SURVIVAL, GROWTH, AND ACORNET PRODUCTION OF ARTIFICIALLY REGENERATED NORTHERN RED OAK ON TWO HIGH-QUALITY MESIC SITES AT YEAR SEVEN

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ABSTRACT—Open-pollinated, half-sib northern red oak (*Quercus rubra* L.) 1-0 seedlings were grown under an improved nursery protocol. Minimum seedling grading standards for this test were six first-order lateral roots, 8-cm root-collar diameter, and 0.7-m height. At the Brasstown site on a salvage clearcut in North Georgia, we spot-applied glyphosate herbicide annually for 6 years to prevent the seedlings from being overtopped. At the Wayah shelterwood site (30 trees/ha) in western North Carolina, we restricted herbicide applications and used brush saws to clear around each planted seedling after the fourth and the sixth growing seasons. The northern red oak trees on the Brasstown site performed significantly better for all parameters. At Brasstown site, trees from eight of the nine families produced an acornet crop at year seven. We observed no acornets or acorns at the Wayah site. We attributed differences in response between the two primarily to inadequate control of rapidly growing competing vegetation on the Wayah site.

INTRODUCTION

Northern red oak [*Quercus rubra* L. (NRO)] has a broad geographic distribution, but no single regeneration mechanism can explain its presence in current stands. However, NRO is rapidly declining in numbers and importance on high-quality mesic sites throughout its range. Many researchers feel NRO may become threatened or endangered on these sites without new regeneration techniques (Kellison 1993).

Human activity or biological catastrophes such as the chestnut blight fungus, *Cryphonectria parasitica* (Murr.) Barr., that killed American chestnut [*Castanea detata* (Marsh.) Borkh.], started many NRO-dominated stands. Past land use, harvesting practices, and fires have enabled NRO to occupy a broad geographic and physiographic range (Abrams and Norwacki 1992). However, as NRO on high-quality mesic sites were harvested or disturbed, they did not establish new stands.

A shelterwood method for regenerating NRO on low-quality sites (site index$_{50} \leq$ 21 m) reliably produced new stands of both stump sprouts and individuals of seedling origin (Sander 1972). The method consists of thinning the mature stands to specific densities and then allowing NRO seedlings to regenerate under the canopies. When seedlings reach the desired densities and sizes, the overstory canopy is removed. This method popularized the term "advanced oak regeneration" and specified the minimum stem standards for oak management in the eastern and central United States.

Sander's (1972) system proved effective on low-quality sites where faster-growing competitors to NRO were absent or at minimal levels. However, the necessary advanced NRO regeneration might take 10 to 20 years. To shorten this cycle, Johnson (1993) tried artificial regeneration on low-quality upland sites and on high-quality mesic sites. Severe competition from faster growing, more shade-tolerant species (Barton and Gleeson 1996, Crunkilton and others 1992) and the absence of quality NRO planting stock, however, made artificial regeneration impractical. Others modified Sander's prescription to use it on high-quality mesic sites. Their results showed that shade-tolerant species as well as yellow poplar (*Liriodendron tulipifera* L.) responded well to these shelterwood modifications, but NRO did not (Loftis 1983).

In the mid-1980s, we initiated an effort to develop a nursery protocol to produce the proper-sized, high-quality 1-0 hardwood planting stock that would be comparable to size requirements described for advanced oak regeneration by Sander (1972). Many researchers and forest managers had essentially discounted the usefulness of 1-0 oak planting stock. Even now many still recommend 2 or even 3 years in the nursery to achieve proper-sized seedlings (Hill 1986, Zaczek and others 1997). Our nursery protocol for growing 1-0 oak seedling also evaluated seedlings for beneficial root and stem characteristics (Kormanik 1986; Kormanik and others 1994, 1995). Given new technology and the continued critical need for oak regeneration on high-quality mesic sites, evaluation of oak seedling field performance is crucial.

In this study we observed survival, growth, and early acornet production potential of artificially regenerated NRO on two high-index sites. We employed a specific nursery protocol to produce large, high-quality 1-0 NRO stock and compared half-sib family effects on these parameters of NRO seedlings grown on either clearcut or shelterwood sites.

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MATERIALS AND METHODS

Nursery Practices

Open-pollinated half-sib acorns were collected during the fall of 1993 from individual NRO mother trees at the Watauga Seed Orchard in eastern Tennessee. The acorns were collected daily from shade cloth placed beneath the trees' crown area and were immediately placed in water-filled buckets. Floating acorns were discarded. Acorns that sank were presumed to be sound and were used in this study. Acorns were stored at 4 to 6 °C for approximately 40 to 55 days until sowing at the Georgia Forestry Commission's Flint River Nursery near Montezuma, GA.

Acorns were sown during early December 1993 in seedling beds at a density of 54 to 57/m^2. The acorns from specific mother tree seed lots were sown continually within a bed with a 2-m void left between seed lots. Approximately 3-cm depth of well-decomposed sawdust was then applied to the surface of all beds. The nursery fertilization schedule reported by Kormanik and others (1994) was used in all nursery beds throughout the growing season. Prior to sowing, the extractable soil nutrient concentrations were determined and adjusted to maintain calcium at 500, potassium at 130, phosphorus at 100, magnesium at 75, copper at 0.3 to 3, zinc at 3 to 8, and boron at 0.4 to 1.2 ppm. A total of 1,322 kg/ha of NH_4NO_3 was applied to the developing seedlings incrementally through the growing season. Initial increments were gradually increased as the seedlings developed. The first two applications equaled 17 kg nitrogen (N)/ha; the third was 56 kg N/ha. The next six applications were 168 kg N/ha, and the final two were 112 kg N/ha. These N applications began in mid-May and continued at 10- to 14-day intervals until mid-September. Irrigation was provided through the growing season when rainfall was < 2.5 cm per week. After October 15, irrigation continued at a reduced rate until leaf abscission layers developed in early December.

The seedling taproots were undercut at approximately 30-cm depth prior to lifting in February 1995. The lifted seedlings were then graded, and their first-order lateral roots trimmed to 15 cm. The minimum acceptable seedling morphological grading standards for this study were six first-order lateral roots, 8-mm root-collar diameter (rcd), and 0.7-m height (hgt) for all progeny groups. The seedlings were packaged and kept at 4 to 6 °C until outplanting.

Site Conditions, Outplanting, and Silvicultural Management Practices

Both planting sites had comparable site quality. The site indices$_{50}$ ranged between 28 and 32 m for yellow poplar, which was the original dominant species in both stands. The Wayah site had approximately 30 co-dominant yellow poplar trees/ha left in the shelterwood created during spring and summer of 1993. All understory stems were cut, and the logging debris was moved to the perimeter of the planting site. The soil at Wayah is a Trimont fine loam (mixed, active Humic Hapludult) with a northeast aspect, an elevation between approximately 885 to 900 m, and a slope of 25 to 35 percent.

The Brasstown site on the Brasstown Ranger District in north Georgia was about 100 km southwest of the Wayah site and was clearcut in late summer 1993 in a salvage operation, after a severe wind incident 2 years earlier. Slash and other logging debris were moved to the perimeter of the planting. The soil at Brasstown is a Tusquittee fine loam (mesic typic Dystrudept); the site has a northeast aspect, an elevation of approximately 830 to 850 m, and a slope of 15 to 25 percent.

The study design consisted of separate randomized block experiments with 10 replications at each of the 2 sites. In February 1995, in each replication at both sites, progeny from nine NRO families were planted at 3.1 by 3.1 m in five tree plots. In addition, each site had a unique set of 16 NRO families. Because these additional families were not common to both sites, they were not used in the statistical analysis. However, they did provide supplemental information for data interpretation.

Seedling hgt and rcd at lifting (year zero) were recorded. The Brasstown site was measured after year one and then annually from year four through year seven for hgt and diameter at breast height (d.b.h.). The Wayah site was measured annually from year two through year five and at year seven for the same parameters. In addition, a surrogate for total stem relative volume (vol) was defined as the product of d.b.h.^{2} and hgt and was also analyzed. Since no reliable volume equations were available for NRO saplings at these sites, the surrogate allowed us to compare the relative productivity. We evaluated all trees at both locations for acornet presence in year seven and acorn production in year eight.

Originally, glyphosate herbicide was to be applied on both sites at recommended rates, beginning with stump treatment prior to planting, to control sprouting and other competing vegetation (Loftis 1978). Thus, the only silvicultural difference between the two sites would have been yellow poplar as shelterwood on the Wayah site. However, herbicide application was delayed until in year two (1996) at Brasstown, and no herbicide was ever used at Wayah. In year two, glyphosate was used to control stump sprouts and to reduce competition from innumerable newly established yellow poplar seedlings at Brasstown. These new seedlings were spot treated with glyphosate during year three (1997). From years four to seven, spot application of glyphosate was primarily used to control grapevine (*Vitis* spp.), which invaded along the perimeter of the planting. Annual weeds such as asters and ragweed (*Ambrosia* spp.) on either site were not controlled.

On the Wayah site, where herbicide use was not permitted, stump sprouts prior to planting were removed by chain saw or brush saw. However, these stumps resprouted, along with new yellow poplar seedlings, blackberry (*Rubus* spp.), and grapevine that apparently responded well to the openings created during the first 3 years. All such competing vegetation was removed around each tree with hand tools and brush saws following the fourth growing season. This release treatment was again applied after year six to control the rapidly growing competition.

STATISTICAL ANALYSIS

Separate randomized block experiments were established at each site to determine the family effect (a fixed factor) on survival and growth. The Brasstown site had 10 replications, but the Wayah site had only 9 replications, because 1 incomplete replication was deleted from subsequent analyses. Variables for analysis were survival, hgt, rcd, d.b.h., and vol on a plot mean basis. During the course of the study, we interpreted any stump sprouts from previously recorded dead trees as dead in any subsequent year's analyses.

Analysis of variance was performed with PROC GLM (SAS Institute 1989) to detect family differences. For simplicity, Tukey's mean separation tests are presented only for year seven. Initially, hgt, diameter, and vol were analyzed for individual trees with a generalized linear model to reflect the unbalanced statistical design at the subsampling level. Least square means were computed, and F-tests were performed by synthesizing the appropriate denominator mean squares by using the RANDOM statement with the TEST option in SAS. Despite the unbalanced statistical design, these results were virtually identical to those based on the plot means. In addition, since survival was defined as the proportion of surviving trees per plot, it had to be analyzed on a plot basis. Thus, for consistency and simplicity, the analysis of variance based on plot means was used in the study.

To formulate a comparison between the two sites (fixed effect) and thus increase the scope of inference for the family effects, a combined analysis over sites was performed by using the nine common families at each site in a randomized block design. The site-family interaction was tested, and, when nonsignificant, the main effects of site and family were analyzed for the same variables as those in the separate analyses. Analysis of variance procedures tested the site effect with the block (site) mean square, while the family and site-family interaction was tested with the residual mean square (McIntosh 1983).

Growth models were developed to predict hgt, d.b.h., and vol as a function of years. The nonlinear exponential model was fitted on an individual tree basis for the nine families. PROC NLIN (SAS Institute 1989) was used to obtain the parameter estimates and the mean square error.

RESULTS

No statistical significance was found for survival between the nine families on either the Brasstown or Wayah sites (table 1). Year seven survival ranged from 56 to 86 percent at Brasstown and from 60 to 87 percent at Wayah (data not shown). In the combined analysis of survival, the effects of site, family, and the site-family interaction were not significant. Survival at year seven was 76 percent for Brasstown compared to 72 percent for Wayah (table 2). Vole (*Cricetidae* spp.) predation was a major mortality factor on both sites for 2 years after outplanting.

Seedling hgt, rcd, and vol had significant family differences at both sites at the initial outplanting (year zero). This result reflects the varying genetic growth potentials in the nursery for the nine different families (table 1). Based on randomization of seedlings at study installation, there should be no difference between sites in the growth parameters at year zero. As expected, the mean values for seedling hgt and vol were not different between two sites (table 1). The mean values for hgt and vol were 91 cm and 99 cm^3 for Brasstown and 89 cm and 105 cm^3 for Wayah. Although seedlings at Brasstown had smaller rcd than those at Wayah, 10.1 mm vs. 10.5 mm, respectively, the difference is not of much biological significance.

At the Brasstown site, the family effect became nonsignificant at 5 and 7 years for hgt (table 1). However, d.b.h. and, consequently, vol showed significant family effects. The Wayah site maintained significant family effects for hgt and d.b.h. for years five and seven. The combined analysis revealed no significant interactions for site-family for any of the variables (table 1).

Growth analyses revealed similar results at years five and seven (table 1) and thus, for simplicity, table 2 presents only mean comparisons for year seven. Over both sites, family means ranged from 2.92 m to 3.71 m for hgt, 20.8 to 30.9 mm for d.b.h., and 2,072 to 5,789 cm^3 for vol. Despite highly significant family *p*-values, Tukey's test revealed very few differences among the family means in all growth parameters in the combined analysis (table 2). Based on vol, families 482, 479, and 473 were significantly larger than family 448. Although not statistically significant, family 442 had the largest mean hgt and d.b.h. of all families. Family 442, however, did not have larger mean vol than family 448. This result may have been due to a different hgt-d.b.h. relationship for this family. For example, a tall tree may have a relatively smaller d.b.h., while a small tree may have a relatively larger d.b.h. Since vol was calculated for individual trees, the discrepancy reflected by family mean of vol for family 442 was not alarming.

At year seven, Brasstown's growth parameters were larger than Wayah's, with hgt 27 percent larger, d.b.h. 62 percent larger, and vol , 179 percent larger (table 2). Thus, although survival was similar on both sites, stand productivity was markedly superior on the Brasstown site. The nonlinear exponential growth models for hgt, d.b.h., and vol derived from nine family means on each site appear in figure 1. The growth parameter estimates in the exponent of models were greater at the Brasstown site.

We first observed acornets on trees of the Brasstown site at year seven and mature acorns in the fall of year eight. Eight of the nine families at Brasstown had at least one tree that produced acornets (table 2). A total of 5.3 percent of trees in all nine families produced acornets at Brasstown. Only family 438 did not show any precocious acornet production in year seven (table 2). Of the 16 supplemental families at Brasstown, 8 had at least 1 tree producing acornets. A total of 3.9 percent of all the 16 families produced acornets. We observed no acornets on any trees at the Wayah site through year seven.

DISCUSSION

The same nursery protocol employed in this study has consistently produced large, quality NRO seedlings from well over 100 open-pollinated NRO families (Kormanik and others 1994, 1995, 1998, 1999). These seedlings meet or exceed size standards associated with desirable NRO advanced regeneration (Loftis 1983, Sander 1972). Seedlings meeting our grading criteria, i.e., six first-order lateral roots, 8-mm rcd, and 0.7-m hgt, can survive and develop well after outplanting in various locations in Georgia, North Carolina, South Carolina, and Tennessee (Kormanik and others 1998, P. Kormanik unpublished data). Our results disagreed with previous reports that 1-0 NRO seedlings are unsuitable for artificial regeneration (Dey and Buchanan 1995, Zaczek and others 1997). These studies employed different cultural practices and grading criteria than ours. Varying seedbed density, fertility, and irrigation regimes can alter the absolute value of any size-based seedling grading criteria. However, the grading of seedlings by first-order lateral root numbers remains consistent, because it is a highly heritable trait within a population (Kormanik 1986; Kormanik and others 1998, 1999). As the first-order lateral root count drops below the mean value for a

Table 1—Results (*p*-values) from the analysis of variance for nine families of nursery grown northern red oak 1-0 seedlings outplanted in February 1995

Variable	Source	Year 0	Year 5	Year 7
		Brasstown		
Survival	Family	—	0.065	0.122
Arcsine $\sqrt{Survival}$	Family	—	0.084	0.177
Height	Family	0.000	0.208	0.128
Diameter[a]	Family	0.000	0.047	0.036
Volume	Family	0.000	0.027	0.020
		Wayah		
Survival	Family	—	0.716	0.688
Arcsine $\sqrt{Survival}$	Family	—	0.482	0.455
Height	Family	0.000	0.005	0.005
Diameter	Family	0.000	0.002	0.005
Volume	Family	0.000	0.056	0.056
		Brasstown and Wayah Combined		
Survival	Site	—	0.490	0.415
	Family	—	0.373	0.524
	S*F	—	0.249	0.240
Arcsine $\sqrt{Survival}$	Site	—	0.409	0.363
	Family	—	0.278	0.441
	S*F	—	0.193	0.192
Height	Site	0.164	0.027	0.000
	Family	0.000	0.001	0.002
	S*F	0.071	0.238	0.080
Diameter	Site	0.010	0.001	0.000
	Family	0.000	0.000	0.001
	S*F	0.697	0.479	0.216
Volume	Site	0.083	0.001	0.001
	Family	0.000	0.002	0.003
	S*F	0.295	0.551	0.276

— = not applicable.
[a] Diameter was root collar at year 0 and breast height at years 5 and 7.

given half-sib family, seedling sizes are smaller, and their survival and growth in field plantings are significantly reduced (Kormanik and others 1998, 1999).

Survival of transplanted NRO was similar on Brasstown and Wayah sites through year seven (tables 1, 2). Most of the mortality occurred within the first 2 years of outplanting due to vole damage. However, despite vole damage, the use of large, high-quality 1-0 planting stock may account for > 70 percent seedling survival on both sites. Comparing actual survival among families is of minimum value, because survival may represent rather random results of vole feeding rather than the inherent competitive ability of specific families.

Throughout its range, NRO has the reputation of being difficult to regenerate on high-quality mesic sites. However, most regeneration procedures do not adequately consider the biological requirements of NRO. On high-quality mesic sites, NRO cannot thrive in understory shade. On shelterwood regeneration sites, poor root system development under shade conditions makes this species a questionable choice (Barton and Gleeson 1996, Kormanik and others 1998, Sung and others 1998). Our study shows that early performance of individual NRO seedlings on high-quality mesic sites depends upon the level of maintenance imposed upon the site (table 2, fig. 1). Seedlings at Brasstown had 179 percent greater vol than those at Wayah. Residual shelterwood trees at the Wayah site were not the primary factor affecting NRO growth. Although both sites sustained vole damage during the first 2 years, by year three at Wayah, grasses, brambles, and stump sprouts overtopped seedlings, adversely affecting their growth. At the end of the fourth growing season at the Wayah site, mechanical release temporarily reduced competition; however, with no subsequent vegetation control, severe overtopping again occurred by year six.

Seedlings at the Brasstown site, on the other hand, experienced no overtopping. In many NRO field trials we have observed, although top growth during the first 3 years after outplanting may be limited, root development is rapid. If overtopping occurs during this early period, it is highly unlikely that a competitive root system will develop, and the seedlings

Table 2—Least square means for site and family effects at year 7 for nine families of nursery grown northern red oak 1-0 seedlings outplanted in February 1995

Site[a]	Survival	Height	D.b.h.	Volume	Acornets[b]
	%	m	mm	cm^3	
Brasstown	76 a	3.80a	33.3a	5936a	18
Wayah	72 a	3.00b	20.5b	2128b	0
Family[a]					
435	73 a	2.92b	21.1bc	2964ab	1
438	76 a	3.55ab	27.2abc	3812ab	0
439	79 a	3.26ab	26.6abc	3493ab	1
442	84 a	3.71a	30.9a	4840ab	1
443	74 a	3.67a	28.2abc	3749ab	2
448	72 a	3.01ab	20.8c	2072b	1
473	65 a	3.59ab	30.9a	5254a	5
479	72 a	3.58ab	29.9ab	5407a	5
482	73 a	3.54ab	29.8ab	5789a	2
Site (extra families)[c]					
Brasstown	76	3.49	30.2	4901	24
Wayah	66	2.77	17.7	1620	0

[a] Means within a column followed by the same letter are not significantly different at the 0.05 level based on Tukey's studentized range test.
[b] Number of trees with acornets.
[c] Simple means for 16 additional families at the Brasstown and 16 additional at the Wayah sites.

will not become part of the main canopy (Sung and others 1998). Growth at the Brasstown site was rapid, and some crowns began to touch in year five. By year seven, many more individual crowns of adjacent trees were beginning to touch. No branch touching was observed among the oaks at the Wayah site through year seven. Although not statistically analyzed, the supplemental 16 families also exhibited the trend of better growth at the Brasstown site when compared with the other 16 families planted at the Wayah site at year seven (table 2).

Acorn Production

Oak species, particularly NRO, show considerable variability as to when they initiate acorn production. In a German forest environment, acorn initiation can begin by age 40 (Büsgen and Münch 1929), but more recent research in the United States reports acorn production within 25 to 50 years (Sander 1990). In our study, only the most competitive seedlings were outplanted. Given a favorable growing environment, we assumed that some trees would be genetically capable of early mast production by age 10 to 15. While we observed no acornet development at the Wayah site, at least one tree in 18 of 25 families at Brasstown had produced acornets in year seven (table 2). Even though only a few individuals developed acornets, such early production is unusual in a stand without irrigation or fertilizer application. In year eight, we planned to place nets under the crowns of all trees that had maturing acorns. In September 2002, we completed the necessary clearing beneath the trees and initiated weekly observations of acorn drop. Approximately 2 weeks later, before acorn drop began and netting was in place, squirrels (*Sciuridae* spp.) migrated from adjacent areas and harvested the entire maturing crop. While we do not know the exact number of maturing acorns, the crop varied from few (about 20 to 30 acorns) to heavy (100 to 200 acorns) on individual trees.

Zimmermann and Brown (1971) suggested that tree age may not be the critical factor governing flower production. They speculated that optimal nutrition and increased vigor may be sufficient to switch on the flowering genes at an early age in individual trees. Similarly, Cecich (1993) concluded that while acorn production is highly heritable, maintaining a vigorous crown is critical to enhance this trait. Sugars may play dual roles as an energy source and a signal for flowering (Bernier and others 1993 and references cited therein). Roldan and others (1999) showed that supplying sucrose exogenously to the aerial parts of dark-grown *Arabidopsis thaliana* plants induced flowering. In our study, early mast production occurred only at the Brasstown site where vegetation competition was controlled and the crowns were essentially free from competition. This result supports the concept that adequate sunlight is important to early acorn production, because energy-intensive flower initiation requires high sugar levels from enhanced photosynthesis (Cecich 1993, Kramer and Kozlowski 1960). In other field studies in Northern Carolina, South Carolina, and Georgia, using the same nursery protocol and silvicultural management practices as on the Brasstown site, we have observed acorn production as early as age 5 in NRO, cherrybark oak (*Q. pagoda* Raf.), and white oak (*Q. alba* L.).

CONCLUSIONS

This study clearly established that large plantable 1-0 seedlings can enhance artificially regenerating NRO on high-quality mesic sites where its existence is precarious. However, competing vegetation must be controlled adequately to realize growth of approximately 3.5 to 4.0 m at year seven and early

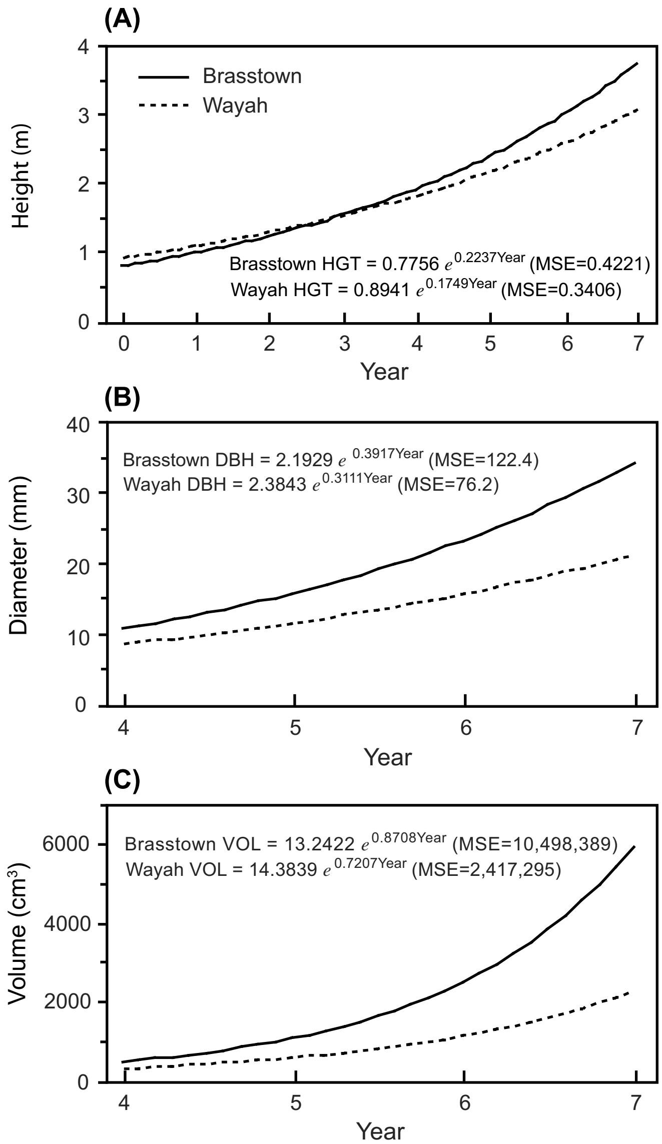

Figure 1—Growth relationships for (A) height, (B) diameter at breast height, and (C) volume for young northern red oak stands established in February 1995 on the Brasstown and Wayah sites.

acorn production. At the Brasstown planting site, artificial regeneration of high-quality NRO produced mast to satisfy both wildlife and regeneration. Judicial use of herbicides and cultural measures, such as fertilization and insect control, helped establish small oak stands and enhanced early acorn production.

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