

DEVELOPING A SYSTEM FOR ARTIFICIAL REGENERATION OF FINE HARDWOOD SPECIES AND MANAGEMENT TO MATURITY ON THE AMES PLANTATION

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Abstract—An integrated agenda for hardwood research has been developed at the Ames Plantation over the last 3 decades that will produce locally adapted, genetically improved seedlings for incorporation into an experimental silvicultural system that yields commercially viable trees. Components include: establishment of hardwood seedling seed orchards with 22 species, the use of seedlings from these orchards for stand enrichment and reforestation in natural stands leading to precision forestry experiments, and crop tree enhancement treatments at mid-rotation to increase growth of successful trees. This long-term agenda will allow for better control of species composition in complex hardwood systems by using robust seedlings established in naturally regenerating stands. The Ames Hardwood Laboratory currently has over 25,000 trees and 40.5 ha of fenced orchards included in the three phases of the project: Hardwood Seed Orchards, Artificial Regeneration Enrichment, and Crop Tree Management.

INTRODUCTION

Planted seedlings established in naturally regenerating stands often fail due to poor seedling quality combined with the impact of aggressive herbaceous and woody competition (Johnson and Krinard 1985, Lay and others 1997, McGee and Loftis 1986). Desired species such as northern red oak (*Quercus rubra* L.) and cherrybark oak (*Q. pagoda* Raf.) are often displaced by fast-growing species such as sycamore (*Platanus occidentalis* L.), yellow-poplar (*Liriodendron tulipifera* L.), maple (*Acer* L. species), and sweetgum (*Liquidambar styraciflua* L.). Consequently, mature stands are often dominated by less desired and less valuable species.

Natural regeneration is routinely employed to initiate hardwood stands. Methods vary across a range of treatment intensities to establish a desirable suite of species. However, establishing a suitable mix and amount of advance regeneration can be difficult, and its development following release is often hard to predict (Loftis 1990, Sander 1972). This can be particularly true on the best sites, where undesirable competition is quick to respond to full sunlight (Dey and others 2008,

Kellison 1993, Lorimer 1993). Once stand composition is established, it will affect a range of objectives for the remainder of the rotation, including values associated with timber, wildlife, and aesthetics.

Throughout human history, domestication of crop and animal species has occurred to meet societal needs, largely as a result of population increase and a need to be more productive on limited land bases (cf. Gepts and others 2012). This has proven true with forest tree species in the United States, as shown by the genetic and cultural improvement of certain coniferous species, e.g., loblolly pine (*Pinus taeda* L.) and Douglas-fir (*Pseudotsuga menziesii* Mirb. Franco) (Byam and others 2005, Silen 1978, cf. Wheeler and others 2015). In contrast, research and development efforts to domesticate highly desirable hardwood species have been minimal, with the possible exception of black walnut (*Juglans nigra* L.). Additionally, research focusing on early seedling growth of high-quality hardwood seedlings in the highly competitive, naturally regenerating systems following mature hardwood harvests has been limited (Clark and others 2015, 2016; Pinchot and others 2015, 2018)

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For the last 3 decades, research has been conducted on the Ames Plantation, to develop an integrated research agenda, from seed to harvest, to ensure the continuing presence of fine hardwood species at adequate stocking levels and to enhance their growth. The research has three primary areas:

- Development of hardwood seedling seed orchards
- Artificial regeneration to enrich naturally developing stands
- Crop tree enhancement at mid-rotation

Until recently, each research area has proceeded independently. The advent of significant seed production in some of the Margaret Finley Shackelford Seed Orchards and growth of species enrichment studies have enabled integration among the research areas. This paper briefly describes the current research and plans for the future.

METHODS

Location

The Ames Plantation is a 7487-ha University of Tennessee Research and Education Center located in western Tennessee, situated on the upper Mississippi Embayment. The plantation is characterized by low rolling hills, loess deposits, and rich bottomlands associated with the North Fork of the Wolf River, a tributary to the Mississippi River. The property is about 80.5 km east of Memphis, TN.

There are 5463 ha of forested land on the property, situated on a wide diversity of sites, ranging across the riparian zones and bottomlands along the North Fork of the Wolf River to rich loess farmlands to increasingly more xeric uplands, with some occurring on highly eroded, sandy slopes. Accordingly, there are a number of forest types occurring on the property and at a scale to be regionally representative. This diversity provides a unique opportunity to establish hardwood orchards and test silvicultural treatments on the same land base, where species and sites can be well-matched.

Hardwood Seed Orchards

Past hardwood tree improvement programs at land grant universities and the Tennessee Valley Authority were often discontinued before seed production occurred in materials from the first generation of genetic testing (Schlarbaum 2000, Wheeler and others 2015). Most of these programs were initiated in the 1950s and 1960s and discontinued when the program leader retired and federal formula funds became stagnated. The lack of seed production, an endpoint in tree improvement research, caused administrations to question further investment and contributed to the demise of tree improvement programs through hiring of scientists that were involved in more basic research.

The University of Tennessee's Tree Improvement Program was founded in 1959 by Professor Eyvind Thor (Thor 1976) and continued by the second author. In response to some of the reasons for closures of other tree improvement programs (Schlarbaum 2000), a seedling seed orchard approach was implemented in 1999 on the Ames Plantation. Hardwood plantations using pedigreed seedlings were established on Ames Plantation. These ranged across a number of species but were focused largely on oak. All plantings supported genetic testing of individual mother trees. Based on selection criteria, including form and acorn production, they were thinned at the earliest possible date to create seedling seed orchards. With one exception, this approach followed the methodology of LaFarge and Lewis (1987), who created a seedling seed orchard from a northern red oak progeny test. An additional characteristic, aside from growth and spacing, was taken into consideration when retaining trees: fruiting data. All genetic tests were observed for seed production, as there are genetic differences in reproduction maturation among genetic families. In addition to the conversion of genetic tests through the seedling seed orchard approach, other approaches were used to create seed orchards with species that did not lend well to orchard development through genetic testing (table 1).

Stand Enrichment Using Artificial Regeneration

Planting of high-quality (*sensu* Kormanik and others 1994), characterized, pedigreed hardwood seedlings on sites with suitable species associations began in 2002 with a 1,250-seedling northern red oak study. The origin of the seedlings was a 28-year-old northern red oak seedling seed orchard on the Ames Plantation. Since that time, a number of similar studies have been established.

For this paper, a bottomland study was selected as an example. The research was established in 2006 and consisted of high-quality, pedigreed seedlings from two species: cherrybark oak and swamp chestnut oak (*Q. michauxii* Nutt.). The acorns were planted at the Georgia Forestry Commission's Flint River Nursery in the 2005 autumn. The resulting seedlings were grown according to fertilization and irrigation protocols developed by Kormanik and others (1994). The 1-0 seedlings were undercut at approximately 20.3 cm and lifted in February, 2006. The best seedlings in each family (i.e., tallest and greatest root collar diameter) were selected for planting. The lateral roots were clipped to 15.2 cm from the taproot to facilitate planting, while the taproot was not clipped. Each seedling received a tag with individual numbers to maintain pedigree and identity. The seedlings were stored in a cooler until transportation to the Ames Plantation for planting.

Planting occurred during the winter of 2006–2007 on five bottomland sites, each approximately 1 ha in size. Soil



Table 1—Summary of the Margaret Finley Hardwood Seed Orchards on the Ames Plantation

Species	Common name	Year established	Type	Seed production
<i>Quercus rubra</i> L.	Northern red oak	1972	SSO	Yes
<i>Q. rubra</i> L.	Northern red oak	2004	2 nd Gen SSO	Yes
<i>Q. rubra</i> L.	Northern red oak	2013	PT	No
<i>Q. alba</i> L.	White oak	1972	SSO	Yes
<i>Q. alba</i> L.	White oak	1985	PT	No
<i>Q. alba</i> L.	White oak	2001	2 nd Gen SSO	Yes
<i>Q. alba</i> L.	White oak	2003/2005/2007	PT	Yes
<i>Q. pagoda</i> Raf.	Cherrybark oak	1983	SSO	Yes
<i>Q. pagoda</i> Raf.	Cherrybark oak	2003/2006	SSO	No
<i>Q. phellos</i> L.	Willow oak	2003	SSO	No
<i>Q. nigra</i> L.	Water oak	2003	SSO	Yes
<i>Q. macrocarpa</i> Michx.	Bur oak	2003/2005	PT	Yes
<i>Q. bicolor</i> Willd.	Swamp white oak	2006	PT	Yes
<i>Q. shumardii</i> Buckley	Shumard oak	2003/2006	PT	No
<i>Q. palustris</i> Muechh.	Pin oak	2003/2006/2007	SSO/PT	No
<i>Q. lyrata</i> Walter	Overcup oak	2003/2006	PT	No
<i>Q. stellata</i> Wangenh.	Post oak	2007	PT	No
<i>Q. falcata</i> Michx.	Southern red oak	2003/2013	SSO/PT	No
<i>Q. michauxii</i> Nutt.	Swamp chestnut oak	2003	PT	No
<i>Prunus virginiana</i> Marshall	American plum	2016	CLO	No
<i>Diospyros virginiana</i> L.	Persimmon	2005	PT	Yes
<i>Carya illinoensis</i> (Wangenh.) K. Koch	Pecan	2013	PT	No
<i>Ilex opaca</i> Aiton	American holly	2011	WL/SSO	Yes
<i>Q. velutina</i> Lam.	Black oak	2003	SSO	No
<i>Q. texana</i> Buckley	Nuttall oak	2003	PT	No
<i>Juglans nigra</i> L.	Black walnut	2007	PT	No
<i>Q. muehlenbergii</i> Engelm.	Chinquapin oak	2005	SSO/CLO	No
<i>Q. margaretta</i> (Ashe) Small	Small sand post oak	Continuous	CON	No

Abbreviations for type: PT= progeny test; SSO = seedling seed orchard; CLO = clonal seed orchard; WL = wildlings; 2nd Gen = 2nd Generation; CON = conservation planting.

series were predominated by Falaya and Collins, both somewhat poorly drained, recently deposited, silt/sand alluvium. Each site was occupied by a mature stand of mixed bottomland hardwood species, including the study species, but largely predominated by sweetgum. Prior to planting, all merchantable timber, non-merchantable trees, and tops were removed from the site. The seedlings were planted on a 3.05- by 3.05-m spacing in an incomplete block, within complete block, using split, split plots, taking into consideration species and multiple seed sources. They were planted with a modified, i.e., widened at the blade, KBC bar. There were no release treatments following planting.

Height and diameter growth were periodically assessed. In 2016, all seedlings were measured and assigned a crown classification using methodology developed by Meadows and others (2001). Position assessments were assigned as shown in table 2.

Table 2—Numerical rating system for assigning a crown class based on crown characteristics as adapted from Meadows and others (2001)

Crown characteristics	Points
Direct sunlight from above	0–10
Direct sunlight from the sides	0–10
Crown balance	1–4
Relative crown size	1–4
Crown class assigned	Total ranking (2–28 points)
Dominant	24–28 points
Codominant	17–23 points
Intermediate	10–16 points
Suppressed	2–9 points



Using a more subjective and rigorous estimation, trees in the dominant and codominant classes were assigned a “free-to-grow” status if they had gained an obvious commanding crown position and could be reasonably envisioned to occupy the mature stand. Growth analyses were conducted using mixed model analyses of variance, and chi-square analysis was used for crown class separation with Chi Square. A p -value of ≤ 0.05 was selected to indicate significant differences.

Crop Tree Management

In 1993, a naturally occurring, 40-year-old, well-stocked upland hardwood stand, dominated by white oak (*Q. alba* L.), was selected for fertilization, release, and combination treatments. The stand was divided into twenty 0.4-ha randomized, complete, blocks. Thirty-six cells were established on each block in a 10.7- by 10.7-m grid. The best tree was chosen inside that grid and where possible, a white oak was chosen. Of 720 cells, 653 cells were filled with a suitable crop tree, with 445 containing white oak.

Three treatments were applied:

- 1) Fertilization applied at rate of 68 kg of available nitrogen per 0.4 ha, and phosphorous, applied as triple super phosphate, at a rate of 13.6 kg per 0.4 kg
- 2) Release based on at least three sides of the crown freed from immediate competition
- 3) Combination of both treatments

In 2003, 10 years after treatments were applied, the study was re-measured.

RESULTS

Hardwood Seed Orchards

Seeding seed orchard or genetic tests intended for conversion to seedling seed orchards of 22 hardwood species have been created since 1999 on the Ames Plantation and are now collectively referred to as the Margaret Finley Shackelford Hardwood Seed Orchards. The Shackelford Orchards encompass species important for timber production, wildlife habitat, and mast production, and a variety of species that can inhabit very wet sites [e.g., overcup oak (*Q. lyrata* Walter)] to dry site species [e.g., southern red oak (*Q. falcata* Michx.)], reflecting the site diversity of the western Tennessee area. Some of the Shackelford Orchards are now producing enough acorns for species enrichment plantings, reforestation on a landscape scale, and precision forestry studies (table 2). The seed orchards are located on various sites that match the silvics of each species and encompass 40.5 ha, surrounded by electric fences to protect the trees from deer herbivory and seed predation.

As the genetic tests are converted to orchards, selections are made for traits important to both timber and acorn production. For example, the water oak (*Q. nigra* L.) orchard contains some trees that produce relatively small acorns, e.g., 0.64 cm in diameter, preferred by wild turkey (*Meleagris gallopavo* L.) (cf. Minser and others 1995), and small enough for consumption by bobwhite quail (*Colinus virginianus* L.). In addition, observations of acorn retention in the water oak orchard have revealed a subset of trees that delay dropping acorns until late January and early February, thereby extending the availability of relatively fresh mast.

Grafting of either wildlife or timber selections, depending on the orchard species, will occur with establishment of a grafted orchard at another location. Following establishment of the grafted orchard, those selections will be cut from the mother orchard, resulting in two orchards, one for timber production and one wildlife-oriented, from the original genetic test.

Stand Enrichment Using Artificial Regeneration

At the end of the 11th growing season, 1,036 cherrybark oaks and 997 of the swamp chestnut oaks were alive, and survival rates (88 percent and 84 percent, respectively) were significantly different. Cherrybark oak height growth averaged 7.4 m and was statistically different than swamp chestnut oak height growth (5.8 m). Average height for both species over the course of the study is shown in figure 1.

Crop Tree Enhancement

Average 10-year diameter growth in the respective treatments was: control (5.0 cm), fertilize (5.8 cm), release (7.9 cm), and combination treatment (9.1 cm), which were statistically different from each other (Twillmann 2004).

In a more striking contrast, 10-year volume growth was: control [1.12 m³ (487 board feet)], fertilize [1.76 m³ (746 board feet)], release [2.02 m³ (858 board feet)], and combination [3.27 m³ (1,385 board feet)]. Modeling indicated significant differences among treatments were maintained for grade 1 lumber to the 80-year mark (fig. 2).

DISCUSSION

Hardwood Seed Orchards

The development of hardwood seedling seed orchards that will produce locally adapted, genetically improved seed for western Tennessee, northern Mississippi, and eastern Arkansas will serve this area for decades to come. Forestry operations in western Tennessee and associated areas will have an opportunity to incorporate seedlings originating from the orchards to enrich



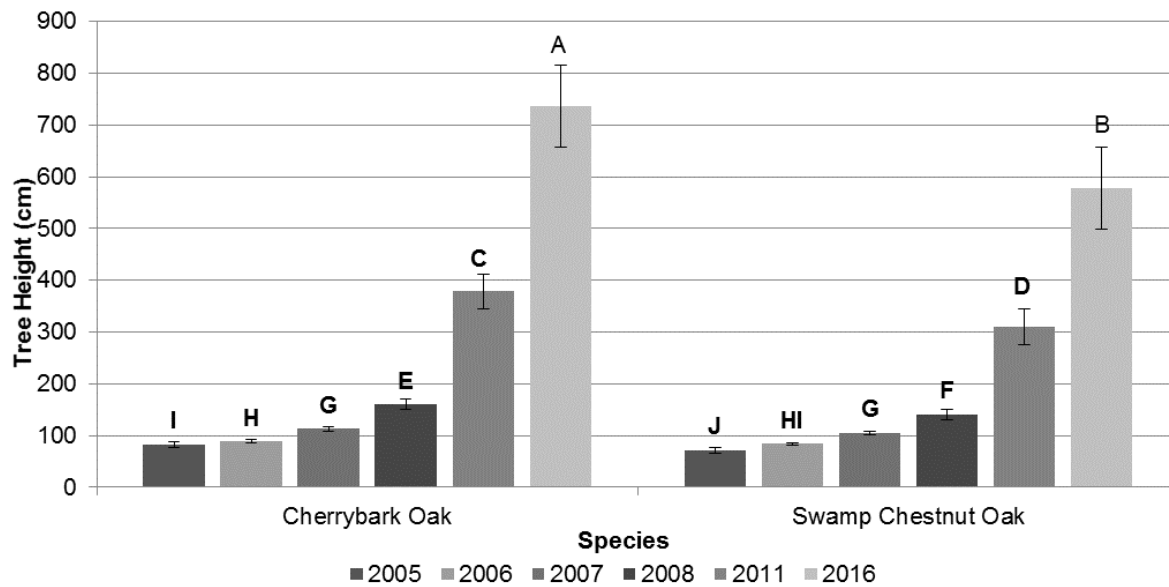


Figure 1—Height growth of cherrybark and swamp chestnut oak, over five sites at the Ames Plantation. Out of the original 2,387 planted trees, a total of 830 trees had achieved either a dominant or codominant crown class, and about 80 percent of these were evaluated as being free-to-grow (53 percent cherrybark oak and 28 percent swamp chestnut oak). Some cherrybark oaks exceeded 12 m in height and 11 cm diameter at breast height.

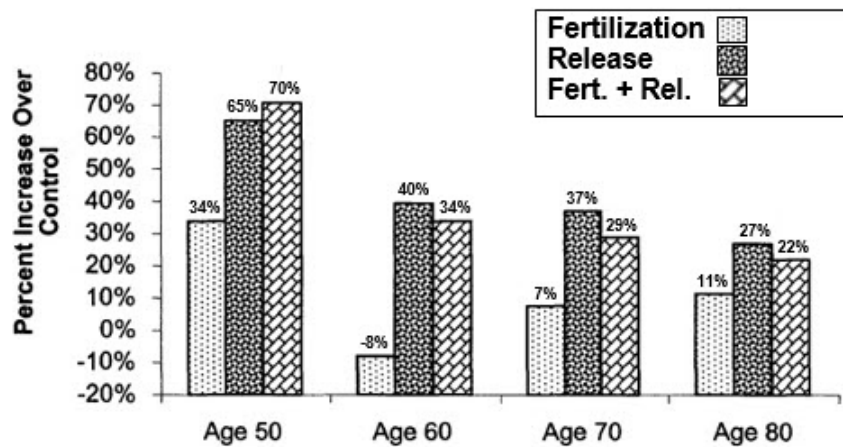
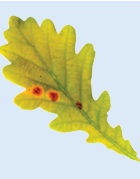


Figure 2—Model showing maintenance of grade 1 sawtimber 40 years beyond Crop Tree Enhancement treatments on the Ames Plantation (Twillmann 2004).



selected species following different types of harvests or to fill natural forest gaps and openings. Additionally, landscape-level restoration with mixed species of appropriate seed source will be readily possible following natural disasters such as tornados or for creating new forests on former marginal agricultural fields.

The Shackelford orchards will provide the Ames Plantation and associated scientists with unique opportunities to initiate a variety of forestry and wildlife studies using pedigreed seedlings from either a single or a mixture of species, depending on the study objective(s). Highly characterized pedigreed orchard-origin seedlings will be used in species enhancement and precision forestry studies and for genetic studies in post-harvest and open field conditions. Evaluation of pedigreed seedlings in such studies will allow for actual genetic gain to be calculated for the seed orchards, as well as for orchard refinement to maximize gain. The orchards themselves will contribute to hardwood seed orchard management protocols, as well as to a better understanding of reproductive biology of hardwood species. Experimental and practical use of orchard-derived seedlings will provide for state-of-the-art forestry field days and workshops, as well as unique learning opportunities for undergraduate and graduate students. Aside from research implications, Shackelford orchard seedlings will be routinely integrated into Ames Plantation forestry operations. The availability of seedlings with appropriate seed source, genetically improved for specific uses and of sufficient quality to withstand the challenges of field planting without post-planting management, will allow Ames Plantation managers to plan land use with more precision.

Stand Enrichment Using Artificial Regeneration

The results of this study are very encouraging for stand enrichment with specific species through planting. Partial or complete planting failure is prohibitively expensive to landowners. If the regeneration phase of a hardwood stand does not develop as planned, it represents a long-term failure, given the relatively long rotations in hardwood stands grown for sawtimber. In this study, about half of all surviving cherrybark oaks and a quarter of the swamp chestnut oaks have achieved dominant or codominant classes. For both species combined, there were 189 planted trees per ha (76 planted trees per acre) having a crown position rated as free-to-grow. Even within the justifiable uncertainties of juvenile:mature correlations, this number of 11-year-old successful trees supports a reasonable prediction for a mature stand having a much larger component of oak than what is naturally occurring (i.e., a stand dominated by sycamore and sweetgum). If only 95 oaks per ha persist to maturity it would very closely match the number chosen for the

crop tree enhancement work at 89 trees per ha (36 trees per acre), and the planted trees would occupy about half of the upper canopy.

Although it is tempting to envision using species enhancement to produce essentially oak plantations, that is not a desired outcome of this research. Evaluation of these studies is focused on the objective of having enough artificially established trees present at maturity to impact stand diversity in such way to add value, in terms of timber income, wildlife support, ecological integrity, and aesthetics. It is a concept best envisioned as species enrichment of the developing stand.

Crop Tree Management

A number of studies have reported the value of fertilization and release treatments on mid-rotation hardwood stands (Kochenderfer and others 2001; LeDoux and Miller 2008; Miller 2000; Miller and Stringer 2004; Miller and others 2007; Perkey and others 1993, 2011). Our study is still ongoing, and the results shown here are only a portion of a range of similar work strongly suggesting that selection of a subset of the best trees at mid-rotation in a natural stand and using fertilization and/or release can significantly increase growth.

Intuitively, there is a strong inference that selection of the best trees in the species enhancement experiments at some point(s) in the mid-rotation for crop tree enhancement could accelerate growth. Correspondingly, this would accomplish two things:

- 1) Rotation would be shortened; and
- 2) The stand would be dominated with a consciously chosen component.

SUMMARY

The integration of seed orchard products, enrichment plantings, and crop tree management at the Ames Plantation is directed toward a rotation-length set of silvicultural treatments to improve naturally forming hardwood stands, allowing the ability to address global markets, impact of invasive pests, ecosystem services, societal needs, wildlife populations, and ecological parameters on a more precise level than natural regeneration systems can regularly provide. Additionally, this system has potential to enable a more agile response to changing weather patterns and associated shifts in site classifications.

The integration of these three areas of research forms a basis for forest design, similar in concept to plantation management, but tremendously more complex when species:site relationships and the vertical structuring



of the forest by shade tolerance are considered, in reference to a central goal to improve composition but also maintain diversity. It is a silvicultural system of enrichment where the composition of the mature stand is significantly impacted in the initial stages of regeneration by embedding a domesticated component into the naturally forming matrix and, at mid-rotation, selecting a portion of the successful trees to favor with release and/or fertilization treatments.

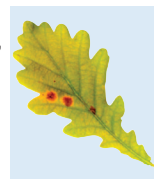
Over time, this system will become more refined as further experimentation with greater precision in experimental materials and site characterization will yield more information on interactions among pedigree, site, and silvicultural protocols. The system lends itself well for experiments that provide information pertinent to seed orchard refinements as well as exploring new approaches to hardwood management, especially where forest diversity might be, to a reasonable extent, designed with the injection of pedigreed, artificial regeneration into naturally developing systems. Through practical use of this system, we believe the Ames Plantation forests can become a prototype for the blending of natural and domesticated hardwood forests. It is a system applied over the life of the stand and, with targeted objectives, has similarities to precision agriculture. In consideration of the experimental and practical aspects of this effort, along with the increasing scale of the project, we have decided to refer to it as the “Ames Plantation Hardwood Laboratory.”

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