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Nursery Practices Influence Seedling Morphology, Field Performance, and Cost Efficiency of Containerized Cherrybark Oak

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ABSTRACT: *To quantify effects of nursery practices on seedling cost and performance, cherrybark oaks (*Quercus pagoda *L.) were grown in three container sizes (170, 650, or 1,250 cm*^{3}*) with or without fertilization and then planted Dec. 1995 at a site near Milledgeville, GA, with or without removal of container soil. Initial size, biomass, and leaf area of seedlings grown in medium and large containers were up to twice those grown in small containers, and they were greater with versus without fertilization. Price efficiency (stem volume divided by estimated nursery price of 1,000 seedlings) was greatest for medium and large containers with soil removed and hypothetically reused. Differences in stem diameter and height due to container size and fertilization continued to diverge through the fifth year after planting. Fifth-year yield (stem volume × proportionate survival of 1,000 planted seedlings) increased 104, 56, and 31% with increasing container size and with fertilization and soil removal, respectively. Cost efficiency (fifth-year yield divided by costs compounded 5 years at 5% interest) was greatest for medium and large containers with soil removed. Joint comparisons of nursery costs, planting costs, and field performance for different seedling stock types provide an objective approach for prioritizing cultural treatments in forestry. South. J. Appl. For. 28(3):152–162.*

Key Words: Seedling quality, plantation, forest regeneration, benefit-cost ratio.

Guidelines for artificial regeneration of oaks (*Quercus* spp.) in the southeastern United States have emphasized the use of morphologically improved planting stock because of its consistent and high level of field performance (Kennedy 1993a, Kormanik et al. 1998, Allen et al. 2001). Field performance of oak seedlings has been correlated with a variety of morphological indicators, including stem size, foliage biomass, leaf area, shoot/root ratio, and number of first-order lateral roots (Moorhead 1981, Hodges and Gardiner 1993, Kormanik et al. 1998). These seedling attributes can be manipulated with nursery practices, such as variation in sowing density, irrigation, and fertilization (Barham 1980).

Although morphological improvements in oak planting stock can improve their field performance, large stock can be difficult to plant (Bowersox 1993). Nursery undercutting and field pruning commonly are used to adjust root system dimensions; however, excessive removal of root biomass can reduce the carbohydrate storage of the seedling, resulting in loss of vigor (Bowersox 1993). Attempts to plant nonpruned seedlings can result in shallow or deformed root systems. Alternatively, depth and width of the planting hole can be tailored, often with great difficulty and expense, to accommodate root system dimensions.

Containerized seedling culture can produce morphologically improved seedlings with compact root systems that are easily planted. However, additional nursery space, materials, and labor associated with containerized seedling

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culture each contribute to the total cost of seedling production. Likewise, the added volume and weight of soil in containerized seedlings increase transport costs and decrease planting production rates, reducing the efficiency of the planting operation. To effectively evaluate the benefits of containerized seedlings, nursery and planting costs and field performance must be evaluated jointly.

Complete cost accounting is essential to developing pricing strategies in forest nursery production. In practice, complete cost accounting is performed empirically through repeated operational trials; however, such valuation methods in research may be limited by resource, scale, and time constraints (Conrad 1999). Nonetheless, the economic side of nursery and forestry practices must be considered if the full benefits and costs of a treatment are to be understood. Commonly, benefit-cost ratios are used in forestry (Clutter et al. 1983) and horticulture (Conrad 1999) to compare inputs ($) and outputs (yield appraised in $), but these ratios result in dimensionless values because dollar units cancel out. Efficiency values (seedling yield per $) have what other ratios offer, but also retain information for benchmark comparisons inside and outside of a given study (Harrington and Howell 1998).

Cherrybark oak (*Quercus pagoda* L.) is a highly productive and valuable bottomland tree species that has demonstrated strong potential for plantation management (Krinard and Francis 1983, Krinard 1990, Kennedy 1993b); thus, there is likely to be a growing need for high quality and reasonably priced planting stock. In this study, cherrybark oak seedlings were grown in several container sizes with or without fertilization and planted at a field site with or without soil removal. The soil removal treatment was included to demonstrate potential savings in nursery and planting costs. Joint comparisons of seedling morphology, nursery and planting costs, and 5-year field performance were conducted across a range of stock sizes and qualities to develop an approach for identifying critical factors influencing choice of oak stock type. Estimated prices for the experimental seedlings were compared to real prices for seedlings produced by two commercial nurseries.

Methods

Nursery phase

Containerized seedling culture of cherrybark oak was studied at Whitehall Forest greenhouse, University of Georgia, Athens, GA. The experiment was established as a completely randomized design with a factorial arrangement of six treatments: three container sizes (170, 650, or 1,250 cm^3) × two fertilization levels (presence or absence). Each treatment was replicated five times with 20 seedlings per replication for a total of 600 containers. Container dimensions were 3.5 × 18 cm, 6.5 × 20.5 cm, and 10.5 × 15.0 cm for small, medium, and large containers, respectively. Although fertilization is a standard practice in forest nurseries, the treatment was varied in this study to create strong differences in initial seedling morphology that could potentially influence nursery and planting costs and subsequent field performance.

Acorns of cherrybark oak were purchased in Jan. 1995 from Louisiana Forest Seed Company, LeCompte, LA, stored for 28 weeks at 5°C, and sown into containers in July 1995. This sowing date was selected to limit seedling development to a 3-month duration in the greenhouse (to avoid root binding in the small containers), followed by initiation of dormancy in the fall and subsequent winter planting. Soil media was a mixture of 50% topsoil (sandy loam, The Stone Store, Athens, GA) and 50% peat-perlite mixture (Peat-lite mix, Fafard, Inc., Agawam, MA). Rate of container preparation ("sowing rate," containers hr^{-1}), including soil addition and tamping and seed sowing, was measured for each treatment replication. Fertilization consisted of single applications of 25, 50, 100, and 100% solutions of 20:20:20 NPK plus micronutrients at 2, 4, 6, and 8 weeks after seedling emergence, respectively. To limit root circling and matting along the inside surface of the large containers, the bottoms were removed and a wire mesh was placed on the bottom inside of each container to induce air pruning of roots. After three months of development in the greenhouse, each seedling was measured for height (cm) and basal stem diameter (mm). Initial container weight (g, container and soil), final container weight (g, container, soil, and seedling), and seedling fresh weight (g) were determined on each of three randomly selected seedlings per treatment replication.

From the remaining seedlings, three were randomly selected from each treatment replication to quantify seedling morphology on a total of 90 seedlings. Roots were rinsed in water to remove soil, and seedlings were divided into components of foliage, stem, and roots. Total leaf area per seedling (cm^2) was determined with video image analysis (AgVision, Decagon Devices, Inc., Pullman, WA), and each component was dried to a constant weight in an oven at 70° C and weighed (nearest 0.1 g). Calculated variables included height:diameter ratio (with both variables expressed in cm), shoot:root ratio (shoot biomass divided by root biomass), specific leaf area (leaf area divided by foliage dry weight), and leaf area ratio (leaf area divided by total biomass) (Hunt 1990).

Estimated nursery costs included greenhouse space, materials, and labor expressed per 1,000 seedlings processed (Table 1). Actual costs of materials included those that differed among treatments (soil and fertilizer) and those that were fixed (seed, pesticides, water, and electricity). A hypothetical labor rate of $15 hr^{-1} was used throughout the cost analysis, derived as $10 for labor plus $5 for worker benefits. Labor costs for seed sowing, seedling handling and transport, and soil removal were estimated from replicated trials (Table 1). Nursery costs were totaled and increased by a profit margin of 30% to provide an estimated seedling price.

The marketability of nursery-grown seedlings will depend on their size, quantified in this study as seedling yield (total stem volume). Seedling price efficiency, a measure of inherent product value to a consumer, was calculated for each treatment replication as the ratio of seedling yield in

Table 1. Cost sources and derivations for nursery culture and field planting of containerized cherrybark oak seedlings. Costs are shown in dollars per 1,000 seedlings, rates were estimated as containers processed hr^{-1}, and all labor was valued at \$15 hr^{-1}.

Cost source	Derivation	Primary influential factor	Cost
Greenhouse space	Assumes \$10,000 per yr for a 10-m × 30-m greenhouse (\$2,500 per 3 months).	Container cross-sectional area.	Container size: small = \$13, medium = \$35, and large = \$83
Sowing rate	Hours of labor to prepare 1,000 containers estimated experimentally from 10 replications per container size and 20 containers per replication.	Container volume.	Container size: small = \$26, medium = \$40, and large = \$68
Fixed costs	Materials and services.		Seeds = \$27, pesticides = \$6, and utilities = \$38.
Fertilization	Materials and labor.		Fertilizer = \$67, application of water = \$50, and application of fertilizer + water = \$67
Soil	Soil removal and recovery assumes 7, 3, and 2% soil losses for small, medium, and large containers, respectively.[a] Non-removal assumes 100% loss of 122, 502, and 1,067 g per small, medium, and large container, respectively.	Container volume and soil removal (recovery).	Assuming a soil cost of \$5 per 18 kg, values were \$34, \$139, and \$296 versus \$2, \$3, and \$4 for small, medium, and large containers with soil retained versus soil removed, respectively.
Initial nursery transport rate	Hours of labor estimated by the number of trips to move 1,000 containers in fixed dimension frames from the headhouse to the greenhouse, assuming a round-trip of 2 minutes per frame.	Container cross-sectional area (determines number of containers per frame: small = 50, medium = 20, and large = 9).	Container size: small = \$10, medium = \$25, and large = \$56
Final nursery transport rate	Hours of labor estimated by the number of trips to move 1,000 containers in fixed dimension frames from the greenhouse to the packing shed, assuming a round-trip of 2.5 minutes per frame.	Same as initial nursery transport but frames now include seedlings.	Container size: small = \$12, medium = \$31, and large = \$69
Container removal rate	Hours of labor estimated experimentally from 3 replications per treatment and 13 containers per replication.	Difficulty of container removal.	Container size: small = \$36, medium = \$28, and large = \$27
Soil removal rate	Hours of labor estimated experimentally from 3 replications per treatment and 13 containers per replication.	Soil volume and difficulty of its removal.	Container size: small = \$36, medium = \$44, and large = \$45
Seedling transport rate	Hours of labor estimated by the number of trips to move 1,000 seedlings in packing bags, each having a weight capacity of 15 kg,[b] from the packing shed to the purchaser's transport vehicle, assuming a round-trip of 3 minutes per bag. Seedling weight was determined experimentally from 5 replications per treatment and 3 seedlings per replication.	Container volume and soil weight.	\$5, \$18, and \$37 for small, medium, and large containers with soil retained, respectively, versus \$1 for soil removed in each container size.
Profit margin	Accounts for hidden (implicit) costs		30% of nursery costs
Field transport rate	Hours of labor estimated by the number of trips to move 1,000 seedlings in packing bags from the transport vehicle to the first planting spot, and then to return to the transport vehicle with an empty bag, assuming a round-trip of 10 minutes per bag.	Container volume and soil weight.	\$12, \$44, and \$91 versus \$1, \$2, and \$3 for small, medium, and large containers with soil retained versus soil removed, respectively.
Planting rate[c]	Hours of labor to plant seedlings estimated experimentally from 3 replications per treatment and 13 seedlings per replication; includes travel time among planting spots and in refilling the planting bag.	Container volume and soil weight.	\$16, \$29, and \$28 versus \$16, \$21, and \$16 for small, medium, and large containers with soil retained versus soil removed, respectively.

[a] Soil loss was derived for each container size as half of the percentage of total container weight represented by the seedling following almost complete removal of its soil in preparation for planting.

[b] Packing bag capacity is based on the approximate weight of 1,000 bare-root, 1-0 seedlings of loblolly pine (*Pinus taeda* L.) (4 mm stem diameter and 25 cm height), which is considered a full load for a cycle of hand planting.

[c] Labor in planting was evenly distributed between time in field transport rate (\$7.50 hr^{-1}) and planting rate (\$7.50 hr^{-1}).

parabolic stem volume (Y_n; cm^3) to estimated price of 1,000 seedlings, with seedling yield derived as follows:

$$Y_n = 1000 \times \left[\pi \times \left(\frac{D}{20}\right)^2 \times \frac{H}{2} \right] \quad (1)$$

where D is mean stem diameter (mm) and H is mean height (cm) of seedlings for a given treatment replication.

To illustrate the influence of nursery practices, average values for price, yield, and price efficiency of fertilized seedlings of each container size and level of soil removal were compared to those for conventional seedlings grown in 11.4-liter containers from two anonymous commercial nurseries, designated as nursery A and nursery B. Conventional bareroot seedlings from each nursery also were included in the comparisons. Quoted seedling prices from the two nurseries were discounted to 1997 assuming a 3% annual inflation rate to correspond to the period during which nursery costs were estimated for this study.

Plantation Phase

The planting site was a former agricultural field located adjacent to the Oconee River near Oconee, GA (T&S Hardwoods, Inc., Milledgeville, GA). Soils are of the Congaree series of fine-loamy, mixed, active, nonacid, thermic Oxyaquic Udifluvents (USDA Natural Resources Conservation Service, ortho.ftw.nrcs.usda.gov/osd/osd.html. Jan. 23, 2004). These sandy to silty loam alluvial soils are deep, well to moderately well drained, and medium to strongly acidic. Long-term (1933–2002) growing season (May to Oct.) rainfall for Dublin, GA, located approximately 34 km south of the planting site, averages 588 mm (www.georgiaweather.net, Jan. 23, 2004). Dominant vegetation on the study site included boxelder (*Acer negundo* L.), blackberry (*Rubus* spp.), and broomsedge (*Andropogon virgininicus* L.). To fully suppress competing vegetation, a 5% solution of Accord herbicide (glyphosate) with 0.5% nonionic surfactant was applied in July 1995 with a backpack sprayer to the point just before foliage runoff. A 3-m fence was installed around the perimeter of the planting site (23.4 × 20.0 m) to exclude herbivory from white-tailed deer (*Odocoileus virginianus*).

An additional experimental factor, presence versus absence of soil removal, was included in the study to simulate seedling root characteristics likely to result from a hypothetical soil removal, recovery, and reuse procedure that would occur at the nursery during seedling processing. Such a procedure would be designed to reduce soil replacement costs, as well as those associated with soil transport within the nursery and at the planting site. To accommodate this factor, seedlings were re-grouped according to the six treatments and randomly assigned to three replications of 26 seedlings each. Half of the seedlings per replication (randomly selected) were planted with container soil removed and half with container soil retained. In an operational context, container soil would be removed during seedling packing, perhaps resulting in some damage to the root system. However, in this study, soil was removed manually at the planting spot immediately before planting, using care to minimize root damage. Each replication of the 12 treatments (3 container sizes × 2 fertilization levels × 2 soil removal levels) was assigned randomly to one of 36 rows arranged in a 3 × 12 grid at the planting site. Spacing was 0.5 m within a row (i.e., within treatment) and 1.8 m between rows (i.e., between treatments). Seedlings were planted in Dec. 1995 with a hoedad, and planting rate (seedlings hr^{-1}) was measured on each treatment replication. Immediately after planting and in the dormant seasons 1, 2, 3, and 5 years after planting, surviving seedlings were measured for basal stem diameter (mm) and height (cm). Stem diameter at breast height (dbh; mm at 1.37 m aboveground) was measured at year 5.

Estimated plantation costs included the cost of seedlings (using the nursery price derived above) and labor in seedling transport and planting expressed per 1,000 seedlings (Table 1). Fifth-year compounded costs for the plantation phase were calculated for each treatment replication, as follows:

$$C_5 = \sum(C_p \times [1 + i]^t) \quad (2)$$

where C_5 is the sum of all costs of the planting phase (C_p) compounded at an interest rate of 5% (i = 0.05) over t = 5 years.

Fifth-year seedling cost efficiency was calculated for each treatment replication as the ratio of fifth-year yield in parabolic stem volume (Y_5; dm^3) to compounded cost (C_5) of 1,000 planted seedlings, with yield derived as follows:

$$Y_5 = 1000 \times \left[\pi \times \left(\frac{D}{200}\right)^2 \times \frac{H}{20} \right] \times S \quad (3)$$

where D and H are defined as before and S is equal to proportionate survival in year 5.

Statistical Analysis

All analyses were conducted in SAS (Statistical Analysis Systems Institute 1999) assuming a 5% significance level. Treatment replication means were calculated for each of the seedling morphology and size variables, and analysis of variance (ANOVA) was performed to quantify effects of the three factors (container size, fertilization, and soil removal) and their interactions. To improve the homogeneity of the residual variances, an angular transformation was applied to the survival means and a logarithmic transformation was applied to the size and morphology means (Sokal and Rohlf 1981). Variance homogeneity was confirmed by plotting the residuals against observed values from each ANOVA. To adjust for differences in sample size that resulted from variation in seedling survival in the field performance comparison, a weighted least squares ANOVA was applied to the survival, stem diameter, and height data with weights equal to the reciprocal of the number of surviving seedlings per treatment replication. In addition, an intertree competition index was assigned to each treatment replication equal to the mean of the two container sizes planted in adjacent rows, coded as 0, 1, 2, or 3 to denote planting site edge, small, medium, or large containers, respectively. The competition index was tested as a covariate in ANOVA (Sokal and Rohlf 1981) to determine whether adjacency of specific container sizes, and hence seedling sizes, significantly influenced treatment responses.

If the F-test in the ANOVA indicated a significant interaction among factors, interaction means and 95% confidence intervals were presented (back-transformed when appropriate). If the interaction F-test was not significant but a main-effect F-test was significant, main-effect means and 95% confidence intervals were presented (back-transformed when appropriate). Multiple comparisons were conducted with Bonferroni-adjusted probabilities (Sokal and Rohlf 1981). Each of the cost components of the nursery and plantation phases of the research (Table 1) were subjected to ANOVA using the same analytical approach as described above. Unless stated otherwise, reported treatment differences are significant at $P \leq 0.05$.

Results and Discussion

Nursery Phase

Nursery Costs

Estimated costs for renting greenhouse space for three months were $13, $35, and $83 for 1,000 small, medium, and large containers, respectively, because their container cross-sectional areas varied as factors of 1:2.6:6.2 (Table 1). Greenhouse rental costs also will depend on the number of seedling crops grown per year. Sowing rate varied inversely with container volume (Table 2). Estimated costs for soil increased in proportion to container volume, which varied among small, medium, and large containers as factors of 1:3.8:7.4. Total replacement costs for soil were $34, $139, and $296 for 1,000 small, medium, and large containers, respectively, versus $2, $3, and $4 if soil was removed and hypothetically reused. The replacement costs estimated for the soil removal and recovery treatment resulted from losses

Table 2. Mean values and 95% confidence intervals for nursery price components, and seedling price, yield, and price efficiency as influenced by main effects of container size, fertilization, soil removal, or their interactions. For a given variable and factor or factor interaction, means followed by the same letter do not differ significantly ($P > 0.05$).

Variable	Experimental factor: Container size	Fertilized?	Soil removed?	Mean	95% conf. int.
Sowing rate (containers hr^{-1})	Small			578 c	550, 606
	Medium			375 b	358, 394
	Large			221 a	211, 232
Container removal (containers hr^{-1})	Small			422 a	397, 447
	Medium			543 b	519, 568
	Large			554 b	530, 579
Soil removal (containers hr^{-1})	Small			414 b	383, 444
	Medium			339 a	309, 370
	Large			330 a	299, 360
Seedling + soil weight (g)	Small		Yes	16 a	4, 28
			No	138 b	127, 150
	Medium		Yes	25 a	14, 37
			No	531 c	519, 543
	Large		Yes	31 a	19, 42
			No	1098 d	1086, 1109
		Yes		314 b	308, 320
		No		299 a	293, 306
Seedling price ($ per 1,000 seedlings)	Small		Yes	390 a	385, 394
			No	390 a	386, 394
	Medium		Yes	482 b	478, 486
			No	623 c	619, 628
	Large		Yes	675 d	671, 679
			No	1038 e	1033, 1042
		Yes		655 b	653, 657
		No		544 a	542, 546
Seedling yield (cm^3 per 1,000 seedlings)	Small			586 a	506, 678
	Medium			1407 b	1215, 1629
	Large			1411 b	1219, 1634
		Yes		1548 b	1386, 1729
		No		715 a	640, 798
Seedling price efficiency (cm^3 per $)	Small	Yes		1.8 b	1.6, 2.1
		No		1.3 a	1.1, 1.5
	Medium	Yes		3.4 d	3.0, 4.0
		No		1.9 bc	1.7, 2.2
	Large	Yes		2.5 c	2.1, 2.9
		No		1.2 a	1.0, 1.3
	Small		Yes	1.5 a	1.3, 1.8
			No	1.5 a	1.3, 1.8
	Medium		Yes	2.9 c	2.5, 3.4
			No	2.3 bc	2.0, 2.6
	Large		Yes	2.1 b	1.8, 2.4
			No	1.4 a	1.2, 1.6

due to soil adhering to the root system, and they were assumed to increase in proportion to seedling fresh weight (Table 1). Seedling transport within the nursery involved three trips: (1) headhouse (for seed germination) to greenhouse; (2) greenhouse to packing shed; and (3) packing shed to the purchaser's transport vehicle. In the first two trips, containers were transported in frames of fixed size; therefore, transport costs increased in proportion to the cross-sectional area of the container (Table 1). A single frame could transport 50 small, 20 medium, or 9 large containers. Costs for the second trip were higher because of the need to protect seedlings in transit. In preparation for packing, the rate of container removal was greater for medium and large containers than for small containers because of observed root binding in the small containers (Table 2). Soil removal was slower for seedlings grown in medium and large containers because their root systems had almost twice the biomass (described below), and therefore, amount of retained soil as that of seedlings grown in small containers.

In the final seedling transport, seedlings were packed in bags having a weight capacity of 15 kg; therefore, the weight of the seedling plus soil determined the rate at which 1,000 seedlings could be processed (Table 1). Seedling plus soil weight varied according to the interaction of container size and soil removal (Table 2). For seedlings with soil retained, weight increased in proportion to container volume, while for those with soil removed, weight did not vary significantly among seedlings grown in respective container sizes. Note that seedlings with soil removal are essentially bareroot seedlings.

The price per 1,000 seedlings charged by a hypothetical nursery was estimated as the sum of costs described above, implicit costs such as nursery storage (not estimated), and a 30% profit margin. Implicit costs were absorbed in the profit margin. Seedling price varied according to the interaction of container size and soil removal (Table 2). The price for small containers ($390 per 1,000 seedlings) was not influenced by soil removal, probably because the lower container removal costs compensated for the higher soil removal costs. However, the price for medium and large containers increased with container size, especially without soil removal and reuse. Fertilized seedlings cost 20% more than nonfertilized seedlings.

Seedling Morphology

Main effects of container size and fertilization were the primary factors that influenced morphology of cherrybark oak seedlings (Table 3). Height, height:diameter ratio, leaf area, and foliage, stem, and root biomass of seedlings each were greater when grown in medium or large containers than when grown in small containers. Effects of container size were marginally significant for stem diameter ($P = 0.06$), although these effects were highly significant in the field performance evaluation (described below). Each of the seedling morphology variables, except root biomass ($P = 0.27$), was greater with versus without fertilization. Specific leaf area was greater for seedlings grown in small versus large containers, indicating thinner versus thicker leaves, respectively. Container size differences were marginally significant ($P = 0.07$) for shoot:root ratio. The interaction of container size and fertilization was significant for leaf area ratio; however, multiple comparisons of means detected only differences due to the main effects of fertilization.

The nearly fourfold difference in soil volume between small containers (170 cm^3) and medium containers (650 cm^3) was associated with strong morphological responses of cherrybark oak seedlings. However, the nearly twofold difference in soil volume between medium containers (650 cm^3) and large containers (1,250 cm^3) did not stimulate

Table 3. Mean values for morphological variables of cherrybark oak seedlings (95% lower and upper confidence bounds below in parentheses) as affected by main effects of container size and fertilization. For a given variable, container size or fertilization level means followed by the same letter do not differ significantly ($P > 0.05$).

Variable	Container size			Fertilization	
	Small	Medium	Large	Absent	Present
Stem diameter (mm)	2.9 a (2.6, 3.3)	3.3 a (2.9, 3.8)	3.6 a (3.1, 4.0)	3.0 a (2.8, 3.3)	3.5 b (3.2, 3.9)
Height (cm)	17.6 a (14.9, 20.9)	24.5 b (20.7, 29.1)	26.0 b (21.9, 30.8)	17.5 a (15.3, 20.0)	28.7 b (25.1, 32.7)
Height:diameter ratio	60.3 a (54.1, 67.3)	74.3 b (66.6, 82.9)	73.9 b (66.3, 82.5)	58.4 a (53.6, 63.6)	82.0 b (75.3, 89.4)
Foliage biomass (g)	0.8 a (0.6, 1.0)	1.5 b (1.2, 2.0)	1.9 b (1.4, 2.4)	1.0 a (0.8, 1.2)	1.8 b (1.4, 2.2)
Stem biomass (g)	0.4 a (0.3, 0.5)	0.7 b (0.5, 0.9)	0.8 b (0.6, 1.1)	0.4 a (0.3, 0.5)	0.9 b (0.7, 1.1)
Root biomass (g)	1.0 a (0.8, 1.3)	2.0 b (1.5, 2.5)	1.9 b (1.4, 2.4)	1.4 a (1.2, 1.7)	1.6 a (1.4, 2.0)
Shoot:root ratio	3.5 a (2.9, 4.2)	3.6 a (3.0, 4.3)	4.5 a (3.8, 5.4)	2.7 a (2.4, 3.2)	5.3 b (4.6, 6.2)
Leaf area (cm^2)	155.8 a (119.0, 203.9)	300.3 b (229.4, 393.2)	329.0 b (251.3, 430.8)	165.9 a (134.4, 204.8)	372.9 b (302.1, 460.2)
Specific leaf area ($cm^2\ g^{-1}$)	207.5 a (196.1, 219.5)	201.5 ab (190.5, 213.3)	186.3 b (176.1, 197.1)	177.9 a (170.3, 186.0)	220.8 b (211.3, 230.8)
Leaf area ratio ($cm^2\ g^{-1}$)	73.3 a (67.5, 79.5)	74.9 a (69.0, 81.2)	73.5 a (67.7, 79.7)	60.3 a (56.6, 64.2)	90.5 b (85.0, 96.5)

proportional responses in seedling morphology. This threshold response of cherrybark oak to container volume indicates that medium containers provided sufficient soil volume for maximum three-month development of seedlings. Probably an extended duration in the greenhouse would have been necessary for seedlings to benefit from the additional growing space of large containers. Fertilization increased carbon allocation to the foliage and stem, but not to the roots, resulting in greater aboveground development and higher values for shoot:root, height:diameter, and leaf area ratios. In a comparable study of cherrybark oak (Moorhead 1981), seedlings were grown for three months in 500, 900, or 1,900 cm^3 containers filled with either peat-perlite or a mixture of 50% peat-perlite and 50% sandy loam soil. Although seedling height in Moorhead's (1981) study increased with container size, both stem diameter and root biomass were not affected. Seedling size and morphology did not differ significantly between the 900 and 1,900 cm^3 containers. These results indicate, as found in the present study, that container volumes of 500–650 cm^3 are adequate to meet the growing space requirements for 3-month development of the root and stem diameter of cherrybark oak seedlings. However, because of potential root binding and density restrictions, extended greenhouse duration is not recommended for seedlings grown in smaller container volumes such as that used in the present study.

Seedling Yield and Price Efficiency

As described previously, seedling size increased with container size and fertilization. Yield of seedlings grown in medium and large containers was almost three times that of seedlings grown in small containers (Table 2). On average, fertilization more than doubled seedling yield. Seedling price efficiency (yield divided by the estimated price of 1,000 seedlings) varied according to the interactions of container size by fertilization and container size by soil removal (Table 2). Fertilization provided an increase in yield at relatively low cost and thereby increased price efficiency for all container sizes. Price efficiency differed between medium and large containers that received fertilization (3.4 and 2.5 cm^3 per \$, respectively), and these values were higher than those found for most other combinations of container size and fertilization (1.2–1.9 cm^3 per \$). Seedlings grown in medium containers with fertilization had superior price efficiency because they produced the same yield as those from large containers but at only two-thirds of the price.

Soil removal increased price efficiency for medium and large containers but not for small containers. The factor most responsible for limiting price efficiency of seedlings grown in large containers with soil retained was the high cost of replacing soil—almost \$300 per 1,000 seedlings (Table 1). Soil recovery reduced estimated soil replacement cost for large containers to \$4 per 1,000 seedlings. Sterilization and reuse of soil is performed routinely in seedbeds of forest nurseries (May 1984) and for containerized seedlings in horticulture (Davidson et al. 1994) and is often preferable to the high cost of soil replacement.

Comparisons of seedling price, yield, and price efficiency from this study to those from two commercial nurseries emphasized the importance of economies of scale in large operations (Table 4). Although commercial prices for 1,000 containerized seedlings (\$3,769–\$6,658) were up to 15 times those estimated for this study (\$444–\$1,093), commercial seedling yields were over 30 times those for large containers in this study. As a result, the two commercial nurseries had substantially greater price efficiencies for containerized seedlings. Yields of bareroot seedlings from the two commercial nurseries were from 51 to 137% greater than those of seedlings grown in large containers for this study; however, the commercial prices for bareroot seedlings were as low as a third of those estimated for soil-removed stock in this study. Besides the absence of economies of scale in the nursery practices used in this study, another shortcoming was the limited duration of seedling growth in the greenhouse (3 months). Increasing this growth period to at least 6 months probably would have doubled seedling yields with only limited additional nursery costs (i.e., increased duration of greenhouse rent, watering, and fertilization), and likely it would have improved seedling price efficiency for this study.

Table 4. Comparison of seedling price, yield, and price efficiency of 1-year-old, fertilized seedlings of cherrybark oak for various sources and stock types. Current year prices have been discounted to 1997 assuming an annual inflation rate of 3%.

Seedling source[a]	Stock type[b]	Container size or nursery bed density[c]	Seedling price (\$ per 1,000 seedlings)	Seedling yield (cm^3 per 1,000 seedlings)	Seedling price efficiency (cm^3 stem volume per \$)
1	C	170	444	818	1.8
		650	678	2,080	3.1
		1,250	1,093	2,246	2.1
	CR	170	445	818	1.8
		650	539	2,080	3.9
		1,250	732	2,246	3.1
2	C	11,356	3,769	86,875	23.0
	B	194	209	3,394	16.2
3	C	11,356	6,658	76,403	11.5
	B	194	846	5,333	6.3

[a] 1 = current study, 2 = nursery A, or 3 = nursery B.
[b] C = containerized stock, CR = containerized stock with soil removed, or B = bare-root stock.
[c] Units are cm^3 for size of container stock or seedlings per m^2 for bed density of bare-root stock.

Plantation Phase

Plantation Costs

Planting rate varied according to the interactions of container size by soil removal and fertilization by soil removal (Table 5). Multiple comparisons of means indicated that planting rate was ranked among treatments as follows: small containers ≈ large containers with soil removal > medium containers with soil removal > medium and large containers without soil removal. This ranking of planting rates resulted from differences in planting difficulty due to presence or absence of container soil and perhaps variation in root length resulting from container lengths of 18, 20.5, and 15 cm for small, medium, and large containers, respectively. Container size and weight also limited the number of seedlings that could be transported in the planting bag, resulting in differences in the number of trips to and from on-site seedling storage to refill the bag (Table 1). Multiple comparisons of fertilization-by-soil-removal treatment means failed to indicate differences other than those due to soil removal; fertilization did not have a detectable influence on planting rate.

Fifth-year compounded costs of plantation establishment were 19% higher with versus without fertilization (Table 5), influenced most by the 20% higher initial seedling price. Compounded costs also varied according to the interaction of container size and soil removal; however, multiple comparisons failed to indicate differences other than main effects of these two treatments. Compounded costs increased two- to threefold with increasing container size, and they were 2, 38, and 67% higher in the absence versus presence of soil removal (and hypothetical reuse) for small, medium, and large containers, respectively. This divergence in costs was affected by the added expense of soil replacement, seedling transport both on and off site, and extra time and effort required in the handling and planting processes (Table 1).

Field Performance

Growing season (May to Oct.) rainfall near the planting site was 687, 662, 337, 474, and 341 mm for the years 1996, 1997, 1998, 1999, and 2000, respectively, or 117, 113, 57, 81, and 58% of the long-term average (www.georgiaweather.net, Jan. 23, 2004). The inter-tree competition index was not significant as a covariate in any of the survival, stem diameter, or height ANOVAs ($P > 0.11$). This result indicates that, although close spacing among planted seedlings (0.5 × 1.8 m) may have limited their growth, row adjacency of differing container sizes (e.g., seedlings from small containers adjacent to those from large containers) did not cause a detectable systematic bias in seedling responses.

As found in other studies (Kormanik et al. 1976, Stanturf and Kennedy 1996), field survival rates for cherrybark oak were high, with the overall average exceeding 90% for the study duration. In the first year after planting, a three-way

Table 5. Mean values and 95% confidence intervals for planting rate and fifth-year seedling compounded cost, yield, and cost efficiency as influenced by main effects of container size, fertilization, soil removal, or their interactions. For a given variable and factor or factor interaction, means followed by the same letter do not differ significantly ($P > 0.05$).

	Experimental factor				
Variable	Container size	Fertilized?	Soil removed?	Mean	95% conf. int.
Planting rate (containers hr^{-1})	Small		Yes	460 c	433, 487
			No	464 c	437, 491
	Medium		Yes	352 b	325, 379
			No	256 a	229, 283
	Large		Yes	474 c	447, 501
			No	267 a	240, 294
		Yes	Yes	415 b	395, 436
			No	337 a	316, 357
		No	Yes	443 b	422, 463
			No	321 a	301, 342
Fifth-year seedling compounded cost ($ per 1,000 seedlings)	Small		Yes	520 a	513, 526
			No	533 b	527, 540
	Medium		Yes	645 c	639, 651
			No	890 d	884, 896
	Large		Yes	885 d	879, 891
			No	1477 e	1471, 1483
		Yes		897 b	894, 900
		No		753 a	750, 756
Fifth-year seedling yield (dm^3 per 1,000 seedlings planted)	Small			1348 a	840, 1856
	Medium			2088 ab	1580, 2596
	Large			2745 b	2237, 3253
		Yes		2513 b	2113, 2913
		No		1608 a	1208, 2008
			Yes	2335 b	1935, 2735
			No	1786 a	1386, 2186
Fifth-year seedling cost efficiency (dm^3 per $)	Small		Yes	2.1 ab	1.3, 3.4
			No	2.3 ab	1.4, 3.8
	Medium		Yes	3.4 b	2.1, 5.5
			No	1.9 ab	1.1, 3.1
	Large		Yes	3.8 b	2.3, 6.2
			No	1.3 a	0.8, 2.0

interaction among experimental factors was detected. Multiple comparisons of means indicated that first-year survival of seedlings grown in small containers without fertilization was greater with (100%) versus without (75%) soil removal. At 2, 3, and 5 years after planting, the interaction of fertilization and soil removal was significant for seedling survival. Multiple comparisons of means indicated that, in each of these years, survival of nonfertilized seedlings was greater with (91–98%) versus without (81–84%) soil removal. These survival responses suggest that nonfertilized seedlings, which were smaller than fertilized seedlings for all container sizes, were better able to survive if their roots had been separated from the container soil.

Initial stem diameter ($P = 0.01$) and height ($P = 0.10$) were slightly smaller with (3.2 mm and 21 cm, respectively) versus without (3.4 mm and 22 cm) soil removal, probably because planting depth was slightly greater for seedlings with soil removal. However, two years after planting, stem diameter and height were slightly larger with versus without soil removal (8.0 mm and 66 cm versus 7.2 mm and 56 cm, respectively). By year five, soil removal had only a marginally significant effect on stem diameter ($P = 0.07$) and no detectable effect on height ($P = 0.28$). It is not known why the positive effect of soil removal on field performance was contrary to previous research in which first-year field performance was greater for soil intact container stock than for bareroot stock of three bottomland oak species (Williams and Craft 1998, Williams and Stroupe 2002). This indicates a need for further study on the impacts of soil removal on containerized seedlings. However, the slightly greater planting depth (1 cm) of soil-removed seedlings in the present research probably did not stimulate increased growth.

Although soil removal had a minor influence on seedling performance, the dominant factors influencing growth of cherrybark oak seedlings were main effects of container size and fertilization. Beginning at planting and continuing through year 5, stem diameter of seedlings grown in medium or large containers averaged greater than that of seedlings grown in small containers (Figure 1a). Container size effects on seedling height were similar in magnitude to those for diameter except in year 5, when height differed only between seedlings grown in small versus large containers (Figure 1c). In each year of the study, stem diameter and height were greater with versus without fertilization (Figure 1, b and d). Five years after planting, dbh averaged 24, 28, and 33 mm for seedlings grown in small, medium, and large containers, respectively, and it averaged 31 and 26 mm for seedlings grown with versus without fertilization, respectively. These fifth-year seedling sizes were similar to those observed 7 years after planting cherrybark oak seedlings at a similar spacing in Mississippi (Kennedy 1993b: 30 mm dbh and 390 cm height). Seedling growth in the present study exceeded that observed 5 years after planting 2–0 bareroot seedlings of cherrybark oak on a floodplain site in South Carolina (Stanturf and Kennedy 1996: 18–23 mm dbh and 230–240 cm height). Cherrybark oak planted on a similar site in the Oconee River floodplain averaged 280 cm in height 4 years after planting (Kormanik et al. 1976). Clearly, increases in container size and addition of fertilizer resulted in substantial increases in growth of cherrybark oak seedlings that continued through the fifth year after planting. The initial size differences that existed at planting continued to diverge for the duration of the study (Figure 1). It can be inferred that effects of inter-tree competition were small given that diameter growth of seedlings from all container sizes continued to accelerate through year 5 at rates comparable to those cited from previous studies for seedlings planted at wider spacings.

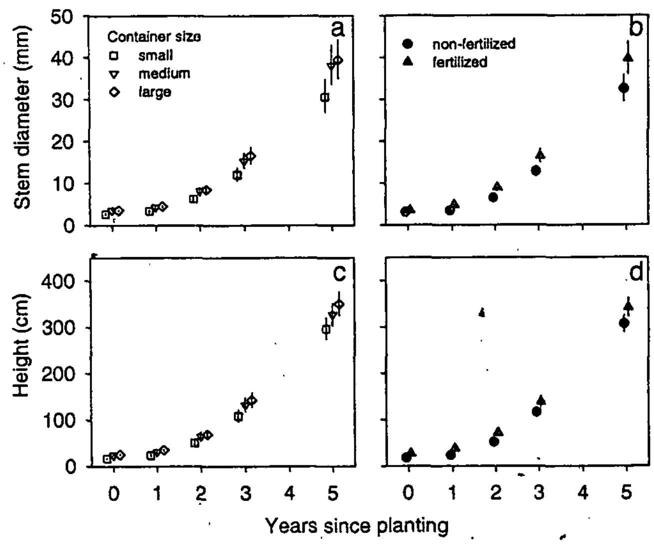

Figure 1. Mean values (with 95% confidence intervals) of cherrybark oak stem diameter as affected by (a) container size and (b) fertilization, and height as affected by (c) container size and (d) fertilization through the fifth year after planting.

Plantation Yield and Cost Efficiency

Fifth-year yield of seedlings varied according to the main effects of each of the factors (Table 5). Yield of seedlings from large containers was over twice that from small containers. Fertilization and soil removal resulted in 56 and 31% increases in fifth-year yield, respectively. Increases in yield from soil removal can be attributed to the combination of increased survival of nonfertilized seedlings and slightly greater growth of all seedlings receiving this treatment.

Fifth-year seedling cost efficiency varied according to the interaction of container size and soil removal (Table 5). Cost efficiency was greatest for medium and large containers with soil removal (3.4 and 3.8 dm^3 per \$, respectively), while it was least for large containers without soil removal (1.3 dm^3 per \$). Fertilization increased cost efficiency by 31% (data not presented); however, this difference was not large enough to be statistically significant ($P = 0.11$). These field performance results contrast with those from the nursery in which fertilization stimulated large increases in both seedling yield (117%) and price efficiency (38–108%), in part, because fertilizer effects on growth were large in comparison to seedling size.

Management Implications and Future Research

This research has provided an objective framework for jointly evaluating tree seedling cost and performance, both for the nursery manager (the producer) and the regeneration forester (the consumer). Although nursery production costs for growing seedlings in medium containers without soil removal were 60% greater than those for growing seedlings in small containers, the yield from medium containers was more than double that of small containers. Likewise, the doubling of seedling yield from fertilization more than compensated for the 20% additional cost of this treatment, translating into significantly greater price efficiency indices (38% to 108% greater) for each of the container sizes. Using this index, a regeneration forester can justify paying more for fertilized medium container stock versus the cheaper small container stock, since increased seedling size generally corresponds with improved stem morphology and field performance. Soil removal and reuse at the nursery would reduce nursery costs further, but only for medium (23% reduction) or large (35% reduction) containers, and these savings presumably would be passed on to the consumer. Large containers did not result in additional gains in seedling yield over that of medium containers because the three-month duration of growth did not allow seedlings to fully occupy all growing space and develop to their potential.

At 5 years after planting, compounded costs were lowest for small container stock because of their lower purchase price and planting cost. The plantation established with medium or large container stock had compounded costs that were 67 and 177% greater without soil removal, respectively, versus only 24 and 70% greater with soil removal. Fifth-year yields of medium and large container stock were 55 and 104% greater, respectively, than that of small containers. For unknown reasons, soil removal stimulated a 31% increase in fifth-year yield, and when combined with the lower purchase price, soil removal increased fifth-year cost efficiency of medium and large container stock by 79 and 192%, respectively. Using this index, a regeneration forester would conclude that planting either medium- or large-container, soil-removed stock provides a substantially greater return on investment than planting small-container stock, given the lower cost resulting from soil removal. The 56% increase in fifth-year yield from nursery fertilization more than compensated for the 19% increase in compounded cost, although the resulting 31% increase in cost efficiency was not statistically significant. This finding is in contrast to what was observed at plantation establishment, when fertilization was associated with large gains in price efficiency.

Containerized nursery culture combined with soil removal and reuse provides an approach for confining an oak seedling's root system for planting ease without incurring the large costs associated with replacing nursery soil and transporting it to the planting site. Future research like this is needed to assess the practicality of ultra-large container sizes (e.g., the 11.4-liter containers from nurseries A and B) because of their considerable requirements for soil volume, growing and storage space, and labor to handle and plant them. Additional operational comparisons are needed to establish benchmark cost efficiency values for different methods of nursery culture (e.g., variation in container size and shape, soil removal and reuse, greenhouse duration, and fertilization regimes).

Literature Cited

ALLEN, J.A., B.D. KEELAND, J.A. STANTURF, A.F. CLEWELL, AND H.E. KENNEDY, JR. 2001. A guide to bottomland hardwood restoration. USDA For. Serv., South. Res. Sta., Gen. Tech. Rep. SRS-40. 132 p.

BARHAM, R.O. 1980. Effects of seedbed density on nursery-grown cherrybark oak. Tree Planters' Notes 31(4):7–9.

BOWERSOX, T.W. 1993. Artificial regeneration of oaks in the uplands. P. 250–263 *in* Proc. of a conf., Oak regeneration: Serious problems, practical recommendations, Loftis, D.L. and C.E. McGee (eds.). USDA For. Serv., Southeastern For. Expt. Sta., Gen. Tech. Rep. SE-84, Asheville, NC. 319 p.

CLUTTER, J.L., J.C. FORTSON, L.V. PIENAAR, G.H. BRISTER, AND R.L. BAILEY. 1983. Timber management: A quantitative approach. John Wiley and Sons, New York, NY. 333 p.

CONRAD, J.M. 1999. Resource economics. Cambridge University Press, New York, . 213 p.

DAVIDSON, H., R. MECKLENBURG, AND C. PETERSON. 1994. Nursery management: Administration and culture. Prentice Hall, Upper Saddle River, NJ. 486 p.

HARRINGTON, T.B., AND K.D. HOWELL. 1998. Planting cost, survival, and growth one to three years after establishing loblolly pine seedlings with straight, deformed, and pruned taproots. New Forests 15(2):193–204.

HODGES, J.D., AND E.S. GARDINER. 1993. Ecology and physiology of oak regeneration. P. 54–65 *in* Proc. of a conf., Oak regeneration: Serious problems, practical recommendations, Loftis, D.L. and C.E. McGee (eds.). USDA For. Serv., Southeastern For. Expt. Sta., Gen. Tech. Rep. SE-84, Asheville, NC. 319 p.

HUNT, R. 1990. Basic growth analysis. Unwin Hyman, London, United Kingdom. 112 p.

KENNEDY, H.E., JR. 1993a. Artificial regeneration of bottomland oaks. P. 241–249 *in* Proc. of a conf., Oak regeneration: Serious problems, practical recommendations, Loftis, D.L. and C.E. McGee (eds.). USDA For. Serv., Southeastern For. Expt. Sta., Gen. Tech. Rep. SE-84, Asheville, NC. 319 p.

KENNEDY, H.E., JR. 1993b. Effects of crown position and initial spacing on foliar nutrient composition of seven bottomland hardwoods. USDA For. Serv., South. For. Expt. Sta., Res. Note SO-371. 6 p.

KORMANIK, P.P., R.P. BELANGER, AND E.W. BELCHER. 1976. Survival and early growth of containerized and bareroot seedlings of cherrybark oak. Tree Planters' Notes 27(3):9–10.

KORMANIK, P.P., S.S. SUNG, D.J. KASS, AND S. SCHLARBAUM. 1998. Effect of seedling size and first-order-lateral roots on early development of northern red oak on mesic sites. P. 247–252 *in* Proc. Ninth Biennial Southern Silvicultural Research Conf., Waldrop, T.A. (ed.). USDA For. Serv., South. Res. Sta., Gen. Tech. Rep. SRS-20, Asheville, NC. 628 p.

KRINARD, R.M. 1990. *Quercus falcata* var. *pagodifolia* Ell. Cherrybark oak. P. 644–649 *in* Silvics of North America: Vol. 2. Hardwoods, Burns, R.M., and B.H. Honkala (tech. coords.). USDA For. Serv. Agric. Handb. 654. Washington, DC. 877 p.

KRINARD, R.M., AND J.K. FRANCIS. 1983. Twenty-year results of planted cherrybark oak on old fields in brown loam bluffs. Tree Planters' Notes 34(4):20–22.

MAY, J.T. 1984. Seedbed preparation. P. 48–56 *in* Southern Pine Nursery Handbook, Lantz, C.W. (compiler). USDA For. Serv., Southern Region.

MOORHEAD, D.J. 1981. Container size and growth media influence early growth and survival of southern oaks in Mississippi. P. 20 *in* Proc. of workshop on seedling physiology and growth problems in oak planting, Johnson, P.S., and H.E. Garrett (compilers), USDA For. Serv., Gen. Tech. Rep. NC-62. St. Paul, MO. 26 p.

STATISTICAL ANALYSIS SYSTEMS INSTITUTE. 1999. SAS/STAT User's Guide. Vol. 2. Version 8. Statistical Analysis Systems Institute, Inc., Cary, NC. 2,552 p.

SOKAL, R.R., AND J.F. ROHLF. 1981. Biometry, 2nd Ed. W.H. Freeman, New York, NY. 859 p.

STANTURF, J.A., AND H.E. KENNEDY. JR. 1996. Survival and growth of planted and direct-seeded cherrybark oak in South Carolina. South. J. Appl. For. 20(4):194–196.

USDA NATIONAL RESOURCES CONSERVATION SERVICE. 2003. Official description of the Congaree soil series. ortho.ftw.nrcs.usda.gov/osd/osd.html. Accessed January 23, 2004.

Williams, H.M., and M.N. Craft. 1998. First-year survival and growth of bareroot, container, and direct-seeded Nuttall oak planted on flood-prone agricultural fields. P. 300–303 *in* Proc. of the Ninth Biennial Southern Silvicultural Research Conference, Waldrop, T.A. (ed.), USDA For. Serv., Gen. Tech. Rep. SRS-20, Asheville, NC. 628 p.

Williams, H., and M. Stroupe. 2002. First-year survival and growth of bareroot and container water oak and willow oak seedlings grown at different levels of mineral nutrition. P. 338–341 *in* Proc. of the Eleventh Biennial Southern Silvicultural Research Conference, Outcalt, K.W. (ed.), USDA For. Serv., Gen. Tech. Rep. SRS-48, Asheville, NC. 622 p.