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Container Production Strategies Influence Root Ball Morphology

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Abstract. Poor anchorage and delayed establishment have been associated with root circling and ascending, descending, and kinked roots occurring in nursery containers. The main goal of this study was to find methods of producing from seed *Swietenia mahagoni* (L.) Jacq. with straight, non-deformed roots. In contrast to smooth-sided (SM) propagation containers (liners), roots grown in pots constructed of thin paper were straight with few deflections. Root pruning 12-month-old SM liners when shifting to 3.8 L containers dramatically reduced the imprint on the root system left by root deflections. Aggressive growth at the bottom of 3.8 L and 9.5 L smooth-sided containers appeared to inhibit growth in horizontal roots closer to the substrate surface, and resulted in a vertically oriented root system. In contrast, growing trees in 3.8 L and 9.5 L containers with exceptionally porous walls produced a more horizontal-oriented root system similar to well-anchored trees in the landscape. Vertical roots were discouraged from developing due to an elevated and porous bottom, forcing roots to grow more horizontally higher in the root ball profile. Root deflections increased with retention time in all containers.

Key Words. Air Root Pruning; Deflected Roots; Descending Roots; Field-grown Trees; Horizontal Roots; Liners; Mechanical Root Pruning; Propagation; Straight Roots; *Swietenia mahagoni*.

Trees with some large diameter, straight roots close to the soil surface are well anchored in shallow (Coutts et al. 1990) and deep soils (Gilman and Wiese 2012). This compels development of field and container nursery production systems that mimic this root morphology. Roots on established trees often proliferate close to the surface in soil with low oxygen content typical in disturbed urban soils (Gilman et al. 1987; Watson and Kupkowski 1991). Some roots elongate from existing short roots within the root ball, from cut roots at the top edge of the root ball, or adventitiously from the flare. Many large roots are oriented downward in the planted root ball for certain production systems and species (Hewitt and Watson 2009; Gilman and Orfanedes 2012). The tree redirects the root system toward the surface after planting, which contributes to transplant shock as the tree generates either adventitious roots from near the trunk or new roots from root pruning cuts.

The downward growth and circling of roots that result from deflection in propagation (liner) container encourages new roots to grow from the bottom of the liner root ball once planted into field soil or a larger container (Salonius et al. 2000). Decades ago, Harris et al. (1971) recognized that root pruning seedlings as they were shifted could reduce the imprint left by root deflections. Research on liners used in reforestation efforts also suggests that root-pruned seedlings produce a more symmetrical root system with ample surface roots (Krasowski 2003).

Roots on shade trees in larger containers also deflect around and downward, often proliferating at the bottom (Marshall and Gilman 1998), likely due to availability of suitable air, nutrition, and water at the bottom. Root defects of temperate (Weicherding et al. 2007) and tropical (Gilman and Orfanedes 2012) trees growing in containers with more or less smooth sides are fairly easy to remove with mechanical root pruning (shaving all roots and substrate from the periphery), because many roots are at the extreme edge of the root ball. From field observations, evaluation of these practices is only now beginning in mainstream horticulture operations.

Certain container types have been associated with reduced root defects at the root ball periphery (Arnold and McDonald 2006; Gilman et al. 2010). Treating the interior plastic container surface with copper is a time-tested, effective method for reducing root growth on the periphery of container root balls (Burdett 1978; Struve 1993; Marshall and Gilman 1998). Orlander (1982) and Ortega et al. (2006) found that exposing the open container bottom to air (air pruning) resulted in fewer deflected roots in the propagation container. The number and total length of *Acer rubrum* L. roots from stem cuttings deflected up, around, and down by container walls were approximately an order of magnitude greater in four types of plastic containers compared to those made from thin paper (Gilman et al. 2012). This was presumably due to a combination of root tip dieback on roots growing through the paper and into the air outside the container (i.e., air pruning), and growth of some of these roots into adjacent containers.

The objective of this study was to find a nursery production system that produced a root ball with attributes similar to those of well-anchored landscape trees; i.e., with straight roots, some close to the surface. Mahogany [*Swietenia mahagoni* (L.) Jacq.] was chosen due to: 1) its popularity as an urban landscape tree in tropical and subtropical regions of Florida, U.S., and in the Caribbean, and 2) a general lack of nursery production research on tropical shade tree root systems.

MATERIALS AND METHODS

On February 11, 2009, in Loxahatchee, Florida (USDA hardiness zone 10a), mahogany seeds were placed into propagation (liner) containers in substrate consisting of 45% super fine pine bark, 20% Florida peat, 10% horticultural perlite, 15% Allgro compost, and 10% coarse sand. Three propagation container types tested were: 1) Bottomless Ellepot (EP) constructed of paper 50 mm diameter × 90 mm tall, with a volume of 137 cm^3 (Ellegaard, Esbjerg, Denmark, Ellepot paper made by Ahlstrom Stalldalen AB, Stalldalen Sweden from spruce, pine, and polyester long fibers, 27g/m^2, 190 microns thick, 1320 N/m dry tensile strength in machine direction, 2.0 N tear strength), arranged 10 mm apart in a plastic tray (27 cm × 53 cm), which exposed 100% of the paper sides to air and rested on a plastic ring (8 mm wide) as part of the holder tray; 2) EP with same dimensions placed in a tray of smooth (EPS) black plastic cells (60 mm tall × 50 mm wide), spaced about 5 mm apart; and 3) a tray of smooth-sided (SM) black plastic containers 40 mm top diameter × 90 mm tall (volume 105 cm^3) with a slightly tapered cone and a single drainage hole at the bottom. Trays (each with 40 to 55 containers) were arranged in a randomized fashion on wire mesh benches 80 cm from the ground in full sun in a non-climate controlled, open-sided greenhouse.

Retained in Propagation Container (5 months)

On July 27, 2009 (5 months retention time in propagation container), trees were either 1) washed of substrate for root evaluation, 2) shifted into 3.8 L containers, or 3) retained in the propagation containers. On 10 randomly chosen, washed trees, roots >1 mm diameter were evaluated for number of roots in the top half of root ball that branched, estimated % of total root ball root length that was in the top half of the root ball, tap root deflected by liner bottom or not, tap root length after deflection, number of primary lateral roots deflected by the container bottom, number of primary lateral roots deflected downward by the container sides, and a visual estimate of where active root growth was occurring: either mostly in the top half of root ball, mostly in the bottom half of root ball, or evenly distributed in the root ball. Tree height and trunk diameter at substrate level were also recorded.

One-hundred liners of each propagation container type were shifted into either 3.8 L, 1) black plastic smooth-sided slightly-tapered containers (SC1; 15.5 cm top diameter × 15.5 cm tall; Nursery Supplies, Inc., Chambersburg, Pennsylvania, U.S.) or 2) into containers with exceptionally porous walls and bottom (Pioneer pot®; PC1; 19 cm top diameter × 17 cm tall, all container surfaces composed of about 15% plastic and 85%, air including a bottom elevated 8 cm from ground, Pioneer Farms, Visalia, California, U.S.) and placed several cm apart on woven ground cloth, on the ground, pot-to-pot in a randomized fashion. Side of PC1s were lined with paper (as described in EP) to ensure substrate would not leach through the large (10 mm square) openings in the side. The resulting experimental design was a complete factorial with three propagation container types × two 3.8 L container types, totaling 600 trees. Substrate volume was equivalent in both 3.8 L containers; it reached the top in the PC1 containers and was 1 cm below the top in the SM1 containers. The

EP paper was not removed when shifting into 3.8 L containers. Controlled release fertilizer (18N-6P_2O_5-1$_2K_2O$, Nurserymen's Sure Gro, Vero Beach, Florida, U.S.) was surface applied to substrate (60% pine bark: 30% Florida peat: 10% sand) following shifting to the 3.8 L container, and no other fertilizer was applied. Trees in 3.8 L containers were overhead irrigated typically two or three times daily in the growing season, less in the dormant season. Roots remained inside containers without rooting into the ground and without rooting into adjacent containers. Shoots were pruned once to maintain a dominant leader.

In January 2010 (6 months retention time in 3.8 L containers), trees were either 1) washed, 2) retained in 3.8 L containers, or 3) shifted to 9.5 L containers. Ten trees in both 3.8 L container types from three propagation container types (60 trees total) were washed of substrate to measure root and shoot attributes. Root (>1 mm diameter) attributes measured in 3.8 L containers included % trunk circumference circled with roots; root cull, according to Florida Grades and Standards for Nursery Stock (Anonymous 1998); number of roots deflected by propagation container; visual rating of the imprint formed by the deflected roots at the position of the liner; root depth and diameter of the 10 largest-diameter roots measured just beyond the edge of the propagation container position; number of the largest 10 roots that grew outward at less than 45 degrees to substrate surface without deflecting laterally more than 60 degrees and reached the 3.8 L container edge (straight roots); root depth and diameter at the periphery of the 3.8 L container; and diameter of the five largest horizontal (0 to 45 degrees from substrate surface) and vertical (45 to 90 degrees) roots measured just beyond the edge of the propagation container. Half of the remaining trees were retained in the 3.8 L container until September 2010 (13 months retention time in 3.8 L containers), when either the same measurements were made on eight randomly chosen trees of each treatment combination, or trees were shifted into 9.5 L containers of the same type (SC3, model PF1200, 27 cm top diameter × 24 cm deep; PC3, 28 cm top diameter × 17 cm deep). Substrate volume was equivalent in both containers; it reached the top in the PC3 containers and was 1 cm below the top in the SM3 containers. The other half of the remaining 3.8 L trees was shifted January 2010 into 9.5 L containers of the same type (PC3 and SC3). Paper was not used to line the PC3 because it did not appear to be needed to retain substrate. All trees remained in 9.5 L containers for six months regardless of when they were shifted, at which time they were washed of substrate to measure roots as described for 3.8 L containers. Trees grown under the EPS treatment were not shifted into 9.5 L containers due to lack of available plants.

Retained in Propagation Container (12 months)

In February 2010, 40 trees retained in EP and 40 retained in SM propagation containers for 12 months were root pruned; 20 of each went into SC1 and 20 into PC1 3.8 L containers for a total of 80 trees (two propagation types pruned × two 3.8 L types × 20 reps). The outer 5 mm of the root ball sides and bottom was removed with sharp scissors (Fiskars, FSK01004342) by one person to standardize procedure. The remaining 80 trees were not root pruned when shifted into the SC1 (40 trees) and PC1 (40 trees) containers. The completely randomized experimental design was a complete factorial with two propagation types × two 3.8 L types × two root pruning treatments × 20 reps = 160 trees. Substrate in the propagation container was positioned a few mm below the surface of the 3.8 L container substrate to account for some substrate settling around the liner root ball. Trees were placed in a randomized manner in full sun and overhead irrigated on nursery ground cloth. In August 2010 (6 months retention time in 3.8 L containers) and March 2011 (12 months retention time in 3.8 L containers), trees were shifted into 9.5 L containers of the same type. Trees remained in 9.5 L containers for six months regardless of when they were shifted, at which time root systems were washed of substrate. Measurements included those described for 3.8 L containers.

Statistical Analysis

All designs were completely randomized complete factorials. Attributes in three propagation containers harvested in July 2009 were analyzed with one-way analysis of variance (ANOVA) using the GLM procedure of SAS (version 9.2, SAS Institute, Cary, North Carolina, U.S.) (Table 1). Attributes in two 3.8 L container types shifted from three propagation liner types harvested January

2010 were analyzed with two-way ANOVA (Table 2). Attributes in two 3.8 L container types, grown from three propagation liner types, and retained 5 or 12 months in propagation, liners were analyzed with three-way ANOVA (Table 3). Attributes in two 3.8 L container types, grown from three propagation liner types, and root pruned or not, were analyzed with three-way ANOVA (Table 4). Attributes in two 3.8 L containers types retained in two propagation liner types 5 months, and harvested 6 and 13 months later, were analyzed with three-way ANOVA (Table 5). Attributes in two 3.8 L and 9.5 L container types, grown from three propagation liner types, in each of these three treatment combinations: 1) 5 months or 2) 12 months retention in propagation container without root pruning when shifting to 3.8 L container, or 3) 12 months retention with root pruning, were analyzed with three-way ANOVA (Tables 6 and 7). Attributes in two 3.8 L and 9.5 L container types, grown from two propagation liner types for 5 months, and retained in 3.8 L containers for 6 or 13 months, were analyzed with three-way ANOVA (Table 8). Percentages were Arcsine transformed prior to analysis. Duncan's multiple range test was used to separate main effect means; interaction means were compared with LS means at $P < 0.05$. Main effects are presented and were averaged across insignificant factors when interactions were insignificant.

RESULTS

Three-way interactions were mostly insignificant, so they are not described in this analysis. Mahogany propagated in SM had slightly smaller trunk diameter and were shorter than trees in EP when harvested from the propagation container (Table 1). Trees in EP had greater root branching and root length in the top half of liner root balls, fewer deflected tap roots and lateral roots, and actively growing roots more evenly distributed vertically when compared to SM and EPS (Table 1; Figure 1).

Mahogany harvested from both 3.8 L container types that were propagated in EPS had a much larger percentage of the trunk circled at the liner position (78%), produced more trees graded as root culls (79%), and the imprint on the root system imposed by the propagation container was highly visible (rating = 4.6) when compared to seedlings grown in SM and EP (Table 2). Trees propagated in EP had the least deflected (lower % trunk circled, % culls, imprint rating) root systems, and those from SM had shallower roots than EPS.

Mean root depth was greater in both 3.8 L container types measured just beyond the position of the liner root ball when trees were retained in propagation containers 12 months (87 mm) compared to 5 months (50 mm, data not shown). Response to retention time depended on the propagation container type for four measured root attributes

Table 1. Trunk diameter, tree height, and root (>1 mm diameter) attributes of mahogany [*Swietenia mahagoni* (L.) Jacq.] harvested from three propagation container types 5 months (July 2009) after seed germination.

Propagation container (liner) type	Trunk diameter (mm)	Tree height (cm)	No. of roots in top half of root ball that branched (cm)	% total root length in top half of root ball	% trees with tap root deflected at bottom	Tap root length after deflection (mm)	No. of lateral roots deflected down	No. of lateral roots deflected around bottom	% trees with active root growth evenly distributed vertically in root ball
SM	3.1 b[z]	18 b	0.4 b	23 b	100 a	55 b	4.4 a	6.6 a	0 a
EP	3.8 a	22 a	3.2 a	55 a	10 b	2 c	0.4 b	0 b	40 b
EPS	3.4 ab	16 b	0.4 b	18 b	100 a	174 a	0.2 b	8.9 a	0 a

[z] Means in a column with a different letter are statistically different at $P < 0.05$; n = 10.

Table 2. Effect of propagation container type on roots (>1 mm diameter) of mahogany harvested six months (January 2010) after shifting into 3.8 L containers[z].

Propagation container (liner) type	% trunk circled at liner wall position	% trees graded as cull[y] at liner wall position	Root system visual[x] imprint from liner wall (1–5)	Root depth just beyond position of the liner wall (mm)
SM	29 b[w]	20 b	2.6 b	47.3 b
EP	2 c	0 b	1.4 c	52.1 ab
EPS	78 a	79 a	4.6 a	55.7 a

[z] Values for the same attributes were similar for trees in 9.5 L containers (data not shown).
[y] Root cull according to Florida Grades and Standards for Nursery Plants (Anonymous 1998).
[x] 1 = no visible deflection or retained "cage" formed by deflected roots at the position of the propagation liner; 5 = highly visible "cage" formed by deflected roots at the liner.
[w] Means in a column with a different letter are statistically different at $P < 0.05$; n = 20 averaged across 3.8 L container type due to insignificant interaction.
Note: Roots measured just beyond the propagation container position; trees not root pruned when shifting to 3.8 L containers.

Table 3. Interaction of propagation container type with retention time on mahogany roots (>1 mm diameter) harvested 6 months later from 3.8 L containers.

Propagation container (liner) type	Retention time in propagation container (months)	% trunk circled at liner wall position	% trees graded as root cull[z] at liner wall position	No. of roots deflected at liner wall position	No. of straight roots[y] from flare
SM	5	29 b[x]	20 b	2.7 ab	5.2 a
	12	66 a	86 a	3.6 a	2.5 b
EP	5	2 c	0 b	2.0 b	5.1 a
	12	12 bc	0 b	0.7 c	4.7 a

[z] Root cull according to Florida Grades and Standards for Nursery Plants (Anonymous 1998).
[y] Straight roots were those >1 mm diameter measured just inside the 3.8 L container sides that grew from trunk at <45 degree angle to substrate surface without making a turn of >60 degrees relative to parent root azimuth at trunk.
[x] Means in a column with a different letter are statistically different at $P < 0.05$; n = 16 averaged across 3.8 L container type due to insignificant interaction.
Note: Trees not root pruned when shifting to 3.8 L containers.

Table 4. Interaction of propagation container type with root pruning on mahogany roots (>1 mm diameter) harvested from 3.8 L containers 13 months after shifting (March 2011).

Propagation container (liner) type	Roots pruned when liner was shifted into 3.8 L container	% trees graded as root cull[z] at liner wall position	% trunk circled at the liner wall position
SM	Yes	21 b	12 b
	No	86 a	66 a
EP	Yes	0 b[y]	5 b
	No	0 b	12 b

[z] Root cull according to Florida Grades and Standards for Nursery Plants (Anonymous 1998).
[y] Means in a column with a different letter are statistically different at $P < 0.05$; n = 14 averaged across 3.8 L container types due to insignificant interaction. Results were similar for trees harvested in 9.5 L containers.
Note: Trees retained in propagation containers 12 months (February 2009 to February 2010) prior to root pruning when shifting.

Table 5. Interaction of 3.8 L container type with retention time on mahogany roots (>1 mm diameter) harvested from 3.8 L containers.

3.8 L container type	Retention time in 3.8 L container (months)	% of total root CSA in top 2 cm at 3.8 L root ball periphery	CSA five largest horizontal roots at 3.8 L root ball periphery[z] (mm^2)	No. of horizontal roots[z]	Ratio diameter five largest horizontal: five largest descending roots[y] just beyond liner position	Maximum arc lacking roots[x] (degrees)	Root depth just beyond position of the liner periphery (mm)
PC1	6	17 a[w]	25 bc	7.8 a	5.7 a	117 b	46 c
	13	13 b	97 a	6.8 a	2.9 b	90 b	67 b
SC1	6	6 d	8 c	2.9 c	0.7 c	258 a	53 c
	13	8 c	35 b	4.2 b	1.0 bc	104 b	95 a

[z] Horizontal roots were those growing from the trunk at less than a 45 degree angle to substrate surface.
[y] Descending roots were those growing at an angle of between 45 and 90 degrees to substrate surface.
[x] The largest arc (in degrees) looking down at the top of the root ball lacking roots > 1 mm diameter.
[w] Means in a column with a different letter are statistically different at $P < 0.05$; n = 16 averaged across propagation container type due to insignificant interaction.
Note: Trees retained in propagation containers 5 months (February 2009 to July 2009) and not root pruned when shifted. Finished trees in 9.5 L containers had similar values for most attributes (data not shown).

Table 6. Effect of container type on mahogany trunk diameter, tree height, and roots (>3 mm diameter) harvested in 9.5 L containers in April and October 2011.

3.8 L and 9.5 L container type	Trunk diam. (mm)	Tree height (m)	% trunk circled in top half of 3.8 L container	% trunk circled in bottom half of 3.8 L container	3.8 L visual imprint[z] rating (1–5)
PC3	14 b[t]	1.0 b	13 b	2 b	1.5 b
SC3	16 a	1.2 a	24 a	48 a	4.5 a

[z] 1 = no visible deflection or retained "cage" formed by deflected roots at the position of the propagation liner; 5 = highly visible "cage" formed by deflected roots at the liner.
[y] Root cull according to Florida Grades and Standards for Nursery Plants (Anonymous 1998).
[x] Straight roots were those measured at the edge of root ball that grew from trunk at <45 degree angle to substrate surface without making a turn of >60 degrees relative to parent root azimuth at trunk.
[w] Horizontal roots were those growing from the trunk at less than a 45 degree angle to substrate surface; descending roots are those growing at an angle of between 45 and 90 degrees.
[v] These grew from the top of the main structural roots or trunk base and were distinguished from existing roots by their straight orientation and light coloration, typically with a long, white root tip.
[u] Measured just beyond the edge of the propagation container.
[t] Means in a column with a different letter are statistically different at $P < 0.05$; n = 42 averaged across propagation container type, and across these three treatment combinations due to insignificant interaction: 5 or 12 months in propagation container without root pruning when shifting to 3.8 L container, and 12 months retention with root pruning.

(Table 3). In contrast to SM propagation containers, increasing retention time in EP containers had no impact on % trunk circled, % root culls, and number of straight roots in 3.8 L containers. When held five months, propagation container type had no impact on number of roots deflected at the position of the container; however, when held 12 months, fewer roots deflected in EP than in SM containers.

Root pruning SM liners by shaving (pruning) 5 mm from the periphery reduced by a factor of 4 or 5 the % trees in both 3.8 L containers graded as culls and % trunk circled, respectively (Table 4). Root pruning EP liners had no impact on 3.8 L trees (Table 4) because there were few roots deflected by the EP periphery (Table 1). Root pruning SM also increased the % of total root (>3 mm diameter) number (56%, root pruned; 42%, not root pruned; $P < 0.05$) that grew to the periphery of both 9.5 L containers (data not shown).

Percentage of total-tree root cross-sectional area (CSA) in the top 2 cm measured at the periphery of the 3.8 L root ball was larger for trees grown in PC1 than in SC1 containers for both retention times from both propagation containers (Table 5). Both the number of horizontal roots (those growing 0 to 45 degrees from the surface) and CSA of the five largest horizontal roots were approximately two to three times larger for trees in PC1 than SM1 containers. The ratio of diameter in the five largest horizontal to diameter in the five largest descending roots (those growing 45 to 90 degrees from surface) was eight and three times greater for PC1 than SC1 for 6 and 13 months retention time, respectively. Growing trees in SC1 containers resulted in a greater arc without roots (>1 mm diameter) than growing in PC1 after 6 months in 3.8 L containers; there was no difference at 13 months. Root depth for trees from both propagation container types was not affected by 3.8 L container type 6 months after shifting but was significantly greater in SC1 than PC1 13 months after shifting (Table 5).

Impact from growing mahogany trees in 3.8 L and 9.5 L containers of two types was consistent (i.e., there was no interaction) across propagation container type, retention time in propagation container, and root pruning for 11 measured attributes (Table 6; Figure 2). Trees harvested from SC3 containers had slightly larger trunk diameter and total-tree height ($P < 0.05$) than trees from PC3. Roots on trees from SC3 had higher values of attributes associated with lower quality, including % trunk circled with roots, 3.8 L container imprint rating, root cull (graded according to Florida Grades and Standards, Anonymous 1998), and total deflected root length. Trees in PC3 containers had about six times the number of straight roots (69% vs. 11% of roots > 3 mm diameter) as those in SC3 containers. Trees in PC3 had 44% of root system CSA deeper than 8 cm at the periphery of the 9.5 L container, whereas 83% was positioned there on trees in SC3 containers. Ratio CSA of five largest horizontal to five largest descending roots was 49 times greater on trees from PC3 than SC3 containers (Table 6; Figure 2).

Impact on growing trees in 3.8 L and 9.5 L containers depended on the propagation container type for four root attributes (Table 7). Growing trees in EP and then shifting to PC1 and PC3 resulted in the least % trunk circled and % trees with roots that touched or crossed within the dimensions of the propagation container. For both propagation

% root cull[y] in 3.8 L container	Total root length down, up, or around side of 9.5 L container (mm)	% roots that grew straight[x] to 9.5 L container periphery	% trees with >2 straight horizontal roots[w] initiated from trunk while in 9.5 L container[v]	% total root CSA deeper than 8 cm at 9.5 L container periphery	Ratio CSA five largest horizontal: five largest descending roots[u]
11 b	216 b	69 a	42 a	44	4.9 a
28 a	1019 a	11 b	21 b	83	0.1 b

Table 7. Interaction of propagation container type with 3.8 L and 9.5 L container type on mahogany roots (>3 mm diameter) harvested in 9.5 L containers April and October 2011.

Propagation container (liner) type	3.8 L and 9.5 L container type	% trunk circled at liner position	% trees with roots within liner dimension that cross or touch	No. of horizontal straight roots[z] from flare	% roots that grew to 9.5 L container periphery[y]
SM	PC3	40 a[x]	57 b	7.8 a	63 b
	SC3	34 a	81 a	2.2 b	16 c
EP	PC3	3 b	5 c	8.7 a	76 a
	SC3	22 a	71 ab	1.1 c	5 d

[z] Straight roots were those >3 mm diameter measured just inside the 9.5 L container sides that grew from trunk at <45 degree angle to surface without making a turn of >60 degrees relative to parent root azimuth at trunk.

[y] Roots that remained larger than 3 mm diameter while growing to the 9.5 L container side, not including those that touched the bottom first.

[x] Means in a column with a different letter are statistically different at $P < 0.05$; n = 21 averaged across these three treatment combinations: 5 or 12 months in propagation container without root pruning when shifting to 3.8 L container, and 12 months retention with root pruning due to insignificant interaction. Results were similar for trees harvested in 3.8 L containers (data not shown).

Table 8. Effect of retention time in 3.8 L container on mahogany in 9.5 L containers September 2010 and April 2011.

Retention time in 3.8 L containers (months)	% trunk circled in top half of 3.8 L container position	% cull at 3.8 L container position	Total length of roots growing down, up, or around side of 9.5 L container (mm)	% CSA of horizontal roots[z] deeper than 8 cm at 9.5 L container periphery
6	6 b[y]	3 b	474 b	66 a
13	25 a	31 a	798 a	61 b

[z] Horizontal roots were those growing from the trunk at less than a 45 degree angle to substrate surface.

[y] Means in a column with a different letter are statistically different at $P < 0.05$; n = 32 averaged over propagation container type and 9.5 L container type due to insignificant interaction.

Note: Trees retained in propagation containers 5 months (February 2009 to July 2009) and not root pruned when shifted.

container types, growing trees in PC3 resulted in a threefold or more increase in number of horizontal straight roots (those > 3 mm diameter) and % roots that grew to the 9.5 L container periphery compared to trees in SC3. The longer retention time in both 3.8 L containers was associated with greater root circling and deflection, reduced quality, and slightly greater depth of horizontally oriented roots (Table 8).

DISCUSSION

Retaining trees in containers for different time periods, and root pruning or not when shifting the liner, resulted in few meaningful differences in trunk diameter and tree height at the end of the study when trees were in 9.5 L containers; container type had only a slight effect. Trees in SC containers were larger than those in PC probably due to drier conditions (not measured) in PC containers. This was attributable to the porous nature of the container sides and bottom; fabric containers with porous sides have been shown to increase evaporation from the container root ball (Arnold and McDonald 2006). Irrigation management could be adjusted to maintain higher moisture content.

Finished liners in EP had attributes associated with high quality root systems best described as an abundance of horizontal straight roots growing from an aborted tap root (Balisky et al. 1995; Svensen et al. 1995); roots in the other two liners were deflected downward and around the container (Table 1; Figure 1). EP propagation containers that were inserted into smooth-sided liner cells (EPS) produced root systems similar to those in SM (Table 1), which indicated that the paper comprising the sides of EP should be exposed to air, not placed against a solid plastic wall. When finished in 3.8 L containers, root systems from EPS containers had a more prominent liner imprint (Harris et al. 1971) than those propagated in SM (Table 2). The slim air gap between the plastic sides and the EP paper created an ideal environment for root growth and caused this imprint formed by roots circling, ascending, and descending mostly outside of the paper. Mahogany should not be grown using the EPS system because it encouraged a severe root imprint at the position of the liner. In contrast, trees propagated in EP and finished in either 3.8 L container type had almost no measurable root circling or imprint at the position of the liner (Table 2).

Mahogany root defects at the liner position on trees in 3.8 L containers increased with retention time in SM propagation containers but not for EP containers (Table 3) as in other studies (Salonius et al. 2000; Gilman et al. 2012). However, root pruning SM liners retained 12 months when shifting to 3.8 L containers dramatically reduced defects at the liner position (Table 4) without impacting trunk or height growth (data not shown). This enhancement of quality did not occur for trees propagated in EP because there were far fewer defects to remove (Table 1). Mechanical root pruning was also a reliable method of managing roots of other tree species when shifting liners to larger containers (Gilman et al. 2012), or when planting into field soil (Krasowski and Owens 2000). This eliminates the imprint imposed on the root system by the container, which reduces the likelihood of stem girdling roots and can enhance anchorage (Gilman and Wiese 2012).

Propagation container type failed to influence consistently any measured attribute across both 9.5 L container types; i.e., the effect of propagation type depended on which larger container was used when data was averaged across 5 and 12 months retention time in propagation containers and root pruning (Table 7). In contrast, the effect of larger container type (either PC or SC) was consistent for nine root attributes of trees propagated from either propagation type (Table 6). This analysis could falsely lead us to conclude that root quality depended more on the 3.8 L and 9.5 L container type, and less on the propagation container type. However, when data was averaged across retention time in 3.8 L containers on trees retained for 5 months in propagation containers, propagation type had a significant effect on root morphology in the 9.5 L root balls. For example, root defects at the SM liner position including % trunk circled (51), % culls (42), and imprint rating (3.7) were much greater ($P < 0.01$) than the same attributes for trees grown in EP propagation containers (8%, 3%, and 1.7, respectively, data not shown). This analysis shows that both propagation container and the larger container impacted root quality.

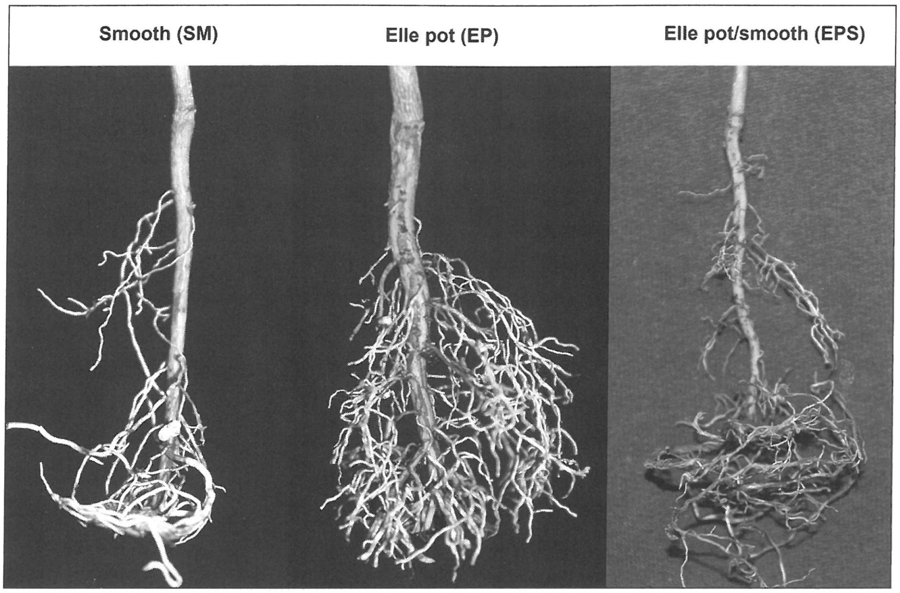

Figure 1. Root systems after 5 months in three propagation containers. The large-diameter lateral woody roots emerging from the tap root in EP are lacking on the other two.

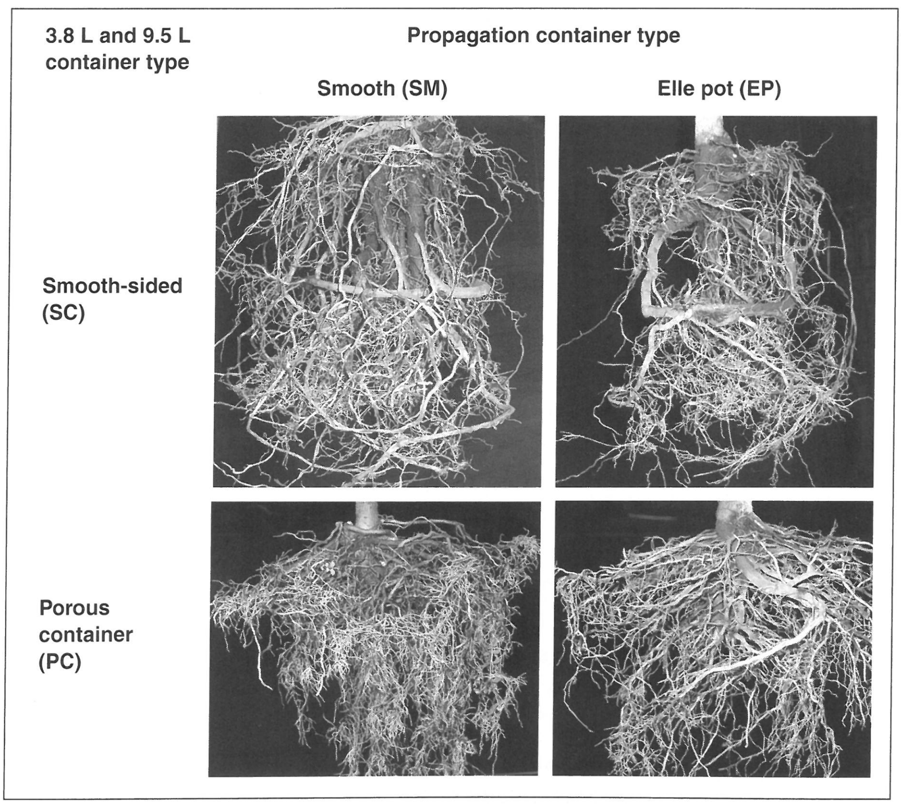

Figure 2. Root systems in 9.5 L containers for six months, grown in four combinations of propagation container and larger (3.8 L and 9.5 L) container.

The deeper and deflected nature of the root system in finished SM liners (Table 1) likely explains the abundance of root defects at the liner position in both 9.5 L container types (Table 7). Trees did not grow out of that condition created in the propagation liner in either larger container type. The lack of root deflection in EP propagation containers (Table 1) was responsible for the small imprint at that position and far greater number of roots reaching the side walls (periphery) of the PC 9.5 L container (Table 7; Figure 2). Root tips in EP liners remained in the horizontal position near the liner periphery without deflection, which positioned them for growing horizontally into the PC container. However, in SC 9.5 L containers, root defects on trees propagated in EP mimicked those of trees propagated in SM liners, suggesting that the benefits of growing a high-quality root system in the liner (i.e., in EP) disappeared when shifting into a larger SC container. This was attributable to the largest roots from both propagation container types growing downward from the bottom of the liner to the bottom of the 3.8 L and 9.5 L SC containers (Table 4). Once at the bottom, roots deflected and continued to grow along the bottom forming an imprint that remained with the tree in the 9.5 L container (Table 6; Figure 2) as others have found for smaller containers (Selby and Seaby 1982). Aggressive growth at the bottom of the 3.8 L SC containers appeared to inhibit initiation or growth of horizontal roots closer to the substrate surface, and resulted in a vertically oriented and circling root system on finished 9.5 L SC trees (Figure 2). Deflection of structural roots downward in the container forced them to grow parallel and cross one another directly under the trunk (Table 7) causing constrictions and inclusions that can restrict passage of substances through vascular tissue (Lindström and Rune 1999).

In contrast to SC containers, growing trees in PC produced a root system with a more horizontal than vertical orientation (Table 6; Figure 2). This has not been reported before for containers of this large size. Vertical root growth was discouraged by the elevated and highly porous bottom that stopped elongation of roots that penetrated it. Vertical roots died back (brown root tips growing through the bottom were visible) once exposed to the dry air beneath the elevated bottom which effectively root pruned them. Air pruning at the bottom appeared similar to that of at least one other container that prunes with air (Gilman et al. 2010). Inhibition of descending vertical roots induced formation of new roots or growth on existing roots close to the soil surface, and promoted growth in horizontal-oriented roots distributed throughout the root ball profile. The tremendous (49-fold, Table 6) increase in horizontal growth in 9.5 L PC was caused by a combination of 1) continued growth on existing non-deflected horizontal roots in the 3.8 L PC containers (Table 5), and 2) initiation of new horizontal roots at the flare in the 9.5 L container (Table 6). Neither of these phenomena occurred in SC containers. Mahogany trees with horizontal-oriented lateral roots close to the top surface of the root ball develop a different root system in the landscape than those with vertical and circling roots, leading to better anchorage (Gilman and Harchick 2014).

CONCLUSION

Mahogany root systems in a container can be grown with attributes associated with well-anchored landscape trees (i.e., with straight roots, some close to the surface).

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Résumé. Dans des pots de pépinière, un mauvais ancrage et une mise en place retardée ont été associés avec l'observation de racines tournantes, ascendantes et descendantes, ainsi qu'entortillées. L'objectif principal de cette étude était de trouver des méthodes de production à partir des graines de *Swietenia mahagoni* (L.) Jacq . qui produisent des racines droites non déformées. Contrairement à des pots de propagation à parois lisses (géo membranes), les racines qui poussent dans des pots de papier fin sont restées droites et très peu déformées. L'élagage des racines provenant de pots à géo membrane de 12 mois au moment de leur déplacement dans un pot de 3,8 L a considérablement réduit l'empreinte des déformations des racines sur le système racinaire. Une croissance agressive dans le fond des pots à parois lisses de 3,8 L et 9,5 L semble inhiber la croissance horizontale des racines près de la surface du substrat, et aboutit à un système racinaire orienté verticalement. En revanche, pour les arbres qui poussent dans des pots de 3,8 L et 9,5 L à parois extrêmement poreuses, un système racinaire plus orienté horizontalement a été observé, semblablement aux arbres bien ancrés dans la nature. Le développement des racines verticales a été freiné en raison du fond surélevé et poreux du pot, ce qui a obligé celles-ci à pousser de façon plus horizontale et plus haut dans le profil de la motte. Les déformations des racines ont augmenté en concordance avec le temps de rétention dans tous les pots.

Zusammenfassung. Schlechte Verankerung und verzögerte Entwicklung wurden bislang mit der Bildung von Würgewurzeln, auf- oder absteigenden sowie geknickten Wurzeln in Baumschulcontainern gebracht. Das Hauptziel dieser Studie lag darin, Methoden der Produktion von *Swietenia mahagoni* (L.) Jacq. aus Samen mit graden, undeformierten Wurzeln zu finden. Im Gegensatz zu weichen Vermehrungscontainern (SM-liner) waren die Wurzeln aus Töpfen mit dünnen Papierwänden gerade mit ein paar Windungen. Ein Wurzelschnitt bei 12-Monate alten SM-linern, wenn diese in 3,8 l Containern verpflanzt wurden, reduzierte dramatisch die Wirkung auf das verbliebene abgelenkte Wurzelsystem. Aggressives Wachstum am Boden der 3,8 l und 9,5 l weichwandigen Container schien das Wachstum horizontaler Wurzel, die dichter an der Oberfläche des Substrates wuchsen zu behindern und resultierte in einem vertikal orientiertem Wurzelsystem. Im Gegensatz dazu führte die Aufzucht der Bäume in 3,8 l und 9,5 l Containern mit außergewöhnlich porösen Wänden zur Bildung von mehr horizontal orientierten Wurzelsystemen, ähnlich wie sich Bäume in der freien Landschaft gut verankern. Vertikale Wurzeln wurden am Wachstum durch einen hochgezogenen und porösen Boden gehindert, da die Wurzeln gezwungen werden, weiter oben mehr in die Horizontale des Wurzelballens zu wachsen. Wurzelverdrehungen nahmen zu mit der Verweildauer in allen Containern.

Resumen. El anclaje pobre y el establecimiento retardado de los árboles se han asociado con raíces enrolladas, ascendentes, descendentes y estranguladoras que se producen en los contenedores de vivero. El objetivo principal de este estudio fue encontrar métodos de producción con raíces rectas no deformadas a partir de semillas de *Swietenia mahagoni* (L.) Jacq. En contraste con los contenedores de propagación de lados lisos (SM), las raíces cultivadas en macetas fabricadas con papel delgado fueron derechas con pocas deflexiones. La poda de raíces de 12 meses de edad de contenedores SM, al cambiar a recipientes de 3,8 L, redujo drásticamente la huella en el sistema de la raíz dejada por las desviaciones. El crecimiento agresivo en la parte inferior de los contenedores de lados lisos de 3,8 L y 9,5 L pareció inhibir el crecimiento de raíces horizontales más cerca de la superficie del sustrato y dio lugar a un sistema de raíces orientado verticalmente. En contraste, los árboles que crecen en contenedores con paredes excepcionalmente porosas de 3,8 L y 9,5 L, lograron un sistema de raíces orientado horizontalmente, similar a los árboles bien anclados en el paisaje. Las raíces verticales no se desarrollaron debido a un fondo elevado y poroso, obligándolas a crecer más horizontalmente y a mayor altura en el perfil de la bola del cepellón. Las deflexiones de raíz aumentaron con el tiempo de retención en todos los contenedores.

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Root System Morphology Influences Lateral Stability of *Swietenia mahagoni*

Edward F. Gilman and Chris Harchick

Abstract. Propagation containers modify root systems, which affect post-planting anchorage in reforestation efforts, but little is known about larger-sized trees typical in urban landscapes. The main goal of this study was to determine the role of root morphology on post-planting anchorage and growth on *Swietenia mahagoni* (L.) Jacq., a common landscape tree in warm climates. Two propagation container types, two larger container types, and root pruning were used to impose various root morphologies inside root balls. Anchorage was evaluated by winching trees at two bending stresses to simulate wind events. Interaction between propagation container type and root pruning when the liner was shifted into 3.8 L containers prevented either from consistently influencing anchorage. Trunk tilt (i.e., instability) immediately following pulling was greatest for trees with the most root CSA deflected by the 9.5 L container; trees with straighter main roots in the root ball were better anchored. Researchers found seven root attributes associated with trunk tilt during winching tests that evaluated anchorage. Results show that straight roots in the root ball were associated with stable trees after planting into field soil.

Key Words. Anchorage; Bending Stress; Deflected Roots; Root Depth; Stability; Straight Roots; *Swietenia mahagoni*.

Root deformations caused by deflection in the propagation container can lead to poor rooting out, resulting in unstable trees (Lindgren and Örlander 1978). For example, Scots pine (*Pinus sylvestris* L.) trees developed spiraling roots when in 75 ml propagation containers, causing them to be less stable in the soil seven to nine years after planting compared to naturally regenerated trees (Lindström et al. 2005). Other root defects, such as downward deflected roots, were later recognized as causing problems with stability following planting jack pine (*Pinus banksiana* Lamb.) (Chapman and Colombo 2006). 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), probably because of suitable air, nutrition, and water at the bottom, but the impacts on health and anchorage are poorly documented.

Selby and Seaby (1982) attributed poor anchorage of out-planted pines to a dearth of lateral support roots. The root segment growing against the container wall can suberize when retained in containers for too long, thus losing the capacity to generate secondary roots. This results in aggressive root growth primarily from the bottom of the container once planted into soil (Salonius et al. 2000). For this reason, Lindström et al. (2005) tested a stabilized or reinforced substrate that could be removed easily from the container 8–12 weeks after seed germination, thus preventing most container-induced root deflections. Burdett (1990) tested a mesh-walled container that encouraged roots to be distributed evenly along the sides of the liner root ball due to air-pruning at the bottom. A number of growers still use these today. Rooted cuttings in copper-treated containers in one representative study produced a greater percentage (40%) of roots in the top one-third of the liner compared to trees grown in untreated containers (18%); there were also more roots in the interior of the root ball and fewer on the outside forming an imprint (Smith and McCubbin 1992). Root pruning liners as they were shifted into a larger container has been associated with a substantial increase in the number of straight roots inside the root ball (Gilman et al. 2010); however, there are few studies evaluating anchorage.

Reduced anchorage of trees from nursery containers compared to trees transplanted from a field nursery is attributable to a combination of root deflection in the containers, less root ball mass, and low root ball soil strength due to voids created by decomposition of the organic substrate typical of container-grown trees (Gilman and Masters 2010; Gilman et al. 2013). Although relative contribution was not assigned to each of these three attributes, previous models developed in forest stands suggest that root-soil plate depth, shape, and mass were responsible for a significant (13%–45%) portion of overturning resistance (Coutts 1983; Ennos 1995). Roots growing in the windward direction (Stokes 1999) and the location of the rotation axis (hinge point), among other factors, also contribute (Fourcaud et al. 2008).

Though advances have been made in describing anchorage mechanics on trees planted from small propagation-sized root balls typical of plantations, few studies have been performed on trees planted from the much larger root balls typical in urban landscapes. The strategy of growing roots radially away from the base of the trunk, instead of deflecting down, up, or around, appears well-suited for binding together a large mass of soil and roots into a root-soil plate that resists overturning (Gilman et al. 2010b; Gilman et al. 2013). Root diameter decreases suddenly at the transition point of one container to the next larger size because roots that grow beyond the deflection point are typically much smaller in diameter than the deflected root (Gilman and Paz 2013). Sudden reductions in root diameter from root deflections (Gilman and Masters 2010) and at branch points (Coutts 1983) are a source of leeward hinge points in root-soil plates when trunks are subject to lateral forces such as winching or wind. Stability may be improved by reducing these deflections inside the root ball, and planting root balls containing a large number of roots that either stop elongating or branch once they meet the container wall.

Because straight lateral roots appear to be associated with well-anchored trees planted from propagation containers (Salonius et al. 2000), the main goal of the present study was to determine the influence of root form in a container root ball on root attributes and anchorage one growing season after planting into landscape soil. *Swietenia mahagoni* (L.) Jacq. (mahogany) was chosen due to its popularity as urban landscape trees in tropical and subtropical regions of Florida, U.S., and the Caribbean.

MATERIALS AND METHODS

February 2009 seeds of *Swietenia mahagoni* were germinated in two propagation containers with different wall attributes (EP = Elle pots or SM = smooth-sided) and retained for 12 months (as described in Gilman and Paz 2014). Root balls on 80 trees from each propagation container were root pruned (shaved) as they were shifted in February 2010 into 3.8 L containers with different wall attributes (SC = smooth-sided black plastic, 19 cm top diameter × 19 cm tall, model PF400, Nursery Supplies, Chambersburg, Pennsylvania, 40 trees; and PC = black plastic container with porous sides and bottom, Pioneer pot®, 19 cm top diameter × 17 cm tall, Pioneer Farms, Visalia, California, U.S., 40 trees) by removing the outer 5 mm of the liner root ball sides and bottom with sharp scissors (Fiskars, #FSK01004342). Roots were pruned by one person to standardize procedure. Remaining 80 trees from each were not root pruned when shifted into the SC (40 trees) and PC (40 trees) containers. In August 2010, trees in SC and PC were shifted into larger-sized 9.5 L containers of the same type (SC, model PF1200, 27 cm top diameter × 24 cm deep; PC, 28 cm top diameter × 17 cm deep) and placed on ground cloth randomly in rows.

In April 2011, 10 randomly chosen trees of each treatment combination (two liners × two root pruning treatments × two 3.8 L then 9.5 L containers × 10 trees = 80 trees) were planted into field soil [Millhopper fine sand (loamy, silicaceous, hyperthermic Grossarenic *Paleudults*)] with less than 2% organic matter) in Gainesville, Florida. Trunk diameter (mean = 14 mm) and tree height (mean = 111 cm) were recorded at planting. Top of the root ball was positioned even with surrounding soil, and trees were placed 0.9 m apart within three rows spaced 2 m apart. Some main roots emerged from the trunk base within 1 cm of the substrate surface. No root manipulation was performed at planting. One tree from each treatment combination was randomly assigned to a block of eight trees for a total of 10 blocks. A 0.5 m diameter circular soil area around each tree was irrigated with 8 L through a Roberts spray stake (Model SS-AG160BLK-100), which was divided into three daily applications to encourage rapid growth. Fertilizer (20 N, 0 P_2O_5, 8 K_2O; 65 g in April, 120 g in June and August 2011) was applied to a 50 cm diameter circular area around each tree. Shoots were not pruned at or after planting. A wood chip (utility pruning waste) mulch layer 10 cm thick was placed across the whole plot, almost up to the trunk, and glyphosate was applied periodically for weed control.

In November 2011, all 80 trees were winched with a hand crank that was crafted of a bent steel rod to evaluate lateral stability. No rain occurred during the three days required to pull trees. A force transducer (Model SSM-BYJ-50, 22.7 Kg, Interface Scottsdale, Arizona, U.S., non-repeatability—±0.02% RO) was placed in line with a non-stretch string secured around the tree with a tightened zip tie at 20 cm from the ground. Trees were pulled at a rate of approximately 10 mm·sec^{-1} once in the NE, NW, SE, and SW compass directions to a bending stress (σ) of 4.1 MN/m^2 calculated individually for each tree from trunk diameter measured 10 cm from the ground using Equation 1. This slow, winching rate allowed researchers to pull at the targeted bending stress. This bending stress was chosen so that the trunk nearly returned to the pre-pulling start angle following practice winching, on extra trees from the same group planted nearby, indicating slight root or soil failure. During winching tests, load was sampled at 2 Hz using a 16-bit data acquisition system (National Instruments Corporation, Austin, Texas, U.S.) and displayed and archived in real-time on the laptop running LabView software (v: 7.0; National Instruments, Austin, Texas, U.S.). Trunk angle was recorded just prior to each winching by placing a digital level (18 cm long, M-D SmartTool Angle Sensor Module 92346) accurate to the tenth of a degree on the bottom 18 cm of trunk on the side opposite the hand crank (windward). A fifth and final winching to the SW applied a bending stress of 13.8 MN/m^2. With the tree held in position after each of the five winchings, the angle under tension and the rest angle following release of the winching string were recorded. The pre-winching trunk angle was subtracted from these angles to calculate change in angle as a result of winching.

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

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).

All 80 trees were dug up in December 2011 following winching, using a square-tipped shovel forming a circular root ball 40 cm across and 40 cm deep shaped in a cone typical of a tree dug from a field nursery. This shape and volume was large enough to harvest the planted 9.5 L container root ball intact. Soil and container substrate were washed from roots. Roots were measured for many attributes described in the appropriate tables. Root diameter was measured to 0.1 mm; root depth was measured to the nearest mm.

Statistical Analysis

Root and shoot attributes and bending stress on planted trees in December 2011 were analyzed in a three-way complete factorial analysis of variance (ANOVA) with the main effects propagation container type (2), root pruning (2), and larger-container wall attributes (2) using 10 replicates each (total 80 trees) in a randomized complete block design using the GLM procedure of SAS (version 9.2 SAS Institute, Cary, North Carolina, U.S.). Duncan's multiple range test was used to separate main effect means; interaction means were compared with Least Squares (LS) means at $P < 0.05$. Pearson's correlation coefficient was used to relate root attributes to bending stress.

RESULTS AND DISCUSSION

Root pruning liners, when shifting into 3.8 L containers, did not impact aboveground growth after landscape planting; however, two measured root attributes were affected. Shaving liners increased cross-sectional area (CSA, calculated from diameter measured just beyond trunk) of straight roots equally for both propagation containers (Table 1). Shaving liners grown in EP had no influence on CSA of deflected roots because there were few deflected roots to remove (Gilman and Paz 2014); however, shaving SM liners dramatically reduced deflected root CSA compared to not shaving (Table 1) as with red maple (*Acer rubrum* L., Gilman et al. 2012). Reported effects on crown growth from manual root pruning of trees planted from propagation containers into field soil vary in the literature. Some authors found reduced crown growth (Arnold and Young 1991), no effect (Persson 1978; Gilman and Wiese 2012), or greater growth (Krasowski and Owens 2000) following root pruning at planting. Although trunk angle during winching was not impacted by root pruning the liner in the current study (data not shown), anchorage on other species has been compromised when roots deformed from growing in propagation containers were not corrected at planting (Sibley and Seaby 1982; Balisky et al. 1995). Deflections down or around the propagation container in the current study may not have been severe enough to influence stability because trees were retained in propagation containers for only 12 months. Some nurseries retain trees longer.

Although trunk diameter increased in the landscape most for trees propagated in EP and then shifted to PC, the 3–4 mm difference might be imperceptible (Table 2). There was also no tree height response due to liner or larger container wall attributes (data not shown), indicating little impact on growth for the first seven months after landscape planting from root form imposed by containers.

Trunk angle during winching in the initial direction (NE) at 4.1 MN/m^2 was not different among treatments; however, trunk rest angle following winching was greatest (least stable, 0.7 degrees) for the treatment combination with the most root CSA (653 mm^2, which was about 2 to 15 times greater than other treatments) deflected by the 9.5 L container (i.e., those grown in EP liners then shifted to SC containers, Table 2). This was likely due to roots dislodging permanently within the root ball, and could be explained by EP containers sending roots more laterally (44 degrees from horizontal, Table 3) than downward (52 degrees for SM), forcing more to grow into the 9.5 L sidewall. This was also described for red maple (Gilman et al. 2012), implying that a liner with a desirable root system shifted to a larger container with smooth walls resulted in a poor 9.5 L root system. In contrast, the large imprint resulting from deflection by the SM liner (3.2, Table 3) appeared to have a lesser impact on anchorage because root CSA deflected by liner was about 5 times greater (487 mm^2, or 30% of the CSA in the five largest roots, Table 2) in the SM/SC treatment combination than all others (which had ≤7% deflected) with no difference in winching-trunk angle. The new roots initiated near the flare after liners were shifted to larger containers (Gilman and Paz 2014; Figure 1) helped trees overcome the potential instability associated with the large deflections that occurred within the liner.

Table 1. Interaction of propagation container with root pruning on CSA of straight and deflected roots seven months after planting from 9.5 L containers.

Propagation container (liner)	Root prune[z]	CSA of straight roots[y] (mm^2)	CSA (% total CSA) of roots that were both deflected > 60 degrees by liner and among the 5 largest (mm^2, %)
EP	None	812 b[x]	72 (5) b
	Shaved	982 a	72 (6) b
SM	None	721 b	402 (24) a
	Shaved	852 a	158 (11) b

[z] Liners were root pruned by removing the peripheral 5 mm (shaved) with sharp scissors, or not, as they were shifted into 3.8 L containers.
[y] Straight roots were those >3 mm diameter (measured at the edge of the dug root ball) that grew from trunk into field soil (following the largest at forks) at <45 degree angle to the soil surface without making a turn >60 degrees relative to azimuth of the parent root at trunk. CSA calculated from diameter measured just beyond trunk.
[x] Means in a column with a different letter were statistically different at $P < 0.05$; n = 18 averaged across 3.8 L and 9.5 L containers; no interactions with 3.8 L and 9.5 L containers were significant for these two attributes.

Table 2. Interaction of propagation container with 3.8 and 9.5 L container on trunk rest angle, trunk diameter, and selected root attributes on trees planted 7 months earlier.

Propagation container (liner)	3.8 L and 9.5 L container[z]	Trunk rest angle[y] after applying 4.1 MN/m^2 NE (degrees)	Trunk diameter 10 cm from ground when winched (mm)	Trunk diameter increase after field planting (mm)	End minus start angle of the five largest roots[x] (degrees)	CSA in the five largest roots deflected by 9.5 L container[w] (mm^2)	% total CSA in the five largest roots deflected by liner (%)
EP	PC	0.3 b[v]	28.3 a	16.3 a	13.6 a	43 c	4 b
	SC	0.7 a	28.3 a	12.8 b	-18.4 c	653 a	7 b
SM	PC	0.3 b	25.1 b	12.1 b	1.5 ab	55 c	6 b
	SC	0.4 b	29.0 a	12.5 b	-6.7 bc	352 b	30 a

[z] Trees were shifted from liners into 3.8 L and then into 9.5 L containers.
[y] Angle of trunk base relative to vertical start position immediately following release of winching cable pulled toward the northeast.
[x] End angle = angle from horizontal measured on the terminal 5 cm long root segment at dug root ball edge of the five largest roots (measured at trunk) following the largest at forks minus angle of the 5 cm long segment starting at trunk; negative number indicates roots grew up into substrate of the 3.8 L and 9.5 L container.
[w] Total CSA of roots that were among the five largest-diameter roots (measured at trunk) and were deflected by 9.5 L container walls.
[v] Means in a column with a different letter were statistically different at $P < 0.05$; n = 18 averaged across root pruning when shifting liners to 3.8 L containers; no interactions with root pruning were significant for these two attributes.