Research Reports

Effect of Container Type on Root Form and Growth of Red Maple[1]

Edward F. Gilman, Chris Harchick and Maria Paz[2]
Environmental Horticulture Department
University of Florida, Gainesville, FL 32611

Abstract

The study was designed to evaluate impacts of #3 container wall attributes on root morphology. Trunk diameter of 'Florida Flame' red maples (*Acer rubrum* L.) growing in smooth-sided containers was no different than for any other container type. Trees in Smart Pot® grew more in height than trees in Florida Cool Ring™. Only trees in smooth-sided containers had roots 100% around the top of containers. As a result all 9 trees excavated from smooth-sided containers were graded a cull according to Florida Grades and Standards for Nursery Stock. Trees in smooth-side pots had lesser root ball quality rating than all other container types except RootMaker®, but trees in Jackpot™ had a higher quality rating than those in smooth-sided and RootMaker® pots. No container reduced length of descending, ascending, or kinked roots compared to smooth-sided containers. RootBuilder® had fewer descending roots than Jackpot™. RootMaker® developed more roots growing up the container wall than any other container except smooth-sided. Diameter of the 5 largest roots emerging from the trunk was smaller in Jackpot™ than smooth-sided, RootBuilder®, RootMaker®, and Smart Pot® containers. RootMaker® had larger diameter peripheral roots than Fanntun pot, Jackpot™ and Smart Pot®. Jackpot™ had smaller diameter peripheral roots than smooth-sided and Smart Pot®. A higher percentage of the largest 5 roots branched as they met the container wall in Smart Pot®, RootBuilder®, and Fanntum Pot compared to smooth-sided. A larger percentage of the 5 largest roots circled in the RootMaker® than in Air-Pot™, Florida Cool Ring™, and Jackpot™.

Index words: circling roots, descending roots, kinked roots, root defects.

Significance to the Nursery Industry

With a growing number of trees produced in plastic and fabric containers there is a new focus on root system quality. We tested impacts of container wall configuration on root morphology of red maple growing in #3 containers for 7 months. Finished trees were slightly smaller than the maximum size recommended for container volume. Caliper and height were affected only marginally by container type. Circling and descending roots were the most common defects on root systems in all container types. Smooth-sided black plastic containers were associated with the most defects. The seven other containers tested reduced circling and descending roots to varying degrees. Defects were common on the cooler north and east periphery of root balls, rarely on the south and west presumably due to high container wall and substrate temperature from direct sun exposure. No one container type stood out as unique in reducing root defects. Mechanical root pruning may be needed to reduce defects to an acceptable level.

[1]Received for publication June 25, 2009; in revised form August 7, 2009. Acknowledgements: GreatSouthernTreeConference.org funded this project.

[2]Professor <egilman@ufl.edu>, Farm Manager, and Biologist, resp.

The *Journal of Environmental Horticulture* (ISSN 0738-2898) is published quarterly in March, June, September, and December by the Horticultural Research Institute, 1000 Vermont Avenue, NW, Suite 300, Washington, DC 20005. Subscription rate is $75.00 per year for scientists, educators and ANLA members; $120.00 per year for libraries and all others; add $25.00 for international (including Canada and Mexico) orders. Periodical postage paid at Washington, DC, and at additional mailing offices. POSTMASTER: Send address changes to Journal of Environmental Horticulture, 1000 Vermont Avenue, NW, Suite 300, Washington, DC 20005.

Introduction

Trees grown in containers develop root systems that are different from trees grown by other nursery production methods. Instead of spreading to their natural distance (37, 41) roots on shade trees are deflected up, down, or around by container walls (17), and this can affect how roots grow out into landscape soils (22). Roots growing away from the trunk can also be deflected 180 degrees and grow back to and close to the trunk forming a root kink (11). Root systems on trees planted from containers also have more constricted, circling, and kinked roots. Naturally regenerated seedlings had greater sinker root development, and possessed self-grafted roots (15).

Root deformation occurs even before trees root in enough to lift out of a container (7), and these can persist to cause instability many years later. Many studies on conifer seedlings show that root deflection in small containers can contribute to long-term growth problems after planting in the forest (27). Plants grown in standard black plastic containers for too long often have deformed roots which are kinked or grow along sides or bottom of the root ball. Many alternative container types were designed to reduce formation of deformed roots. These typically utilize one or more of the following: air root pruning technology, specialized container shapes, bottomless containers, woven or non-woven fabrics, mechanical deflection, or chemical manipulation (9, 20).

The type of nursery container used during production can impact root morphology (3, 12). Copper compounds applied to the interior surface of plastic containers reduce root deflection on many woody species (39) and caused an increase (8), decrease (6) or no effect (23) on root:shoot ratio. Roots in porous-walled plastic containers stop growing when they reach the container wall-substrate interface (30); however authors did not report for how long. This results in less root circling compared to non-manipulated roots systems grown in standard smooth-sided containers (12, 22). Roots in square plastic (40) or wood (22) containers had less circling roots than in standard round plastic containers.

Container dimensions, size, and container surface porosity can change root morphology for the better (3, 22, 38). *Pinus radiata* D. Don seedlings in air-pruning 5 cm (2 in) diameter containers had less packed roots, less spiraling roots, and fewer L-shaped roots (28). Authors noted that tree seedlings in air-pruning containers produced less root defects than those grown in solid-walled containers, but also had slower root and canopy growth due to lateral air-pruning (28).

Young hardwood liners raised in alternative containers and transplanted to field soils produced either more (3, 9) or the same amount (9) of roots as trees raised in standard containers. Root and canopy growth were similar among #15 container types five months (22) and five years (13) after landscape planting.

Container grown trees planted in a nursery or landscape sometimes develop lateral roots on only two or three sides on the plant (18). This can lead to uneven root distribution in the landscape (31). Marler and Davies (21) reported that root circling and kinks on container grown citrus (*Citrus*) were responsible for uneven root development following planting. Roots that do not grow directly away from the trunk because they are deflected by container wall can lead to tree instability (19).

Many container types currently on the market have characteristics that are quite different from those of even ten years ago. Therefore objectives of this experiment were to determine influence of #3 container design on root system morphology and top growth in the nursery.

Materials and Methods

In April 2008, 384 'Florida Flame' *Acer rubrum* L. liners [18 cm (7 in) tall] on their own roots were planted from 5.1 cm (2 in) diameter × 13 cm (5 in) tall ribbed containers (38 Groovetube, Growing Systems, Inc., Milwaukee, WI) into eight different #3 container types with liner substrate surface even with substrate in #3 containers. No roots were pruned at planting. Container types tested were smooth-sided black plastic (Nursery Supplies, Inc., Chambersburg, PA), Smart Pot® black non-woven fabric (Root Control, Inc., Oklahoma City, OK), RootMaker® and RootBuilder® black plastic (Rootmaker® Products Company, LLC, Huntsville, AL), Fanntum Pot woven green plastic cloth (Fanntum Products, Inc, Statesville, NC), Florida Cool Ring™ woven black plastic cloth (The Florida Cool Ring Company, Lakeland, FL), Superoots® Air-Pot™ black plastic (Caledonian Tree Company, Ltd., Scotland), or Jackpot™ black non-woven cloth (Legacy Nursery Products, LLC, Palm City, FL). Containers were in full-day sun pot to pot within rows and rows were 75 cm (2.5 ft) apart on a woven black nursery ground cloth.

Substrate was 20:60:20 (New Florida peat:pine bark:sand, by vol) for RootMaker®, RootBuilder®, Fanntum Pot, Florida Cool Ring™ and Jackpot™ , and 50:40:10 (New Florida peat:pine bark:sand) for Air-Pot™, Smart Pot® and smooth-sided. New Florida peat is a compost of Florida peat and hardwood fines (Florida Potting Soil, Inc.) as recommended by each manufacturer. Substrates were recommended by the container manufacturers and are considered an integral part of the growing systems. Volume of substrate in each container was 11.4 liter (3 gal) except in Jackpot™ which was about 15% smaller (container had a smaller diameter) in volume than others. This volume filled the smooth-sided pot to the top rim, but was below the rim for other container types. Jackpot™ was also filled to the rim. Fertilizer (18-5-10 controlled release, Harrells, Inc., Lakeland, FL) was incorporated into substrate prior to planting at (18 $lbs \cdot yd^{-3}$), and no other fertilizer was applied. Trees were irrigated 3 times daily totaling 3.8 liters (1 gal), trunks were staked straight in May 2008, and trees pruned to a central leader by reducing competing branch length twice during the growing season. Weeds were periodically pulled from container substrate. No trees rooted out of pots and into the ground.

Eight trees (one tree in each container type) were placed into each of 48 blocks for a total of 384 trees in a randomized complete block design. Trunk diameters at 15 cm (6 in) above substrate surface (caliper) and tree heights were collected in October 2008 on all trees. Substrate on all 8 trees in each of nine randomly chosen blocks was washed with water from root balls November 2008. Roots were measured in a variety of ways following removal of all substrate (Table 1). Data were analyzed using one-way ANOVA with container type as the main fixed effect in a randomized complete block design in the GLM procedure of SAS (33). Duncan's multiple range test was used to separate means at $P < 0.05$. The GENMOD procedure in SAS (33) was used on non-parametric data. Percentage data were not arcsin transformed prior to analysis because data had equal variances and the residuals were normally distributed. Means were separated with Tukey's HSD test at $P < 0.05$.

Table 1. Measurements and ratings collected on roots > 2 mm diameter in the root ball of 8 (#3 size) different container types.

Data shown in Table 2

- Distance from substrate surface to point where top-most (first) root emerged from trunk.
- Substrate rating (5 = substrate holds together well when container is removed, 1 = substrate is loose so ball falls apart when removed from container).
- Root ball quality rating (5 = highest quality with few roots growing along periphery of root ball, 1 = lowest quality with many deflected roots down, up, or around the periphery of root ball).
- Root mat rating (5 = little root matting at container bottom, 1 = heavy matting at bottom).
- Cull (at #3 container position) or not according to Florida Grades and Standards for Nursery Stock (Anonymous 1998). A cull has a root larger than 1/10 trunk diameter in the top half of root ball circling more than 1/3 way around trunk.
- Visible root defect rating (Y = circling, descending, and/or ascending roots visible on root ball periphery prior to removing substrate, N = no defects visible).

Data shown in Table 3

- Circling root length = length of roots in the peripheral 2.5 cm growing around container wall after making a 90 to 120 degree turn at container wall and positioned at less than 45 degree angle from horizontal.
- Descending root length = length of roots in the peripheral 2.5 cm growing around or down container wall at more than 45 degree angle from horizontal.
- Kinked root length = length of roots after making more than a 120 degree turn when meeting the container wall so they grow across root ball surface.
- Ascending root length = length of roots in the peripheral 2.5 cm growing up at more than a 45 degree angle from horizontal.
- Total root length = length of roots in the peripheral 2.5 cm of the root ball growing in any direction.
- Circle root percentage = percent of root ball circumference (top half of ball only) with roots growing around in a circle in the peripheral 2.5 cm of #3 root ball at less than 45 degree angle to horizontal.

Data shown in Table 4

- Mean diameter of the 5 largest roots measured 5.1 cm behind root ball periphery prior to deflection by container wall.
- Mean diameter of the 5 largest roots measured in the peripheral 2.5 cm of root ball after deflection by container wall.
- Percent of the 5 largest roots emerging from trunk that branched into at least two roots > 2 mm diameter at container wall (branched).
- Percent of the 5 largest roots emerging from trunk that circled at container wall.
- Percent of the 5 largest roots emerging from trunk that descended at container wall.
- Percent of the 5 largest roots emerging from trunk that ascended at container wall.
- Percent of the 5 largest roots emerging from trunk that kinked at container wall.

Results and Discussion

Caliper on red maples growing in smooth-sided #3 containers was no different than for any other container type (Table 2). However, trees in RootMaker® pots produced larger caliper and height than trees in either Jackpot™ or Florida Cool Ring™, and trees in RootBuilder® and Smart Pot® grew more caliper than trees in Jackpot™. Jackpot™ had 15% less substrate than other containers which may have accounted for smaller caliper. Trees in Smart Pot® grew more in height than trees in Florida Cool Ring™. There were no other differences in caliper or height among container types.

Only trees (4 of 9 excavated) in smooth-sided containers had roots 100% around top of the container (data not shown). No other container type grew trees with circling roots 100% around the container. Roots that circled 100% were almost always at the substrate surface. Perhaps the substrate surface could support root growth because it was a bit cooler than the substrate along the container wall (24).

Distance between substrate surface and origin of top-most root growing from stem base differed among container types (Table 2). Roots in smooth-sided, Florida Cool Ring™, RootMaker® and Smart Pot® emerged at or close to substrate surface; whereas, others emerged deeper in the substrate.

Trees in smooth-side pots had lesser root ball quality rating than all other container types except RootMaker® (Table 2). Trees in Jackpot™ had a higher quality rating than those in smooth-sided and RootMaker® pots. Despite some differences in root quality rating, roots matted similarly at the bottom of all containers (Table 2). Root balls in Jackpot™ were held together loosely (lower substrate rating) compared to Air-Pot™, RootBuilder®, Root Maker®, and Smart Pot® which had a higher substrate rating (Table 2). One reason for this was that unlike other containers, roots on root ball periphery of Jackpot™ were embedded into the fabric and some were torn off as fabric was peeled from the root ball. Fabric was more difficult to remove from Jackpot™ and hence appeared to remove more roots from the ball than from

Table 2. Caliper, height and root ratings for red maple grown in 8 (#3 size) different container types for 7 months.

Container type	Caliper (mm)	Height (m)	Distance to first root[z] (cm)	Substrate rating[z]	Root ball quality rating[z]	Root mat rating[z]	Percent trees graded a cull[z]	Percent trees with visible root defects[z]
Smooth-sided	19.2abc[y]	2.3ab	0b	4.1abc	1.4c	3.2	100a	100a
Air-Pot™	19.9abc	2.2abc	58a	4.7a	4.1a	3.6	33b	89ab
Fanntum Pot	18.7abc	2.2abc	37a	3.6abc	3.2ab	3.8	44b	89ab
Florida Cool Ring™	17.5bc	2.0c	33ab	3.4bc	3.1ab	3.0	56ab	100a
Jackpot™	16.4c	2.1bc	51a	3.2c	3.9a	4.8	22b	89ab
RootBuilder®	20.4ab	2.3ab	57a	4.7a	3.4ab	3.3	56ab	63b
RootMaker®	20.8a	2.4a	0b	4.7a	2.5bc	3.9	56ab	100a
Smart Pot®	19.9ab	2.3ab	32ab	4.4ab	3.0ab	4.0	67ab	100a

[z]See Table 1 for heading description.

[y]Means in a column followed by different letters are statistically different at $P < 0.05$.

Table 3. **Length of roots > 2 mm diameter growing on periphery of root ball of red maple grown in 8 (#3 size) different container types for 7 months.**

Container type	Circling[z] root length (mm)	Descending[z] root length (mm)	Ascending[z] root length (mm)	Kinked[z] root length (mm)	Total root length[y] (mm)	Circling root percentage[z,x] (%)
Smooth-sided	1530a[w]	502ab	116ab	68	2215a	85a
Air-Pot™	563cd	558ab	38b	94	1253b	30b
Fanntum Pot	1008bc	352ab	31b	211	1601ab	41b
Florida Cool Ring™	859bc	458ab	0b	106	1422b	29b
Jackpot™	336d	669a	34b	81	1120b	30b
RootBuilder®	874bc	298b	59b	77	1309b	29b
RootMaker®	1052b	388ab	217a	108	1765ab	47b
Smart Pot®	940bc	334b	62b	105	1442b	51b

[z]See Table 1 for heading description.

[y]Total length of roots > 2 mm diameter growing on peripheral 2.5 cm (not including bottom) of root ball.

[x]Percent of root ball circumference with circling roots.

[w]Means in a column followed by different letters are statistically different at $P < 0.05$.

Smart Pot® despite the apparent similarity of fabric. This probably explains why substrate rating for Smart Pot® was similar to that for smooth-sided containers.

All 9 trees excavated from smooth-sided containers were graded as culls (Table 2) according to Florida Grades and Standards for Nursery Stock (1). This was an indication of circling and kinked root severity around the edge of #3 containers. Air-Pot™, Fanntum Pot, and Jackpot™ had the lowest cull rating, and all three had fewer culls than trees in smooth-sided pots. Air-Pot™ and Jackpot™ also had the least circling root length, although all container types had less circling root length than smooth-sided containers (Table 3). Smooth-sided containers had a larger percentage of circumference with circling roots on top halves of the root balls than all other containers, and all other containers had a similar percentage.

No container reduced length of descending, ascending, or kinked roots compared to smooth-sided, but some containers performed better than others (Table 3). RootBuilder® had fewer descending roots than Jackpot™. RootMaker® developed more roots growing up the container wall (ascending) than any other container except smooth-sided. This appeared to result from roots redirecting at crevices in RootMaker® wall. Total length of roots growing on the periphery of root balls in Air-Pot™, Florida Cool Ring™, Jackpot™, RootBuilder® and Smart Pot® was less than in smooth-sided pots (Table 3). Root length on the periphery of Fanntum Pot and RootMaker® was similar to smooth-sided.

Diameter of the 5 largest roots emerging from the trunk was smaller in Jackpot™ than smooth-sided, RootBuilder®, RootMaker®, and Smart Pot® containers (Table 4). All containers except Jackpot™ had similar root diameter as smooth-sided. There were no other differences in lateral root diameter among container types. Diameter of roots growing on root ball periphery after they were deflected differed among container types (Table 2). RootMaker® had larger diameter peripheral roots than Fanntun pot, Jackpot™ and Smart Pot®. Jackpot™ had smaller diameter peripheral roots than smooth-sided and Smart Pot®.

A higher percentage of the largest 5 roots branched as they met the container wall in Smart Pot®, RootBuilder®, and Fanntum Pot compared to smooth-sided containers (Table 4). Roots in the four remaining container types did not branch more than smooth-sided pots; instead they deflected down or around the wall. A larger percentage of the 5 largest roots circled in RootMaker® than in Air-Pot™, Florida Cool Ring™, and Jackpot™; however, no containers resulted in more or less circling than smooth-sided pots. RootMaker® had fewer of the largest diameter roots descending down the side of container wall than Jackpot™ and Florida Cool

Table 4. **Form of the 5 largest lateral roots of red maple grown in 8 (#3 size) different container types for 7 months.**

Container type	Diameter of five largest roots inside[z] (mm)	Diameter of five largest roots on periphery[y] (mm)	Percent of the 5 largest roots reaching the container wall that:				
			branch[x]	circle[x]	descend[x]	ascend[x]	kink[x]
Smooth-sided	6.0a[w]	4.5ab[v]	23.5d[v]	31.1ab[v]	37.3abc[v]	8.1	0.0
Air-Pot™	5.4ab	3.7abc	36.0abcd	21.2b	37.6abc	5.3	0.0
Fanntum Pot	5.6ab	3.5bc	39.3abc	29.0ab	27.7bc	2.1	1.9
Florida Cool Ring™	6.0ab	3.9abc	28.3cd	23.3b	38.4ab	0.0	10.0
Jackpot™	4.6b	3.0c	27.3cd	20.1b	46.3a	4.4	1.9
RootBuilder®	6.3a	3.9abc	40.8ab	26.9ab	21.2bc	7.6	3.4
RootMaker®	6.0a	4.9a	31.1bcd	41.2a	19.8c	7.1	0.7
Smart Pot®	6.0a	3.3bc	44.4a	25.5ab	23.5bc	3.6	3.1

[z]Diameter of the 5 largest roots emerging from trunk measured 5.1 cm (2 in) behind root ball periphery.

[y]Diameter of the 5 largest roots growing in the peripheral 2.5 cm of root ball after deflection.

[x]See Table 1 for heading description.

[w]Means in a column followed by different letters are statistically different at $P < 0.10$. No difference at $P < 0.05$.

[v]Means in a column followed by different letters are statistically different at $P < 0.05$.

Ring™. There were no differences in percent of the largest 5 roots growing up the container wall (ascending) or kinked back toward the trunk among container types.

Although root mass was not measured, all root balls appeared to have ample fine root development without noticeable differences among container types. Excepting copper treated containers, others have shown few differences in tree root mass among container types (22) including RootBuilder® (20) or RootMaker® (29), and smooth-sided. Although substrate differences do not appear to impact root defects at the root ball periphery (4), results reported in the current study might be different with different substrates. Results might also have been different if trees remained in containers for a longer period of time.

Roots from original liners grew out the bottom, sides, and top of the liner root ball to fill substrate in the #3 containers. Occasionally roots circled liner container walls; more commonly roots grew down or up container walls. Roots growing down the side of original liner root ball either continued to grow down after planting into #3 containers or they were deflected up the side of original liner wall prior to planting. Salonius (34) and Lindstrom and Rune (19) describe both these forms as a serious root defect resulting in unstable, failure-prone conifers. Some roots that grew up the liner wall crossed over top of the root ball tangent to the trunk. Some of these potential stem girdling roots were touching the trunks 7 months after planting into #3 containers, although none were embedded into the trunk. This can be reduced in other species by growing trees in liner pots that prevent or reduce defects (28), removing trees earlier (16, 34), or mechanical root pruning at planting (3, 7). Eliminating these roots should be the focus of additional research for a variety of temperate and tropical species.

Although we did not separate roots by compass direction, there were clearly more roots > 2 mm diameter deflected down, around, or occasionally up by #3 container walls on the cooler north and east sides (24) than in other directions. High substrate temperatures are known to cause root death especially on the sunnier, hotter container side (i.e. south and west side in northern hemisphere, 29, 31). Container temperatures are cooler in winter than summer (24) so results could have been different if this test was conducted throughout winter. Roots may have grown back during winter on south and west sides due to cooler temperature at root ball periphery.

The small difference in caliper among container types in the current study was not surprising (Table 2). Marshall and Gilman (22) in Florida also found no difference in red maple caliper and height growth in 7 container (#15 size) types. Owen (29) in Oregon found no difference in red maple or honeylocust (*Gleditsia triacanthos* L.) height among 5 container (#3 size) types. Owen (29) found 10% more caliper growth in Air-Pot™, Accelerator® and smooth-sided pots compared to Smart Pot®; however, Smart Pot® in the current study had the same caliper as trees in these 3 (#3 size) container types. Neal (26) in New Hampshire also found few growth differences among various container growing systems. It appears safe to conclude that trees grow about the same caliper and height in most container types given adequate water and nutrient management.

Differences in distance from substrate surface to first root among container types are inexplicable and may have been an artifact (Table 2). Although air-pruning and copper treated containers (35) have been associated with increased lateral root growth close to substrate surface in liners compared to smooth-sided pots, this has not been reported in the much larger #3 sized containers used in the current study. In addition, there appears to be nothing in common among the four container types that had deepest roots.

Both smooth-sided and RootMaker® pots are nearly solid plastic except that RootMaker® has a crevice and small holes at three levels along the wall. This similarity in attributes may explain the similarity in root system quality rating for these two container designs in the current study (Table 2). RootMaker® and smooth-side pots had similar root length growing up the wall of #3 containers (Table 3) resulting in what has been called a 'J' root defect. Trees with this root defect in liner-sized [5 cm (2 in)] containers are less stable after planting than trees with lateral roots growing straight out from the trunk (10). It is not known if this causes stability problems in the larger containers tested in the current study. Further work in this area is certainly warranted.

Arnold and McDonald (4) showed that Smart Pot™ dramatically reduced (by a factor of five) the amount of rose roots at periphery of the root ball compared to smooth-sided containers. Marler and Willis (20) said (no data were presented) that there were fewer circling roots on trees in RootBuilder® than smooth-sided for two tropical species. Moore (25) found that many Australian tree types grown in 20 cm (8 in) diameter Air-Pot™ had far fewer circling roots than smooth-sided containers 8 months after potting. Owen (29) noted circling roots in all container types tested including some in the current study. Red maple in Air-Pot™ for 14 months (14) and in other pots for 15 months (22) eventually develop circling and descending roots, even prior to growing too large for the container (2). Circling roots have been associated with tree instability (19) and growth reductions in forest plantings 12 or more years after planting (15). Although all container types tested in the current study reduced circling root length by about one-third compared to smooth-sided, circling root length still represented about half of the total root length (roots > 2 mm diameter) growing on periphery of the root ball (Table 3). This should be further reduced mechanically (14) to improve quality of root systems.

Roots that quickly reach the container wall and continue to grow after deflection may be in a different physiological state than roots that were slowed or stopped at the wall. Secondary roots growing from air-, copper-, and fabric-pruned lateral roots emerge from behind the root tip (39) and probably meet the periphery days or weeks after lateral roots from smooth-sided containers. Instead of growing along the periphery, some of these secondary roots may also be pruned resulting in perhaps secondary and tertiary roots eventually growing along the periphery (6). The result is some roots on the periphery of many container types may be younger in age that those in smooth-sided pots. Salonius et al. (34), South and Mitchell (36), and others found that older root tissue on the periphery of 5 cm (2 in) diameter containers (liner trays) becomes suberized and generates fewer new roots into field soils compared to younger juvenile root tissue. We do not know if this suberization and reduced root growth potential of older roots occurs on the periphery of larger (#3 and up) containers.

All containers reduced circling roots (> 2 mm diameter) compared to smooth-sided pots (Table 3) which others have shown. All except smooth-sided are designed to introduce air into substrate through the container wall. This allows more water to evaporate from the substrate periphery which may dry and cool the substrate near the periphery (5, 29). However, irrigation 3 times daily prevented substrates from drying in the current study. Roots on the south and west sides of most root balls of all container types appeared smaller in diameter, were more highly branched, and were oriented mostly radially away from the trunk, not circled or descending on the periphery. Some substrate peripheral drying from air intrusion through walls (4) combined with high temperatures (29, 32) could have caused this branching and reduction in defects on the hot side of root balls. The less branched root system with more defects on the cooler side may have resulted from lack of substrate drying and substrate cooling which allowed roots to grow down or around the root ball periphery without branching. Perhaps heat can be used to reduce root defects by killing young roots growing along the periphery by periodically turning containers.

In addition to air intrusion through the wall, fabrics in Smart Pot® and Jackpot™ trapped root tips. Some of these were removed as fabric was torn away from the root ball. This could have caused the reduction in circling roots in Jackpot™ compared to other containers except Air-Pot™ (Table 3). However the dwarfing effect (Table 2) of the smaller container substrate volume can not be ruled out as the cause for less circling.

The smaller roots on the periphery of Jackpot™ compared to smooth-sided and RootMaker® could result in more root growth into the next larger container size or into field soil. This could occur due to less suberization on smaller diameter roots (34, 36). Further work should evaluate this. Roots on the periphery of all container types except RootBuilder® were largely visible on outer substrate surface (Table 2). Circling and descending roots on RootBuilder® were typically about 1 cm behind substrate periphery, or were just barely visible without removing any substrate. No containers reduced length of descending, ascending or kinked roots compared to smooth-sided, although Air-Pot™, Florida Cool Ring™, Jackpot™, RootBuilder® and Smart Pot® had fewer total root defects in the peripheral 2.5 cm (1 in) of the root ball compared to smooth-sided (Table 3). Smart Pot®, RootBuilder®, and Fanntum Pot promoted more root branching at the container periphery than smooth-sided (Table 4). More branching could result in a root ball with more radially-oriented, straight roots as they grow out into a larger container. Further research should evaluate this since trees with straight roots appear to be more stable than trees with deflected roots (10, 27).

Although all container types had less circling roots than smooth-sided pots, amount of circling roots needed to cause tree health or stability problems is not well understood. Although impact of circling roots on health has been documented in small liner containers (19), impact of circling roots on stability is not clear for containers of this size. Ortega et al. (28), Lindstrom and Rune (19) and others showed that descending roots in trees planted from 5 cm (2 in) diameter liner pots reduce stability, but again little is known about impacts from planting trees from larger containers. Further research should evaluate impact on stability and tree health when planting from larger containers.

Future research should find, develop, and test additional containers with different wall characteristics. There may also be mechanical root pruning methods that can reduce or perhaps eliminate roots growing around, down, up, or kinked back toward the trunk. For example, shaving off root ball periphery when shifting to larger containers has been shown to increase number of straight roots and reduce root defects on 7 temperate and tropical trees species (14).

Literature Cited

1. Anonymous. 1998. Florida Grades and Standards for Nursery Stock. Florida Department of Agriculture and Consumer Services, Div. of Plant Industry, Gainesville FL.

2. Anonymous. 2004. American Standard for Nursery Stock. American Nursery Association, Washington DC.

3. Arnold, M.A. 1996. Mechanical correction and chemical avoidance of circling roots differentially affect post-transplant root regeneration and field establishment of container-grown Shumard oak. J. Amer. Soc. Hort. Sci. 121:258–263.

4. Arnold, M.A. and G.V. McDonald. 1999. Accelerator™ containers alter plant growth and the root zone environment. J. Environ. Hort. 17:168–173.

5. Arnold, M.A. and G.V. McDonald. 2006. Shrub rose responses to production in Smart Pots and conventional containers using two contrasting substrates. Subtropical Plant Science J. of the Rio Grande Valley Hort. Soc. 58:1–4.

6. Arnold, M.A. and D.K. Struve. 1989. Growing green ash and red oak in $CuCO_3$-treated containers increases root regeneration and shoot growth following transplant. J. Amer. Soc. Hort. Sci. 114:402–406.

7. Balisky, A.C., P. Salonius, C. Walli, and D. Brinkman. 1995. Seedling roots and forest floor: Misplaced and neglected aspects of British Columbia's reforestation effort. For. Chron. 71:9–65.

8. Beeson, R.C., Jr. and R. Newton. 1992. Shoot and root responses of eighteen southeastern woody landscape species grown in cupric hydroxide-treated containers. J. Envir. Hort. 10:214–217.

9. Brass, T.J., G.J. Keever, D J. Eakes, and C.H. Gilliam. 1996. Styrene-lined and copper-coated containers affect production and landscape establishment of red maple. HortScience 31:353–356.

10. Colombo, S.J. and K.A. Chapman. 2005. Root form on Jack pine seedlings in a variety of containers. *In*: The Thin Green Line: A Symposium on the State-of-the-Art in Reforestation. p. 80. Forest Research Information Paper No. 160. ed. S.J. Colombo. Ontario Forest Research Institute. Sault Ste. Marie, Ontario.

11. Fare, D. 2005. Should potting depth be a concern for container trees? Proceedings of Trees and Planting: Getting the Roots Right Conference. pp. 25–28. Morton Arboretum, IL. Nov. 10.

12. Gilman, E.F. 2001. Effect of nursery production method, irrigation, and inoculation with mycorrhizae-forming fungi on establishment of *Quercus virginiana*. J. Arboriculture 27:30–39.

13. Gilman, E.F., J. Grabosky, A. Stodola, and M.D. Marshall. 2003. Irrigation and container type impact red maple (*Acer rubrum* L.) 5 years after landscape planting. J. Arboriculture 29:231–236.

14. Gilman, E.F., M. Paz, and C. Harchick. 2010. Root ball shaving improves root systems on seven tree species in containers. J. Environ. Hort. (in review).

15. Halter, M.R., C.P. Chanway, and G.J. Harper. 1993. Growth reduction and root deformation of containerized lodgepole pine saplings 11 years after planting. For. Ecol. Manag. 56:131–146.

16. Harris, R.W., W.B. Davis, N.W. Stice., and D. Long. 1971. Root pruning improves nursery tree quality. J. Amer. Soc. Hort. Sci. 96:105–108.

17. Harris, J.R. and E.F. Gilman. 1991. Production system affects growth and root regeneration of Leyland cypress, laurel oak and slash pine. J. Arboriculture 17:64–69.

18. Ingram, D.L. 1981. Characterization of temperature fluctuations and woody plant growth in white poly bags and conventional black containers. HortScience 16:762–763.

19. Lindstrom, A. and G. Rune. 1999. Root deformation in plantations of container-grown Scots pine trees: effects on root growth, tree stability and stem straightness. Plant and Soil 217:29–37.

20. Marler, T.E. and D. Willis. 1996. Chemical or air-root pruning containers improve carambola, longam, and mango seedling root morphology and initial root growth after planting. J. Environ. Hort. 14:81–87.

21. Marler, T.E. and F.S. Davies. 1987. Growth of bare-root and container grown 'Hamlin' orange trees in the field. Proc. Fl. State Hort. Soc. 100:89–93.

22. Marshall, M.D. and E.F. Gilman. 1998. Effects of nursery container type on root growth and landscape establishment of *Acer rubrum* L. J. Environ. Hort. 15:55–59.

23. Martin, C.A. and S. Bhattacharya. 1995. Effects of cupric hydroxide treated containers on growth of four southwestern desert landscape trees. J. Arboriculture 21:235–238.

24. Martin, C.A. and D.L. Ingram. 1988. Temperature dynamics in black poly containers. Proc. Southern Nurseryman Assoc. Res. Conf. 33:71–74.

25. Moore, D. 2001. Nursery practices and the effectiveness of different containers on root development. Treenet proceedings of the 2nd National Street Tree Symposium: Sept 6–7. ISBN 0-9775084-1-2.

26. Neal, C. 2009. Production systems for small trees and shrubs in New Hampshire. *In*: Landscape below ground III, eds. G.W. Watson, B. Scharenbroch, L. Costello, and E.F. Gilman. Morton Arboretum, October 2008, International Society of Arboriculture, Champaign, IL.

27. Nichols, T.J. and A.A. Alm. 1983. Root development of container-reared, nursery-grown and naturally regenerated pine seedlings. Can. J. For. Res. 13:239–245.

28. Ortega, U., J. Majada, A. Mena-Petite, J. Sanchez-Zabala, N. Rodriguez-Itturrizar, K. Txarterina, J. Azpitarte, and M. Duñabeitia. 2006. Field performance of *Pinus radiata* D. Don produced in nursery with different types of containers. New For. 31:97–112.

29. Owen, J. and H. Stoven. 2008. Searching for the perfect pot. Digger, Mar. p. 40–45, 57, Oregon Assoc. Nurs., Wilsonville, OR.

30. Privett, D.W. and R.L. Hummel. 1992. Root and shoot growth of 'Coral Beauty' cotoneaster and Leyland cypress produced in porous and nonporous containers. J. Environ. Hort. 10:133–136.

31. Ruter, J.M. 1993. Growth and landscape performance of three landscape plants produced in conventional and pot-in-pot productions systems. J. Environ. Hort. 11:124–127.

32. Ruter, J.M. and D.L. Ingram. 1992. High root-zone temperatures influence RuBisCO activity and pigment accumulation in leaves of 'Rotundifolia' holly. J. Amer. Soc. Hort. Sci. 11:154–157.

33. SAS Institute, Inc. 1992. SAS/STAT users guide, vers. 9.1.3. SAS Institute, Inc., Cary, NC.

34. Salonius, P., K. Beaton, and B. Roze. 2000. Effects of cell size and spacing on root density and field performance of container-reared black spruce. Information Report M-X-208E. Natural Resources Canada, Canadian Forest Service, Fredericton, NB.

35. Smith, I.E. and P.D. McCubbin. 1992. Effect of copper tray treatment on *Eucalyptus grandis* (Hill Ex Maiden) seedling growth. Acta Hort. 319:371–376.

36. South, D.B. and R.G.Mitchell. 2005. A root-bound index for container-grown Pines. *In*: The Thin Green Line: A symposium on the state-of-the-art in reforestation. p. 88–93. Forest Research Information Paper No. 160. ed. S.J. Colombo. Ontario Forest Research Institute. Sault Ste. Marie, Ontario.

37. Stout, B.B. 1956. Studies of the root systems of deciduous trees. Black For. Bul. 15, pp. 45.

38. Struve, D.K. 1993. Effect of copper-treated containers on transplant survival and regrowth of four tree species. J. Environ. Hort. 11:196–199.

39. Struve, D.K., M.A. Arnold, R.C. Beeson, Jr., J.M. Ruter, S. Svenson, and W. Witte. 1994. The copper connection. Amer. Nurserymen 179:52–56.

40. Warren, S.L. and F.A. Blazich. 1991. Influence of container design on root circling, top growth, and post-transplant root growth of selected landscape species. J. Environ. Hort. 9:141–144.

41. Watson, G.W. and E.B. Himelick. 1982. Root distribution of nursery trees and its relationship to transplanting. J. Arboriculture 8:305–310.