ARTIFICIAL REGENERATION IN THE SOUTHERN APPALACHIANS

Stacy L. Clark and Scott E. Schlarbaum

Abstract—Reforestation of upland oak species on productive forest sites in the Southern Appalachian region will require different prescriptions than in other regions where yellow-poplar (*Liriodendron tulipifera* L.) is not a primary competitor. We present results from three studies on highly productive sites [site index, base age 50, for northern red oak (*Quercus rubra*) ranged from 78 to 98 feet] that represented a broad range of residual basal areas and competition control methods. In all studies, we used seedlings produced using the most advanced bare-root nursery protocols currently available (averaging 1.6 to 3.6 feet in height). Seven to 10 years after harvest, approximately 15 percent of planted seedlings were in canopy positions where recruitment into the overstory was probable, and recruitment capabilities were similar at all three study sites despite differences in site conditions and silvicultural prescriptions. Assuming a planting density of 300 trees per acre, a recruitment density of approximately 50 trees per acre would be expected. After 10 years, trees were capable of attaining 20 to 26 feet in height and averaged 9 to 10 feet for the two oldest plantings. The study that received the most targeted competition control treatment and the largest seedlings had a significant positive relationship between seedling height at the time of planting and recruitment density. Variability in silvicultural treatments, genetics, and site conditions probably masked this relationship for the other studies. We recommend planting high-quality seedlings from a diverse genetic mixture and targeted herbicide competition control to improve recruitment success rates of planted oak seedlings.

INTRODUCTION

Forest resources are increasingly pressured in the United States by land conversion, invasive and exotic plants and disease, and climate change. Human population is increasing while forest lands have remained stable over the last 100 years (Oswalt and Smith 2014), requiring improved production of natural resources. Domestication of plants and animals has improved efficiency for food and timber commodities on a per-area basis, but hardwoods remain largely undomesticated, particularly oak (*Quercus* L.) species. Tree improvement and research on artificial regeneration of upland oak species have been limited to primarily northern red oak (*Q. rubra* L.) and white oak (*Q. alba* L.), which have high economic and ecological values. Oaks in general are difficult to improve, however, due to inherent slow growth, relatively high intraspecies variability, and limited long-term resources to sustain research and development programs (Beineke 1979, Schlarbaum 2000).

Managers require practical prescriptions with predictable outcomes to regenerate oak naturally or artificially, particularly on private land in the Southern Appalachian region. While research has improved our understanding of requirements for regenerating oak, successful regeneration is rarely achieved in practice due to high cost or lengthy time required for implementation. From the 1970s to the 2000s, practical recommendations for planting oak were developed and tested in the Ozark and Boston Mountain region (Spetich and others 2002, Weigel and Johnson 2000) and in the Northeastern United States (Zaczek and Steiner 2011). Research focused on seedling quality and physiology, stock types, and silvicultural prescriptions for competition control and browse protection (Dey and others 2008). However, recommendations derived from this research were largely outside the Southern Appalachian region where fast-growing, shade-intolerant species, like yellow-poplar (*Liriodendron tulipifera* L.), compete with planted oaks.

Approximately 25 years ago, advancements in artificial regeneration in the Southern Appalachians were made through two primary processes: development and maturation of seed orchards that provided a basis for multi-year research projects from pedigreed sources (Schlarbaum and others 1994), and development of nursery prescriptions that improved seedling quality (Kormanik and others 1994). Since that time, the U.S. Department of Agriculture Forest Service, Southern Research Station (formerly Southeastern Forest

Author information: Stacy L. Clark, Research Forester, Southern Research Station, USDA Forest Service, Knoxville, TN 37996-4563; and Scott E. Schlarbaum, Professor, Department of Forestry, Wildlife, and Fisheries, The University of Tennessee, Knoxville, TN 37996-4563.

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Experiment Station) and Southern Region, and The University of Tennessee's Tree Improvement Program have cooperated on research and development of northern red oak. A primary goal of this effort was to conduct research to provide practical recommendations to enrich sites that were experiencing natural regeneration failures through the planting of high-quality oaks.

As a result of this cooperation, the objectives of this research were to:

1) present general performance metrics (survival, growth, and recruitment capability) of seedlings grown using advanced nursery prescriptions and planted on high-quality sites in the Southern Appalachians; and

2) determine if an easily identifiable seedling quality metric (height) can be used to predict recruitment capability.

Our goal has been to provide practical recommendations to artificially regenerate upland oak (primarily northern red oak) on moderate to productive sites in the Southern Appalachian region. Three research projects are presented (from youngest to oldest) where successful enrichment of northern red oak looks promising.

METHODS

Specific site descriptions are briefly described below in the results section. Experimental material consisted of putative half-sibling progeny from open-pollinated mother trees in the wild or in a seed orchard on the Cherokee National Forest (Schlarbaum and others 1994). Acorns were sown at a density of six per square foot in state commercial tree nurseries in Bryomville, GA, or Delano, TN, and subsequent seedlings were grown for 1 year using advanced nursery protocols to maximize overall seedling size (Kormanik and others 1994). Seedlings were lifted from the nursery using a Fobro™ machine lifter that undercut seedlings (10–12 inches) and loosened soil around the roots. Seedlings were manually removed from the nursery beds, roots sprayed with a hydrogel slurry solution to prevent desiccation, and placed in poly-coated paper tree bags in cold storage until planted in March. Trees were planted on a 10- by 10-foot or 12- by 12-foot spacing using a planting bar (Jim Gem® KBC) modified to be 12 inches in width and length to accommodate relatively large root systems.

Seedling height measurements were collected during the dormant season at the time of planting and in 2016 or 2017, depending on study. For all studies, a planted tree was determined to be 'free to grow' if the terminal bud of the planted seedling was not directly overtopped by stems or leaves from competing trees in the understory or midstory canopy layer. For study 3, a planted tree was determined to have 'understory dominance' if it was at least 80 percent of the height of the tallest understory competitor occurring within a 4.3-foot-radius plot around the planted seedling (adapted from Spetich and others 2002). Understory describes trees >1 foot in height and <1.5 inches in diameter at breast height (DBH), and midstory describes trees 1.5 to 5.4 inches DBH. Free-to-grow and dominance data were collected in the late growing season of 2016 or 2017, depending on study.

The studies were originally established to test various treatments including family, seedling grade, and root pruning treatments, and these treatment effects have been previously reported (Clark and others 2015, 2016). Raw means and associated standard deviations for the entire seedling population were computed for each study. Trees were considered capable of successful recruitment to the canopy if they were greater than the mean height of planted seedlings for the site, and were free to grow in the understory and midstory. A recruitment density was calculated by multiplying the fraction of trees capable of recruiting to the canopy by 302, which represents a planting density of a 12- by 12-foot spacing. Logistic regression analysis was performed separately for each study using SAS® 9.3 software (SAS Institute Inc. 2011) to predict recruitment capability from seedling height at planting. Linearity assumptions of the predictor variable were tested, and assumptions were not violated for any study. Hosmer and Lemeshow goodness of fit tests were conducted, and all models were determined to adequately fit the data. An associated *P*-value of 0.05 was used to indicate significance of the Wald chi-square value, where larger Wald chi-square values indicate a stronger relationship between the height predictor variable and recruitment capability.

RESULTS

Study 1. Shelterwood-Burn, Cold Mountain Game Lands, NC (ca. 2010)

Seedlings (n = 252) were planted in three stands (n = 84 in each stand) treated with a shelterwood with reserve harvest, resulting in a two-age stand (Clark and others 2016, Westby-Gibson and others 2017). Site index (base age 50) for northern red oak ranged from 78 to 98 feet, and residual basal area was 30 to 39 square feet per acre. The stands were treated with a prescribed fire in March after their fifth (one stand) or sixth (two stands) growing season. Pre-burn data represented 5- or 6-year post-planting data, depending on stand, and post-burn data represented 7-year post-planting data for all trees. Trees averaged 3.4 feet in height at the time of planting, ranging from 1.3 to 6.2 feet. The stand that was burned in year 5 was low severity (i.e., 11 percent of trees affected), but the two stands burned in year 6 had moderate severity fires (i.e., 90 percent of trees affected). Prior to the burn, survival was 87 percent and height was 7.5 feet. After burning, survival was reduced by 5 percent and height by 1.6 feet, on average. After seven growing seasons, trees could reach over 17 feet in height, and 75 and 64 percent of trees were free to grow in the understory and midstory, respectively (table 1). Forty-seven trees per acre (15 percent of total planted) were considered to be capable of successful recruitment. Recruitment capability at age 7 was positively related to nursery seedling height, but this relationship was bordering on significance (Wald chi-square value = 3.60; *P*-value = 0.06). The relationship between nursery seedling height and recruitment capability increased at an increasing rate according to the logistic regression analysis (fig. 1).

Study 2. Thinning, White County, TN (ca. 2008)

Seedlings (n = 252) were planted on a site that was thinned from below to a residual basal area of 60 square feet per acre. Site index (base age 50) for northern red oak was 85 feet. A mechanical release was implemented 6 years after planting that included cutting stems <1.5 inches DBH [excluding other oaks, hickory (*Carya* Nutt.), dogwood (*Cornus florida* L.), or cherry (*Prunus serotina* Ehrhart)] that were directly overtopping the planted seedling. Seedlings were 1.6 feet at the time of planting, ranging from 0.7 to 4.1 feet. After 10 growing seasons, survival and average height were 67 percent and 9.2 feet, respectively (table 1). The tallest tree was

Table 1—Means (standard deviations) of performance metrics for three northern red oak plantings 7 or 10 years after planting

	Study 1 (age 7)	Study 2 (age 10)	Study 3 (age 10)
Survival	83 (37)	67 (47)	57 (50)
Average height (feet)	5.9 (4.5)	9.2 (4.8)	9.9 (5.6)
Maximum height (feet)	17.8	20.3	25.8
Understory dominance (percent)	--	--	68 (47)
FTG in understory (percent)	75 (43)	64 (48)	73 (44)
FTG in midstory (percent)	64 (48)	55 (50)	48 (50)
Recruitment density (trees per acre)[a]	47	54	45

FTG = free to grow.

NOTE: Data for understory dominance were not collected at Studies 1 and 2.

[a] Recruitment density was based on planting 302 trees per acre.

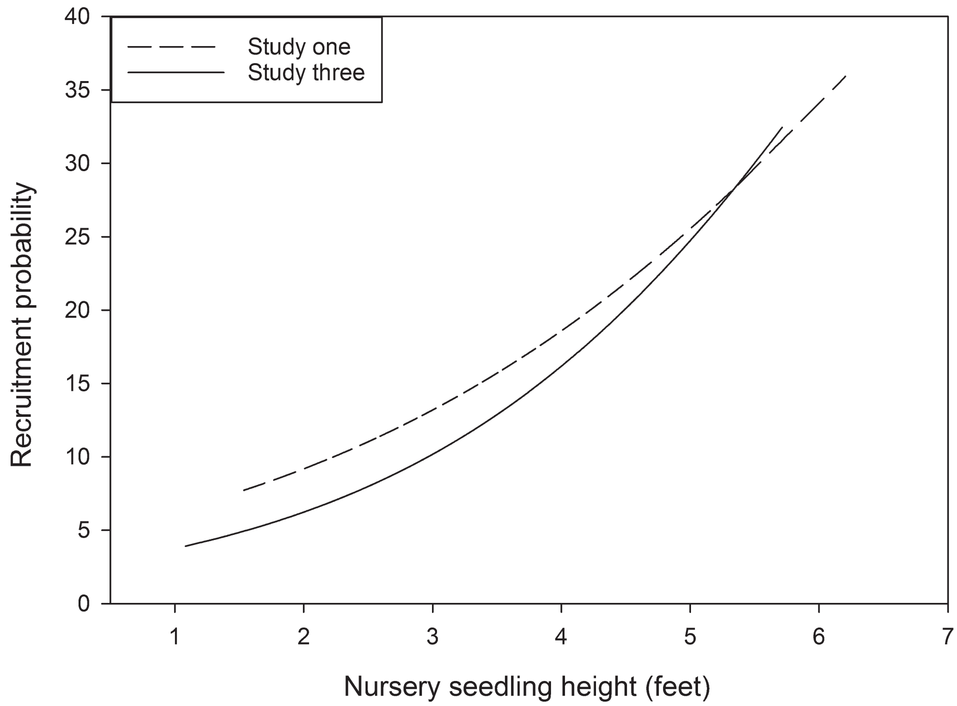

Figure 1—Probability of canopy recruitment at year 10 based on nursery seedling height for northern red oak seedlings planted in a thinning (study 1) and a two-age retention stand (study 3).

20.3 feet tall, and 64 and 55 percent of trees were free to grow in the understory and midstory, respectively. Approximately 54 trees per acre (18 percent of total planted) were considered to be capable of successful recruitment. Recruitment capability was positively related to nursery seedling height, but this relationship was not significant (Wald chi-square value = 1.91; *P*-value = 0.17).

Study 3. Two-Age Retention Harvest, North Cumberland Wildlife Management Area, TN (ca. 2007)

Seedlings (n = 292) were planted in a shelterwood with reserve harvest resulting in a two-age stand (Clark and others 2015). Site index (base age 50) for upland oaks was 82 feet, and residual basal area was 56 square feet per acre. Seedlings were released from competition using a triclopyr herbicide mix applied as a basal bark spray 5 years after planting. Seedlings averaged 3.6 feet tall at the time of planting, ranging from 1.1 to 5.7 feet. After 10 years, survival was 57 percent, and trees averaged 9.9 feet in height (table 1). The tallest tree was 25.8 feet tall. Sixty-eight percent of trees attained dominance in the understory, and 48 percent of stems were free to grow in the midstory. Approximately 44 trees per acre (15 percent of total planted) were considered to be capable of successful recruitment. Recruitment capability was significantly related to nursery seedling height (Wald chi-square value = 8.13; *P*-value = 0.0043). The relationship between nursery seedling height and recruitment capability increased at an increasing rate according to the logistic regression analysis (fig. 1).

DISCUSSION

Successful oak recruitment on productive sites requires the presence of tall advanced reproduction (i.e., 3 to 4 feet tall) prior to overstory canopy removal (Loftis 1983). Silvicultural prescriptions, including artificial regeneration, necessary to obtain advanced reproduction must be balanced with practical considerations (e.g., costs, time) to improve efficacy of treatments (Spetich and others 2009). In practice, many managers desire a simple ‘plant and walk away’ approach to restore or enrich an upland oak stand that is transferable across multiple site types and silvicultural prescriptions. Planting relatively tall seedlings, as conducted in our studies, resulted in similar recruitment success densities across sites despite variability in silvicultural prescriptions and site conditions. Compared to natural regeneration methods, planting eliminated the need to coordinate silvicultural treatments with acorn crops and shortened the time necessary to obtain tall natural regeneration, which can take up to 10 years if herbicide is applied prior to harvest (Loftis 1990) or 3 or 4 years if burning is applied after the harvest (Brose 2010). Our results showed that 45 to 57 stems per acre of oak out of a planting density of 302 per acre were in positions favorable for recruitment approximately 10 years after harvest with minimal competition control. The recruitment density and success rate (ranging from 15 to 18 percent of planted seedlings) may appear insufficient, but could be enhanced with additional forest management practices such as crop tree release or pre-harvest competition control (Johnson and others 1989, Miller and others 2007). In 10-year-old stands, approximately 800 codominant or dominant trees per acre will be present, and approximately 80 per acre will be considered ‘crop trees’ capable of remaining competitive and responding to future management (Miller and others 2007); thus, the results indicate planted seedlings could potentially constitute 60 to 70 percent of a stand’s crop tree population at age 10.

We expected to find a stronger relationship between recruitment capabilities and nursery seedling height, but our results did show positive relationships in all three studies, albeit not always significant. Studies 1 and 3 yielded similar predictions of recruitment success using nursery seedling height (fig. 1). While our goal was to test a seedling characteristic commonly used during grading in commercial nurseries, we suspect that other physiological or morphological parameters may have had better correlations to recruitment success. The tallest seedlings (i.e., >4 feet) may have had dieback related to unbalanced root:shoot ratio (Struve and others 2000), which weakens relationships between recruitment capability and seedling height at planting. Additionally, most of our studies incorporated treatments or practices (e.g., root pruning, genetic family, burning) that may have masked effects of seedling size on field performance. Each study was subject to varying forms of wildlife damage (e.g., deer browsing) and drought (study 3; Clark and others 2015), and seedling quality also varied. Study 3 had the strongest relationship (largest Wald chi-square value and lowest *P*-value) between nursery seedling height and recruitment capability, and this study held genetics constant by using seedlings from one genetic family, used the most targeted competition control, and had the largest seedlings at the time of planting (Clark and others 2015). These results provide some anecdotal evidence that the use of high-quality (i.e., tall) bare-root seedlings may be most effective when coupled with herbicide competition control, as suggested by previous research (Kormanik and others 2002, Weigel and Johnson 2000). However, empirical research is needed to quantify relationships between herbicide treatments and seedling quality of larger sized seedlings.

Some form of competition control will be beneficial for artificial regeneration (Dey and others 2008), but timing and method of application need further study. The mechanical release in study 2 was largely ineffective due to aggressive resprouting of competition. The prescribed fire effects on competition in study 1 has not yet been quantified, but observations to date indicate the effects were highly variable within the sites and not reliable for control of faster growing shade-intolerant species. While targeted herbicide competition control was not used on most of our studies due to constraints by landowners or lack of resources, it would have almost certainly improved recruitment densities and will probably be necessary when residual basal area is low (Weigel and Johnson 2000, Zaczek and Steiner 2011). Lack of competition control is typical for many management situations and will result in lower success rates, particularly for stands with low residual basal area. Oak is difficult to regenerate without some form of competition control, and we are currently investigating the most efficacious methods in other studies on productive sites in the Southern Appalachians.

These results indicate that approximately 15 percent of seedlings will be successful across a diversity of silvicultural prescriptions and site conditions due to planting tall nursery seedlings that were produced using the most advanced nursery protocols available (Kormanik and others 1994). Planting seedlings with mean heights of 3 to 4 feet and large root systems will improve competitive ability and reduce deer browsing effects across many stocking densities or competition control treatments (Dey and others 2008). Genetics will also affect nursery and outplanting performance (Clark and others 2016). Thus, relatively tall nursery seedlings from a diverse genetic mixture should be used for reforestation.

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