GROWTH AND DEVELOPMENT OF FIRST-YEAR NURSERY-GROWN WHITE OAK SEEDLINGS OF INDIVIDUAL MOTHER TREES

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Abstract—White oak (*Quercus alba* L.) acorns from individual mother trees at Arrowhead Seed Orchard (ASO, Milledgeville, GA), Beech Creek Seed Orchard (BSO, Murphy, NC), and Savannah River Site (SRS, Aiken,SC) were sown in December 1999 at Whitehall Experiment Forest Nursery (Athens, GA). All 6 mother trees from BSO were grafted. By early April, germination exceeded 80percent for all but six families. Five of these six families were from BSO. Seedlings that emerged after mid-April generally were much smaller in size than those emerging earlier. More than 60 percent of seedlings from each seed source group had fewer than mean first-order lateral root (FOLR) number. Buds for the first flushes started swelling near the end of April for most seedlings. Time span from current bud swelling to next bud swelling in most seedlings was approximately 33 days for all flushes. Regardless of seed sources, elongation of the third, fourth, and fifth flushes occurred mainly between 4 and 12 days post bud break (dpbb) with most active elongation occurring approximately 10 dpbb. About 89, 55, and 9 percent of ASO and SRS seedlings had three, four, and five flushes, respectively. Only 60, 15, and 2 percent of BSO seedlings had three, four, and five flushes. Seedlings with first flush length shorter than 5 centimeter generally had lower values in growth parameters including height, root collar diameter, flush number, and FOLR number. Based on germination rate and first flush length, it may be possible to assess progeny quality of given mother trees as early as mid-May. Progeny from grafted mother trees performed poorly in nursery as compared to progeny from other groups based on all parameters except for diameter.

INTRODUCTION

There have been two *Quercus* regeneration practices used to maintain a significant oak component in new stands following a harvest. One practice depends on obtaining advanced oak regeneration by shelterwood or selection harvesting the current stands. Although this may be successful on lower quality upland sites (Sanders 1971, Lortis 1983), it may not be successful on high quality mesic sites due to the presence of fast growing, competing woody species that will generally occupy the site once the final canopy is removed (Loftis 1990, Hodges and Gardiner 1993, Lorimer 1993). The other practice, artificial oak regeneration, involves planting high quality 1-0 nursery stocks on clearcut sites as advocated by Kormanik and others (1997,1998,2000). This practice takes only the top 50 percent of 1-0 oak seedlings grown under a specific hardwood nursery protocol developed by Kormanik and others (1995). Seedlings are graded by their height, root collar diameter (RCD), and number of first-order lateral roots (FOLR) that are greater than 1 mm in diameter. It has been proven with loblolly pine (Kormanik and others 1990) and various oak species including white oak (Kormanik and others 1997, 2000) that FOLR number is highly heritable and a good indicator of seedling quality in nursery and outplanted performance in field.

Here we investigated the growth and development of 1-0 white oak seedlings from different mother trees from different states. The primary interest was to identify and quantify any early indicator of seedling quality that might be used with progeny from future mother tree selections.

MATERIALS AND METHODS

Open pollinated white oak (*Quercus alba* L.) acorns from individual mother trees in Arrowhead Seed Orchard (ASO, Milledgeville, GA), Beech Creek Seed Orchard (BSO, Murphy, NC) and Savannah River Site forest stands (SRS, Aiken, SC) were sown at a density of 54 to 57 per meter^2 in December 1999 at Whitehall Experiment Forest Nursery (Athens, GA). Seedlings were grown using the oak nursery protocol of Kormanik and others (1994). There were 25, 6, and 15 half-sib families from ASO, BSO, and SRS, respectively. All 6 mother trees from BSO were grafted. Four ASO, six BSO, and 14 SRS families were planted in a randomized block design with two blocks each consisting of 130 acorns per family. The other families were planted in an identical manner but with only 65 acorns per family per block. Germination percent was assessed as shoot emergence on March 23 and April 5, 2000. Numbers of seedlings with swelling first flush bud that was at least 3 millimeter long or elongating first flush were recorded for

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Table 1—Germination and flush development of all white oak seedlings from individual mother trees at Arrowhead Seed Orchard (ASO), Beech Creek Seed Orchard (BSO), and Savannah River Site forest stands (SRS)

	ASO[a]	BSO	SRS
Acorn FW[b] (g)	4.6±1.2	4.3±1.1	4.3±1.1
Mar 23 Germ (pct)	85±8.9	60±29.0	87±7.4
Apr 5 Germ (pct)	90±8.0	62±30.0	92±4.9
Apr 25 1st Fl[c] (pct)	28±10.9	20±10.5	18±12.5
May 29 2nd Fl (pct)	55±9.2	27±8.1	37±17.3

[a] In December 1999, acorns from 25 ASO, 6 BSO, and 15 SRS mother trees were sown.
[b] Mean acorn fresh weigh (± sd) were obtained by weighing the entire family before sowing.
[c] Seedlings with swelling flush bud or elongating flush were considered to have initial flush development.

each family on April 25. Seedlings with swelling second flush bud or elongating second flush were counted for all families on May 29. All seedlings were lifted in late January 2001. Height, root collar diameter (RCD), and FOLR number were recorded for all seedlings of each of the 12 ASO, 6 BSO, and 15 SRS families. Thirteen ASO families with 65 acorns per family per block were not evaluated for these growth parameters.

In mid-April, 2000 we established the "All Flush Development Sub-study" that intensively followed 10 ASO, five BSO, and five SRS families. These families were part of those assessed for height, RCD, and FOLR number at lifting. For families with 65 acorn per replication every fifth seedlings were tagged for observation. For those families with 130 acorns per replication, every tenth seedling was tagged. This resulted in 13 seedlings per replication in each of the 20 families. Thus, a total of 520 seedlings were assessed for flush development two to three times a week throughout the growing season. The date of bud break as determined by the first appearance of a flush leaf, flush length, and leaf length were recorded.

On June 12, the "Detailed Flush Development Sub-study" was initiated on an additional 144 seedlings with swelling third flush buds. These seedlings were labeled and followed daily for flush elongation and leaf expansion. Development of the fourth and fifth flushes were followed every other day. This sub-study consisted of 68 seedlings from 18 ASO families, 9 seedlings from five BSO families, and 67 seedlings from 13 SRS families. Flush length was modeled on an individual seedling basis with the logistic equation defined as:

$$\text{FLUSH} = \frac{a}{(1 + e^{b + c\,\text{DAY}})}$$

where FLUSH = flush length (cm), DAY = days post bud break, and a, b, c = parameters of the logistic function. Nonlinear regression was used to estimate the parameters using PROC NLIN (SAS Institute Inc. 1989). The instantaneous rate of flush growth at a given day was obtained by determining the slope of the specific logistic

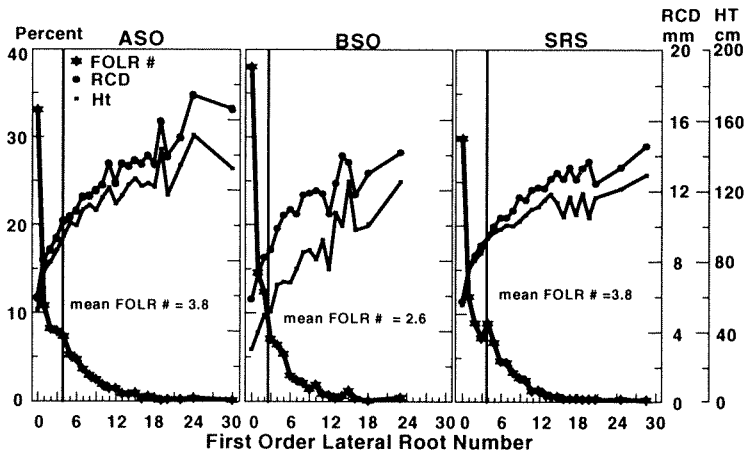

Figure 1—Frequency distribution of first-order lateral root (FOLR) number of 1-0 white oak seedlings with height and root collar diameter in each FOLR group. Acorns were from 12, 6, and 15 individual mother trees at Arrowhead Seed Orchard, Beech Creek Seed Orchard, and Savannah River Site forest stands, respectively.

Table 2—Comparisons between late emerging (after April 15, 2000) and normal emerging white oak seedlings from individual mother trees at Arrowhead Seed Orchard (ASO), Beech Creek Seed Orchard (BSO), and Savannah River Site forest stands (SRS)

Emergence time	Seed source	Germination Pct	Height cm	RCD mm	FOLR #
Normal[a]	ASO[b]	90.0	82±35.0	9.0±3.3	3.8±4.9
Late	ASO	0.5	52±28.0	5.6±2.2	1.4±2.2
Normal	BSO	72.0	49±28.3	8.1±2.7	2.7±3.6
Late	BSO	7.2	33±16.8	6.1±2.0	0.9±1.7
Normal	SRS	86.0	82±30.6	8.6±2.8	3.9±4.5
Late	SRS	2.4	48±29.8	5.1±2.5	1.0±2.3

[a] Seedlings germinated before April 15.
[b] Twelve ASO, 5 BSO, and 15 SRS families were assessed. Family NAWO-23 was not included because it only had 5 percent germination.

equation evaluated at that day. This was found by differentiation with respect to DAY, yielding

$$\text{SLOPE} = \frac{-a\,c\,e^{b+c\,\text{DAY}}}{(1+e^{b+c\,\text{Day}})^2}$$

and then substituting the appropriate day in this equation. The inflection point of the logistic function is where the instantaneous rate of flush growth reaches its maximum and begins to slow down. It is found by setting the second derivative equal to zero and solving for DAY, which yields Inflection Day = -b/a

RESULTS AND DISCUSSION

Main Study

Germination percentages were similar between ASO and SRS families with BSO having 25 percent less germination in March and April (table 1). By April 5, all but six families had more than 80 percent germination (data not shown). Families ASO-1, NAWO-23, SAWO-38, SAWO-28, NAWO-29, and NAWO-28 had 55, 5, 48, 73, 78, and 79 percent germination, respectively. The latter five families were from the Beech Creek Seed Orchard. No correlation existed between acorn weight and germination percent of individual families. Of these seed sources, more ASO seedlings started forming the first flush on April 25 and the second flush on May 29 than seedlings of the other two groups. More SRS seedlings had the second flush than BSO on May 29 (table 1).

When seedlings were pooled within each seed source and stratified based on their FOLR numbers, all three seed sources exhibited a reversed J distribution (figure 1). This relationship was also exhibited on an individual family basis (data not shown). Similar FOLR distributions have been reported for loblolly pine (Kormanik and others 1990) and various oak species including white oak (Kormanik and others 1997). Sixty-seven percent of ASO, 65 percent of SRS, and 70 percent of BSO seedlings had fewer than their respective mean FOLR number (figure 1). These values were comparable to the white oak results observed by Kormanik and others (1997). In the present study, 33, 30, and 38 percent of ASO, SRS, and BSO seedlings, respectively, had zero FOLR. Correlation coefficients between FOLR number and RCD were 0.75, 0.74, and 0.72 for ASO, BSO, and SRS seedlings. Correlation coefficients between FOLR number and height were 0.64, 0.69, and 0.55 for ASO, BSO, and SRS seedlings. Mean RCD were similar among three seed sources whereas BSO seedlings were 40 percent shorter than ASO or SRS seedlings (figure 1, table 2). There was a higher percent of late emerging BSO seedlings than SRS seedlings (table 2). Only a few ASO seedlings emerged after April 15. All the late emerging seedlings were smaller in size and had fewer FOLR than the normal seedlings (table 2).

Family SRS-596 had 85 percent germination on April 5 and about 35percent of these seedlings were albino, that is, their leaves had very low levels of chlorophyll. These seedlings eventually died. Furthermore, compared to the SRS group means, the green SRS-596 seedlings were smaller in size with 47 centimeter height and 6.8 millimeter RCD, but had 4.2 FOLR which is comparable to SRS group mean. Family KYWO-31 is the only grafted tree that had 91 percent germination in April. Still, mean height for this family was only 55 centimeter. Results from previous studies of acorns collected from grafted mother trees at BSO, including some of the same families in this study, showed low germination percent and short seedling size (Kormanik and others 1997). Reasons for poor germination and shorter stem for progenies from most grafted mother trees in Beech Creek Seed Orchard are unclear. This study indicated that based on germination percent, morphology, and growth parameters, ASO-1, SRS-596, and all BSO mother trees produce poor quality progeny.

Detailed Flush Development Sub-study

Figure 2 shows the daily growth of the third flush of an ASO-16 seedling with leaf length (long axis) expansion for the fourth leaf from the bottom of the flush. Most of the 144

Table 3—Growth and developmental parameter means (± sd) of 520 white oak seedlings from individual mother trees at Arrowhead Seed Orchard (ASO), Beech Creek Seed Orchard (BSO), and Savannah River Site forest stands (SRS)

	ASO	BSO	SRS
		General Growth Parameters	
Height (cm)	80±32.8	50±29.6	76±33.6
Root collar diameter (mm)	9.4±2.9	8.3±2.6	8.0±2.9
First-order lat root number	3.9±5.1	2.6±3.8	4.3±6.0
		From Bud Swelling to Bud Swelling (d)	
1st flush to 2nd flush	32.5±5.2	32.4±3.9	32.8±6.1
2nd flush to 3rd flush	32.2±4.1	35.9±6.0	33.2±3.9
3rd flush to 4th flush	33.0±4.6	35.8±5.4	33.0±3.5
4th flush to 5th flush	32.4±3.0	32.0±1.4	33.0±5.5
		Flush Length (cm)	
Epicotyl	10.3±2.1	8.0±2.3	9.1±2.0
1st flush[a]	7.9±3.2	4.6±2.4	7.1±2.5
2nd flush	16.7±5.6	14.9±6.1	14.5±5.2
3rd flush	26.2±6.4	27.0±10.0	25.2±7.1
4th flush	36.2±9.1	38.0±17.7	35.2±9.9
5th flush	31.0±9.8	26.2±4.7	27.6±8.8
		Seedling Percentage (pct)	
1st flush	99	100	100
2nd flush	98	89	98
3rd flush	87	60	88
4th flush	53	16	57
5th flush	9	2	9

[a] Mean flush length was derived from sum of flush length divided by number of seedlings with that given flush, instead of total seedling number. Therefore, sum of epicotyl length and all five flush lengths is greater than measure height.

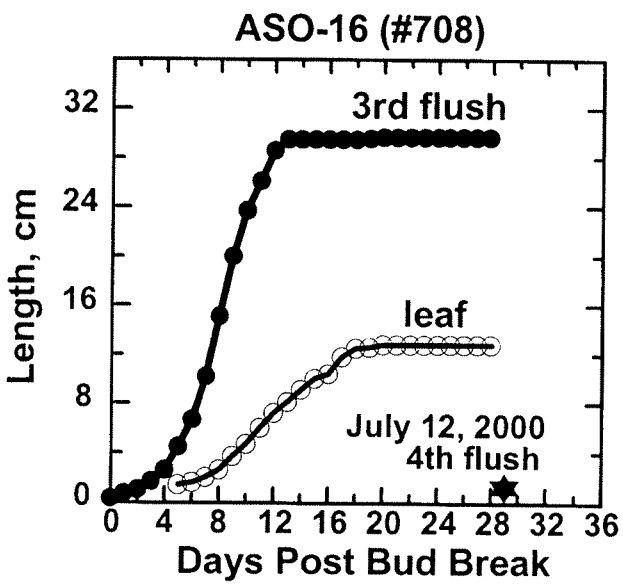

Figure 2—Daily elongation of the third flush and leaf length extension of the fourth leaf from the bottom of the third flush in a white oak seedling from family ASO-16.

seedlings selected for the Detailed Flush Development Sub-study had similar temporal patterns for flush elongation and leaf expansion curves. Generally, flush elongation was linear between 4 and 13 dpbb (figure 2). Leaf expansion lagged several days behind active flush elongation. There seemed to be a span of one week between leaf maturation and appearance of the next flush bud for most seedlings.

For the Detailed Flush Development Sub-study, only the third, fourth, fifth flush growth curves of ASO seedlings were presented in figure 3. Similar curves were observed with SRS seedlings (data not shown). Inflection points for the third, fourth, and fifth flushes of ASO seedlings were 9.7, 12.4, and 10.9 dpbb. Slopes, (i.e., elongation rates, centimeter/day), at the inflection point for the third, fourth, and fifth flush were 3.9, 3.7, and 4.6 (figure 3). Inflection point (dpbb) and its slope for the third, fourth, and fifth flushes of SRS seedlings were as follows: 9.6 and 3.4, 11.1 and 3.5, and 10.1 and 4.3, respectively. The third flush growth curve of BSO seedlings had the inflection point at 10.9 dpbb with a slope of 4.5.

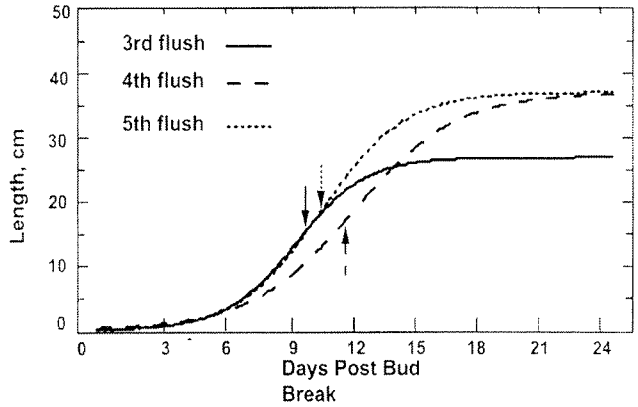

Figure 3—Logistic curves for third, fourth, and fifth flush development of the same white oak seedlings from Arrowhead Seed Orchard. The inflection points were indicated with arrows. Sixty-eight seedlings were included for the third flush development. Of these seedlings, 63 had the fourth flush and 37 produced the fifth

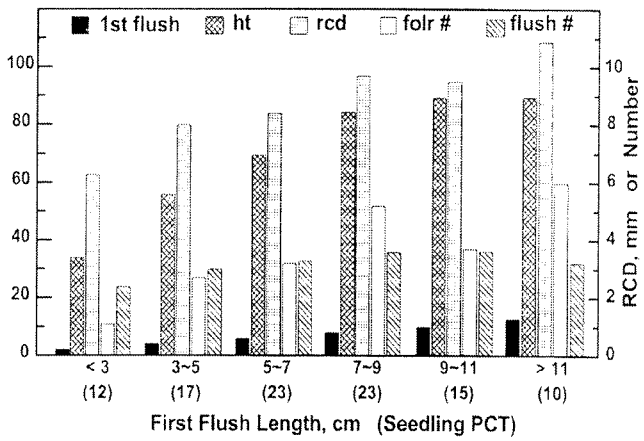

Figure 4—Growth parameter means of 520 1-0 white oak seedlings grouped by the length of their first flushes. Acorns were from 10, 5, and 5 individual mother trees at Arrowhead Seed Orchard, Beech Creek Seed Orchard, and Savannah River Site forest stands, respectively. Values in parentheses were centages of seedlings in each group.

All Flush Development Sub-study

The 520 seedlings selected for the All Flush Development Sub-study had similar height, RCD, and FOLR number to their corresponding group in the Main Study (table 3 versus figure 1). Seedlings of ASO and SRS were also comparable in all growth parameters including individual flush length and flush number (table 3). More than half of ASO and SRS seedlings had four flushes as compared to only 16 percent for BSO seedlings. Furthermore, BSO seedlings had the shortest first flushes.

First flush buds began to swell in late April. Mean julian days for swelling of the first flush buds were 118 ± 5.0, 120 ± 6.8, and 121 ± 7.7 for ASO, BSO, and SRS, respectively. A span of 33 days existed from the swelling of a flush bud to the swelling of the subsequent flush bud for all flushes of ASO and SRS seedlings (table 3). However, BSO seedlings had a span of 36 days for second to third and for third to fourth flush bud swelling. For some seedlings, when a bud appeared much later than the average bud to bud span of 33 to 36 days, these buds usually remained tight for the rest of the growing season. For all seedlings, each flush was longer than its previous flush except for flush five which was shorter than the fourth (table 3). This might be related to a shortening photoperiod during the fifth flush development in September.

It has been reported that heritability estimates are in the range of 0.55 to 0.92 with small standard errors for various oak species (Kormanik and others 1997) and loblolly pine (Kormanik and others 1990). Seedlings with many FOLR are competitors in the nursery and perform well after outplanting (Kormanik and others 1998, this proceedings). Thus, in our effort to artificially regenerate oak stands on high quality mesic sites, three criteria have been used to grade 1-0 seedlings at lifting (Kormanik and others 1997,1998,2000). They are $60 centimeter height, $7 millimeter RCD, and $ 5 FOLR for white oak (Kormanik and others 2000). The mean FOLR was suggested to be the most important seedling selection criterion (Kormanik and others, 1997, 1998, 2000). In this study, mean FOLR for ASO and SRS was about 4 (table 2). Mean FOLR for BSO was 2.6. Seedlings which met at least two of the three criteria, namely $ mean FOLR, $ 8 millimeter RCD, and $ 70 centimeter height were outplanted on various National Forests in Georgia, South Carolina, North Carolina, and Tennessee in February 2001 for seed orchard establishment. Field performance of these seedlings will be followed over time.

Figure 4 presents the 520 seedlings in the All Flush Development Sub-study based on their first flush length. It is evident that seedlings with first flushes shorter than 5 centimeter did not meet two of our three nursery grading standards. About forty percent of the seedlings were evaluated as low quality stocks (figure 4). Since most seedlings finished their first flush elongation by mid-May, it might be feasible to assess the quality of first year nursery-grown seedlings by mid-May. All seedlings in this sub-study were transplanted into nearby nursery beds at Whitehall Experiment Forest. Their performance also will be monitored.

Combining the data of germination percent, seedling morphology (such as albino leaf), and first flush length, one should be able to identify competitive progeny before June. For example, most seedlings from BSO had first flush lengths shorter than 5 centimeter, mean heights less than 70 centimeter, and germination rates less than 80 percent (tables 1, 3). Acorns from these grafted mother trees should not be collected in the future for artificial oak regeneration. Our future study will test the following two hypotheses: that heritability estimates for first flush length of 1-0 nursery-grown oak seedlings are similar to those for FOLR number and that there are high correlations between these two parameters. In addition to FOLR number, first flush length might be a good indicator of seedling competitiveness and performance in the nursery and field.

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