of crop trees successfully competing for upper canopy status compared to the control. Using initial tree diameter as a reflection of crown size and position of crop trees, diameters of 12.5 to 20 cm were more likely to be a component of the overstory 18 years following crop tree treatments. Crop trees less than 12.5 cm in diameter were likely to remain in the subordinate crown classes. Trees greater than 20 cm in diameter were already in the overstory and maintained their upper canopy position. These results suggest that crop tree management can be an effective management tool for improving growth as well as improving overstory presence of green ash in pole-sized, mixed-species, bottomland hardwood stands.

Keywords Green ash · Crop tree management · Mixed species · Stand dynamics · Bottomland hardwoods

Introduction

Land managers often desire to utilize crop tree management in early-to-mid-rotational, mixed hardwood stands to improve species composition and growth of selected trees. Silvicultural treatments that favor the development of individual

crop trees generally include targeted release and/or fertilization (Miller et al. 2007; Ellis 1979). Research on the effects of crop tree management has demonstrated an increase in growth and the proportion of high-valued trees in a stand (Smith and Lamson 1983; Lamson and Smith 1989; Perkey et al. 1993; Houston et al. 1995; Miller 2000; Ward 2002, 2009; Schuler 2006; Vogel et al. 2022).

Except for a few long-term studies (Leak and Solomon 1997; Vogel et al. 2022), most reported research on crop tree management has not followed growth and development of crop trees beyond ten years. Additionally, the impacts of crop tree management have not been investigated for the abundance of species and site conditions common in southern hardwood bottomland stands (Houston et al. 1995), where differing climate, water regimes, soil composition and moisture regimes, topographical micro-variations, disturbance intensities, and species mixtures make for complex management scenarios requiring multifaceted approaches.

Crop tree management with green ash (*Fraxinus pennsylvanica* Marsh.) is the subject of this research. Green ash is a commonly occurring species in bottomland systems and historically has been, and remains, a highly-desired species for wood products with shock resistance properties for tool handles and baseball bats, as well as lumber and veneers for furniture, flooring, and cabinetry (Cassens 2007). Hodges (1995) suggests that green ash has the greatest relative value for wood products of any bottomland hardwood species. Green ash can reach heights of 37 m and diameters at breast height (DBH-1.4 m) of 61–76 cm (Fitzgerald et al. 1975). Seed, foliage (browse), and stems from green ash provide food and cover for many birds and mammals (Brakie 2013).

Green ash regenerates prolifically from different sources: seed, advance reproduction, and coppice (Rives et al. 2020). Abundant seed are produced during most years and seeds remain viable for several years accumulating in the forest duff. Advance reproduction of green ash survives in the understory for many years. Some advance reproduction is of poor form from browsing damage to terminal buds or low light levels that lead to weak seedlings, allowing lateral buds to assume ascendancy which contributes to poor seedling form and slower apical stem growth. However, advance reproduction is still a substantial source of green ash regeneration (Sinz et al. 2011). If stumps are present, or advance reproduction is severed during the harvest operation, green ash coppices readily through stump and seedling sprouts (Kennedy 1990).

The fecundity of green ash reproduction following a harvest or other disturbances often forms stands of dense, overcrowded, green ash seedlings and saplings. As growing space decreases and stems begin to lose apical dominance, the amount of green ash diminishes during stand development with green ash becoming an increasingly marginal species (Kennedy 1990). Stands often become stagnated through intraspecific competition. Other species such as sweetgum (*Liquidambar styraciflua* L.) and sycamore (*Platanus occidentalis* L.), although much fewer in number, often outgrow the diminishing green ash and compose a greater proportion of the overstory, stratifying to effectively limit canopy emergence of green ash. An early-to-mid-rotation treatment such as crop tree management may allow a greater proportion of the mature overstory to be occupied with a desirable species.

A limiting factor for species composition and growth in bottomlands is a seasonally high or perched water table in hydric soils which creates anaerobic conditions inhibiting rooting depth and nutrient uptake. The presence of grey soils, referred to as mottling, is indicative of periodic saturation (Diers and Anderson 1984). Mottles are the result of a soil redox process and identified using the Munsell color chart (Munsell Color 2000). Depth to mottling is central to classification in these bottomland soils and diagnostic for species suitability and growth (Hebb 1960).

The emerald ash borer (EAB) (*Agrilus planipennis* Fairmaire) is an invasive wood-boring insect unintentionally introduced from China and first detected in Michigan in 2002. Despite efforts to control its spread, including listing it as a quarantine pest, as of 2022 EAB was present in 37 American states and 5 Canadian provinces (Sun et al. 2024). Once introduced, ash mortality has spread rapidly and a cascade of economic and environmental realities has resulted. Economic losses due to all invasive species in the United States is estimated to be \$20 billion per year and those costs continue to increase annually (Fantle-Lepczyk et al 2022). Substantial ash mortality has ensued in forests jeopardizing their sustainability.

We are unaware of any studies that have been conducted on the impacts of crop tree management on green ash in mixed-species, hardwood bottomland forests, specifically in improving green ash ascendance into the overstory. This study is focused on 34-year-old, green ash crop trees in a natural, mixed-species, bottomland stand in west Tennessee having received a crown-touching release and release plus one-time fertilization at 16 years of age with the following objectives: (1) to examine the response of DBH, total height, crown spread (width and length) and crown classification; (2) to assess DBH as an indicator of response potential of 16-year-old green ash stems; and 3) to investigate depth to soil mottling as a predictor of response to treatments.

Methods

Study Area

The study site is located on a tributary of southwest Tennessee's North Fork of the Wolf River, on the University of Tennessee, Ames AgResearch and Education Center (AREC) (35.07'48.25" N, 89.14'16.06" W). The Ames AREC is located within the greater Mississippi Alluvial Floodplain, and more specifically within the Brown Loam Bluffs sub-regions of the southern bottomland hardwood forest region (Hodges 1995) and is characterized with broad rolling hills and coastal plain river bottoms, having a large loess influence. The climate is temperate with warm summers and mild winters. Average annual high and low temperatures are 22°C and 9°C, respectively. Average annual precipitation is 142 cm (US Climate Data 2024).

The research was conducted in an even-aged cohort originating from a 1980 silvicultural clearcut of a mature, mixed-species hardwood stand predominated by sweetgum and having a well-distributed understory of green ash seedlings. The ensuing stand, regenerating from coppice, advance reproduction, and seed, is comprised of a typical suite of southern bottomland species, including sweetgum, green ash, eastern

cottonwood (*Populus deltoides* W. Bartram ex Marshall), sycamore, cherrybark oak (*Quercus pagoda* Raf.), American elm (*Ulmus americana* L.), boxelder (*Acer negundo* L.), yellow-poplar (*Liriodendron tulipifera* L.), river birch (*Betula nigra* L.), and black willow (*Salix nigra* Marsh.). The crop tree release was conducted in 1996, 16 years after the harvest. This research reports 18 years of growth and development (through 2014) after the release. The study site encompasses approximately 4.25 ha.

Soils are of alluvial origin and are comprised of primarily Falaya and Waverly series with some Lexington soils along an adjacent slope. All soils are classified as silt loams (Soil Survey Staff 2024). Drainage ratings range from somewhat poorly-drained Waverly and Falaya to the well-drained Lexington. Drainage is described by depth to mottling, the anaerobic zones created with a perched or seasonal water table. Soils are productive for tree growth, with site indices of 27 to 30 m at base age 50 years for green ash and cherrybark oak (Broadfoot 1976).

The emerald ash borer (EAB) had not been observed in the United States when this study was begun in 1996. However, during the span of this study the spread and impact of EAB in the United States has been significant (McCullough and Kativich 2004, Klooster et al. 2014). The borer was first detected in eastern Tennessee in 2010 (Tennessee Dept. of Agriculture 2010), approximately 482 km (300 miles) east of the study area. However, the insect has not spread to west Tennessee or been observed on the study area through 2025 when this manuscript was written.

Study Establishment

Crop tree selection occurred in January 1996 and followed the procedures outlined by Houston et al. (1995). The premise was predicated on the assumption that 90 crop trees/ha are adequate to enrich composition in a developing mixed species stand. To ensure dispersal of crop trees, 90 cells/ha were established with centers 10.6 m apart yielding a 10.6 × 10.6 m square cell, essentially six rows of six crop trees on every 0.4 ha. A single green ash crop tree, if available, was selected within each cell based on form, tree health and the best possible crown class relative to other trees in the cell. Given that the cells were fixed, a relatively poorer green ash tree, one with a less desirable bole due to crook or sweep or having relatively weaker crown position, was sometimes all that was available. No attempt was made to standardize the sample of green ash crop trees by diameter or crown class thereby using the natural distribution of potential crop trees across the study area. In cells where a green ash stem could not be located, secondary species such as cherrybark oak and river birch were chosen or the cell was unfilled. The paper reports only on the response of green ash crop trees.

Fifteen adjacent blocks of 25 crop tree cells were established for a total of 375 crop tree cells. Green ash crop trees were selected in 264 (70%) of the cells. The research design was three treatments, with five repetitions in a randomized block design. The three treatments were: (R) a crop tree release ($n = 84$) where four sides of the crop tree were given a crown-touching release from adjacent tree crowns; (RF) a crop tree release and fertilizer treatment ($n = 89$), where release

was accompanied with 20N-10P-0 K (% of element by weight) applied approximately 91.4 cm beyond the dripline at a rate of 0.45 kg/2.5 cm of DBH; and (C) a no treatment control (n = 91).

Release treatments were applied at a pre-commercial age. All stems were felled with a chainsaw and left in place. Fertilizer applications and release occurred in late spring, prior to leaf-out.

Soil Classification

Using a soil probe, a soil sample was extracted for every crop tree, approximately 1.5 m away and on what was judged to be the highest ground. The probe extracted approximately 75 cm of the soil profile. Every 30.5 cm was evaluated for mottling and texture to distinguish between the Waverly and Falaya soil series. Both soils are considered poorly drained with Waverly having a higher seasonal moisture content and corresponding lower aeration in the rooting zone, both primary limiting factors on these bottomland soils (Denton et al. 1996). Chroma for the presence of mottling was grey 2, value 6 or greater on pages 7.5 YR and 10YR (Munsell Color 2000).

Field Measurements

Crop tree data were collected after crop tree selection and prior to treatment implementation during January and February of 1996. Total height, live crown length, and DBH were recorded. Mean crown spread was attained from North/South and East/West azimuths. Crown class for each crop tree was evaluated using the crown rating system for southern hardwoods developed by Meadows et al. (2001). This rating system (Table 1) provides a consistent quantitative classification of crown class. Each of these measures were repeated during the summer of 2014, 18 growing seasons following study establishment.

Table 1 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

Crown Characteristic	Points
Direct Sunlight from Above	0–10
Direct Sunlight from the Sides	0–10
Crown Balance	1–4
Relative Crown Size	1–4
<i>Crown Class</i>	<i>Total Rating (2–28)</i>
Dominant	24–28 Points
Codominant	17–23 Points
Intermediate	10–16 Points
Suppressed	2–9 Points

Statistical Analysis Procedures

Analysis of variance (ANOVA) was used to test for treatment differences among DBH, total height, mean crown spread, live crown length, and crown position in 1996 and 2014. ANOVA also determined differences in growth and/or change of these response variables over 18 years from 1996 to 2014. 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 $p=0.05$. The data met the assumptions of the statistical procedures and were normally distributed. No data transformations were required. Data were limited to a narrow range with a small study area (4.25 ha), fairly uniform soils, and a single species, green ash in a mixed species stand that was 16 years of age before treatments were designated.

Simple correlations in SAS 9.4 were used to establish the strength of relationship between green ash growth (DBH, total height, crown spread and crown class score) and three depth to mottling ranges (0–30.5 cm, 30.5–61 cm, 61 + cm.) for comparisons of treatment impacts utilizing ANOVA in Proc Mixed, SAS 9.4 (SAS Institute 2015). Contingency tables and Pearson's Chi-square analysis investigated relationships with several categorical variables such as soil mottling depth and discrete crown classes utilizing NCSS (NCSS 10 Statistical Software 2015).

This research focuses on green ash crown class ratings for 1996 pre-treatment crop trees and the 2014 post-treatment crop trees. These two analyses were evaluated to determine how the treatments (R, RF, and C) and 18 years of growth post-treatment influenced crown class distribution and tree diameters.

Results

Soil Parameters

Most (60%) of the crop trees occurred on the 30.5–61 cm depth-to-mottling zone (25% in 0–30.5 cm; 15% in 61 + cm). While relative extremes did occur, classification of mottle depth from one zone to the next involved only a few centimeters of depth. Given the general soil uniformity of the study area, few strong relationships were observed on-the-ground or in the data between depth to mottling and vegetational response of the treatments. However, based in visual observations and consistent with expectations, more green ash appeared in suppressed and intermediate crown classes on the wettest sites (Waverly soils) where sweetgum, sycamore, and river birch predominated.

Survival

Survival rates were 90% in the release treatment and 91% for both the control and the release and fertilization treatments. Six crop trees (four R, one RF, and one C) were omitted from the analysis after being adversely impacted by factors external to the research such as vine suppression and weather damage.

Growth in DBH and Total Height

Diameter between R, RF, and C green ash crop trees did not differ ($p=0.457$) at the beginning of the study in 1996 (Table 2a). By 2014, R and RF DBH was significantly larger than the control ($p=0.004$). Diameter growth after 18 years was also significantly greater ($p<0.001$) for R and RF trees than C trees. No significant differences occurred between R and RF crop trees for 2014 DBH and 18-year DBH growth (Table 2a).

Table 2 a: Diameter at breast height (DBH); b: Total height; c: Crown spread; and d: Crown length at study initiation in 1996 and 18 years later in 2014, 18-year total growth, standard errors (SE) and letter groupings for green ash crop trees are presented by treatment (Release, Release + Fertilization (Rel + Fert), and Control) for the crop tree management study at Ames AgResearch & Education Center in west Tennessee, USA

Table 2a	1996 DBH (cm)	2014 DBH (cm)	18-Year DBH Growth (cm)
Treatment ¹	Mean $\pm$ SE ²	Mean $\pm$ SE ²	Mean $\pm$ SE ²
Release	13.7 $\pm$ 1.1 ^A	27.7 $\pm$ 2.1 ^A	13.0 $\pm$ 1.1 ^A
Rel + Fert	14.5 $\pm$ 1.1 ^A	27.9 $\pm$ 2.0 ^A	13.7 $\pm$ 1.1 ^A
Control	14.2 $\pm$ 1.1 ^A	24.3 $\pm$ 2.0 ^B	9.9 $\pm$ 1.1 ^B
Table 2b	1996 Total Height (m)	2014 Total Height (m)	18-Year Total Height Growth (m)
Treatment	Mean $\pm$ SE	Mean $\pm$ SE	Mean $\pm$ SE
Release	14.9 $\pm$ 0.8 ^A	22.9 $\pm$ 1.0 ^{AB}	7.9 $\pm$ 0.4 ^A
Rel + Fert	15.2 $\pm$ 0.8 ^A	23.8 $\pm$ 1.0 ^A	8.5 $\pm$ 0.4 ^A
Control	15.2 $\pm$ 0.8 ^A	21.9 $\pm$ 1.0 ^B	6.7 $\pm$ 0.4 ^B
Table 2c	1996 Crown Spread (m)	2014 Crown Spread (m)	18-Year Crown Spread Growth (m)
Treatment	Mean $\pm$ SE	Mean $\pm$ SE	Mean $\pm$ SE
Release	2.6 $\pm$ 0.1 ^A	6.2 $\pm$ 0.7 ^A	3.7 $\pm$ 0.6 ^A
Rel + Fert	2.6 $\pm$ 0.1 ^A	5.8 $\pm$ 0.7 ^{AB}	3.2 $\pm$ 0.6 ^{AB}
Control	2.6 $\pm$ 0.1 ^A	5.3 $\pm$ 0.7 ^B	2.7 $\pm$ 0.6 ^B
Table 2d	1996 Crown Length (m)	2014 Crown Length (m)	18-Year Crown Length Growth (m)
Treatment	Mean $\pm$ SE	Mean $\pm$ SE	Mean $\pm$ SE
Release	5.7 $\pm$ 0.4 ^A	9.4 $\pm$ 0.9 ^A	3.8 $\pm$ 0.6 ^A
Rel + Fert	6.1 $\pm$ 0.4 ^A	9.4 $\pm$ 0.9 ^A	3.0 $\pm$ 0.6 ^B
Control	5.9 $\pm$ 0.4 ^A	8.0 $\pm$ 0.9 ^B	3.1 $\pm$ 0.6 ^C

¹N = 72, 80, and 82 sample crop trees for the Release, Rel + Fert, and Control treatments, respectively

²Different letters within the same column indicate significant differences at the $p=0.05$ level

In 1996, no significant difference ($p=0.418$) in crop tree total height was detected between the three treatments (Table 2b). By 2014, total heights of RF crop trees were significantly greater ($p=0.007$) than C crop trees, but similar ($p=0.179$) to R crop trees. Total height was not different ($p=0.233$) between the R crop trees and the C crop trees. For height growth over 18 years, R and RF crop trees did not significantly differ from one another (Table 2b). However, both increased in height significantly more ($p=0.001$) than C crop trees.

Growth in Mean Crown Spread and Crown Length

Mean crown spread between treatments in 1996 was not different ($p=0.545$). In 2014, mean crown spreads of R crop trees were significantly greater ($p=0.023$) than C crop trees (Table 2c). RF 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 ($p=0.003$) than the C trees, but no difference was detected between RF crop trees and the other two treatments (Table 2c).

Crown lengths of the three treatments did not significantly differ in 1996 ($p=0.119$). By 2014, treatment differences were apparent, where the crown lengths of R and RF treatments were significantly larger ($p=0.001$) than C treatments by a margin of approximately 1.5 m (Table 2d). Crown length growth after 18 years was significantly different ($p<0.001$) between all three treatments, where R crop trees were larger than crop trees in the other two treatments and RF crop trees were only larger than C crop trees.

Treatment Impact on Crown Class Distribution

Mean crown class scores did not significantly differ ($p=0.321$) in 1996; all three treatments averaged in the co-dominant range (Table 3). By 2014, R and RF crop trees had significantly greater ($p<0.001$) crown class scores than C crop trees. Release and RF crop trees did not differ in crown class score. Eighteen years

Table 3 Mean crown class scores according to the system developed by Meadows et al. (2001), standard errors (SE), letter groupings, and ratings for green ash crop trees at study initiation in 1996 and 18 years later in 2014 are presented by treatment (Release, Release + Fertilization (Rel + Fert), and Control) for the green ash crop tree management study at Ames AgResearch & Education Center in West Tennessee, USA

Treatment ¹	1996 Crown Class Score		2014 Crown Class Score	
	Mean $\pm$ SE ²	Rating	Mean $\pm$ SE ²	Rating
Release	19.5 $\pm$ 0.7 ^A	Co-Dominant	17.8 $\pm$ 1.1 ^A	Co-Dominant
Rel + Fert	20.0 $\pm$ 0.7 ^A	Co-Dominant	18.0 $\pm$ 1.1 ^A	Co-Dominant
Control	20.5 $\pm$ 0.7 ^A	Co-Dominant	14.1 $\pm$ 1.0 ^B	Intermediate

¹N = 72, 80, and 82 sample crop trees for the Release, Rel + Fert, and Control treatments, respectively

²Different letters within the same group column indicate significant differences at the $p=0.05$ level

post-treatment, R and RF crop trees had maintained co-dominant crown classes on average, while C crop trees had receded to the intermediate crown class range, submerging in the developing canopy and losing their ability to emerge into the overstory.

At the beginning of the study in 1996, in the R treatment there were 21 dominant (30%), 35 co-dominants (49%), 12 intermediate (17%), and 3 suppressed (4%) crop trees. After 18 growing seasons, the R crown class distribution had 13 dominant (18%), 39 co-dominant (55%), 12 intermediate (17%) and 7 suppressed (10%) crop trees (Fig. 1).

In 1996 for RF, there were 15 dominant (19%), 53 co-dominant (66%), 10 intermediate (12%), and 2 suppressed (3%) crop trees. By 2014, the RF crown class distribution had shifted to 10 dominant (13%), 48 co-dominant (60%), 16 intermediate (20%), and 6 suppressed (7%) crop trees (Fig. 1).

In 1996 for C, there were 18 dominant (22%), 54 co-dominant (66%), 9 intermediate (11%), and 1 suppressed (1%). By 2014, the C crown class distribution was 1 dominant (1%), 33 co-dominant (40%), 27 intermediate (33%), and 21 suppressed (26%) crop trees (Fig. 1).

Impact of Initial Diameter on Crown Class Response

Larger diameter released (Fig. 2) and control (Fig. 3) crop trees were in the upper canopy crown classes (dominants and co-dominants), while more crop trees in the smaller diameter classes were in the intermediate or suppressed crown classes. The 10-cm diameter class of released trees had a nearly equal proportion of overstory and subordinate crown classes, despite release (Fig. 2). The 20-cm diameter class of control trees had a nearly equal proportion of overstory and subordinate crown

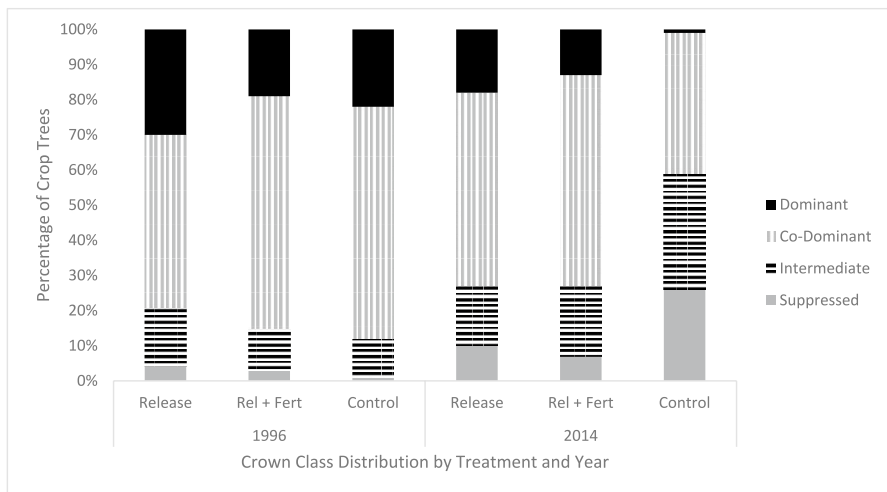


Fig. 1 Crown class distributions for green ash crop trees by treatment (R-release, Rel+Fert-release + fertilization, and C-control) before crop tree management treatments in 1996 and 18 years later in 2014. Crop tree sample size per treatment: R = 71, RF = 80, and C = 82

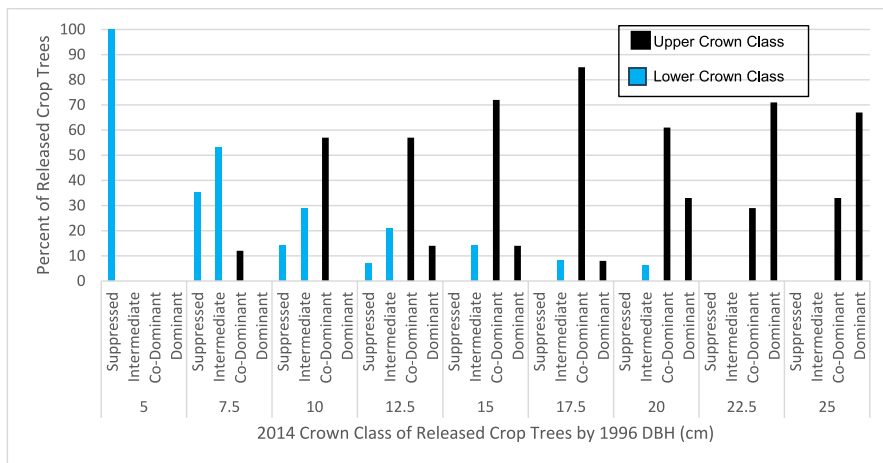


Fig. 2 Relationship of DBH (cm) in 1996 at the time of treatment to eventual crown class 18 years later in 2014 for released (release and release + fertilization treatments combined) green ash crop trees as a percentage of total released green ash crop trees ($n = 151$)

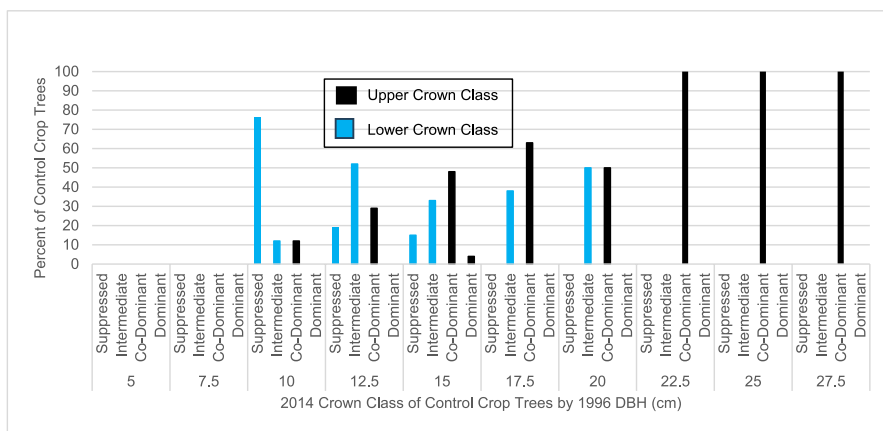


Fig. 3 Relationship of DBH (cm) in 1996 at the time of treatment to eventual crown class 18 years later in 2014 for control treatment green ash crop trees as a percentage of total control green ash crop trees ($n = 82$)

classes, without release (Fig. 3). Crop trees (R, RF. And C treatments) larger than 20 cm remained in the overstory after 18 years.

Discussion

Soil Impacts

Even though heavily represented in the study site's natural regeneration, green ash, being more generally suited to somewhat better drained soils (Robertson et al. 1978) was slightly off-site. Even so, the better trees were performing well and competing across the study area, although apt to lose crown position to more aggressive competitors, primarily sweetgum, sycamore, and river birch, all less valuable and all moderately better adapted to these site conditions. Soil cores taken around each crop tree and focused on depth to the perched or seasonal water table as indicated by mottling suggest that the soil substrate was fairly uniform and did not impact treatment response within the range of conditions that prevailed across most of the study site.

Impact of Fertilization Treatment

No significant difference was apparent between the R and RF treatments for DBH or height growth (Tables 2a and b). The one-time application of fertilizer at the time of release may have given an initial, short-term growth boost to the crop trees, but these potential effects were masked between measurements after 18 years of growth. Ellis (1979) reported no significant additional growth response over controls from fertilization in white ash (*Fraxinus americana* L.) crop trees.

The lack of response from the fertilizer application could also be attributed to the inherent fertility of the soils in this study. On soils with adequate amounts of essential nutrients, fertilizers may not provide an additional growth response (Hannah 1985). Additionally, fertilizer applications were applied in late spring. The site experienced some flooding, with pooling and lateral water movement which could have dispersed the impact of soil amendments. More investigation is necessary to determine if fertilization to enhance growth in crop tree management regimes on bottomland sites is beneficial, especially with timing or repeated fertilizer applications after release versus a one-time application.

Growth in DBH, Total Height, and Crown Expansion

The significant increases in diameter growth and crown expansion for R and RF green ash crop trees indicate a crop tree's ability to take advantage of available canopy space, thereby increasing leaf area and photosynthetic capacity (Pallardy and Kozlowski 2008; Oliver and Larson 1996). Crown expansion also is associated with root development, likely another key factor in the increased DBH growth observed in many crop tree management studies (Wendel and Lamson 1987, Stringer et al. 1988, Wood et al. 1996, Miller 1997 and 2000, Ward 2007, 2009, and 2013).

In this study, green ash crop tree height growth was improved following treatment (Table 2b). With this early-rotational release, the crop trees at 34 years of age are still immature, presently 23 m tall. Total height growth was greater for R and RF treatments than the control, by approximately 1.2 and 1.8 m, although total height in 2014 was only significantly greater for the release plus fertilization treatment (Table 2b). These results are somewhat surprising, as several studies have suggested 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 may be stimulated to increase in height so that they achieve canopy positions above their neighbors (stratification) where light resources are most available. Which trees within a stand successfully stratify placing their crowns above adjacent trees 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).

A positive response also was observed in crown length and mean crown spread for the 18-year study period (Tables 2c and d). Released green ash trees gained approximately 1.5 m of crown length and 1 m of crown spread compared to the control. Schuler (2006) reported that crown cross-sectional area increased considerably for black cherry (*Prunus serotina* Ehrh.) and northern red oak (*Quercus rubra* L.) crop trees after 10 years following release. Crop tree growth response is the result of crown expansion (Miller 2000; Pallardy and Kozlowski 2008; Oliver and Larson 1996). Crown expansion is directly related to maintenance of crown position within the stand.

The release treatments occurred early in the rotation where these young trees were vying for crown position, while green ash was showing a tendency to submerge in the canopy. At 16-years-old, the co-dominants of green ash were still able to respond to release with lateral and vertical growth, building crown volume.

With a release treatment, these crop trees received a spatial advantage with a temporal limit. In this young, aggressively competitive, bottomland stand, relatively small crowns were removed. Trees on the periphery of the release zone also benefit from a partial release. Stand closure will continue with crown growth. The study suggests timing and frequency following an early-rotational release will likely be critical for some species. There will be a balance between maintaining growth with available space and improving bole quality with adequate shade to shed lower crown branches.

Crown Class Distribution

Released crop trees maintained their crown position more successfully than controls. In 1996, all treatments averaged co-dominant crown classes (Table 3). By 2014, R and RF treatments were still classified as co-dominants on average, while controls had regressed to the intermediate class. This result demonstrates the ability of crop tree management to maintain green ash as a component of the upper canopy, although there is little evidence to suggest crop tree management 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. Similar outcomes were reported by Wendel and Lamson (1987) and Schuler (2006). Crop tree management encourages persistence of crop trees in the upper canopy of a developing stand. If a certain species is desired at maturity, the recruitment to the canopy should occur before the stem exclusion stage of stand development (Oliver and Larson 1996).

A comparison of crown class distribution between 1996 and 2014 (Fig. 1) is a persuasive example of how crop tree management can retain green ash in a developing stand of mixed hardwoods. In 1996, all treatments had similar crown class distributions, averaging roughly 80 to 85% in upper canopy positions. By 2014, released green ash trees maintained upper canopy positions at a rate of 73%, but controls had declined 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 elsewhere (Kennedy 1990; Sinz et al. 2011). Crop tree management 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 management (Ward 2013). By maintaining greater percentages of more-valuable green ash in the upper canopy, as observed in this study, the timber value is considerably improved compared to stands with greater proportions of less-valuable species, like American sycamore, eastern cottonwood, and sweetgum.

Management Implications

Green ash achieved greater diameter and height growth, and was successfully maintained as an overstory component, 18 years after an early-rotational, crop tree release and release combined with fertilization treatment, providing evidence of the potential to conserve and sustain a desirable species composition in developing bottomland stands.

In this study, the crown class of intermediate and suppressed green ash crop trees were not improved with crop tree management. Crop trees that were already dominant remained so. The co-dominant crown class were the trees most likely assisted with crop tree management, maintaining or improving crown class status.

Growth responses for the control treatment crop trees in this study show a 20 cm DBH should be the maximum crop tree size targeted (Fig. 3). Even without release, 50% of green ash crop trees that were 20 cm in DBH at the time of treatment achieved upper canopy positions after 18 years.

Green ash crop trees with diameters > 20 cm in DBH are likely to maintain upper canopy positions without release, but those with diameters < 12.5 cm will probably have lower canopy positions whether or not release is performed. Green ash crop trees within the 12.5 and 20 cm DBH range at the time of treatment in 1996 when

the stand was 16 years old, mostly ascended or maintained an upper canopy position with increased growing space from crop tree management (Fig. 2).

Based on this study, green ash crop trees with diameters of 12.5 to 20 cm had the strongest likelihood to maintain upper canopy crown positions following release (Figs. 2 & 3). For the 10 cm DBH class, an upper canopy position was attained only 50% of the time or less. Approximately 90% of crop trees < 10 cm DBH had lower canopy positions after 18 years.

Given that DBH will vary from stand-to-stand based on species, site quality and stand age, we are hesitant in suggesting the universal use of DBH as a surrogate and guide in selecting trees for crop tree management. However, DBH is an easily obtained measurement that generally correlates with crown classification within a stand. If the diameter range among the stand's co-dominants (Meadows et al. 2001; Table 1) is determined, these results suggest it can likely be employed to identify trees with the best average potential for response, essentially targeting the middle portion of the diameter distribution to produce the most positive results.

The 90 trees/ha crop tree selection arrangement in this study (Houston et al. 1995) provides an assessment component whether results from crop tree management are feasible. The assessment provides a quantitative evaluation of whether enough crop trees are present that will respond to release. If an insufficient number of promising crop trees can be located across a stand, a poor growth response is likely in attaining or maintaining an overstory position for the desired species.

The timing of crop tree release and/or fertilization will influence crop tree management outcomes. Miller et al. (2007) recommends applying crop tree release early in stand development for even-aged stands. In this green ash study, crop tree management procedures were performed at age 16. Crown closure had occurred by this time with an absence of growing space, but the crown classes of potential crop trees were distinguishable. Increasing growing space through crown release at this time, before crop trees suffered extensive negative impacts from limited growth resources, 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 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. Conducting crop tree management when the stand is younger allows a greater potential pool of crop trees to be maintained in the overstory. However, more effort and cost will be expended during release, especially in young, mixed species stands where trees have not differentiated their crowns and may not respond to release. Crop tree management treatments for green ash should be implemented soon after crown closure and crown class differentiation, but before extensive negative impacts such as space-limited tree stagnation have occurred. Waiting too long can influence crop tree response, especially growth rate and continued crown expansion (Perkey et al. 1993).

The investigated stand was 34-years-old when follow-up measurements were taken; 18 years following release of green ash crop trees. Canopy closure has again occurred placing crop trees under highly-stocked to overstocked conditions limiting crown expansion. Growth more than likely increased directly after the initial release, but gradually diminishes with time as stocking and competition

intensifies. Another release treatment would be beneficial, particularly for crop trees with co-dominant crowns to maintain or increase their growth rates. Economically, the larger size and greater marketability of removed material at this time would further offset costs compared to the earlier pre-commercial release while enhancing growth and value of crop trees through additional growing space.

In a mixed-species stand, where timber value can vary widely between species contesting for the same growing space, crop tree management seeks to enrich overall stand value by increasing the proportion of highly-valued individual species in the stand (Miller et al. 2007). Released crop trees begin to capture the vacated growing space in a developing stand, increasing growth rates and crown dimensions leading to greater occupancy in the stand at the expense of inferior species. The greater occupancy of highly-valued species, like green ash in this study, increases stand value which otherwise would not occur without crop tree management. The increased occupancy of released green ash crop trees in the upper canopy as dominants and co-dominants after 18 years demonstrates that crop tree management can be successful mid-rotation practice in developing stands to enhance stand value in mixed-species bottomland hardwood stands.

While the emerald ash borer will continue expansion of its range and the trees in this study may eventually be affected, there are ecological and environmental implications beyond these species, site quality, and stand age results. This study supports concepts of crop tree management as a viable practice that is closely tied to persistence and maintenance of a species within a stand that contributes directly to management objectives. A more valuable stand composition might be sustained where an ecologically or economically beneficial species is tending to submerge under a developing canopy of less desirable species. Results suggest crown classification and DBH as potential tools to predict response. Other species with intermediate light tolerance and slower growth would benefit from crop tree management. These species include hickories (*Carya* spp.) and particularly oaks (*Quercus* spp.) known to bottleneck during overstory recruitment (Vickers and Goff, 2025). With the changing perspectives of climate change, any positive response to crop tree management supports an ability to impact species diversity and stand structure, if treatments are applied early in a stand's development, but also late enough for crown classifications to be indicative of juvenile:mature correlations.

Summary

No effect of a one-time fertilizer application to 16-year-old green ash crop trees could be detected after 18 years of growth. Crop tree fertilizer applications:

- 1) should be preceded with soil testing to detect potential nutrient deficiencies,
- 2) may be vulnerable to flooding, and

3) likely would be more effective with repeated applications.

The study provides evidence that an early-rotational release treatment can maintain green ash as a viable overstory component where it is being supplanted by less valuable species. An early-rotation release treatment applied to green ash trees in a naturally regenerated, mixed species, highly productive, bottomland stand.

- 1) improves growth rates,
- 2) allows dominants and co-dominants to maintain or improve crown position, enhancing potential for occupation in the mature stand,
- 3) suggests potential for significant response to future release treatments, and
- 4) advances that DBH can be a possible predictor for the best crop trees to release, usually co-dominants.

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Data Availability Information and data about this research are available at TRACE: Tennessee Research and Data Exchange at the following weblink: https://trace.tennessee.edu/utk_gradthes/4259, accessed on 2 June 2025.

Declarations

Conflicts of interest The authors declare no conflicts of interest. No assistance or resources outside the University of Tennessee was provided in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

The authors affirm that there is no personal, financial, or competing interests that could affect the objectivity associated with this research that would influence our objectivity. All authors have read and approve the draft manuscript submitted. The research is the authors' original work, has not received prior publication, and is not under consideration for publication elsewhere.

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References

- Allen, R. H., Jr. and D. A. Marquis. 1970. Effect of thinning on height and diameter growth of oak & yellow-poplar saplings. Res. Pap. NE-173. Upper Darby, PA: USDA Forest Service Northeastern Forest Experiment Station, 11. <https://research.fs.usda.gov/treesearch/23782>
- Brakie, M. 2013. Plant guide for green ash (*Fraxinus pennsylvanica*). USDA Natural Resources Conservation Service. Nacogdoches, TX: East Texas Plant Materials Center, 4. <https://www.nrcs.usda.gov/plantmaterials/etpmcpg11869.pdf>
- Broadfoot, W. M. 1976. Hardwood suitability for and properties of important midsouth soils. Res. Pap. SO-127. New Orleans, LA: USDA Forest Service Southern Forest Experiment Station, 84. <https://research.fs.usda.gov/treesearch/24537>
- Cassens, D. L. 2007. Ash. FNR-272-W. West Lafayette, IN: Purdue University Extension, Hardwood Lumber and Veneer Series, 5. <https://www.extension.purdue.edu/extmedia/FNR/FNR-272-W.pdf>
- Denton, P. H., J. H. Robinson, and J. S. Elder. 1996. PB 727. Land judging guide. Knoxville, TN: University of Tennessee, Agricultural Extension Service, Institute of Agriculture, 28. <https://western.tennessee.edu/wp-content/uploads/sites/68/2020/09/PB727-Land-Judging-Guide.pdf>
- Diers, R., and J. L. Anderson. 1984. Part 1, Development of soil mottling. *Soil Survey Horizons* 24 (4): 9–12. <https://doi.org/10.2136/sh1984.4.0009>
- Ellis, R. C. 1979. Response of crop trees of sugar maple, white ash, and black cherry to release and fertilization. *Canadian Journal of Forest Research* 9 (2): 179–188. <https://doi.org/10.1139/x79-032>
- Fantle-Lepczyk, J. E., P. J. Haubrock, A. M. Kramer, et al. 2022. Economic costs of biological invasions in the United States. *Science of the Total Environment* 806 (3) : 151318. <https://doi.org/10.1016/j.scitotenv.2021.151318>
- Fitzgerald, C. H., R. P. Belanger, and W. W. Lester. 1975. Characteristics and growth of natural green ash stands. *Journal of Forestry* 73 (8): 486–488. <https://doi.org/10.1093/jof/73.8.486>
- Hannah, P. R. 1985. Response of yellow birch and sugar maple to release and fertilizer. *Northern Journal of Applied Forestry* 2 (4): 108–110. <https://doi.org/10.1093/njaf/2.4.108>
- Hebb, E. A. 1960. The relation of soil and other site factors to forest composition and productivity in west Tennessee. Ph.D. dissertation. Knoxville, TN: University of Tennessee, 115. https://trace.tennessee.edu/utk_graddiss/2910
- Hodges, J. D. 1995. The southern bottomland hardwood region and brown loam bluffs subregion. In *Regional Silviculture of the United States*, ed. J. W. Barrett, 3rd Edition, 227–267. ISBN: 0-471-59817-8, ISBN13: 978-0-471-59817-6. New York: John Wiley & Sons, Inc.
- Houston, A. E., E. R., Buckner, and J. S. Meadows. 1995. Romancing the crop tree. *Forest Farmer* 54(5): 32–34. <https://research.fs.usda.gov/treesearch/3262>
- Kennedy, H.E., Jr. 1990. *Fraxinus pennsylvanica* Marsh. In *Silvics of North America: 2. Hardwoods, tech coords.*, R.M. Burns, R.M. and B.H. Honkala, 348–354, Agricultural Handbook 654. Washington, DC: USDA Forest Service. https://www.srs.fs.usda.gov/pubs/misc/ag_654/volume_2/fraxinus/pennsylvanica.htm
- Klooster, W. S., D. A. Herms, K. S. Knight, et al. 2014. Ash (*Fraxinus* spp.) mortality, regeneration, and seed bank dynamics in mixed hardwood forests following invasion by emerald ash borer (*Agrilus planipennis*). *Biological Invasions* 16:859–873. <https://doi.org/10.1007/s10530-013-0543-7>
- Lamson, N. I., and H. C. Smith. 1989. Crop-tree release increases growth of 12-year-old yellow-poplar and black cherry. Res. Pap. NE-622. Broomall, PA: USDA Forest Service Northeastern Forest Experiment Station, 7. <https://doi.org/10.2737/NE-RP-622>
- Leak, W. B., and D. S. Solomon. 1997. Long-term growth of crop trees after release in northern hardwoods. *Northern Journal of Applied Forestry* 14(3):147–151. <https://doi.org/10.1093/njaf/14.3.147>
- McCullough, D. G., S. and A. Katovich. 2004. Emerald ash borer. NA-PR-02-04 Pest Alert. Newtown Square, PA: USDA Forest Service Northeastern Area State and Private Forestry, 2. <https://www.forestpests.org/acrobat/eab.pdf>
- Meadows, J. S., E. C. Burkhardt, R. L. Johnson, and J. D. Hodges. 2001. A numerical rating system for crown classes of southern hardwoods. *Southern Journal of Applied Forestry* 25(4):154–158. <https://research.fs.usda.gov/treesearch/2892>
- Miller, G. W. 2000. Effect of crown growing space on the development of young hardwood crop trees. *Northern Journal of Applied Forestry* 17 (1): 25–35. <https://doi.org/10.1093/njaf/17.1.25>

- Miller, G. W., J. W. Stringer., and D. C. Mercker. 2007. Technical guide to crop tree release in hardwood forests. PB 1774. Knoxville, TN: University of Tennessee Extension, Institute of Agriculture, 23. <https://utia.tennessee.edu/publications/wp-content/uploads/sites/269/2023/10/PB1774.pdf>
- Miller, G. W. 1997. Effect of crown growing space and age on the growth of northern red oak. In: *International Union of Forest Research Organizations (IUFRO) Proceedings: Advances in research in intermediate oak stands, comp.* H. Spiecker, R. Rogers, Z. Somogyi, Z., 140–159. 1997 July 27–30. Freiburg, Germany: University of Freiburg. <https://research.fs.usda.gov/treearch/14307>
- Munsell Color. 2000. Munsell soil color charts. Newburgh NY: MacBeth Division of Kollmorgen Instruments Corporation. <https://munsell.com/color-products/color-communications-products/environmental-color-communication/munsell-soil-color-charts/>
- NCSS (Number Cruncher Statistical Systems), LLC. 2015. NCSS 10 Statistical software. Keyville, UT: NCSS, LLC. <https://www.ncss.com/>
- Oliver, C. D., and B. C. Larson, 1996. Forest stand dynamics. Update Edition. New York: John Wiley & Sons, Inc. 520. ISBN: 0–471–13833–9
- Pallardy, S. G., and T. T. Kozlowski. 2008. Physiology of woody plants. 3rd edition. Amsterdam: Elsevier, 454. ISBN: 978–0–12–088765–1
- Perkey, A. W., B. L. Wilkins, and H. C. Smith. 1993. Crop tree management in eastern hardwoods. NA-TP-19-93. Morgantown, WV: USDA Forest Service Northeastern Area State and Private Forestry, 135. <https://extension.umd.edu/sites/extension.umd.edu/files/2022-05/Crop-Tree-Management-in-Eastern-Hardwoods.pdf>
- Rives, R. G., B. O. Knapp, M. L. Olson, et al. 2020. Regenerating mixed bottomland hardwood forests in north Missouri: Effects of harvest treatment on structure, composition, and growth through 15 years. *Forest Ecology and Management* 475 : 118371. <https://doi.org/10.1016/j.foreco.2020.118371>.
- Robertson, P., G. Weaver, and J. Cavanaugh. 1978. Vegetation and tree species near the northern terminus of the southern floodplain forest. *Ecological Monographs* 48 (3): 249–267. <https://doi.org/10.2307/2937230>.
- SAS (Statistical Analysis System) Institute Inc. 2015. SAS version 9.4., SAS/STAT® 15.3 User's Guide. Cary, NC: SAS Institute Inc. <https://www.sas.com/>
- Schuler, T. M. 2006. Crop tree release improves competitiveness of northern red oak growing in association with black cherry. *Northern Journal of Applied Forestry* 23 (2): 77–82. <https://doi.org/10.1093/njaf/23.2.77>.
- Sinz, A., E. S. Gardiner, B. R. Lockhart, and R. A. Souter. 2011. Morphological acclimation and growth of ash (*Fraxinus pennsylvanica* Marsh.) advance regeneration following overstory harvesting in a Mississippi River floodplain forest. *Forest Ecology and Management* 261 (3): 246–254. <https://doi.org/10.1016/j.foreco.2010.10.013>.
- Smith, H. C., and N. I. Lamson, 1983. Precommercial crop-tree release increases diameter growth of Appalachian hardwood saplings. Res Pap NE-534. Broomall, PA: USDA Forest Service Northeastern Forest Experiment Station, 7. <https://doi.org/10.2737/NE-RP-534>
- Soil Survey Staff. 2024. Web soil survey, natural resources conservation service, USDA. Available online at <http://websoilsurvey.nrcs.usda.gov/>. Accessed 7 Dec 2024.
- Stringer, J. W., G. W., Miller, and R. F., Wittwer. 1988. Applying a crop-tree release in small-sawtimber white oak stands. Res. Pap. NE-620. Broomall, PA: USDA Forest Service Northeastern Forest Experiment Station, 5. <https://doi.org/10.2737/NE-RP-620>
- Sun, J., T.-M. Koski, J. D. Wickham, et al. 2024. Emerald ash borer management and research: Decades of damage and still expanding. *Annual Review of Entomology* 69:239–258. <https://doi.org/10.1146/annurev-ento-012323-032231>.
- Tennessee Department of Agriculture. 2010. Protect tennessee forests – emerald ash borer. Available online at <https://www.tn.gov/protecttnforests/insects/emerald-ash-borer.html>. Accessed 3 February 2025.
- Trimble, G.R., Jr. 1973. Response to crop-tree release by 7-year-old stems of yellow-poplar and black cherry. Res Pap NE-253. Upper Darby, PA: USDA Forest Service Northeastern Forest Experiment Station, 10. <https://research.fs.usda.gov/treearch/23644>
- U.S. Climate Data. 2024 Web. Available online at: <http://www.usclimatedata.com/climate/grand-junction/tennessee/united-states/ustn0733> Accessed: 3 February 2025.
- Vickers, L. A., and T. C. Goff. 2025. White oak sapling dynamics across the eastern US: Quantifying a bottleneck to sustainability. *Forest Ecology and Management* 598 : 123232. <https://doi.org/10.1016/j.foreco.2025.123232>.

- Vogel, P. J., J. M. Lhotka, and J. W. Stringer. 2022. Long-term effects of crop tree release on growth and quality in white-oak (*Quercus alba* L.)-dominated stands. *Forest Science* 68 (3): 343–352. <https://doi.org/10.1093/forsci/fxac015>.
- Ward, J. S. 2002. Crop tree release increases growth of mature red oak sawtimber. *Northern Journal of Applied Forestry* 19 (4): 149–154. <https://doi.org/10.1093/njaf/19.4.149>.
- Ward, J. S. 2007. Crop-tree release increases growth of black birch (*Betula lenta* L.) in southern New England. *Northern Journal of Applied Forestry* 24 (2): 117–122. <https://doi.org/10.1093/njaf/24.2.117>.
- Ward, J. S. 2009. Intensity of precommercial crop tree release increases diameter growth and survival of upland oaks. *Canadian Journal of Forest Research* 39 (1): 118–130. <https://doi.org/10.1139/X08-165>.
- Ward, J. S. 2013. Precommercial crop tree release increases upper canopy persistence and diameter growth of oak saplings. *Northern Journal of Applied Forestry* 30 (4): 156–163. <https://doi.org/10.5849/njaf.13-017>.
- Wendel, G. W., and N. I. Lamson. 1987. Effects of herbicide release on the growth of 8- to 12-year-old hardwood trees. Res Pap. NE-598. Broomall, PA: USDA Forest Service Northeastern Forest Experiment Station, 4. <https://doi.org/10.2737/NE-RP-598>
- Wood, J. E., F. W. Von Althen, and E. G. Mitchell. 1996. Crown release improves growth of 20-year-old *Betula alleghaniensis* in tolerant northern hardwood stands. *New Forests* 12:87–99. <https://doi.org/10.1007/BF00036622>.

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Authors and Affiliations

A. E. Houston¹ · W. K. Clatterbuck¹  · J. L. Bowers^{1,2}

✉ W. K. Clatterbuck
wclatter@utk.edu

A. E. Houston
ahouston@amesplantation.org

J. L. Bowers
johnlukebowers91@gmail.com

¹ School of Natural Resources, University of Tennessee, Knoxville, TN, USA

² Present Address: USDA Forest Service, Mt. Hood National Forest, Sandy, OR, USA