THE INFLUENCE OF CULTURAL TREATMENTS ON THE LONG-TERM SURVIVAL AND GROWTH OF PLANTED *QUERCUS RUBRA*

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Abstract.—A northern red oak (*Quercus rubra* L.) plantation testing 20 nursery stock and planting methods was used to evaluate treatments 3, 6, 10, and 17 years after planting. Survival over all treatments was 92 percent at age 3 and declined to 74 percent, 56 percent, and 39 percent at ages 6, 10, and 17, respectively. At age 17, survival was highest for containerized stock (73 percent) and was independent of nursery undercutting (root-pruning), top-clipping at planting, producing nursery transplant stock, and tree shelters. Surviving trees tended to be initially taller (mean of 44 cm vs. 33 cm for unclipped trees) and had larger mean stem caliper (8.3 mm vs. 6.7 mm) at the time of planting compared to those that died. Trees shorter than mean height (1.3 m) tended to succumb to effects of browsing in early years after fence removal, and later to intraspecific competition after canopy closure. Height at age 10 and diameter at age 17 were greatest for containerized stock that was not top-clipped at planting time, but many of the treatments were not statistically distinguished from each other. Top-clipping did not promote multiple stems.

INTRODUCTION

Typically larger and better-developed seedlings are considered to be higher in quality and are recommended for planting (Johnson and others 1986, Dey and Parker 1997, Ward and others 2000) but do not always exhibit greater growth or survival after planting (Myers and others 1989). Furthermore, older and larger stock can be more costly or difficult to lift, package, ship, and plant (Bullard and others 1992, Countryman and others 1996).

Varying nursery cultural practices are promoted for growing high-quality northern red oak planting stock, including undercutting, top-clipping, containerizing stock, and transplanting in the nursery, but the effects of these treatments differ. Undercutting (sometimes referred to as "root-pruning") in nursery beds can benefit outplanting survival and stimulate lateral root development (Schultz and Thompson 1991, 1996) but can lead to developing smaller seedlings (Zaczek and others 1993). Top-clipping can increase survival (Limstrom 1963, Spetich and others 2002) but also can reduce seedling height and can retard the growth of new roots after planting (Farmer 1975, Larson 1975). Tree shelters have been shown to increase oak survival or height in some comparisons (Stange and Shea 1998, Ward and others 2000, Ponder 2003) but were detrimental or neutral in others (Clatterbuck 1999, Ward and others 2000, Ponder 2003).

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This study was uniquely designed not only to test a wide variety of combined nursery and planting treatments simultaneously but also to use the same seed source to minimize genetic variability among treatments. When a common seed source is used, survival and growth differences expressed among treatments are more reliably attributed to the nursery cultural and planting treatments rather than to potential genetic differences known to exist among varying seed sources. Ultimately, our goal was to demonstrate results to help nursery growers produce higher quality northern red oak stock and to aid land managers in their stock choice and planting regime decisions to improve establishment in the short term, and survival and growth in stands over the long term.

METHODS

A northern red oak plantation was established in April 1988 within a clearcut mixed-oak stand in Huntingdon County, PA, to evaluate performance relative to type of planting stock and cultural factors. The planting site was located in a former mixed hardwood stand that supported several oak species, including northern red oak. It had been clearcut in late 1987 and the slash was removed.

Twenty treatments, each with at least 33 replications per treatment, were originally planted (Table 1) in a completely random design at 1.2-m x 1.2-m spacing. Nursery treatments consisted of various planting stock types: 2-year-old containerized (2-CON, 7.9-liter pots); 2-1 and 1-1 bareroot nursery transplants; and 2-0 and 1-0 bareroot. Some treatments were combined factorially with top-clipping (TC to 15 cm tall vs. UC or unclipped) at planting time and undercutting in the nursery bed. Undercutting or root-pruning (RP) vs. no undercutting or unpruned (UP) was performed on seedlings in the nursery bed to a depth of 20 cm in midsummer of each year. Treatments were sowed in the nursery over 3 years to produce stock that was planted at the field site during the same year, 1988. The same seed source, a bulk seedlot collected in similar parental proportions over years from four seed parents, was used to produce the seedlings of all treatments except the

Table 1.—Summary, abbreviation, description of nursery stock treatments, and the number per treatment compared for outplanting performance.

Treatment Abbrev.	Description	Number per treatment
2-CON/TC	2-yr containerized, top-clipped	35
2-CON/UC	2-yr containerized, unclipped top	35
2-1/TC	2-1 transplants, top-clipped	35
2-1/UC	2-1 transplants, unclipped top	35
1-1/TC	1-1 transplants, top-clipped	35
1-1/UC	1-1 transplants, unclipped top	34
2-0/RP/TC	2-0 seedlings, root-pruned (undercut), top-clipped	33
2-0/RP/UC	2-0 seedlings, root-pruned (undercut), unclipped top	34
2-0/UP/TC	2-0 seedlings, unpruned roots, top-clipped	33
2-0/UP/UC	2-0 seedlings, unpruned roots, unclipped top	33
1-0/RP/TC	1-0 seedlings, root-pruned (undercut), top-clipped	33
1-0/RP/UC	1-0 seedlings, root-pruned (undercut), unclipped top	33
1-0/UP/TC	1-0 seedlings, unpruned roots, top-clipped	33
1-0/UP/UC	1-0 seedlings, unpruned, unclipped top	34
1-0/ALA/TC	1-0 seedlings, Alabama raised, top-clipped	34
1-0/ALA/UC	1-0 seedlings, Alabama raised, unclipped top	33
D-S/TBX	Direct-seeded acorns, Tubex® installed	33
D-S	Direct-seeded acorns, no Tubex®	34
1-0/NURS/TBX	1-0 nursery-run seedlings, Tubex® installed	29
1-0/NURS	1-0 nursery-run seedlings, no Tubex®	35

direct-seeded and the 1-0 nursery-run (1-0 NURS) treatments. All seedling planting stock was grown at Penn Nursery (Pennsylvania Bureau of Forestry) except for the 1-0/ALA, which was grown at International Paper Company's Selma, AL, nursery under a regime designed to produce larger 1-0 stock. Direct-seeded (D-S) acorns were sown directly at the site at the time of the field planting establishment in 1988.

For the first three growing seasons, the planting was enclosed by a six-strand electric fence, which was generally effective at excluding white-tailed deer (*Odocoileus virginianus* Boddaert). The site was maintained weed-free with directed applications of glyphosate herbicide while shielding seedlings from the spray. After the second growing season, two treatments of tree shelters using Tubex® (Tubex Limited, Aberdare, UK) (TBX) were established by installing shelters over seedlings that grew from treatments of D-S acorns (n = 33) and 1-0 nursery-run stock (n = 29) (see Zaczek and others 1993). Survival of tree-sheltered seedlings reflects those trees remaining alive after year 2.

After the third growing season, the fence was removed and herbicide discontinued. Results from this and two other replicated sites were previously reported after the third growing season (Zaczek and others 1993) and from this site only after 6 years (Zaczek and others 1997). Further site and treatment details may be found in these previous papers.

Height (dm) and diameter at breast height (d.b.h. in cm) were recorded for each living tree in late August 1997, essentially 10 growing seasons after planting. We also recorded d.b.h. for each living tree in late July 2004, 17 growing seasons after planting.

Our analysis was designed to answer several other questions that might be asked by a field forester over the long term: Does undercutting improve survival and growth for all types of nursery stock? Does top-clipping increase survival or growth?

Survival comparisons among contrasting treatments of interest at age 10 and 17 were made using chi-square analysis at alpha = 0.05 (Preacher 2001). Testing for treatment differences in height and diameter among treatments and treatment groups was performed with analysis of variance at alpha = 0.05 using SPSS (SPSS Inc., Chicago, IL). Pearson correlation coefficients were generated for initial seedling heights and subsequent measurements of heights and diameter for those trees alive at age 17.

RESULTS

TENTH-YEAR SURVIVAL

Ten years after outplanting, survival was 56.0 percent over all treatments and ranged widely from 17.2 percent to 94.3 percent among treatments (Fig. 1). Chi-square tests among treatment groups indicated that survival was not significantly different for TC vs. UC, 1-0 ALA vs. 1-0 (Pennsylvania grown), D-S vs. 1-0, and TBX vs. unsheltered. Survival was greater for undercut (RP) vs. UP seedlings, 2-yr containerized vs. 2-0 bareroot seedlings, 2-0 vs. 1-0 bareroot stock, and 1-0 vs. 1-0 nursery run seedlings (Table 2). Further analysis within the undercut and not undercut treatment groups determined that survival of 2-0/RP (86.6 percent, n = 67) differed from 2-0/UP (68.2 percent, n = 66) seedlings (p = 0.011). However, survival was similar (p = 0.438) for undercut 1-0/RP (47.0 percent, n = 66) and 1-0/UP (40.3 percent, n = 67) treatments. Transplant stock (2-1 and 1-1) had lower survival than less intensively cultured 2-0 stock. Overall, trees that died between ages 6 and 10 were (p<0.001) shorter at age 6 (mean 10.9 dm) than the height at age 6 (mean 28.9 dm) of the trees alive at age 10.

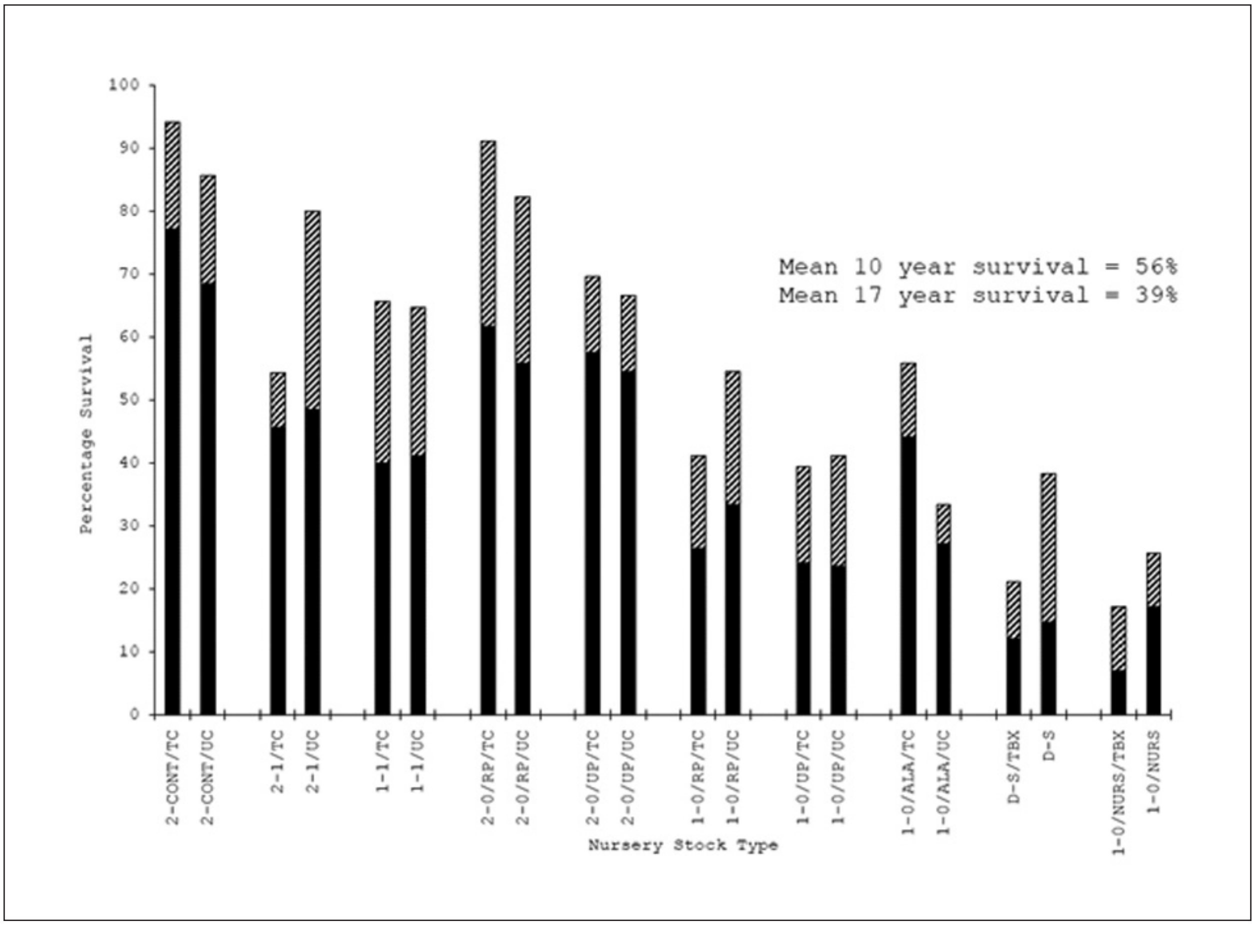

Figure 1.—Percentage survival of northern red oak nursery stock 10 years (top of hatched bar) and 17 years (top of solid bar) after planting by treatment.

SURVIVAL AFTER 17 YEARS

Seventeen years after planting, plantation mean survival was further reduced to 39.4 percent (n = 265) and ranged from 6.9 percent to 77.1 percent among all treatments (Fig. 1). At this time, survival differed among treatment group comparisons: 2-CON vs. 2-0 and 2-0 vs. 1-0 (Table 2). Survival differed between the 2-CON (72.9 percent, n = 70) and 2-0/UP (56.1 percent, n = 66) treatment comparisons (p = 0.041) but not the 2-CON and 2-0/RP (59.7 percent, n = 67) comparisons (p = 0.103). Overall, trees that died between the ages of 10 and 17 were significantly (p<0.001) shorter at age 10 (mean of 37.6 dm) than those that were alive at age 17 (mean height at age 10 of 53.8 dm).

TENTH-YEAR HEIGHT

Mean height at age 10 for surviving trees was 53.8 dm. Although there were some significant differences (p = 0.001) in tree height among treatments (Fig. 2), many treatments were not statistically distinguishable from each other. Trees grown from 2-year-old containerized stock had the greatest overall mean height at 59.4 dm, but could not be statistically distinguished from 15 other treatments (Fig. 2). The direct-seeded tree shelter treatment produced the shortest trees (42.0 dm), but this result was not statistically different from 10 other treatments. When we consider only those 16 treatments grown from the same seed source, height at age 10 differed among this subset of treatments (p = 0.027).

Table 2.—Chi-square analyses of survival at age 10 and 17 amongst specific treatments or treatment groups. For treatment descriptions refer to Table 1. All treatments and treatment groups utilized a common known seedlot except for 1-0 nursery-run, direct-seeded, and the tree shelter (which enclosed seedlings grown from directed seeded acorns) treatment.

Treatment or Treatment Group Comparison	Survival % Age 10	n	Chi-square p value	Survival % Age 17	n	Chi-square p value
Top-clipped (TC)	63.8	271		47.6	271	
Unclipped Top (UC)	63.8	271		44.3	271	
			1.000			0.438
Roots Pruned (RP)	66.9	133		45.1	133	
Unpruned Roots (UP)	54.1	133		39.9	133	
			0.033			0.385
2-yr Container (CON)	90.0	70		72.9	70	
2-0 Bareroot	77.4	133		57.9	133	
			0.028			0.036
2-0 Bareroot	77.4	133		57.9	133	
1-0 Bareroot	44.0	200		30.0	200	
			<0.001			<0.001
1-0 Pennsylvania-grown	43.6	133		27.1	133	
1-0 Alabama-grown (ALA)	44.8	67		35.8	67	
			0.874			0.202
1-0 Bareroot	44.0	200		30.0	200	
1-0 Nursery-run (NURS)	25.7	35		17.1	35	
			0.004			0.118
Direct-Seeded (DS)	38.2	34		14.7	34	
1-0 Nursery-run (NURS)	25.7	35		17.1	35	
			0.265			0.783
Tree shelter (TBX)	19.4	62		9.7	62	
No Tree shelter	31.9	69		15.9	69	
			0.102			0.145

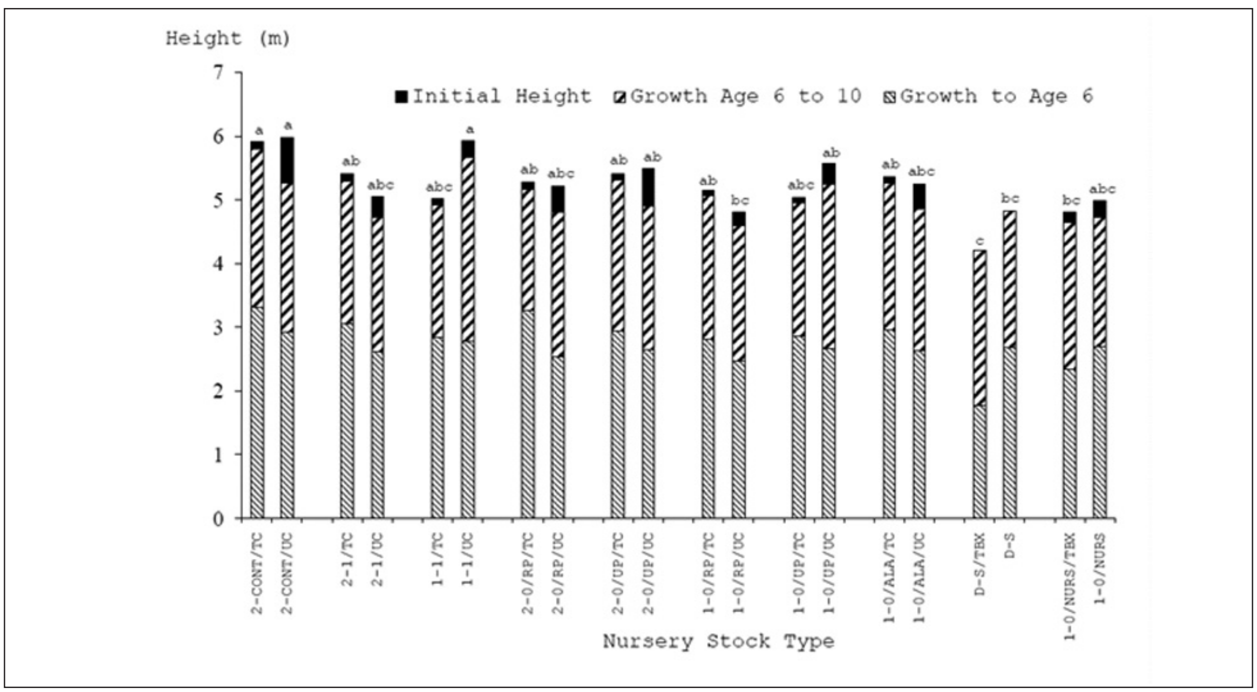

Figure 2.—Mean initial height (dm) of surviving northern red oak trees at planting time, growth (dm) until age 6, growth from age 6 to 10, and total height at age 10 (top of the bars) by treatment. Treatments sharing the same letter are not significantly different at p = 0.05 (Duncan's Multiple Range Test).

DIAMETER AFTER 17 YEARS

Mean DBH among all live trees at age 17 was 7.51 cm and ranged from a high of 9.97 cm for the 2-CON/UC treatment to 3.18 cm for the D-S/TBX treatment (Fig. 3). As was the case in the height analysis, there were significant differences among treatments ($p<0.001$). However, the treatment with the greatest mean d.b.h. (2-0 CONT/UC) was not statistically different from eight other treatments while the treatment with the smallest mean diameter (DS/TBX) was significantly smaller than 17 of the treatments (Fig. 3).

INITIAL SEEDLING SIZE

For trees living through age 17, significant ($p \leq 0.002$) Pearson correlations were found when testing all height and diameter measurements (Table 3). In general, correlations became weaker as the time span between measurements increased.

STEM FORM

At age 17, 14 trees out of the 265 living individuals had two stems and no trees had greater than two stems. Of the multi-stemmed trees, only five trees had both stems living, three trees of which developed from top-clipped stock and two from unclipped stock.

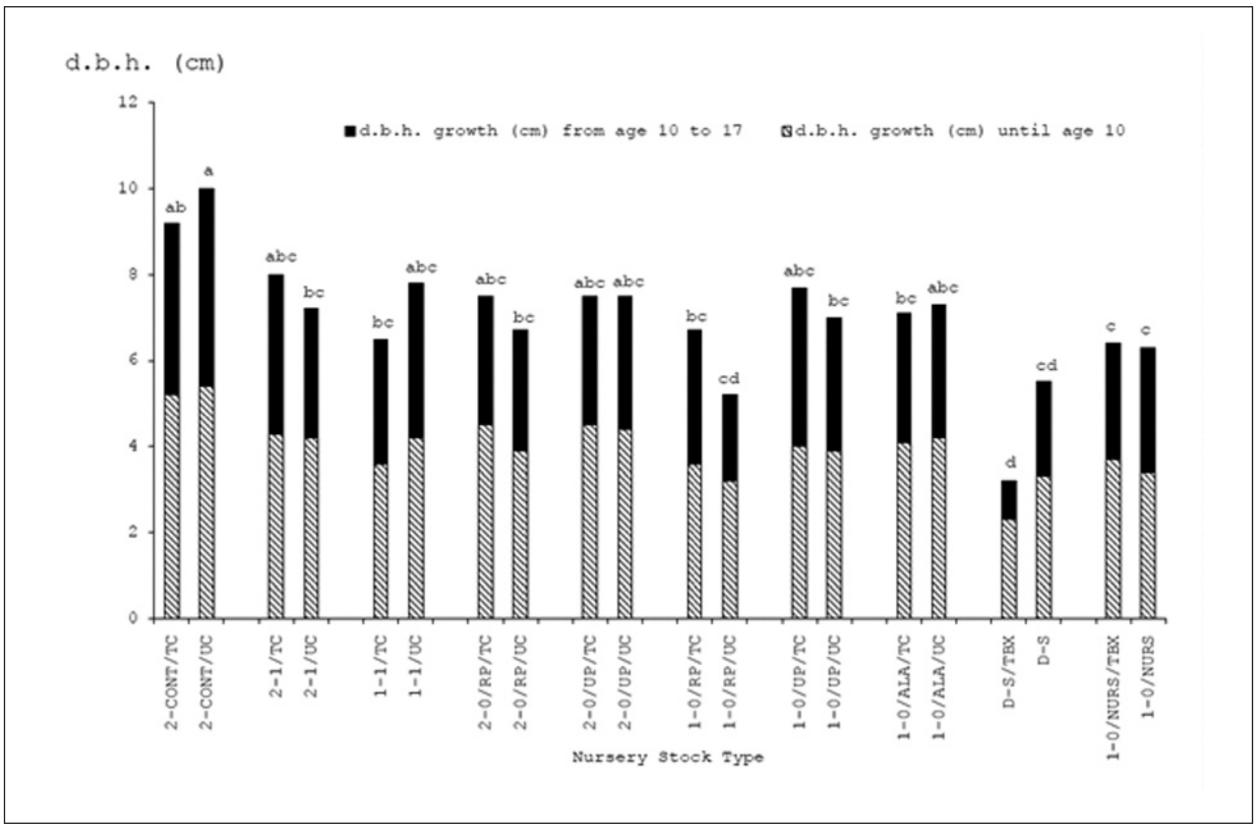

Figure 3.—Mean d.b.h. growth (cm) to age 10 (top of the solid bar) and d.b.h. growth from age 10 to 17 (hollow bar) of surviving northern red oak trees by treatment. Treatments sharing the same letter are not significantly different at p = 0.05 (Duncan's Multiple Range Test).

Table 3.—Pearson correlation coefficient matrix of initial stem caliper (Cal 0) and height at various ages (Ht X, where X = 0, 1, 2, 3, 5, 6, 10 years) and d.b.h at age 17 of trees that survived through age 17. All relationships are significant at p≤0.002.

	Cal 0	Ht 0	Ht 1	Ht 2	Ht 3	Ht 5	Ht 6	Ht 10	d.b.h. 17
Cal 0	1.000	0.361	0.582	0.537	0.495	0.432	0.425	0.280	0.433
Ht 0		1.000	0.529	0.299	0.309	0.264	0.239	0.179	0.257
Ht 1			1.000	0.713	0.619	0.514	0.512	0.352	0.466
Ht 2				1.000	0.849	0.670	0.625	0.475	0.552
Ht 3					1.000	0.793	0.723	0.562	0.598
Ht 5						1.000	0.819	0.701	0.604
Ht 6							1.000	0.735	0.679
Ht 10								1.000	0.649
d.b.h. 17									1.000

DISCUSSION

Although a minority of the trees that were originally planted managed to survive to age 17, this high mortality rate was attributed to competition among the planted trees (the plantation was never mechanically thinned) rather than to “failure” of the plantation establishment. Although there were some differences in tenth-year height and seventeenth-year diameter among treatments, differences in survival among the treatments were paramount. Survival tended to be greater for treatments with larger seedlings, either taller in height (excluding top-clipped seedlings) or larger in diameter at planting time, or for those 2-0 seedlings that had been undercut in the nursery.

Survival at age 10 or at age 17 was not significantly influenced by top-clipping, rearing in another nursery, or tree shelters. Other reports have found top-clipping to be beneficial (Limstrom 1963, Spetich and others 2002) or to have little or no benefit (Crunkilton and others 1989, Gordon and others 1992), and the latter has consistently been the case in all previous reports of this study (Zaczek and others 1993, Zaczek and others 1997). Our experiences with top-clipping were that, after planting, clipped seedlings broke bud several weeks later and the resulting leaves were much larger in area than unclipped seedlings. Even though top-clipping has been shown to somewhat retard the growth of new roots after planting (Farmer 1975, Larson 1975), clipping may allow seedlings to first establish roots before transpirational demands on the seedling begin. Clipped seedlings recovered in height to become similar in height to unclipped counterparts by the second year after planting and this practice had no apparent negative effect on height or survival (Zaczek and others 1993). A potential concern of top-clipping stock at planting is that multiple-stemmed trees may develop, leading to decreased quality. However, of the living top-clipped trees after 17 years, only 2.3 percent had living multiple stems.

Root pruning in the nursery and using more intensively cultured stock (2-CON vs. 2-0; 2-0 vs. 1-0; and 1-0 vs. 1-0 NURS) resulted in greater survival at age 10 vs. contrasting treatments. Others have found root pruning to be beneficial to survival and to result in the development of more lateral roots (Schultz and Thompson 1991, 1996). In the current study, however, survival to age 17 was not consistently benefited by root pruning; a positive effect was seen for older 2-0 stock but not for 1-0 stock. Undercutting tends to produce slightly more compact seedlings and is likely warranted and beneficial for nurseries that produce moderately larger and older stock (Zaczek and others 1993). These more compact undercut seedlings, although neutral in survival and growth benefit after 17 years, are easier for nurseries to handle and ship.

By age 17, the 2-CON stock had significantly greater survival than the contrasting 2-0/UP but not the 2-0 RP bareroot stock. Height at age 10 and d.b.h. at age 17 were similar for 2-CON and 2-0 treatments. The greater inputs (pots, potting media, shipping) and efforts (transporting to field sites, digging large holes, and increased planting time) associated with large containerized stock reduces the feasibility of using this stock type. Older bareroot transplant stock (2-1) did not perform as well over time as less intensively cultured 2-0 material. This outcome is apparently due to transplant shock within the nursery, leaving 2-1 and 1-1 transplants 16 percent and 34 percent smaller in initial stem diameter, respectively, and 46 percent and 60 percent smaller in initial height, respectively, than 2-0/UP/UC seedlings.

Tree shelters were not beneficial to survival or growth in this study. Others have found that shelters can enhance survival or height growth of oaks (Stange and Shea 1998, Ward and others 2000, Ponder 2003) but in some research, shelters were neutral or detrimental to survival or height (Clatterbuck 1999, Ward and others 2000, Ponder 2003). The poor response of shelters in the current study may have been due to our deliberate approach to refrain from any maintenance to the shelters once they were installed. Shelters toppled over because the stakes that held them broke or became rotten. Rodents chewed their fasteners. Black bears (*Ursus americanus* Pallas) damaged the shelters, causing the seedlings inside to either die or resprout from the root collar. The need for repeated shelter maintenance—replacing stakes and fasteners—has been noted by others (Kittredge and others 1992, Minter and others 1992). Additionally, periodic cicada (*Magicicada septemdecim* L.) and gypsy moth (*Lymantria dispar* L.) appeared to thrive in the shelters (Zaczek and others 1997). The added costs of shelters and the lack of a survival or growth benefit fail to justify their use in applications similar to those in our study.

Although there were significant differences among treatments for height at age 10 and diameter at age 17, most treatments were similar in mean growth. This result largely reflects the stock types; a greater proportion of smaller trees tend to have greater mortality of their smallest trees over time. This mortality pattern, in turn, removed the small trees from the calculations of mean height and tended to bias upward the heights of those treatments. Consequently, in cases like this, where survival varied greatly among treatments, choosing planting stock based on height or diameter performance in later years does not appear to be the most appropriate approach. Rather, survival differences are the superior indicators to base stock choice decisions. Ultimately, the size of a tree is critically important and drives survival and future growth. All treatments produced at least some seedlings that were larger than the overall average and thus survived to age 17. Treatments that have greater proportions of seedlings that are larger tend to have higher percentage survival. Nearly all trees that were below average in height during the course of the study failed to survive. For individual trees, survival was tied closely to size and competitive position relative to their neighbors.

The decline in survival in later years is in part due to intraspecific competition among relatively closely-spaced trees, which tended to result in higher mortality for those trees that were shorter than the overall average. To help illustrate this result, we calculated mortality between consecutive measurement periods (years 3 to 6, 6 to 10, and 10 to 17) by size class of the preceding period (Fig. 4). The vast majority of mortality occurred in the smaller size classes of the trees in an age cohort. Averaging over the three comparisons, 94.4 percent of the trees that died in the following measurement period were below average in height in the preceding measurement period. Between years 3 and 6, canopy closure was not complete and although the influence of intraspecific competition among the planted oaks was likely beginning to occur, a significant proportion of mortality was attributed to white-tailed deer browsing of seedlings shorter than 130 cm (Zaczek and others

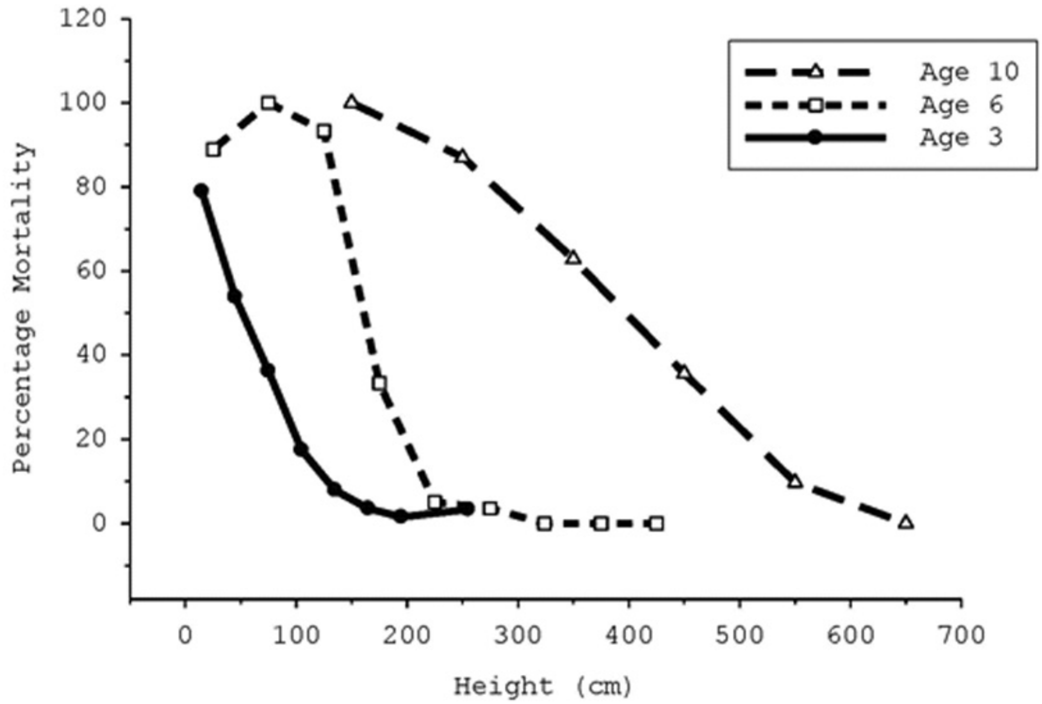

Figure 4.—Percent mortality between measurement periods (years 3 to 6, 6 to 10, 10 to 17) by size class at the beginning of the period. Mean heights: age 3 = 134 cm, age 6 = 245 cm, and age 10 = 538 cm.

1997). Browsing has been shown to negatively affect survival and growth of seedling oak (Buckley and others 1998, Jacobs and others 2004). In later years, with the onset of canopy closure and the development of some understory vegetation, tree-to-tree (intraspecific) competition was most likely the primary influence on survival.

Trees were planted at 1.2 m x 1.2 m or 6,726 stems ha^{-1} in this study. The site in later years had a nearly complete canopy coverage of northern red oak with very few other woody plant species growing within the oak overstory. This result was influenced by herbicide treatments in the first 3 years, which kept all other vegetation from becoming established. After 17 years, the understory vegetation consisted of a moderate cover of ferns and some grass.

Oak seedling density of this magnitude or greater is common in developing stands in this part of the Appalachians. In a location near this study, tree seedling densities early in development of a mixed-oak shelterwood (age 1) were 23,756 stems ha^{-1} or at age 3, 43,318 stems ha^{-1} with the overwood intact (Zaczek 2002) or later (age 6) at 40,382 stems ha^{-1} with the overwood removed (Zaczek and Lhotka 2004). Seedling densities ranged from 1,557 to 12,231 stems ha^{-1} for 10-year-old developing mixed-species stands in the Central Hardwoods (Myers and Buchman 1988) and 5,541 stems ha^{-1} 14 years after harvest in a bottomland hardwood forest (Bowling and Kellison 1983).

It is uncertain whether the competitive effects that are experienced by northern red oak individuals in a single-species planting such as this are more severe or less so than what might be experienced in developing natural stands or plantings of mixed species. Individuals of a species can be more adversely affected by intraspecific competition than by interspecific competition (Kimmins 1997) because of the requirements for using the same resources. However, northern red oak has been estimated to be a strong competitor among 14 co-occurring species in a study of New England forests (Canham and others 2006). In that study, the strong competitive effect on growth that sugar maple (*Acer saccharum* Marsh.) and white ash (*Fraxinus americana* L.) exerted on northern red oak was similar to the strength of the competitive effect that northern red oak exerted on itself. Consequently, a northern red oak planting at this density can approximate the competitive forces that occur in stands that naturally develop after disturbance.

Our results demonstrate that smaller than average planted seedlings and developing oak trees typically persist for only a few years and are subject to self-thinning when in a subordinate competitive position. However, all treatments produced at least some trees that survived through age 17. For the highest survival in planting oak, it is crucial to utilize larger and more intensively cultured oak planting stock that can initiate and maintain rapid growth to grow beyond the reach of deer early on and then to develop a favorable competitive position relative to neighboring trees.

LITERATURE CITED

Bowling, D.R.; Kellison, R.C. 1983. **Bottomland hardwood stand development following clearcutting.** Southern Journal of Applied Forestry. 7: 110-116.

Buckley, D.S.; Sharik, T.L.; Isebrands, J.G. 1998. **Regeneration of northern red oak: positive and negative effects of competitor removal.** Ecology. 79: 65-78.

Bullard, S.; Hodges, J.D.; Johnson, R.L.; Straka, T.J. 1992. **Economics of direct seeding and planting for establishing oak stands on old-field sites in the south.** Southern Journal of Applied Forestry. 16: 34-40.

Canham, C.D.; Papaik, M.J.; Uriarte, M.; McWilliams, W.H.; Jenkins, J.C.; Twery, M.J. 2006. **Neighborhood analysis of canopy tree composition along environmental gradients in New England Forests.** Ecological Applications. 16: 540-554.

Clatterbuck, W.K. 1999. **Effects of tree shelters on growth of hardwood seedlings after seven growing seasons.** In: Haywood J.D., ed. Tenth biennial southern silvicultural research conference. Gen. Tech. Rep. SRS-30. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station: 43-46.

Countryman, D.W.; Bardon, R.; Tate, S. 1996. **Economics of direct seeding northern red oak in southern Iowa.** In: Teclaw, R.M., ed. Proceeding of the sixth workshop on seedling physiology and growth problems in oak plantings. Gen. Tech. Rep. NC-182. St. Paul, MN: U.S. Department of Agriculture, Forest Service, North Central Research Station: 23 [Abstract].

Crunkilton, D.D.; Garrett, H.D.; Pallardy, S.G. 1989. **Growth of northern red oak seedlings planted in a central Missouri clearcut and shelterwood.** In: Miller, J.H., comp. Proceedings of the fifth biennial southern silviculture conference. Gen. Tech. Rep. SO-74. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station: 81-85.

Dey, D.C.; Parker, W.C. 1997. **Morphological indicators of stock quality and field performance of red oak (*Quercus rubra* L.) seedlings underplanted in a central Ontario shelterwood.** New Forests. 14: 145-156.

Farmer, R.E., Jr. 1975. **Dormancy and root regeneration of northern red oak.** Canadian Journal of Forest Research. 5: 176-185.

Gordon, A.M.; Simpson, J.A.; Williams, P.A. 1992. **Shelterwood harvesting and underplanting to enhance the red oak component of shallow-site forests in central Ontario: 6-yr results.** In: Thompson, J.R.; Schultz, R.C.; VanSambeek, J.W., eds. 5th workshop on seedling physiology and growth problems in oak plantations. Gen. Tech. Rep. NC-158. St. Paul, MN: U.S. Department of Agriculture, Forest Service, North Central Research Station: 10. [Abstract].

Jacobs, D.F.; Ross-Davis, A.L.; Davis, A.S. 2004. **Establishment success of conservation tree plantations in relation to silvicultural practices in Indiana, USA.** New Forests. 28: 23-36.

Johnson, P.S.; Dale, C.D.; Davidson, K.R.; Law, J.R. 1986. **Planting northern red oak in the Missouri Ozarks: a prescription.** Northern Journal of Applied Forestry. 9: 66-68.

Kimmins, J.P. 1997. **Forest ecology: a foundation for sustainable management.** 2nd ed. Upper Saddle River, NJ: Prentice Hall. 596 p.

Kittredge, D.B.; Kelty, M.J.; Ashton, P.M.S. 1992. **The use of tree shelters with northern red oak natural regeneration in southern New England.** Northern Journal of Applied Forestry. 9: 141-145.

Larson, M.M. 1975. **Pruning northern red oak seedlings: effects on root regeneration and early growth.** Canadian Journal of Forest Research. 5: 381-386.

Limstrom, G.A. 1963. **Forest planting practices in the Central States.** Agric. Handbk. 247. Washington, DC: U.S. Department of Agriculture, Forest Service. 69 p.

Minter, W.F.; Myers, R.K.; Fischer, B.C. 1992. **Effects of tree shelters on northern red oak seedlings planted in harvested forest openings.** Northern Journal of Applied Forestry. 9: 58-63.

Myers, C.C.; Buchman, R.G. 1988. **Silvicultural opportunities ten years after clearcutting Central Hardwoods.** Northern Journal of Applied Forestry. 5: 22-25.

Myers, R.K.; Fischer, B.C.; Wright, G.M. 1989. **Survival and development of underplanted northern red oak seedlings: 6-year results.** Gen. Tech. Rep. NC-132. St. Paul, MN: U.S. Department of Agriculture, Forest Service, North Central Research Station: 150-155.

Ponder, F., Jr. 2003. **Ten-year results of tree shelters on survival and growth of planted hardwoods.** Northern Journal of Applied Forestry. 20: 104-108.

Preacher, K.J. (2001, April). **Calculation for the chi-square test: an interactive calculation tool for chi-square tests of goodness of fit and independence [Computer software].** Available: http://www.quantpsy.org.

Schultz, R.C.; Thompson, J.R. 1991. **The quality of oak seedlings needed for successful artificial regeneration in the Central States.** In: Laursen, S.B.; DeBoe, J.F., eds. The oak resource in the Upper Midwest. NR-BU-5663-S. St. Paul, MN: Univ. of Minnesota Extension Service: 180-186.

Schultz, R.C.; Thompson, J.R. 1996. **Effect of density control and undercutting on root morphology of 1+0 bareroot hardwood seedling: 5-year field performance of root-graded stock in the central USA.** New Forests. 13: 297-310.

Spetich, M.A.; Dey, D.C.; Johnson, P.S.; Graney, D.L. 2002. **Competitive capacity of *Quercus rubra* L. planted in Arkansas' Boston Mountains.** Forest Science. 48: 504-517.

Stange, E.E.; Shea, K.L. 1998. **Effects of browsing, fabric mats, and tree shelters on *Quercus rubra* seedlings.** Restoration Ecology. 6: 29-34.

Ward, J.S.; Gent, M.P.N.; Stephens, G.R. 2000. **Effects of planting stock quality and browse protection-type on height growth of northern red oak and eastern white pine.** Forest Ecology and Management. 127: 205-216.

Zaczek, J.J. 2002. **Composition, diversity, and height of tree regeneration three years after soil scarification in a mixed-oak shelterwood.** Forest Ecology and Management. 163: 205-215.

Zaczek, J.J.; Lhotka, J.M. 2004. **Seedling reproduction established with soil scarification in an oak overwood after overstory removal.** Northern Journal of Applied Forestry. 21: 5-11.

Zaczek, J.J.; Steiner, K.C.; Bowersox, T.W. 1993. **Performance of northern red oak planting stock.** Northern Journal of Applied Forestry. 10: 105-111.

Zaczek, J.J.; Steiner, K.C.; Bowersox, T.W. 1997. **Northern red oak planting stock: 6-year results.** New Forests. 13: 177-191.