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Retention Time in Three Nursery Container Volumes Impacts Root Architecture

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Abstract. Roots descend and circle once they meet nursery container walls, sometimes resulting in severe defects. This has been attributed to extended retention time in small containers. Four retention times in 11 and 57 L containers were tested for their impact on root architecture inside finished 170 L containers. All taxa (*Acer rubrum*, *Magnolia grandiflora*, *Ulmus parvifolia*) retained for four months in 11 L containers required delicate handling to shift into 57 L containers because roots had not bound substrate together, making the shortest retention time (four months) impractical. Although shifting was easier for longer retention times (seven, nine, and twelve months), root system quality measured by root deflections declined with increasing retention time in 11 and 57 L containers. A greater percentage of the five largest roots grew down container walls than either circled or grew straight into substrate of 170 L containers. Nearly all the largest roots were deflected by the 11 or 57 L container with almost none reaching the 170 L container wall. Shorter retention time in 11 and 57 L containers was associated with a smaller percentage of trunks circled, more roots reaching the 170 L periphery, and for elm and magnolia, more trunk growth.

Key Words. *Acer rubrum*; Circling; Descending; *Magnolia grandiflora*; Nursery Production; Straight Roots; *Ulmus parvifolia*.

Trees and shrubs are easily shifted to larger containers once roots bind substrate together so the root ball remains intact when lifted from the container. Shifting too early can result in loss of substrate and possible root deformations as young, non-lignified roots become bent in the process. Retaining trees for a longer period of time allows roots deflected by container walls to become lignified and stiff in the deformed position. This can cause future stem-girdling roots, circling roots, descending roots, and other deformations that can impact health and anchorage (Burdett 1978; Balisky et al. 1995).

Dunn et al. (1997) and Salonius et al. (2000) showed a direct relationship between length of time tree seedlings were retained in propagation containers and the development of deformed root systems. Deformations in the root system can lead to poor rooting out, resulting in unstable trees (Lindgren and Örlander 1978). For example, Scots pine (*Pinus sylvestris* L.) trees planted from 75 ml propagation containers developed spiraling (circling) roots, causing them to be less stable in the soil seven to nine years after planting than naturally regenerated trees (Lindström and Rune 1999). Many studies on conifer seedlings show that root deflection in propagation containers can contribute to long-term growth problems after planting in the forest (Krasowski 2003). Roots on shade trees in larger containers also deflect around or downward and proliferate at the bottom of containers (Marshall and Gilman 1998).

Balisky et al. (1995) provided evidence that root deformation occurred on trees growing in walled container systems before root density had increased sufficiently to facilitate normal extraction, handling, and transportation. Selby and Seaby (1982) found that seedlings of certain taxa develop lateral roots from the primary tap root in the first several weeks after seed germination. These authors attributed poor anchorage of out-planted pines to the lack of properly oriented lateral support roots and the inability of these seedlings to generate new lateral roots large enough after planting to support the tree. Permanent roots were formed in the first few weeks after seed germination and all were deflected by the container wall. For this reason, Lindström et al. (2005) tested a stabilized or reinforced substrate that could be easily removed from the container, intact, before all permanent roots were formed from the tap root and deflected by container walls. Stabilized substrates were developed to bind the root ball together to facilitate easy lifting and transfer to larger containers without loss of substrate. However, few trees are grown in this substrate (personal observation). In contrast, Coutts et al. (1990) found that some taxa are stabilized after planting by adventitious roots that develop after out-planting from propagation containers.

There is good evidence in the forestry (Salonius et al. 2000; Ortega et al. 2006) and horticulture (Harris et al. 1971; Marshall and Gilman 1998; Amoroso et al. 2010; Gilman et al. 2010a) literature that root architecture is more important than root mass to the health and anchorage of trees as they become established. Straight lateral roots radiating from the trunk are associated with well-anchored trees (Lindgren and Örlander 1978; Lindström and Rune 1999; Ortega et al. 2006; Gilman and Weise 2012). The objective of the present study was to determine impact of retention time in 11 and 57 L nursery containers on subsequent root architecture in the root ball on finished trees in 170 L containers. The taxa chosen for study were selected due to their popularity in many parts of temperate North America and elsewhere.

MATERIALS AND METHODS

In February 2007, 80 uniform rooted cutting liners of *Magnolia grandiflora* L. Miss Chloe® rooted in square 7.3 cm across × 14 cm deep smooth-sided containers (Anderson Band AB39, Stuewe and Son, Inc., Tangent, Oregon, U.S.), and *Acer rubrum* L. 'Florida Flame' and *Ulmus parvifolia* Jacq. Allée® rooted in circular (5.1 cm top diameter, 13 cm tall ribbed containers, 38 Groovetube, Growing Systems, Inc., Milwaukee, Wisconsin, U.S.) propagation containers were potted into 11 L round, black, solid-walled nursery containers (Table 1). Magnolia roots originated primarily near the end of the cutting, whereas roots on maples and elms emerged near the end and from along the buried stem. The point where the topmost root emerged from stem was placed 13 mm below substrate surface by removing an appropriate amount of substrate from the top of liner root ball. This depth was found to be the ideal liner planting depth, for the one taxa tested (Gilman and Harchick 2008). The plot was located on woven black ground cloth in USDA hardiness zone 8b (mean low temperature -10°C) in Gainesville, Florida, U.S.

Table 1. Retention time in 11, 57, and 170 L containers.

	Container size[z] (L)		
Retention time	11	57	170
treatment	Retention time in container (months)		
A	4	8	20
B	7	10	15
C	9	11	12
D	12	14	6

[z] Container dimensions as follows: 11 L = 27 cm top diameter, 25 cm tall; 57 L = 44 cm top diameter, 38 cm tall; 170 L = 75 cm top diameter, 48 cm tall, round, solid-walled, black plastic containers (Nursery Supplies, Inc., Chambersburg, Pennsylvania, U.S.).

Trees in 11 L containers were grouped by taxa and spaced pot-to-pot (i.e., touching one another) except for a 0.5 m walk row every four rows. Trees were irrigated two or three times daily, totaling 3.8 L through one Roberts (Roberts Irrigation Products, Inc. San Marcos, Idaho, U.S.) Spot-Spitter per container until autumn 2007 when irrigation frequency and volume was reduced for the dormant season. Trees in 11 L containers were randomly chosen for shifting into 57 L round, black, solid-walled nursery containers (Table 1); they were spaced 1.8 m apart and irrigated three times daily (weather dictating) in the growing season with a maximum of 15 L through two Roberts Spot-Spitters. Trees were shifted into 170 L round, black, solid-walled nursery containers (Table 1) in place, remaining 1.8 m apart. Irrigation occurred two to three times daily in the growing season, with a maximum of 45 L through three Roberts Spot-Spitters, until October 2009 when volume was dropped to 15 L daily or less frequently as weather dictated. Elm and maple shoots were pruned, and trunks staked, to develop one leader and to shorten and remove large lower branches, creating a 1.5 m trunk clear of branches to mimic standard practice. Magnolias were pruned only to maintain a central dominant leader. All trees were secured to a wire trellis system for stability in wind.

Trees were retained in 11 and 57 L containers before shifting to the larger size for four combinations of time (Table 1). Root balls were not pruned when shifted and were planted even with the substrate surface in the larger container. Total production time to reach marketable dimensions (Anonymous 2014) was 32 months for each set of four retention time treatments. Twenty magnolia and maple trees, and 12 elms (32 elms died from low winter temperature by June 2007) were randomly assigned to each treatment totaling 80 trees each for magnolia and maple, and 48 for elm.

Substrate was 50:40:10 (New Florida peat: pine bark: sand, by volume). New Florida peat is a compost of Florida peat and hardwood bark fines (Florida Potting Soil, Inc., Orlando, Florida, U.S.). Fertilizer (18-5-10 controlled release, Harrells Inc., Lakeland, Florida, U.S.) was incorporated into substrate prior to planting at 10.74 kg/m^3, and no other fertilizer was applied. Weeds were periodically pulled from container substrate. Excepting some elms, trees did not root out of pots and into ground.

Trunk diameter (15 cm from substrate) and tree height were measured at the end of each growing season in October 2007, 2008, and 2009. Root balls of the 170 L containers were too dense to wash substrate from the entire root ball. Therefore, the top 12 cm of each root ball was severed from the bottom using a mechanical saw blade cutting parallel to the substrate surface on five randomly chosen trees of each treatment and taxa in October 2009. Substrate was washed from the 12 cm thick disc to expose all roots, and many attributes were measured on the cut disc surface (see appropriate Table notes).

Taxa were arranged in their own randomized complete block design adjacent to one another once they were in 57 L containers; there were four treatments randomized in every block, with 20 (magnolia and maple) or 12 (elm) blocks. Blocks of 57 L containers were complete once the longest retention time in 11 L containers occurred (12 months). Analysis of variance (ANOVA) in the GLM procedure within SAS (SAS Institute, Cary, North Carolina, U.S.) was used to evaluate impact of the main effect (retention time) on measured parameters for each taxa independently. Tukey's multiple comparison test separated means at $P < 0.05$.

RESULTS

Elms and magnolias retained four or seven months in 11 L containers had greater trunk diameter at the end of the study period, when trees were in 170 L containers, than those retained 12 months (Table 2). Maple response was opposite—those in 11 L containers four months were smaller than those retained 12 months. Magnolias in 11 L containers for four months were taller than trees retained longer; height trends for elms and maple were less clear.

Table 2. Effect of retention time in three container sizes on final trunk diameter and height (data collected October 2009) of elm, maple, and magnolia in 170 L containers.

Retention time (months) in containers:				
11 L	57 L	170 L	Trunk diameter (cm)	Height (m)
Elm				
4	8	20	6.7 az	3.9 b
7	10	15	6.7 a	4.3 a
9	12	11	6.4 a	4.5 a
12	14	6	6.0 b	4.2 ab
Maple				
4	8	20	6.5 b	4.5 ab
7	10	15	7.1 a	4.7 a
9	12	11	7.0 a	4.4 b
12	14	6	6.9 a	4.7 a
Magnolia				
4	8	20	6.1 a	3.3 a
7	10	15	6.2 a	3.1 b
9	12	11	5.6 b	3.2 b
12	14	6	5.1 b	3.1 b

[z] Means in a column within species with a different letter are statistically different at $P < 0.05$; n = 5.

Few trees of any taxa in 170 L containers were graded as culls according to Florida Grades and Standards for Nursery Plants (Anonymous 2015) at the end of the study period (Table 3). Roots circled less than 22% of the trunk circumference for all three taxa and retention times. Elm and maple retained the longest in the 11 L containers (treatment D) had a greater percentage of the trunk circled than trees retained four months. The number of elm roots >5 mm diameter measured just inside the former position of the 11 L container was not impacted by retention time; however, the number of maple and magnolia roots was greater for trees retained in 11 L containers for 12 months than for four months. The number of roots inside the former position of the 57 L container decreased as retention time in small containers increased for elm but not for maple and magnolia. The number of roots >5 mm diameter inside the 170 L container edge decreased with retention time in 11 L containers from seven to 12 months for all taxa. The number of roots >5 mm diameter growing straight (radially from the trunk) to the 57 L container edge decreased with increasing 11 L retention time for elm, not for maple or magnolia. The number of magnolia roots that grew straight to the 170 L container edge increased as 11 L retention time decreased.

Mean diameter and total cross-sectional area (CSA) of maple roots (>5 mm diameter) inside the position of the 11 L container was larger for nine months retention time in 11 L containers than four; elm and magnolia were not affected (Table 4). Mean magnolia root diameter inside the position of the 57 L container was smaller with 12 months retention in 11 L containers compared to shorter retention times; total root CSA at 12 months was less than at four months. Mean elm and maple root diameter and CSA just inside 170 L container edge was larger with seven months retention than nine and 12 months retention time in 11 L containers; magnolia root CSA was larger for four months than nine and 12 months (Table 4).

The most common fate of the five largest roots was deflection downward (descending) by the 11 or 57 L containers for all retention times; circling and straight roots were significantly less common (Table 5). Retaining trees in 11 L containers only seven months compared to 12 resulted in a 50% or greater increase in straight roots for each taxa. A greater percentage of the five largest roots for all taxa were deflected by the 11 than by the 57 L container except elm retained four months (Table 6). The percentage of roots deflected by the 11 L container generally increased—and that in the 57 L container decreased—with 11 L retention time for elm and magnolia, but not for maple. Almost none of the five largest diameter roots were measured at the edge of the 170 L container (Table 6). The mean root diameter for five largest roots just inside the 170 L container generally decreased with increasing 11 L retention time for elm and maple, not magnolia (Figure 1).

Table 3. Effect of retention time in three container sizes on elm, maple, and magnolia root number in 170 L containers.

Retention time (months) in containers: 11 L	57 L	170 L	% trunk circled with roots[z]	% cull[y] trees	No. of roots >5 mm diameter: At position of 11 L container[x]	At position of 57 L container[x]	At position of 170 L container[x]	Straight roots at 57 L container edge[w]	Straight roots at 170 L container edge[w]
Elm									
4	8	20	8.8 c[v]	0	14.4	17.8 a	0.6 ab	6.6 a	0.6
7	10	15	16.8 ab	20	16.8	15.4 a	1.2 a	6.2 a	0.8
9	12	11	14.6 b	0	15.8	7.8 b	0.2 b	4.0 ab	0.8
12	14	6	21.6 a	0	15.8	6.6 b	0 b	3.2 b	0
Maple									
4	8	20	8.7 b	20	12.6 b	16.6 b	1.8 ab	5.4	1.4
7	10	15	0 c	0	20.8 a	27.0 a	6.6 a	7.0	2.0
9	12	11	12.1 ab	20	17.8 a	24.0 a	0.4 b	4.6	0.6
12	14	6	16.7 a	20	20.6 a	18.2 b	0 b	6.6	0.6
Magnolia									
4	8	20	0	0	11.0 bc	26.6	13.6 a	9.4	3.2 ab
7	10	15	4.4	0	9.8 c	20.6	11.0 a	10.4	4.4 a
9	12	11	0	0	14.2 ab	24.6	6.6 b	8.2	1.8 bc
12	14	6	0	0	16.2 a	20.8	3.6 c	7.6	0.8 c

[z] Percent of circumference with root bark touching trunk bark.
[y] Percent of trees rated as cull based on root circling according to *Florida Grades and Standards for Nursery Plants* (Anonymous 2015).
[x] Number of roots >5 mm diameter one cm inside 11 L container position, between the 11 and 57 L position, and between the 57 and 170 L container position, respectively.
[w] Number of roots >5 mm diameter that grew to the position of the 57 or 170 L container without turning more than 45 degrees left or right.
[v] Means in a column within species with a different letter are statistically different at $P < 0.05$; n = 5.

Table 4. Effect of retention time in three container sizes on root size of elm, maple, and magnolia in 170 L containers.

Retention time (months) in containers:			Mean diameter[z] (mm) roots >5 mm			Total CSA[z] (mm^2) roots >5 mm		
11 L	57 L	170 L	At position of 11 L container	At position of 57 L container	At position of 170 L container	At position of 11 L container	At position of 57 L container	At position of 170 L container
Elm								
4	8	20	13.9	8.6	1.2 b[y]	2647	1195 a	17 ab
7	10	15	13.3	9.0	4.9 a	3160	1089 a	41 a
9	12	11	13.8	8.1	1.0 b	3388	440 b	4 b
12	14	6	12.7	7.8	0 b	2557	349 b	0 b
Maple								
4	8	20	11.7 b	9.6	4.6 ab	1891 b	1427 b	79 ab
7	10	15	12.0 b	11.1	6.6 a	3027 ab	3179 a	291 a
9	12	11	15.9 a	9.0	1.5 bc	5018 a	2019 ab	19 b
12	14	6	14.2 ab	9.3	0 c	4219 a	1513 b	0 b
Magnolia								
4	8	20	15.2	11.7 a	7.9	3033	3673 a	844 a
7	10	15	15.5	11.6 a	7.8	2831	2975 ab	513 ab
9	12	11	15.0	11.1 a	7.5	3057	2971 ab	307 b
12	14	6	12.6	7.6 b	6.6	2708	1068 b	120 b

[z] Diameter and cross-sectional area (CSA) of roots >5 mm diameter one cm inside 11 L container position, between the 11 and 57 L position, and between the 57 and 170 L container position, respectively.
[y] Means in a column within species with a different letter are statistically different at $P < 0.05$; n = 5.

Table 5. Effect of retention time in three container sizes on elm, maple, and magnolia root architecture in 170 L containers.

Retention time (months) in containers			Percent five largest roots circling at position of 11 or 57 L container[z]	Percent five largest roots descending at position of 11 or 57 L container[y]	Percent five largest roots straight at position of 11 or 57 L container[x]
11 L	57 L	170 L			
Elm					
4	8	20	12 a[w]B[v]	84 A	4 cB
7	10	15	12 aB	76 A	12 aB
9	12	11	8 bB	84 A	8 bB
12	14	6	4 cB	88 A	8 bB
Maple					
4	8	20	20	44 c	36 a
7	10	15	20	40 c	40 a
9	12	11	16 B	84 aA	0 cB
12	14	6	20	60 b	20 b
Magnolia					
4	8	20	8 bB	80 aA	12 aB
7	10	15	20 aB	68 bA	12 aB
9	12	11	24 aB	68 bA	8 bB
12	14	6	8 bB	84 aA	8 bB

[z] Percent of the five largest roots measured on cut root ball disc 12 cm below root ball top surface that circled at <45 degree angle relative to horizontal at either the 11 or 57 L container position.
[y] Percent of the five largest roots measured on cut root ball disc 12 cm below root ball top surface that descended relative to horizontal at >45 degree angle at either the 11 or 57 L container position.
[x] Percent of the five largest roots on cut root ball disc 12 cm below root ball top surface that grew without branching or deflecting at the 11 or 57 L container position, or if they branched the largest segment grew to the edge of the 170 L container without deflecting >45 degrees left or right.
[w] Means in a column within species with a different lower case letter are statistically different at $P < 0.05$; n = 5.
[v] Means in a row within species with a different upper case letter are statistically different at $P < 0.05$; n = 5 using one way ANOVA for each retention time independently.

DISCUSSION

Trees of all taxa retained for four months in 11 L containers required delicate handling to shift to 57 L containers because roots had not bound substrate together. Roots were not stiff enough to remain in position when 11 L substrate fell from the root ball, resulting in some roots bending and re-orienting when placed into 57 L containers. For this reason, it would be impractical to recommend retaining these taxa in 11 L containers for only four months because a commercial operation (Pat Miller, Cherry Lake Tree Farm, Groveland, Florida, U.S.) would be unlikely to handle trees as carefully as required to keep root balls intact. Root balls were easier to handle when shifting from 11 L containers at seven months with less substrate loss; some roots (not measured) inevitably

Table 6. Effect of retention time in three container sizes on deflected position of the five largest roots of elm, maple, and magnolia in 170 L containers.

Retention time (months) in containers 11 L	57 L	170 L	% roots deflected down or around by 11 L container[z]	% roots deflected down or around by 57 L container[z]	% roots deflected down or around by 170 L container[z]
Elm					
4	8	20	56 b[y]A[x]	44 aA	0 B
7	10	15	64 bA	32 bB	4 B
9	12	11	76 aA	24 cB	0 B
12	14	6	84 aA	16 dB	0 B
Maple					
4	8	20	80 aA	20 bB	0 C
7	10	15	68 bA	32 aB	0 B
9	12	11	76 abA	24 bB	0 B
12	14	6	80 aA	20 bB	0 B
Magnolia					
4	8	20	72 bA	28 aB	0 C
7	10	15	80 abA	20 bB	0 B
9	12	11	76 bA	24 abB	0 C
12	14	6	88 aA	12 cB	0 B

[z] Percent of the five largest roots measured one cm inside indicated container size that deflected down or around at the 11, 57, or 170 L container size.
[y] Means in a column within species with a different lower case letter are statistically different at $P < 0.05$; n = 5.
[x] Means in a row within species with a different upper case letter are statistically different at $P < 0.05$; n = 5 using one way ANOVA for each retention time independently.

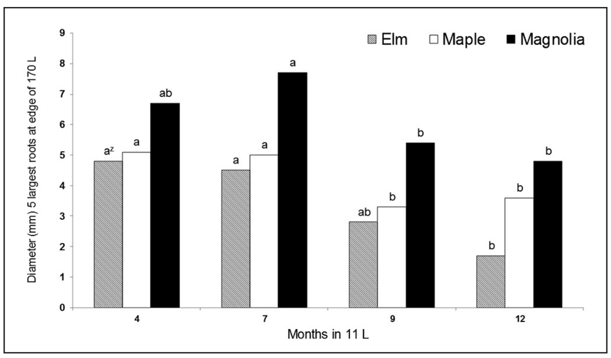

Figure 1. Mean diameter of five largest roots (measured 1 cm inside 170 L root ball periphery) with increasing retention time in 11 L container. [z]Means within each species with a different letter are statistically different at $P < 0.05$; n = 5.

became re-orientated during shifting. Despite substrate and some root disturbance at four- and seven-month retention times in 11 L containers, trunk diameter growth was greater than for longer retention times for two of the three taxa tested (Table 2). Tree height in the four-month retention time (treatment A) was greater than (magnolia) or equal to (elm and maple) height in the 12 month treatment (treatment D). These results appear to support adoption of treatment B, which includes a seven-month retention time in 11 L containers for maximizing trunk and crown growth rate. Growth appears to slow as the container substrate fills with deflected roots despite rigorous irrigation and fertilizer management.

Percent trunk circled with roots that touched trunk bark increased with retention time in 11 and 57 L containers for elm and maple, not magnolia (Table 3). This was also found for the same maple (Gilman et al. 2012) and other tree taxa (Balisky et al. 1995; Salonius et al. 2000) in smaller propagation containers. However, there was no relationship between retention time and percent trees grading as a cull (the lowest grade, Anonymous 2015) for any taxa (Table 3). This could indicate that the longest retention times in 11 and 57 L containers (treatments C and D) were too short to induce circling root defects associated with some nursery trees. Trees in 170 L containers in this test were at least 2 cm less in trunk diameter than largest allowable in ANSI Z60 (Anonymous 2014), suggesting there are many trees with more developed root defects planted into landscapes. Future tests should grow trees to the largest standard size, or larger, for a given container, in order to test what could be a more typical condition.

An increase in the number of roots deflected at 11 L position with increasing 11 L retention time for two (maple and magnolia) of three taxa tested generally corresponded to fewer (Table 3) and smaller-diameter (Table 4) roots growing out into the top 12 cm of the larger container. This was demonstrated by the reduction in mean root diameter for elm and maple (measured one cm inside the 170 L container edge, Figure 1), and general reduction in root CSA between the 57 and 170 L containers (Table 4) with increasing 11 L retention time. The number of straight roots at 57 or 170 L container positions decreased with increasing retention time in the 11 L; lack of straight roots has been associated with poor anchorage (Lindgren and Örlander 1978; Lindström and Rune 1999; Ortega et al. 2006; Gilman and Weise 2012). Essentially, the woody portion of the root system was deflected by and largely contained within 11 and 57 L container dimensions of the 170 L root ball (Table 6). Others also showed that deflected roots for maple (Gilman et al. 2012) and other taxa (Harris et al. 1971) continue to gain size in the deformed position, forming a root system imprint, and lateral roots growing from them were less abundant (Gilman and Paz 2014). Post-planting anchorage was reduced when woody roots were mostly deflected by the container instead of spreading out laterally (Gilman and Masters 2010; Gilman and Harchick 2014).

A much higher percentage of the five largest roots of all taxa grew down (descending) the container sidewall at the position of 11 or 57 L containers than either circled or grew straight into 170 L container substrate (Table 5). This tendency to deflect downward has been described for many taxa (e.g., Lindström and Rune 1999; Salonius et al. 2000). Presence of large roots deflected down or around has been associated with poor anchorage three years after planting *Quercus virginiana* Mill. from similar-sized containers and the same substrate as in the current study (Gilman and Masters 2010). The increase in percentage of five largest roots growing straight at seven- (treatment B) compared to twelve- (treatment D) months retention time in 11 L containers for all taxa tested (Table 5) has been associated with higher-quality root systems in other taxa (Gilman and Weise 2012; Gilman and Harchick 2014).

Deflection of the largest five roots by the smaller containers (Table 6) indicated that roots produced in the first two years from stem cuttings remained the largest roots for the duration of the study period (3.5 years). Some roots initiated while trees were in 11 and 57 L containers for the shorter retention times may not have reached the container side when they were shifted to larger containers. This likely explained increase in percentage of five largest roots growing straight into 170 L substrate with shorter retention time in the two smaller containers. Most permanent structural roots in treatments C and D (the longer retention times in the smaller containers) may have been initiated before trees were shifted to 170 L containers and therefore became deflected. Although new roots may have initiated from the root collar after shifting trees to 170 L containers, they were not the dominant roots in the end. Foresters have reported this on trees retained in much smaller (propagation) containers for long periods before planting (Burdett 1978; Chapman and Colombo 2006). The present study shows that roots deflected by 11 and 57 L containers can have a lasting impact on root architecture.

Shorter retention time in 11 and 57 L containers appears to be associated with more trunk growth (except maple, Table 2), a smaller percentage of trunk circled with roots (except magnolia), and more (Table 3) or larger (Table 4; Figure 1) roots reaching the 170 L periphery. However, great care was required to keep root balls intact at four- and seven-months retention times because roots had not sufficiently bound substrate together; perhaps a different substrate would respond in a different manner. Some defects resulted from roots drooping and becoming displaced and bent as substrate fell from the root ball during shifting. An alternative to short retention time includes allowing roots to grow sufficiently to bind substrate together. Deflected roots on the periphery can then be eliminated by root pruning (i.e., shaving, Weicherding et al. 2007; Gilman et al. 2010b; Gilman et al. 2012) or reduced in number by using certain container designs (Arnold and Young 1991; Chapman and Colombo 2006; Amoroso et al. 2010). This strategy may prove more effective or reliable than short retention times under certain growing conditions.

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Résumé. Dans un contenant de pépinière, les racines descendent dans le substrat et adoptent un développement circulaire lorsqu'elles atteignent les parois, conduisant parfois à de graves problèmes dans le futur. La période de rétention prolongée des jeunes plants dans de petits contenants en est la cause. Quatre types de périodes de rétention prolongées dans des contenants de 11 L et de 57 L furent été testés quant à leur impact sur l'architecture des racines une fois replantés dans les contenants de 170 L. Tous les taxons (*Acer rubrum*, *Magnolia grandiflora*, *Ulmus parvifolia*) maintenus pendant quatre mois dans des contenants de 11 L ont ensuite été délicatement transférés dans des contenants de 57 L parce que les racines ne s'étaient pas encore liées au substrat, il en a été par conséquent conclu que la période de rétention la plus courte, soit 4 mois, était irréalisable. Bien que la transplantation ait été plus facile pour les contenants des plus longues périodes de rétention (sept, neuf et douze mois), la qualité du système racinaire mesurée selon la quantité de déviations de racines diminuait avec l'augmentation du temps de rétention dans les contenants de 11 L et de 57 L. Un plus grand pourcentage des cinq plus grosses racines se sont développées vers le bas des parois des contenants par rapport à celles qui ont poussé de manière circulaire le long des parois ou en s'allongeant directement dans le substrat des contenants de 170 L. Presque toutes les grosses racines ont été déviées par les parois des contenants de 11 L ou de 57 L mais presqu'aucune n'a atteint les parois des contenants de 170 L. Une période de rétention plus courte dans les contenants de 11 L et de 57 L a été associée avec un plus faible pourcentage de racines encerclantes, davantage de racines atteignant la périphérie des contenants de 170 L et, chez l'orme et le magnolia, une plus importante croissance du tronc.

Zusammenfassung. Wurzeln wachsen nach unten und drehen sich, wenn sie den Boden des Pflanzcontainers erreicht haben, manchmal führt das zu ernsten Defekten. Das wird der langen Verweildauer in kleinen Pflanzcontainern geschuldet. Vier Verweilzeiten in 11 und 57 Liter Containern wurden auf ihren Einfluss auf die Wurzelarchitektur innerhalb eines 170 Liter Containers getestet. Alle Taxa (*Acer rubrum, Magnolia grandiflora, Ulmus parvifolia*), die für vier Monate in 11 Liter Containern blieben, erforderten einen sensiblen Umgang beim Umsetzen in einen 57 Liter Container, weil die Wurzeln das Substrat nicht zusammen hielten und dabei die kürzeste Verweildauer von vier Monaten unpraktisch machten. Obwohl die Umsetzung bei längeren Verweilzeiträumen (sieben, neun und zwölf Monate) leichter war, sank die Qualität des Wurzelsystems gemessen an der Wurzelbiegung mit zunehmender Verweildauer in 11 und 57 Liter Containern. Ein großer Prozentsatz von den fünf größten Wurzeln wuchs den Container hinunter und wuchs dann eintweder kreisförmig am Boden oder wuchs direkt in das Substrat des 170 Liter Containers. Fast alle großen Wurzeln wurden in den 11 oder 57 Liter Containern umgelenkt und fast keine erreichte die Wand des 170 Liter Containers. Kürzere Verweildauer in 11 und 57 Liter Containern war verbunden mit einem kleineren prozentualen Anteil von Ringwurzeln, mehr Wurzeln, die die 170 Liter Peripherie erreichten und bei Ulmen und Magnolien mit mehr Stammwachstum.

Resumen. Las raíces descienden y enrollan una vez que topan con las paredes del contenedor en el vivero, resultando algunas veces en defectos severos. Esto se ha atribuido al tiempo que ha permanecido en pequeños contenedores. Se probaron cuatro períodos de retención en contenedores de 11 y 57 L para probar su impacto en la arquitectura de las raíces, hasta terminar en contenedores de 170 L. Todos los taxones (*Acer rubrum, Magnolia grandiflora, Ulmus parvifolia*) retenidos durante cuatro meses en contenedores de 11 L requirieron manejo delicado para cambiarlos a contenedores de 57 L porque las raíces no habían amarrado suficiente sustrato, haciendo impráctico el menor tiempo de retención (cuatro meses). Aunque el cambio era más fácil para tiempos más largos de retención (siete, nueve y doce meses), la calidad del sistema de raíces medida por desviaciones de la raíz disminuyó con el aumento en el tiempo de retención en contenedores de 11 y 57 L. Un mayor porcentaje de cinco grandes raíces creció hacia abajo de las paredes del recipiente, que enrolladas en el sustrato de contenedores de 170 L. Casi todas las raíces más grandes fueron desviadas por el recipiente 11 o 57 L y casi ninguna llegó a la pared del recipiente de 170 L. El menor tiempo de retención en contenedores de 11 y 57 L se asoció con un menor porcentaje de tallos enrollados, más raíces en la periferia de 170 L, y para el olmo y la magnolia, mayor crecimiento del tronco.