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Effect of Container Type and Root Pruning on Growth and Anchorage After Planting *Acer rubrum* L. into Landscape Soil

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Abstract. *Acer rubrum* L. 'Florida Flame' were grown in #3 containers of eight types, then shifted to #15 containers, then finally into #45 containers. Half the trees were root pruned by removing periphery 3 cm of root ball at each shift to larger containers. In addition to and simultaneous with being shifted into successively larger containers, some trees from each container size were planted directly into soil. Type of container and root pruning had no impact on trunk diameter, tree height, or root cross-sectional area on trees planted into soil from any container size. Type of container influenced architecture of planted root systems evaluated when all trees were five-years-old with limited impact on anchorage. Container type only impacted anchorage of trees planted from #45 containers, and impact was small. In contrast, shaving root balls during production substantially reduced imprint left by all containers evaluated when trees were five-years-old. Shaving during production also improved anchorage by 20%–25% compared to not root pruning. More roots grew on north than the south side of tree in the nursery and landscape. Bending stress increased with trunk angle and its square while winching trunks to five degrees tilt.

Key Words. Lateral Stability; Root Architecture; Root Circling; Root Cross-Sectional Area; Root Defects; Tree Health.

The type of container used during nursery production can impact root ball architecture in nursery and landscape (Arnold 1996) and can slow development of root deflections on many woody species (Struve et al. 1994), which can influence root and shoot growth (Arnold and Struve 1989; Beeson and Newton 1992; Martin and Bhattacharya 1995). Roots in some porous-walled plastic containers slow or stop growing when they reach the container wall–substrate interface, although it is not clear how long this effect lasts (Privett and Hummel 1992); it may depend on climate and taxa. This cessation of root growth can result in less root deflection compared to root systems grown in containers with smooth plastic sides, which appear to encourage growth on the periphery of the substrate (Marshall and Gilman 1998; Gilman 2001). However, roots in porous containers made from various fabrics and plastics deflect when retained for a period of time typical in the industry (Gilman et al. 2010a). Deflections occur several centimeters inside of the periphery compared to smooth-sided containers, where roots are often found on the periphery (Gilman and Orfanedes 2012). Under certain cultural conditions, root and crown growth can be slowed due to root tips dying from dry substrate caused by air intrusion (Ortega et al. 2006). This can be overcome by adjusting cultural management in the nursery.

Deflection of main roots downward by container walls forces them to grow parallel to one another and touch directly under the trunk (Gilman and Paz 2013), causing constrictions and inclusions that restrict passage of substances (Lindström and Rune 1999). Container-grown trees with deflected roots planted into field soil sometimes develop lateral roots on only two or three sides on the plant (Selby and Seaby 1982; Balisky et al. 1995; Salonius et al. 2000; Gilman and Paz 2013). This can lead to uneven root distribution and instability on trees planted from propagation containers (Lindström and Rune 1999). Marler and Davies (1987) also reported that root circling and kinks on container-grown *Citrus* were responsible for uneven root development following planting in slightly larger containers. It is not clear if root deflection in much larger containers typical of the landscape nursery industry would also result in compromised anchorage.

Distributing root tips in the lateral (horizontal) position throughout the root ball instead of vertically—causing a collection of circling roots at the container bottom—on young mahogany (Gilman and Paz 2013) in #3 containers allowed many lateral roots to grow into landscape soil in a more natural position parallel to the soil surface. Young trees with an abundance of straight roots inside the root ball at planting appear better secured to soil after planting than those with bent roots (Gilman and Harchick 2013). Despite differences in root architecture at, and after planting, there may be little impact on shoot and trunk growth (Ruter 1993; Marshall and Gilman 1998).

One method of managing root architecture is manual root pruning. Early work showed that manual root pruning of tree seedlings raised in containers reduced root defects (Harris et al. 1971a; Harris et al. 1971b) and produced more symmetrically distributed lateral roots after planting (Krasowski 2003). One recent study showed that light cutting of circling roots on shrubs enhanced the amount of roots growing into substrate of the slightly larger container (Blanusa et al. 2007). Slicing (*Quercus virginiana* Mill., Gilman et al. 2009) or shaving (*Acer rubrum*, Gilman et al. 2010b) the #3 container periphery when shifting into a #15 container improved root system quality by removing roots that grew down, around, and up the container wall.

There is more experience studying the impact of root pruning during the process of planting into field soil than when shifting to larger nursery containers. Gilman et al. (1996) showed that cutting Burford holly (*Ilex cornuta* 'Burfordii') #3 root balls from top to bottom (slicing or scoring) at planting resulted in a redistribution of roots, not an increase in roots, compared with non-pruned 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 did not affect root length following planting, but root pruned trees had more main lateral roots (>2 mm diameter) originating from the primary seedling radicle when compared to control. Krasowski and Owens (2000) found that, despite a smaller root ball at planting, root systems of mechanically pruned *Picea glauca* (Moench) Voss seedlings produced greater root growth in field soil than control or chemically root pruned treatments. Removing all roots by shaving the periphery of several tree taxa has shown to be very effective at almost eliminating deflected roots within the root ball (Gilman et al. 2010b; Gilman et al. 2015), but its impact on roots and growth after planting into soil remains untested.

The goal of this project was to determine if nursery container type, root pruning in the nursery, and tree orientation during production influence growth and anchorage after planting trees into landscape field soil. Specific objectives were to relate root architecture within the planted root ball—described in the companion study (Gilman et al. 2015)—with anchorage 26 months after planting from four container sizes, and with growth and root architecture measured when trees were five-years-old. Different root morphologies were induced by growing trees in eight different types of containers and by root pruning while shifting to larger containers.

MATERIALS AND METHODS

A cultivar of *Acer rubrum* ('Florida Flame') was chosen for this study because red maple and hybrids are common shade trees grown throughout much of the United States. 'Florida Flame' red maple is propagated by rooting current year's shoots removed from parent trees; use of clonal trees should reduce root system variability among replicate trees compared to a cultivar grafted onto seedling root stock.

Planting into Containers and Landscape Soil

In April 2008, 384 uniform rooted cutting liners (13 cm tall) in circular (5.1 cm top diameter, 13 cm tall ribbed containers, 38 Groovetube, Growing Systems, Inc., Milwaukee, Wisconsin, U.S.) were shifted (planted) into eight different #3 (approximately 11 L) container types described fully in Gilman et al. (2010a). The container types were smooth sided (SS, Nursery Supplies, Inc., Chambersburg, Pennsylvania, U.S.); SmartPot® (SP, Root Control, Inc., Oklahoma City, Oklahoma, U.S.); RootBuilder® (RB) and RootMaker® (RM, RootMaker® Products Company, LLC, Huntsville, Alabama, U.S.); Fanntum™ (FN, Fanntum Products, Inc., Statesville, North Carolina, U.S.); Florida Cool

Ring™ (CR, The Florida Cool Ring Company, Lakeland, Florida, U.S.); Airpot™ (AP, Caledonian Tree Company, Ltd., Scotland); and Jackpot™ (JP, Legacy Nursery Products, LLC, Palm City, Florida, U.S.).

In April 2008, 40 liners were also planted into landscape soil [Millhopper fine sand (loamy, siliceous, hyperthermic Grossarenic Paleudults)] in four rows 3.4 m apart and approximately 100 m from trees in containers. The point where the topmost root emerged from stem was placed 13 mm below substrate or soil surface by removing an appropriate amount of substrate and roots from top of liner root ball. Chipped whole branches and leaves from utility line clearance operations were applied as mulch 12 cm thick (before settling) down each of four rows 1.8 m wide on trees planted into the ground. Trunks were marked on the north side to maintain trees in the same compass orientation throughout the study, including at all shifts to larger containers and at landscape planting.

In November 2008, nine #3 root balls from each container type (72 trees) were washed to measure roots (see Gilman et al. 2010a). In February 2009, 24 trees in #3 containers (8 container types × 3 replicates = 24) were planted, without root pruning, on 1.8 m spacing in one row directly into the same field soil as previously mentioned in a randomized complete block design with single-tree replicates in each block. Root ball top surface was positioned even with landscape field soil. The same mulch was applied (as described) to a 1.8 m–wide continuous strip down the row. In February 2009, remaining trees were shifted into #15 containers (approximately 57 L) of the same type; half the root balls were root pruned by shaving as part of the shifting process; half were not (Gilman et al. 2015). Figure 1 summarizes the protocol for the entire study.

In November 2009, some #15 root balls were washed to measure roots (see Gilman et al. 2015) and 48 trees in #15 containers (8 container types × 2 root pruning × 3 replicates = 48) were planted without root pruning on 2.7 m spacing in two rows directly into the same field soil as above. Trees were arranged in a randomized complete block design with single-tree replicates in each block. Root ball top surface was positioned even with landscape soil. The same mulch was applied (as described) to a 1.8 m–wide strip down each row. In February 2010, the remaining trees were shifted into #45

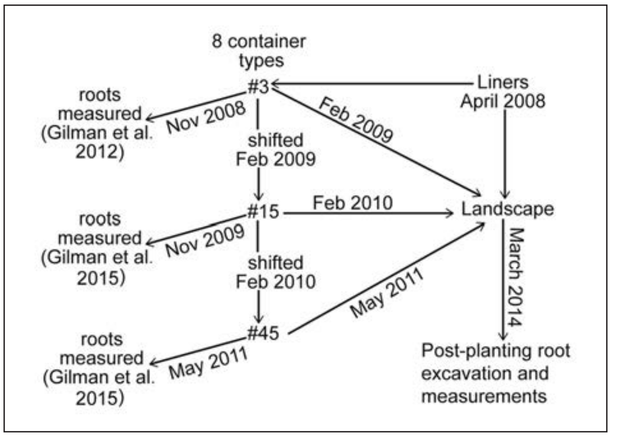

Figure 1. Timeline for measuring roots, shifting to larger containers, planting into landscape, and post-planting root measurement.

containers (approximately 170 L) of the same type; half the trees were root pruned by shaving root ball as part of the shifting process; half were not.

In May 2011, some #45 root balls were washed to measure roots (see Gilman et al. 2015) and the remaining 80 trees in #45 containers (8 container types × 2 root pruning × 5 replicates = 80) were planted into the field without root pruning on 2.4 m spacing in five rows alternating 2.4 m and 4.2 m apart. Trees were arranged in a randomized complete block design with single-tree replicates in each block. Root ball top surface was positioned even with landscape soil. The same mulch was applied as described. Mulch was not re-applied during the study period. Vegetation was periodically mowed between rows.

Cultural Practices

Trees planted as liners into the landscape and into #3 containers received 2.5 L irrigation three times daily (total 7.5 L daily) from April 2008 through November 2008, then application was changed to three times each irrigated day Monday, Wednesday, Friday. Trees planted from liners, #3, and #15 containers received 3.8 L three times daily May through August 2009; volume was increased to 5 L three times daily through early November 2009 when it was adjusted to 2.5 L three times daily. Trees planted from liners, #3, #15, and #45 containers received 7 L three times daily March 2010 through April 2011. All trees received 9.5 L (May), 11 L (June), and 15 L (July 2011) three times daily until early November 2012 when it was adjusted to 15 L twice daily. In May 2013, 15 L was applied three times daily through

December 2013. Weeds were controlled with periodic application of glyphosate to mulch surface.

Trees planted into the landscape as liners and from #3 containers received 226 g fertilizer (12 N - 2 K_2O - 14 P_2O_5) in May 2009, spread evenly under the crown. Trees planted from liners, #3, and #15 containers received 300 g (20 N - 0 K_2O - 8 P_2O_5) in March and 400 g in May 2010. Trees planted from liners, #3, #15, and #45 containers received 400 g (20 N - 0 K_2O - 8 P_2O_5) in June 2011, April and July 2012, and April 2013. Trees were not pruned after planting other than to remove twigs and small branches that drooped in the way of the mower used to periodically cut surface vegetation.

Evaluating Post-Planting Anchorage and Growth

Trees from liners #3, #15, and #45 container sizes were winched due north to five degrees trunk tilt from vertical start position to evaluate anchorage 26 months after landscape planting. This began June 2010 for the ten trees planted from liners that represented the mean trunk diameter of the 40 planted. In May 2011, trees from #3 containers were winched (one or two blocks each rain-free day) with an electric winch attached to a cable about 1.2 m from the ground. The cable remained parallel to ground. A 3629 kg capacity load cell (SSM-AF-8000; Interface Inc., Scottsdale, Arizona, U.S.) was placed in-line with the winching cable. An inclinometer (model N4; Rieker Inc., Aston, Pennsylvania, U.S.) was mounted to a fabricated steel plate (5.1 × 7.6 cm). The plate was secured to the trunk base 15 cm from soil surface which was just above the swollen flare at the trunk base. Cable was winched at 2 cm·sec^{-1} until the inclinometer tilted five degrees from vertical start position; tree was held for 60 seconds before allowing cable to release. Sixty seconds following cable release, final angle at the trunk base was recorded as rest angle. Trees from #15 and #45 containers were also winched 26 months after landscape installation in the manner described.

Data from load cell and inclinometer were collected at 2 Hz by Data Acquisition System (National Instruments Corporation, Austin, Texas, U.S.) and recorded on a laptop. Data during pulling tests were displayed in real-time on a laptop running LabView software (v: 7.0; National Instruments, Austin, Texas, U.S.). Trunk bending stress was calculated according to Equation 1.

$$\sigma = \frac{F \cdot d \cdot R}{\frac{\pi}{4} \cdot R^4} \quad [1]$$

where σ = bending stress; F = pulling force; d = distance from pulling point to inclinometer; and R = trunk radius (calculated as halving diameter measured with a diameter tape).

In March 2014, an air excavation device removed soil from the top 10 cm of the soil profile within a 50 cm radius around each trunk to measure roots on 24 (#3) + 48 (#15) + 80 (#45) + 10 (liners) = 162 planted trees. Root measurements included: 1) one visual rating, conducted by two individuals, of the imprint on the root system (1 = no imprint; 5 = large imprint with many roots kinked, circling, descending, and/or ascending) from root deflection at any container size (#3, #15, or #45), excluding the original propagation container; and 2) diameter of the ten largest roots measuring 5 cm beyond the edge of the planted root ball (five in the northern and five in the southern 90 degree quadrants) in the top 10 cm soil profile. Root diameter was converted to cross-sectional area (CSA). Trunk diameter was measured at planting and each October thereafter.

Experimental Design and Statistical Analysis

Trees of each container size (liners, #3, #15, and #45) were planted in a separate randomized complete block design in four adjacent plots of the same field and soil type. Responses from #3 containers types were analyzed with one-way analysis of variance (ANOVA), and the main effect container type means were separated with Tukey's multiple range test. Responses from #15 and #45 were analyzed with two-way ANOVA, and means for the main effects container type and root pruning were compared using Tukey's; interaction means were compared using LSD. Pearson's correlation coefficient was used to compare imprint rating with top diameter of containers. The GLM procedure was used to calculate regression coefficients for predicting bending stress from trunk angle.

RESULTS

Shoots

Trunk diameter, trunk diameter annual increase, tree height, and tree height annual increase after planting into landscape soil from any container size (#3, #15, #45) were not impacted by container type ($P > 0.08$) or root pruning during nursery production ($P > 0.26$) in any post-planting year except cumulative height increase the first three years for trees planted from #3 containers. Trees from #3 SS grew more (4.6 m, $P = 0.0008$) in height in the three years after planting than those from AP (3.3 m) and JP (3.8 m). Table 1 shows trunk diameter of trees planted from each container size at the end of the landscape study when trees were five-years-old; experimental design did not allow for statistical comparisons among container sizes.

Table 1. Trunk diameter when 'Florida Flame' maple were approximately five-years-old (October 2012) after planting into the landscape from propagation containers (liners), #3, #15, and #45 nursery containers.

Container size[z]	Landscape planting date	Trunk diameter end 2013 (mm)
Liner	Apr 2008	119[y]
#3	Feb 2009	120
#15	Nov 2009	114
#45	May 2011	127

[z] See Gilman et al. (*in review*) for description of containers.
[y] n = 40 (liners), 24 (#3), 48 (#15), and 80 (#45). Experimental design did not allow statistical comparisons among container sizes.

Roots

Interactions between container type and nursery root pruning were not significant for any measured root attribute ($P > 0.05$); therefore, only main effects will be discussed. Container type did not impact total root CSA (7251 mm^2 for liners; 3192 mm^2 for #3, $P > 0.07$; 1710 mm^2 for #15, $P > 0.26$; 1482 mm^2 for #45, $P > 0.36$) in the ten largest roots (either the five largest in the northern or southern quadrants or the ten largest in a combined analysis) in the top 10 cm landscape soil profile evaluated once in March 2014 when all trees were five-years-old. Root pruning during nursery production also had no impact ($P > 0.26$) on root CSA evaluated on five-year-old trees planted from either #15 or #45 containers.

Container type impacted container imprint rating for trees planted from #3 and #15 containers, but not those planted from #45 containers (Table 2). Trees from #3 JP had a smaller imprint than those from four other container types; only RT had a larger imprint than trees from SS. Trees planted from #15 CR had a smaller imprint than all but one other type (SS); trees from RB had a larger imprint than four other types. There were other small differences among container types (Table 2). Root pruning reduced container imprint rating across container types at $P < 0.008$ for both #15 and #45 container sizes (Table 3). Root CSA in the northern quadrant was equal to that in the southern quadrant for all container sizes, except that trees planted from #45 containers had more roots on the north side than south (Table 4).

Table 2. Effect of container type on container imprint rating[z] of 'Florida Flame' maple planted into the landscape from #3 and #15 containers[y] 49 and 40 months earlier, respectively.

Container type[x]	Imprint rating on trees planted from #3 containers (1–5)	Imprint rating on trees planted from #15 containers (1–5)
AP	2.2 ab[w]	2.1 cd
CR	1.5 bc	1.5 e
FN	1.5 bc	2.7 ab
JP	1.3 c	2.2 bc
RB	2.0 ab	3.1 a
RT	2.5 a	2.6 abc
SP	2.0 ab	2.8 ab
SS	1.7 bc	1.7 de

[z] Container imprint rating ranged from 1 (no imprint) to 5 (high imprint), visually estimated by two observers independently.
[y] There was no difference (mean = 2.8, $P = 0.20$) among container types for trees planted as #45 containers.
[x] See Gilman et al. 2015 for description of containers.
[w] Numbers followed by a different letter within columns are statistically different at $P < 0.01$; n = 3 (#3) or 6 (#15), averaged across root pruning due to insignificant interaction ($P > 0.06$).

Table 3. Effect of root pruning in the nursery on container imprint rating[z] of 'Florida Flame' maple planted in the landscape from #15 and #45 containers 49 and 34 months earlier, respectively.

Root pruning[y]	Imprint rating on trees planted from #15 containers (1–5)	Imprint rating on trees planted from #45 containers (1–5)
Yes	1.8 a[x]	2.1 b
No	3.0 b	3.4 a

[z] Container imprint rating ranged from 1 (no imprint) to 5 (high imprint), visually estimated by two observers individually.
[y] Shaving removed the outer 3 cm of the #3 and #15 root ball periphery and bottom prior to shifting into current container.
[x] Numbers followed by a different letter within columns are statistically different at $P < 0.008$; n = 24, averaged across container type due to insignificant interaction [$P = 0.06$ (#15) and 0.40 (#45)].

Table 4. Tree orientation[z] effect on root CSA[y] for 'Florida Flame' maple planted from four container sizes.

Tree orientation	Root CSA on trees planted from four container sizes (mm^2)			
	Liner	#3	#15	#45
North	4189	1416	909	830 a
South	3062	1775	801	652 b
P-value	0.21	0.30	0.37	0.01

[z] Except for liners, north side of trees in nursery were planted to the north in the landscape. Roots measured in the north and south 90 degree quadrants.
[y] Root CSA = root cross-sectional area measured 5 cm outside root ball edge; n = 10 (liners), 24 (#3), 48 (#15), 80 (#45) means averaged across container type (#3, #15, and #45) and root pruning (#15 and #45) due to insignificant interaction.

Anchorage

Bending stress required to winch trees one to five degrees trunk tilt planted 26 months earlier into the landscape from #3 ($P = 0.83$) and #15 ($P = 0.55$) containers was not affected by container type (data not shown). However, container type had a small impact on trees planted 26 months earlier from #45 containers, but only when winched to four and five degrees trunk tilt (Table 5). Trees planted from #45 JP required less bending stress to pull to four and five degrees than three other container types. Incrementally less bending stress was required to winch trees planted from all container sizes an additional degree with increasing angle as indicated by the negative squared term in the regression Equations 2 through 5 (Figure 2).

Root pruning by shaving when trees were shifted to larger nursery containers impacted anchorage when trees were installed in the landscape from #15 and #45 containers (trees four- and five-years-old, respectively, Table 6). Specifically, shaving when #3 and #15 root balls were shifted to #15 and #45 containers, respectively, resulted in a reduction in trunk rest angle following pulling 26 months after planting compared to not shaving.

Table 5. Effect of container type on bending stress required to tilt trunks to four and five degrees[z] for 'Florida Flame' maple planted into the landscape from #45 containers[y] 26 months earlier.

Container type[x]	Bending stress four degrees (MN/m^2)	Bending stress five degrees (MN/m^2)
AP	20.2 abc[w]	22.1 abc
CR	20.0 abc	21.7 abc
FN	20.6 ab	22.7 ab
JP	18.4 c	20.1 c
RB	21.4 a	23.4 a
RT	19.0 bc	20.8 bc
SP	20.3 abc	22.2 abc
SS	21.1 a	23.1 a

[z] Container type was not significant when trees were winched to 1, 2, or 3 degrees.
[y] Bending stress for trees from #3 and #15 containers was not impacted by container type.
[x] See Gilman et al. 2015 (companion paper, *in review*) for description of containers.
[w] Numbers followed by a different letter within columns are statistically different at $P = 0.04$ (left) and 0.03 (right); n = 6, averaged across root pruning due to insignificant interaction ($P > 0.32$).

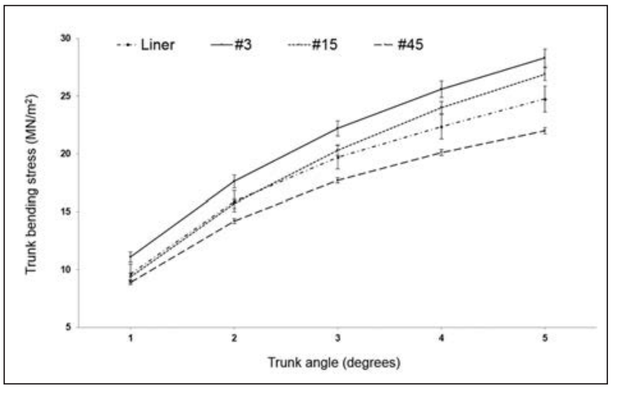

Figure 2. Relationship between bending stress while winching trunks to five degrees tilt 26 months after planting from four sizes of nursery containers. Vertical bars represent SE. Equation 2: Liner trunk bending stress = 3.1 + 7.4 (trunk angle) - 0.6 (trunk angle2); $R^2 = 0.76$, $P < 0.0001$. Equation 3: #3 trunk bending stress = 3.8 + 8.0 (trunk angle) – 0.6 (trunk angle^2); $R^2 = 0.80$, $P < 0.0001$. Equation 4: #15 trunk bending stress = 2.4 + 7.6 (trunk angle) – 0.5 (trunk angle2); $R^2 = 0.80$, $P < 0.0001$. Equation 5: #45 trunk bending stress = 2.9 + 6.6 (trunk angle) – 0.6 (trunk angle2); $R^2 = 0.83$, $P < 0.0001$.

Table 6. Effect of root pruning in the nursery on trunk rest angle for 'Florida Flame' maple winched to five degrees trunk tilt[z] planted into the landscape from #15 and #45 containers 26 months earlier.

Root pruning[y]	Trunk rest angle of trees planted from #15 containers (degrees)	Trunk rest angle of trees planted from #45 containers (degrees)
Yes	0.9 b[x]	0.9 b[x]
No	1.2 a	1.1 a

[z] Angle of trunk base relative to vertical start position following release of winching cable.
[y] Shaving removed the outer 3 cm of the #3 and #15 root ball periphery prior to shifting into planted container size.
[x] Numbers followed by a different letter within columns are statistically different at $P < 0.005$; n = 24, averaged across container type due to insignificant interaction [$P = 0.75$ (#15), 0.06 (#45)].

DISCUSSION

Trees remained well within ANSI Z60 (Anonymous 2014) and *Florida Grades and Standards for Nursery Plants* (Anonymous 2015) size requirements when finished in each container size and planted. Results could have been different if trees became larger by remaining in containers longer, which is commonly practiced (pers. obs.). For example, older roots of red maple (Gilman et al. 2012) and other taxa (Salonius et al. 2000; South and Mitchell 2005) can become suberized with increasing retention time in the container, making them resistant to producing new roots into landscape soil. Additionally, likelihood of developing a large imprint rating increases with retention time in container, and this has been associated with poor root growth into field soil (Salonius et al. 2000; Gilman et al. 2012). This can make trees less stable than those with roots growing straight from the trunk without deflection (Nichols and Alm 1983; Blanusa et al. 2007; Gilman et al. 2013; Gilman and Harchick 2014).

Excepting one year (2011, three years after planting #3 containers, data not shown), the lack of impact on trunk and height growth (Table 1) from installing trees from different nursery container types agrees with most other findings for other taxa planted from containers (Arnold 1996; Marshall and Gilman 1998; Gilman 2001). In contrast, there was a significant effect of container type on trunk cross-sectional area five years after planting red maple from seven container types, six of them different from the current study (Gilman et al. 2003). Despite being more stressed in that study in the weeks following landscape installation, trees planted from low profile containers with perforated side walls had larger trunks than those planted from four other types. Perhaps trees, such as red maple, which develop a shallow root system in soil regardless of soil type (Lyford and Wilson 1964; Gilman and Kane 1990), respond best when planted from a low profile (short and wider than most others) root ball because they become established quicker. Low profile containers position roots close to the soil surface so there are no deep roots that have to make their way to the landscape soil surface to proliferate. In contrast, roots at the bottom of a traditional shaped container (about as tall as they are wide) would have to grow up to near the soil surface before they proliferate; this could be the reason why trees from three of the five standard dimensioned containers grew slowest in that study (Gilman et al. 2003). There are other studies that show an impact of container type on shoot and root growth after planting (Arnold and Struve 1989). Lack of trunk diameter growth differences among container types in the current study could be due to the similarity of dimensions among the eight container types—none were considered low-profile.

There appeared to be no relationship between the amount of root circling or other root attributes at planting (Gilman et al. 2015) and container imprint rating following landscape planting when trees were five-years-old (Table 2). In other words, container types with the least circling roots at planting did not necessarily have the smallest imprint after growing in the landscape for several years. To support this finding, Gilman et al. (2003) found that despite significant differences in root weight and amount of deflected roots among seven different #15 container types when red maple trees were planted into the same field soil as the current study, all measured root attributes were identical five years after planting. There were some slight exceptions in the current study. For example, trees planted from #45 JP containers not shaved during nursery production had a lesser amount of circling roots at the #3 position at planting than all others (Gilman et al. 2010a), but three other containers joined JP as the group that produced the smallest imprint at the #3 position two years later (Table 2). This indicated that JP did not hold its position as the sole container with the least root deflections when evaluated 26 months after planting (Table 2). This could suggest that some roots circling while trees remained in the nursery container did not grow to become the largest roots that formed an imprint after planting into the landscape.

In apparent contrast, recent work on 'Florida Flame' maple showed that circling roots present at planting still remained in that position after five years in the landscape (Gilman et al. 2003) indicating the imprint formed early by deflections against container walls can remain for some time after planting. However, trees in that study were retained in #15 containers longer (14 months) than in the current study (12 months). Increased retention time in containers has been shown to encourage formation of a more severe container imprint in propagation (Salonius et al. 2000; Gilman et al. 2012) and much larger (Gilman et al. 2014) containers. Data from these studies combine to show that container type had little impact on short-term (five years) red maple shoot growth, root growth, or anchorage on trees planted from #45 containers, but could affect those planted from #3 and #15 containers (Table 2) if retained in containers too long. It is possible that root attributes could vary—deeper in the soil—than measured in this study, although red maple roots typically grow from the top of the root ball (Gilman and Kane 1990; Gilman et al. 2003) and remain there (Lyford and Wilson 1964). Deeper roots are likely less able to cause health issues by girdling the trunk. What remains unanswered is how long a retention time is too long, and what are the impacts on long-term health, growth, and stability. There is much to learn about the ultimate fate and impact of circling roots in containers.

There was no correlation between imprint rating and top diameter of any size container (#3, $P = 0.72$; #15, $P = 0.83$; #45, $P = 0.88$), indicating differences in root response among #3 and #15 types were largely due to the nature of the container walls—not container dimensions—as found for this same set of finished red maple in #3 containers (Gilman et al. 2010a). Roots growing up (ascending) the liner container side wall and crossing over the root collar close to the trunk were not embedded into the trunk on the same set of trees finishing in #3 containers. These roots, sometimes as large as a finger, had embedded into the trunk by the time trees were five-years-old (March 2014), and although not quantified, did not appear to be impacting growth. These roots were not grafted to the trunk as indicated by little or no white wood connecting one to the other, presence of swollen trunk tissue and bark cracking just above the root, and bark inclusions between the two tissues indicating poor connection. Occurrence of these potential health issues can be reduced in this species (Gilman et al. 2012) and others by growing trees in propagation containers that prevent or reduce defects (Ortega et al. 2006), removing trees earlier (Harris et al. 1971a; Harris et al. 1971b; Salonius et al. 2000), or mechanical root pruning at planting (Balisky et al. 1995; Arnold 1996).

There is evidence that tree orientation influenced red maple root growth in the nursery (Gilman et al. 2010a; Gilman et al. 2015), and that some of this carried over into the landscape. Increased root CSA growing to the north side compared to the south on landscape trees planted from #45 containers (Table 4) appears to have resulted from more root growth on that side in the nursery (Gilman et al. 2015). High substrate temperatures are known to cause root death especially on the sunnier, hotter container side (i.e., south and west side in the Northern Hemisphere, see Ruter 1993; Owen and Stoven 2008). This relationship suggests that some of the root growth variation among trees in a landscape and in research plots can be attributed to orientation in the nursery and how the tree might be ultimately oriented in the landscape. Some of this effect could also have been due to the more shaded and probably cooler container substrate and landscape field soil on the shaded side of the crown (north side in the Northern Hemisphere).

In contrast to container type, root pruning by shaving while shifting to larger nursery containers was consistently effective at dramatically reducing the imprint (measured 40 (#15 containers) and 34 (#45 containers) months after field planting) imposed on the root system by all nursery containers (Table 3). This is supported by others on a variety of tree taxa (Weicherding et al. 2007). Unlike container type, which impacted anchorage (as measured by bending stress) only for trees planted from #45 containers (not those planted from #3 and #15) and then only when winched to four and five degrees, root pruning had a considerable impact on anchorage. Shaving trees when shifting to larger containers resulted in better anchorage (smaller trunk rest angle following winching) to landscape soil 26 months after planting from both container sizes (#15 and #45) tested, compared to not shaving (Table 6). Reduced rest angle indicated less root ball overturning and hence stronger attachment to landscape soil. Straight roots have been associated with improved anchorage for *Quercus virginiana* (Gilman and Weise 2012), *Acer rubrum* (Gilman et al. 2014), and *Swietenia mahagoni* (Gilman and Harchick 2014) planted from containers; data from the current study supports this. Deep roots under the trunk are also extremely important for anchorage on certain taxa and in certain soils, and they function structurally in combination with relatively straight roots close to the surface (Danjon et al. 2005). Deep roots are rare in *Acer rubrum* (Lyford and Wilson 1964).

The data presented show that root deflections by container walls can influence root architecture at an early age, and some of these can remain with the tree for at least five years (Table 2). The container-induced imprint was significantly reduced (Table 3), and anchorage to landscape soil increased (Table 6), by shaving root balls during nursery production. Differences in imprint among container types (Table 2) were not related to anchorage, but deflected roots comprising the imprint could impact health, or anchorage, later. The long-term implications from differences in imprint rating among container types for trees planted from #3 and #15 containers (Table 2) remains unknown; longer-term studies will be needed to address this question. However, arborists report (pers. comm. and obs.) trees of the genus *Acer* are prone to developing roots that grow tangent to the trunk that can eventually form stem-girdling roots. Data presented in the current and past studies show that nursery production practices can influence formation of some of these roots.

CONCLUSIONS

Shaving the root ball periphery when shifting a container-grown nursery tree to the next larger container size had a greater impact on root system architecture and post-planting anchorage than did type of container. Root system architecture in the nursery container impacted architecture up to five years after planting into the landscape. Roots with architecture considered defective (i.e., sharply turned roots in a circling or downward direction) retained that defect several years after planting. However, the current data and cited literature mostly showed that *Acer rubrum* root architecture differences among container types when planted into the landscape did not appear to persist.

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Résumé. Des *Acer rubrum L. "Floride Flame"* ont été cultivés dans huit différents types de pots de grosseur # 3, puis transplantés dans des pots de grosseur # 15, et finalement dans des pots de grosseur # 45. Les racines de la moitié des arbres ont été taillées par l'enlèvement d'une bande de 3 cm sur le pourtour de chaque motte avant sa transplantation dans un pot plus gros. Simultanément avec le transfert des arbres dans des pots plus grands, un certain nombre d'arbres provenant des différentes dimensions de pots furent plantés directement dans le sol. Le type de pot et la taille des racines n'ont eu aucune incidence sur le diamètre du tronc, la hauteur des arbres ou la surface terrière des arbres plantés dans le sol et ce, peu importe la dimension du pot. Le type de pot a influencé l'architecture des systèmes racinaires des arbres plantés qui furent évalués lorsqu'ils atteignirent cinq ans et a montré une incidence limitée sur l'ancrage. Le type de pot a causé une incidence uniquement sur l'ancrage des arbres provenant des pots de grosseur # 45 et son influence fut faible. À l'inverse, la taille des mottes racinaires en cours de production a réduit significativement l'influence des différents types de pots tel qu'évalués lorsqu'ils atteignirent cinq ans. La taille des racines en cours de production a également amélioré l'ancrage de 20 % à 25 % par rapport aux arbres dont les racines n'ont pas été taillées. La croissance racinaire était plus abondante du côté nord que du côté sud de l'arbre tant en pépinière qu'en plantation directe dans le sol. La contrainte de flexion augmentait selon l'angle du tronc et à leur base lors du treuillage des troncs avec une inclinaison de cinq degrés.

Zusammenfassung. *Acer rubrum* L. 'Florida Flame' wurden in acht verschiedenen Typen von 3 L-Pflanzcontainern vorgezogen, dann in 15 L-Container umgepflanzt und abschließend in 45 L-Container verpflanzt. Bei der Hälfte der Bäume wurden bei jeder Verpflanzung die Wurzeln um je 3 cm des peripheren Wurzelballens eingekürzt. Zusätzlich und gleichzeitig mit der Verpflanzung in größere Behälter wurden einige Bäume aus jeder Containergröße direkt ins Freiland gepflanzt. Der Behältertyp und der Wurzelrückschnitt hatten keinen Einfluss auf den Stammdurchmesser, Baumhöhe oder den Wurzelquerschnitt der aus dem Container ins Freiland verpflanzten Bäume. Der Typ des Containers beeinflusste die Architektur der gepflanzten Wurzelsysteme aller Bäume, die nach fünf Jahren bewertet wurden, mit einem begrenzten Einfluss auf die Verankerung. Der Containertyp beeinflusste nur die Verankerung der gepflanzten Bäume aus den 45 L-Containern und der Einfluss war klein. Im Gegensatz dazu reduzierte der Wurzelrückschnitt deutlich bei allen nach fünf Jahren bewerteten Bäumen die Auswirkungen des jeweiligen Pflanzcontainers. Der Wurzelrückschnitt während der Produktion verbesserte die Verankerung um 20%-25% im Vergleich zu unbeschnittenen Wurzelballen. In der Baumschule und im Freiland wachsen mehr Wurzeln auf der nordseite als auf der Südseite der Bäume. Der Biegestress stieg mit dem Stammwinkel und seinem Quadrat, während die Bäume um 5 Grad umgezogen wurden.

Resumen. Se evaluaron ejemplares cultivados de *Acer rubrum* L. 'Florida Flame' en envases #3 de ocho tipos, luego se cambiaron a contenedores #15 y por último, en contenedores #45. Se podó la raíz de la mitad de los árboles mediante la remoción de 3 cm de la periferia del cepellón en cada cambio de contenedor. Además, algunos árboles de cada tamaño de envase se plantaron directamente en el suelo. El tipo de contenedor y la poda de raíz no tuvieron impacto en el diámetro del tronco, altura de los árboles, o área transversal de la raíz en los árboles plantados en el suelo de cualquier tamaño del contenedor. El tipo de contenedor influyó en la arquitectura de los sistemas de raíces de los árboles plantados, evaluados a los cinco años de edad. Además, con un impacto limitado en el anclaje. El tipo de contenedor sólo impactó el anclaje de árboles plantados de contenedores #45, pero el impacto fue pequeño. Por el contrario, en los cepellones afeitados durante la producción se redujo sustancialmente huella dejada por los cortes en todos los recipientes evaluados cuando los árboles tuvieron cinco años de edad. El afeitado durante la producción también mejoró el anclaje en un 20% -25% en comparación con las raíces no podadas. Crecieron más raíces en el lado norte que en el lado sur del árbol en el vivero y en el paisaje. El esfuerzo de flexión aumenta con el ángulo del tronco cuando se doblan los troncos a cinco grados de inclinación.