Arboriculture & Urban Forestry 2010. 36(4): 183–190

Effect of Tree Size, Root Pruning, and Production Method on Establishment of *Quercus virginiana*

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Abstract. Significant differences may exist in establishment rate between trees planted from containers and those from field nursery. Container-grown plants have root balls with deflected roots which could impact establishment. Slicing root balls at planting could improve post-planting performance of container-grown trees. Sixty live oak 170 L containers were planted into landscape field soil. Root balls from 30 of these containers were sliced prior to planting. Thirty field-grown trees of slightly larger size, and 30 smaller trees from 57 L containers, were also planted. During dry periods in the first 432 days after planting (DAP), 57 L container trees had the least negative xylem potential. Field-grown trees had the most negative xylem potential when irrigation was withheld 12 DAP. Slicing root balls had little impact on xylem water potential in drought. Defoliation was greater for 170 L container trees than for 57 L containers. Trunk diameter increase of 57 L containers and field-grown trees was greater than for 170 L containers. Field-grown trees grew less in height. Root system radius was similar for 170 L containers and field-grown trees, and greater than 57 L containers. Small trees appear to establish quicker than larger trees.

Key Words: B&B; Containers; Drought; Field-Grown; Irrigation; Planting; Root Ball; root:shoot Ratio; Transplanting; Tree Survival; Xylem Water Potential.

Nearly 300 years ago, nursery operators understood that trees were more likely to establish in a poorly drained soil if a seed was planted direct into soil than if a tree was transplanted from a nursery (Langley 1728). Roots from seeds grown in place respond to soil conditions present at the planting site; whereas, roots from a transplanted tree are forced to adapt and adjust to conditions at the planting site. Planting site soil attributes are often different than in the nursery, and this can impact water relations (Spomer 1980) and root growth (Coutts and Nicoll 1991), after landscape planting. Trees from certain nursery production methods and trees with sliced root balls at planting may adapt quickly to the new landscape soil environment.

Planting seeds into urban landscapes is not practical, at least by way of current urban forestry practices. However, Watson (1985) modeling root growth rates in USDA hardiness zone 5, suggested that small nursery stock (10 cm caliper) would establish and grow quicker than large (25 cm caliper) trees. Gilman et al. (1998) confirmed that small caliper trees (6.3 cm) grew at a faster rate than large trees (10 cm) in the three years after planting from a container, but not when planted from a field nursery. In addition, the smaller field-grown trees were statistically similar in trunk caliper three years after planting to the large container-grown trees. On the other hand, Struve et al. (2000) found no difference in growth rates between small and large-sized trees. This suggests tree size or age at planting impacts establishment rate in urban landscapes, at least in certain soil types.

Trees have been transplanted bare root or with an intact soil ball for hundreds of years (Langley 1728), and probably longer with good success. Trees planted bare root have been shown to grow as well after landscape planting as trees from other nursery production methods (Buckstrup and Bassuk 2000; Anella et al. 2008). Container production has become increasingly popular in the past 50 years, especially in the warmest parts of North America. Many types of containers have been developed for growing trees and shrubs (Appleton 1993). Container type impacts post-transplant growth for seedling-sized liners of certain species (Struve 1993), but may not impact larger-sized nursery stock typically planted in urban landscapes (Marshall and Gilman 1998; Gilman 2001). Various comparisons among nursery production methods including bare-root, container, field-grown balled-and-burlapped (B&B), and in-ground fabric containers were made in the past 30 years measuring transplant survival, water stress after planting, growth rates, and root form.

Appropriate irrigation management is often cited as important for trees planted from all production methods due to inadequate rainfall to maintain turgor after planting. Freshly dug field-grown B&B East Palatka holly (*Ilex* x *attenuata* 'East Palatka') trees were more stressed and more likely to die than trees planted from containers if they were not regularly irrigated after transplanting due to the sudden loss of roots (Harris and Gilman 1993). However, with regular irrigation, laurel oak (*Quercus laurifolia*) and East Palatka holly trees from either production method experienced similar post-transplant water stress (Gilman and Beeson 1996). Irrigating newly planted trees not only improved their survivability and growth but lead to better branch structure (Martin and Stutz 1994; Struve 1994). More rapid root growth from well-watered field-grown B&B laurel oak trees resulted in faster establishment than trees planted from containers filled with bark:peat:sand substrate. Beeson and Gilman (1992) proposed that field-grown live oak trees may osmotically adjust when roots were severed, helping

prepare them for sub-optimal soil moisture conditions common on many landscape sites. Later work appeared to confirm this when Gilman (2001) found that live oak root pruned regularly during production and held in the ground in a nursery for several months after digging (i.e., hardened-off), had a much higher survival rate in drought following planting than trees installed from containers. However, there are few studies comparing production methods that extend beyond approximately one year after planting.

Reported effects of mechanical root pruning in small containers (11.3 L size or smaller) on root growth and morphology vary. Blanusa et al. (2007) found that light cutting of circling roots of shrubs increased the amount of roots growing into container substrate outside the original root ball in agreement with Krasowski and Owens (2000). In contrast, Gilman et al. (1996) showed slicing (11.3 L, 25 cm tall x 25 cm top diameter) root balls top-to-bottom on Burford holly (*Ilex cornuta* 'Burfordii') at planting resulted in redistribution of roots, not an increase in roots compared to nonpruned controls. Harris et al. (2001) reported root pruning treatments (5, 10, or 15 cm below soil) on pin oak (*Quercus palustris* Münchh.) liners in containers increased number of lateral roots but not total root length following planting. Other than Weicherding et al. (2007) on 38 L (36 cm tall x 40 cm top diameter) containers and smaller, there are few published mechanical root pruning studies on large landscape-sized containers measuring water stress and growth following planting. There may be an effect of root pruning on tree development, and perhaps this influences the magnitude of water stress following planting.

Communities would use resources most efficiently by understanding how trees from various planting treatments, production methods, and tree sizes become established. Objectives were to evaluate impact of 1) radial slicing of the outer edge of container root balls, 2) initial tree size at planting, and 3) nursery production method on post landscape planting water stress and growth. Live oak was tested because it is a commonly planted shade tree in the southern one-quarter of the U.S.

MATERIALS AND METHODS

Tree Production Techniques

In August 2001, 80 cutting-propagated liners in 3.8 L (20 cm tall x 18 cm top diameter) smooth-sided black plastic containers of *Quercus virginiana* Mill. 'SNDL', PP#12015, Cathedral Oak® were planted into a field with Millhopper fine sand (loamy, siliceous, hyperthermic Grossarenic *Paleudults*) with less than 2% organic matter. These are referred to as field-grown trees. Eighty of the same 3.8 L liners were planted into 57 L smooth-sided black plastic containers (41 cm tall x 43 cm top diameter, Nursery Supplies Inc., Fairless Hills, PA), 50 m from the field plot. Containers were maintained on woven, black nursery ground cloth to prevent rooting into the ground. In December 2002, the 57 L containers were shifted into 170 L (47 cm tall x 75 cm top diameter) smooth-sided black plastic containers. Plants produced in this manner are referred to as 170 L container trees. All 160 trees were spaced on 2.4 m centers in eight rows 3.6 m apart. An additional thirty 11.3 L smooth-sided black plastic container-grown (24 cm tall x 28 cm top diameter) cutting propagated Cathedral Oak trees were planted May 2004 into 57 L smooth-sided black plastic containers on 1.2 m centers on woven, black nursery ground cloth. These trees are referred to as 57 L container trees. All trees were located at the University of Florida Great Southern Tree Conference demonstration site in Alachua County, Florida, U.S. (USDA hardiness zone 8b).

Substrate in all containers was composed of 60 pine bark: 30 peat: 10 sand by volume (Florida Potting Soil, Inc., Orlando, FL). Irrigation and fertilizer commonly used for these production methods in the region were applied during production. Trees were irrigated two or three times daily during the growing season and once daily at other times, except in wet and cool weather. Tree crowns were pruned twice annually to meet Florida Grades and Standards for Nursery Plants (Anonymous 1998) with one central leader and crown beginning 1.4 m from ground.

Landscape Planting Treatments

Thirty field-grown trees closest to mean trunk caliper (trunk diameter measured with a diameter tape 15 cm from ground) for the 80 field trees (80 mm) were root pruned November 2004 with a tree spade. All blades on the 91 cm diameter three-bladed tree spade (Caretree Nursery Equipment, Hilliard, OH) were inserted into the ground so they cut roots in three one-sixth circumference sections on an 81 cm diameter, centered on the trunk. This allowed us to use the same spade to dig the trees later with a larger (91 cm) root ball as described later in this paper. Root pruning prior to digging is standard practice for oaks in the Florida field nursery industry. Root balls were irrigated two to three times daily for three weeks following root pruning depending on rainfall and temperature, then daily. Ten weeks later, in January 2005, trees were dug with the same spade using the full 91 cm diameter. Trees were placed into wire baskets lined with copper treated natural burlap to fit the root ball, and wire was secured tightly around root ball by twisting wire and tying top of basket tightly against top of soil ball as standard practice. All trees were lowered back into the same hole and irrigated four to six times daily for four weeks; then irrigation was reduced to three to four times weekly depending on weather. This root pruning, digging, and holding in the ground prior to transplanting to the landscape is considered hardening-off and is standard practice in many field nurseries in the region. Eight weeks after digging (March 24 to April 3, 2005), trees were lifted by a tractor with a sling and straps through the second rung of the wire basket, and moved to an adjacent field of the same type soil previously described.

Sixty trees closest to mean trunk caliper (66 mm) for the 170 L container-grown trees were planted into the same field soil as field-grown trees March 24 to April 3, 2005. April 4 was considered the first day after planting (DAP) since all planting was completed April 3. Half the 170 L container trees (30 trees) were root pruned at planting by cutting 3 to 5 cm deep radially into the root ball periphery with a hand pruner in six equidistant places from the top of the root ball to the bottom (referred to as 170 L container/ sliced). The remaining thirty 170 L container trees were planted without root ball cutting (referred to as 170 L container/ not sliced). All 30 trees (29 mm caliper) in 57 L containers were planted into the same field during the same time period. The top of the root ball surface on all 120 trees was positioned even with landscape soil surface; no mulch was applied.

Trees were arranged in the field in a randomized complete block design with one tree of each of the four landscape planting treatments (57 L containers, 170 L containers/ sliced, 170 L containers/

not sliced, and field-grown), in each of 30 blocks. The 120 trees were planted in five rows 2.7 m apart. Weeds in a 1.8 m wide strip down each row were kept in check with periodic applications of Glyphosate. Surface between weed-free strips was mowed regularly.

Maintenance

Trees were irrigated (Table 1) roughly in accordance with the irrigation schedule shown to encourage post-planting survival in Florida (Gilman et al. 1998). Irrigation for 170 L containers and field-grown trees was delivered to the root ball surface through three low-volume Roberts spray stakes (Roberts Irrigation Produces, Inc., San Marcos, CA), equally spaced at the edge of the root ball and directed toward the trunk. Irrigation for 57 L containers was delivered to the root ball surface through one low-volume Roberts spray stake positioned at edge of root ball directed toward the trunk. Immediately after planting, strategy for the first three months was to periodically interrupt the irrigation schedule designed to encourage survival with short periods of moderate stress. Stress was induced by withholding irrigation for two or more days beginning 12, 28, 76, and 104 days after planting. Trees were irrigated in late afternoon on each of these four days following stress measurement. Live oak trees of this size receiving daily irrigation in the nursery—such as trees in this study—are known to stress, drop foliage, or die without regular irrigation following planting in Florida (Gilman 2001). Trees were stressed considerably beginning 104 DAP by withholding all irrigation for 33 days. Rainfall during that period was 13 cm, which was 20 cm below normal. Trees were irrigated daily beginning 137 DAP (July 26, 2005) through 186 DAP (September 13, 2005) to help them overcome obvious water stress that resulted from this extended 33-day dry period. No irrigation was applied in 2006 or 2007 through end of the study in November 2007 with two exceptions because of exceptionally dry weather. One irrigation occurred 423 days after planting (May 29, 2006), and one 433 days after planting (June 8, 2006), when trees appeared moderate to severely stressed (foliage drop on some trees was measured as described below) due to drought in the normally hot dry weather of May.

Trees were fertilized after planting into landscape field soil with 100 g of 16-4-8 (N:P:K) per tree, applied to a 91 cm diameter area around the trunk in March, April, and September 2005. In 2006, 400 g of 16-4-8 were similarly applied to each tree in April, June, and September. In April 2006, lower trunks were cleaned of all branches from the ground up to lower crown 1.4 m from ground; no other pruning was conducted during the study.

Measurements

Trunk caliper, tree height (height from ground to top of crown), and crown spread [(maximum crown spread + crown spread perpendicular to maximum) ÷ 2] on each tree were measured when planted into landscape field soil and in September of each year. Roots were excavated nondestructively April 2006 (386 DAP), in the east and west directions (i.e., within weed-free soil in rows), until root tips farthest from trunk were found. Preliminary excavations indicated that roots farthest from trunk were growing just under soil surface. Root spread was recorded as distance from trunk to edge of root system. Defoliation in drought was evaluated May 18, 2006 (400 DAP) on all four trees in 14 randomly selected replicate blocks due to considerable foliage discoloration and leaf drop. Visual estimates of defoliation were made by two assessors standing next to each tree. Both assessors had to agree on defoliation amount: None (1) = no defoliation; some (2) = up to about one-third of foliage on ground; medium (3) = between one-thirds and two-thirds of foliage on ground; heavy defoliation (4) = most foliage on ground.

Xylem water potential 12:00 to 14:00 hour on sunny or mostly sunny days was measured on all four trees in eight randomly selected blocks (four planting treatments x eight replicate blocks = 32 trees), periodically (Figure 1), for 463 DAP with a pressure bomb (Soil Moisture Inc., Santa Barbara, CA). Terminal portions of stems of current year twigs in full sun on the south side of crown half way up crown were cut roughly 10 cm long. Pressure in the air-tight chamber was increased at a constant rate of 30 seconds per MPa. Pressure was recorded when cut stem surface became uniformly wet. Water stress on trees in the same eight blocks was measured at each measurement date.

Statistical Analysis

Trunk caliper, tree height, crown diameter, defoliation rating, root system radius, and root:crown spread were compared among four landscape planting treatments using one-way analysis of variance (ANOVA) in a randomized complete block design. Xylem water potential means were analyzed with one-way ANOVA for each point in time. Means were compared using Duncan's multiple range test. Defoliation severity data was analyzed as a Poisson distribution and log transformed for analysis using GENMOD procedure because data was discrete; means were compared using CONTRAST statement. SAS Institute Inc. (Cary, NC) analytical software was used for all analysis.

Table 1. Irrigation schedule in the 432 days following landscape installation[z] of Cathedral Oak live oak trees.

	Days after planting														
	1–11[y]	12	15	18–28[y]	40	42	46	48–90[y]	98	102	104	137–186[x]	423	432	Total irrigation applied
Irrigation[w] volume (L) per tree for 57 L containers	76	10	10	10	10	10	20	10	10	10	10	20	227	20	1434
Irrigation[v] volume (L) per tree for field grown and 170 L containers	76	57	28	28	28	28	57	28	28	28	28	57	680	57	4304

[z] Trees planted into field soil March 24 through April 3, 2005. Day 1 was April 4, 2005.
[y] Applied every other day.
[x] Applied daily.
[w] Irrigation delivered in late afternoon to root ball surface through one low-volume Roberts spray stake (Roberts Irrigation Produces, Inc., San Marcos, CA).
[v] Irrigation delivered in late afternoon to root ball surface through three low-volume Roberts spray stakes.

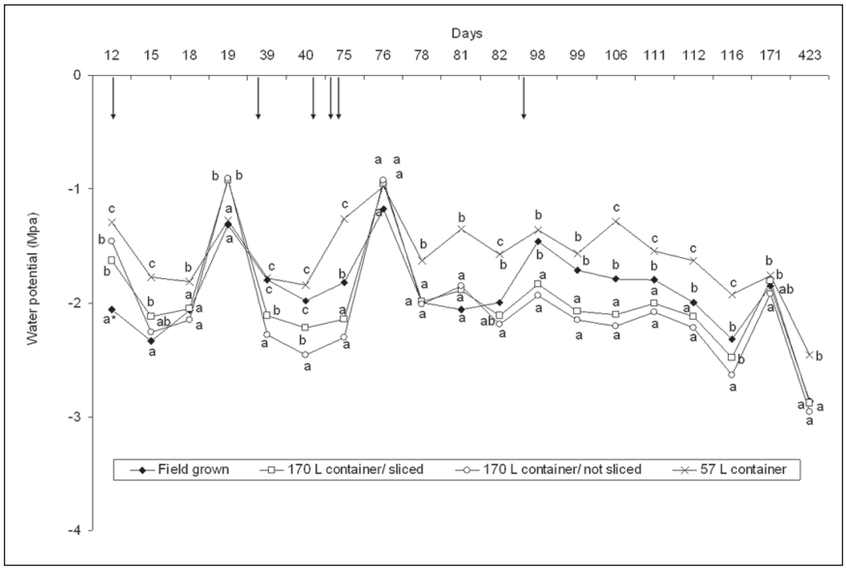

Figure 1. Xylem water potential (12:00–14:00 hours) of current year stems for four landscape planting (planted March 2005) treatments during the first 423 days after planting (DAP). Arrows indicated rainfall events of 13 mm or greater. Asterisk (*) indicates means within a day with a different letter are statistically different ($P < 0.05$).

RESULTS AND DISCUSSION

Trees planted from 57 L containers were less stressed (i.e., had less negative xylem water potential) than trees planted from larger 170 L containers for 16 of 19 measurement dates in the first 432 DAP induced by withholding irrigation during dry weather (Figure 1). Trees had been irrigated the day prior to measurement on the other three dates—19, 76, 171 DAP—so differences among treatments were not expected. Trees from 57 L containers were less stressed than field-grown trees for 12 of 19 measurement dates. Field-grown transplanted trees were more stressed than all other planting treatments the first time irrigation was withheld 12 DAP. Stress on field-grown trees was the same as on 170 L containers not sliced at planting three days later (15 DAP) at end of a three-day dry period. There was no difference among these three planting treatments three additional days later (18 DAP). Trees in all treatments recovered well on 19 DAP following irrigation in the afternoon of the previous day.

In the first extended dry period 28 to 40 DAP, transplanted field-grown trees were less stressed than the slightly but significantly ($P < 0.05$) smaller trees planted from 170 L containers that were either sliced or not at planting. Field-grown trees were less stressed than trees planted from 170 L containers and more stressed than the much smaller trees planted from 57 L containers 75 DAP (i.e., mid-day in the second full day without irrigation or rainfall; Figure 1). Irrigation was applied every other day during this hot dry period. Trees in all treatments recovered to similar xylem water potential middle of next day (76 DAP) following irrigation late afternoon 75 DAP. There was no difference in xylem water potential between 170 L containers and field transplanted trees when irrigated every other day 78 to 81 DAP.

Trees not sliced at planting (170 L container/ not sliced) were more stressed (i.e., had more negative xylem water potential) than trees sliced at planting 39, 40, 116, and 171 DAP. Perhaps roots at this time on sliced trees were distributed more evenly in the soil profile, enabling them to extract moisture more efficiently than trees not sliced as found on Burford holly (Gilman et al. 1998). Trees planted from 57 L containers and field transplanted trees had similar xylem water potential following a week-long period without irrigation or rainfall 98 and 99 DAP; both were less stressed than trees from 170 L containers, sliced or not. Despite their slightly ($P < 0.05$) larger size at planting, field-grown trees were consistently less stressed than trees from 170 L containers 98 through 112 DAP. Laurel oak (Gilman and Beeson 1996) and live oak (Gilman 2001) trees planted from containers were also more stressed and had lower survival rate than trees transplanted from field soil. However, in both cited studies stress and survival was equal among planting treatments when irrigation was applied regularly in the months after planting.

An extended dry period 423 DAP in the normally hot dry late spring (May 2006) induced foliage drop on some trees (Table 2). Live oak trees dropping foliage from drought in the year following planting often die within a few days lacking irrigation or significant rainfall (Gilman 2001). Foliage drop was a little surprising since previous work suggested that trees would be established at this point in time (Gilman and Beeson 1996). However, Gilman and Beeson's (1996) research was performed on smaller trees planted from smaller containers (120 L). It is reasonable to think that the larger trees in the current study could take longer to become established. There were more trees (93%) from 57 L containers without defoliation than from any other planting treatment (Table 2). Every tree planted from 170 L containers not sliced at planting had some amount of defo-

Table 2. Percent defoliation of Cathedral Oak live oak in a drought 14 months after planting April 2005 into field soil.

Landscape planting treatment	Defoliation severity[z] None	Some	Medium	Heavy	Mean defoliation rating[z]
	Percent[y] of trees in each severity				
57 L container	93a[y]	7b	0a	0a	1.1b[x]
170 L container/ not sliced	0c	64a	21a	14a	2.5a
170 L container/ sliced	29b	43a	21a	7a	2.1a
Field grown	43b	36ab	21a	0a	1.8ab

[z] Mean visual foliage drop by two assessors; none (1) = no defoliation; some (2) = up to approximately one-third of the foliage on the ground; medium (3) = between one-thirds and two-thirds of foliage on ground; heavy defoliation (4) = most foliage on the ground.
[y] Percentage of 14 trees in each treatment with a given defoliation severity compared using GENMOD procedure in SAS.
[x] Means in a column with a different letter are statistically different at $P < 0.05$.

liation. However, slicing 170 L container root balls at planting significantly increased percentage of trees with no defoliation (29%) compared to trees that were not sliced at planting (0%).

Mean defoliation rating was higher for both 170 L container treatments than for the 57 L treatment (Table 2). Within a week after foliage began dropping, xylem water potential was equal among all treatments for larger trees (423 DAP); smaller trees planted from 57 L containers were less stressed than all other treatments (Figure 1). Xylem water potential was near -3 MPa 423 DAP, which has been determined lethal for live oak (Gilman 2001), for many trees except those planted from 57 L containers. It appears clear from defoliation and xylem water potential data that live oak trees that were much smaller (57 L containers) at planting were subjected to less water stress in dry periods in the first 423 DAP than larger trees (170 L containers).

Severe water deficits experienced by trees in this study were overcome with irrigation at the appropriate time evidenced by all trees recovering with no visible damage to trunk or branches. This differs from Roppolo and Miller (2001) who demonstrated severe cracking in maple trunks from water deficit following planting. Live oak may be more resistant to trunk cracking in severe water deficit. Past study with live oak of similar size as those in the current study showed trees planted from containers lost more foliage than trees transplanted from a field nursery 11 and 26 weeks after planting (Gilman et al. 1998). However those trees were 6.4 cm caliper planted from 103 L containers, the largest caliper size recommended for that container (Anonymous 1998). Trees from the current study were smaller (6.6 cm) in proportion to their container (170 L) so they were likely establishing quicker. This provides evidence that trees with relatively large trunks for a given root ball size will be more stressed following planting due to rapid substrate drying leading to slow establishment or poor survival. Differences in soil type can be discounted since previous work was performed in the same soil type as the current study.

Although hardened-off (dug and placed in burlap for several weeks prior to landscape planting) field-grown trees in this study and others (Gilman 2001) were less stressed (i.e., had less negative xylem water potential) after planting than container-grown trees of comparable or slightly smaller size, recently dug field-grown plants appear more stressed than container-grown trees (Harris and Gilman 1993, Dana and Blessing 1994; Gilman 2001). This emphasizes importance of root pruning and hardening-off field-grown trees prior to planting into landscape. Slicing container root balls at planting in the manner described in this study has been suggested as a treatment to improve performance on trees planted from containers (Malieke and Hummel 1990), and data from the current study support the suggestion to a small extent. Evidence for this was the four times (39, 40, 116, and 171 DAP) during the 423 DAP when 170 L container/ sliced trees were slightly, but significantly, less stressed than 170 L container/ not sliced (Figure 1). Blessing and Dana (1987) and Weicherding et al. (2007) found no significant reduction in water stress from slicing root balls at planting.

Whitcomb (1985) suggested that performance of liner-sized container-grown trees might be improved by planting from container types that produce greater number of root tips than smooth sided containers. However, planting trees from containers designed to reduce circling roots and enhance root numbers has failed to show enhanced performance on larger trees typically planted into landscapes (Ruter 1993; Marshall and Gilman 1998; Gilman 2001; Gilman et al. 2002). Perhaps lesser ($P < 0.05$) foliage drop (Table 2) on trees with sliced root balls in drought 400 DAP (Figure 1) combined with four times where xylem water potential was less negative indicated some osmotic adjustment and better adaptability in drought. Mechanical root pruning to remove outer peripheral 2.5 cm of a container root ball (shaving) has been shown to about double ($P < 0.01$) the number of roots growing into substrate of the next, larger container size (Gilman et al. 2010). Perhaps this same increase in root number would also occur on larger trees shaved in this manner as they are planted into landscape. An increase in number of roots growing from root ball into landscape soil might help overcome rapid drying that takes place in container substrate (Spomer 1980). Roots on shaved trees may grow out into landscape soil instead of remaining primarily in the root ball. Further study is needed to evaluate whether this could result in container-grown trees performing as well as hardened-off field-grown trees. Shaving would also remove most root defects present on outer root ball surface (Gilman et al. 2010).

Slicing 170 L container root balls at planting had no impact on trunk diameter, crown spread, or tree height increase in the three years following planting (Table 3). Other studies showed similar results; for example there was no impact on trunk caliper or tree height on seven tree species shifted to larger containers following removal of the outer 2.5 cm periphery of 11.3 L sized root balls compared to trees that were not root pruned at planting (Gilman et al. 2010). Others also reported shoots and trunk of trees grew similarly after cutting (by slicing root ball top-to-bottom) and teasing roots away from periphery of container root balls (Arnold and Young 1991). Irrigation was required in both cited studies to maintain comparable growth between pruned and non-pruned trees. This suggests that root balls can be pruned at planting with little if any impact on shoot growth following planting.

Trunk caliper increase on 57 L container-grown and field-grown trees was slightly but significantly greater than for trees planted from 170 L containers. Gilman et al. (1998) also found field-grown trees increased in trunk diameter slightly more than comparably-sized container-grown trees in the first three years after planting to landscape. The smaller trees (those from 57 L containers) also grew more in height than trees from any other treatment, similar to trunk diameter growth on planted container-grown (Gilman et al. 1998) and field-grown trees (Watson 1985). Field-grown trees in the current study grew less in height and crown spread than all other treatments. Despite starting with a significantly smaller ($P < 0.05$) crown spread, 170 L containers ended the study three years later with equal crown spread as field transplanted trees. Marler and Davies (1987) also found that crown spread on 'Hamlin' orange trees (*Citrus sinensis* L. Osb.) planted from containers increased more than on trees transplanted bare root. However, Struve et al. (2000) suggested smaller trees in his study did not grow faster to equal the larger trees because larger trees in the nursery were typically the most vigorous and therefore grew fastest. This keen observation has merit when comparing trees from the same block of trees in the same nursery but may not hold true when comparing small trees from one nursery with larger trees from a different block or from a different nursery.

Root system radius was similar for trees planted from 170 L containers and field-grown, in agreement with Harris and Gilman (1993), and both had wider root systems than trees from 57 L con-

tainers (Table 4). This contrasts with Gilman and Beeson (1996) where laurel oak roots grew slower into landscape soil on trees planted from 120 L containers than on similarly sized trees transplanted from field soil. Dana and Blessing (1994) also found less root growth from *Juniperus* shrubs planted from containers than transplanted from a field soil. Dana and Blessing (1994) for 7 L *Juniperus chinensis* L. planted into soil and Blanusa et al. (2007) for 3.7 L *Buddleja davidii* 'Summer Beauty' and *Cistus* 'Snow Fire' found more roots grew into substrate of a larger container in response to slicing root balls than plants not root pruned. Burford holly from 11.3 L containers (Gilman et al. 1996), *Tilia* and *Salix* from 7 and 10 L containers (Weicherding et al. 2007), and live oak from 170 L containers in the current study sliced at planting showed no increase in root growth compared to those not sliced. Perhaps size of root ball, age of plant, number of shifts from smaller containers, circling root diameter, origin of planting stock, and/or species, impacts response to mechanical slicing of root balls.

A smaller root system 14 months after planting on trees installed from 57 L containers was not surprising given their much smaller size (Table 2; $P < 0.01$) at planting. Ratio of root spread to crown spread was identical (mean root spread:crown spread ratio = 1.65) for all planting treatments despite differences in root spread. Roots reached an average of 1.65 times wider than crowns (Table 4) indicating trees were not yet established since established trees have a ratio closer to 3.0 (Watson and Himelick 1982; Stout 1956). Lack of establishment at this time was also indicated by severe water stress (i.e., negative xylem water potential), inducing foliage drop 14 months after planting on trees from larger (170 L) containers.

CONCLUSIONS

Small nursery stock appears to establish quicker than larger stock of the same species. Except for the first two weeks after planting, hardened-off trees transplanted from the field nursery proved more resistant to moderate drought than slightly smaller trees planted from 170 L containers during the first 14 months after planting. Susceptibility to drought stress in container-grown trees has been attributed to a much denser root system inside the container than inside root balls of field-grown trees (Harris and Gilman 1993; Marshall and Gilman 1998), resulting in earlier drying of root balls of container trees. In addition, trees of a given size in containers have a smaller root ball volume than trees in a field-grown soil root ball (Anonymous 1998). This study was also designed to determine if root pruning by slicing root ball sides at planting could improve performance of large container-grown trees. Results showed there was only a slight impact of root ball slicing on resistance to drought after planting. This makes sense because root spread on trees from 170 L containers not sliced was similar to trees sliced at planting, and growth rates of trunk, crown, and roots were identical for the two treatments. Perhaps shaving off the entire root ball periphery at planting, similar to digging a tree from a field nursery, can increase resistance to drought on trees planted from containers. This might trigger osmotic adjustment and stimulate root growth into surrounding landscape soil. More research is needed to determine if this also occurs on trees planted into field soil as it does in containers (Gilman et al. 2010).

There are many factors influencing water stress and establishment of trees and shrubs into field soil that were not directly measured in this study. Certainly soil water status interacts with effects of nursery production method on transplant

Table 3. Trunk caliper, tree height, and crown diameter of Cathedral Oak live oak at planting (April 2005) and three growing seasons following planting into field soil.

Landscape planting treatment	Trunk caliper at planting (mm)	Trunk caliper after three growing seasons[z] (mm)	Trunk caliper increase[y] (mm)	Tree height at planting (m)	Tree height after three growing seasons[z] (m)	Tree height increase[y] (m)	Crown diameter at planting (m)	Crown diameter after three growing seasons[z] (m)	Crown diameter increase[y] (m)
57 L container	29c[x]	85c	56a	2.1c	4.7c	2.6a	0.6c	2.3b	1.7a
170 L container/ not sliced	66b	113b	47b	3.7b	5.4b	1.7b	1.8b	3.5a	1.7a
170 L container/ sliced	67b	115b	48b	3.7b	5.2b	1.5b	1.8b	3.6a	1.8a
Field grown	80a	132a	52a	4.6a	5.6a	1.0c	2.3a	3.7a	1.4b

[z] Caliper, height, and crown diameter November 2007.
[y] November 2007 measurement – March 2005 measurement.
[x] Means of 30 trees per treatment; means in a column with a different letter are statistically different at $P < 0.05$.

Table 4. Root system radius in the landscape, and ratio of root system radius to crown radius of Cathedral Oak live oak one growing season following planting.

Landscape planting treatment	Root system radius[z] (cm)	Root to crown spread radius ratio
57 L container	133b[y]	1.94a
170 L container/ not sliced	177a	1.58a
170 L container/ sliced	169a	1.51a
Field grown	182a	1.56a

[z] Maximum spread (radius) of the root system measured from trunk to tip of the farthest root in east and west directions. East and west measurements were averaged for each tree.
[y] Mean of seven trees per treatment; means in a column with a different letter are statistically different at $P < 0.05$.

success (Gilman et al. 1998; Gilman 2001). Substrate composition in containers could impact tree establishment by retaining more or less water depending on its properties (Spomer 1980). Soil type in the field-grown root ball and landscape could interact and play an important role in soil moisture and air properties, which could influence root growth and establishment. Unfortunately, this has received almost no attention.

Acknowledgments. Thank you to the TREE fund and GreatSouthernTreeConference.org for funding this study.

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Résumé. Des différences significatives peuvent exister dans le taux de reprise post-plantation entre des arbres produits en contenant et des arbres produits en champs. Les plants produits en contenant ont une motte avec des racines qui sont déviées, ce qui peut avoir un impact lors de la reprise. Trancher la motte de racines lors de la plantation pourrait permettre d'améliorer la performance de la reprise post-plantation des arbres produits en contenant. Soixante chênes verts en contenant de 170 L ont été plantés en pleine terre dans un aménagement. Les mottes de racines de 30 de ces arbres ont été tranchées avant leur mise en terre. Trente arbres produits en champs d'un peu plus grande dimension ainsi que 30 plus petits arbres produits en contenant de 57 L ont aussi été plantés. Lors les périodes de sécheresse durant les 432 premiers jours qui ont suivi la plantation, les arbres produits en contenant de 57 L avaient le potentiel en xylème le plus négatif. Les arbres produits en champs avaient le potentiel en xylème le plus négatif lorsque l'irrigation a été différée durant une durée de 12 jours après la plantation. Trancher la motte de racines a eu peu d'impact sur le potentiel en eau du xylème lors de sécheresses. La défoliation était plus grande pour les arbres produits en contenant de 170 L que chez ceux produits en contenant de 57 L. L'accroissement en diamètre du tronc pour les arbres produits en contenant de 57 L et ceux produits en champs était plus grande que chez ceux produits en contenant de 170 L. Les arbres produits en champs ont poussé moins en hauteur. Le rayon en racines était similaire chez les arbres produits en contenant de 170 L et ceux produits en champs, et plus grand pour ceux produits en contenant de 57 L. Les petits arbres semblent mieux se rétablir que ceux plus grands.

Zusammenfassung. Es existieren signifikante Unterschiede in der Etablierung von Bäumen auf Containern oder direct aus der Baumschule. Container-gezogene Pflanzen haben Wurzelballen mit abgelenkten Wurzeln, welche die Etablierung beeinflussen können. Das Einschneiden von Wurzelballen beim Pflanzen könnte die Leistung der containergezogenen Pflanzen verbessern. 60 Lebeneeichen in 170 l Containern wurden in einem Feldversuch ausgepflanzt. Die Wurzelballen von 30 dieser Containerpflanzen wurden eingeschnitten. 30 feldgezogene, etwas größere Eichen und 30 kleinere Bäume in 57 l Containern wurden auch gepflanzt. Während der Trockenperioden in den ersten 432 Tagen nach der Pflanzung (DAP) hatten die Bäume aus den 57 l Containern das höchste negative Xylem-Potential. Die feldgezogenen Bäume hatten das höchste negative Xylempotential bei einer Bewässerung von12 DAP. Das Einschneiden der Wurzelballen hatte nur wenig Einfluss auf das Xylemwasserpotential während der Trockenheit. Der Blattfall war starker bei den 170 l Bäumen als bei den 57 l Bäumen. Der Stammdurchmesser der 57 l Bäume und der feldgezogenen Bäume war größer als bei den 170 l Pflanzen. Feldgezogene Bäume sind weniger in die Höhe gewachsen. Der Wurzelradius war bei den feldgezogen und den 170 l Bäumen größer als bei den 57 l Containern. Kleine Bäume etablieren sich schneller als große.

Resumen. Pueden existir diferencias significativas en la tasa de establecimiento entre árboles plantados de contenedores y los crecidos en los viveros. Las plantas crecidas en contenedor tienen bolas con raíces reflectadas que podrían impactar su establecimiento. Cortando las bolas de raíces en el momento de la plantación podría mejorar el crecimiento de los árboles crecidos en contenedor. Se plantaron en el terreno sesenta encinos crecidos en contenedor de 170 L. Las bolas de raíces de 30 de estos contenedores fueron cortadas antes de la plantación. Treinta árboles crecidos en el terreno de tamaños mayores, y 30 más pequeños de contenedores de 57 L fueron también plantados. Durante los períodos de sequía en los primeros 432 días después de la plantación (DAP, por sus siglas en inglés), los árboles de los contenedores de 57 L tuvieron los potenciales del xilema más negativos. Los árboles crecidos en el terreno tuvieron el potencial más negativo cuando el riego fue 12 DAP. Las bolas de raíces cortadas tuvieron poco impacto en el potencial del xilema en sequía. La defoliación fue mayor para los árboles de contenedor de 170 L que para los de 57 L. El incremento del diámetro del tronco de los contenedores de 57 L y árboles crecidos en el terreno fue mayor que para los contenedores de 170 L. Los árboles crecidos en el terreno crecieron menos en altura. El radio de las raíces fue similar para contenedores de 170 L y árboles crecidos en el terreno, y mayor para contenedores de 57 L. Los árboles pequeños parecen establecerse más rápido que los grandes.