Urban Forestry & Urban Greening 10 (2011) 3–9

Contents lists available at ScienceDirect

Urban Forestry & Urban Greening

journal homepage: www.elsevier.de/ufug

Quercus virginiana root attributes and lateral stability after planting at different depths

Edward F. Gilman[a,*], Jason Grabosky[b]

[a] Environmental Horticulture Department, 1543 Fifield Hall, University of Florida, Gainesville, FL 32611-06, United States
[b] Ecology, Evolution and Natural Resources, Rutgers University, New Brunswick, NJ, United States

ARTICLE INFO

Keywords:
Bending stress
Overturning bending moment
Root cross-sectional area
Root depth
Root flare
Tree settlement

ABSTRACT

Planting depth and irrigation can impact root and trunk growth following landscape installation in various soil types; however, impact on lateral tree stability is unknown. *Quercus virginiana* Mill. trees were installed at four landscape planting depths into a well drained sandy soil and grown for six years under two irrigation regimes. There was no impact of planting depth on trunk diameter or height in the first five growing seasons after planting; however, trees irrigated regularly had 10 mm larger trunk diameter than trees not irrigated. There was no impact of planting depth or irrigation on bending stress required to tilt trunks to 1°, 2° and 5° from vertical non-deformed start position six growing seasons after planting. Planting depth and irrigation also had no effect on diameter of the ten largest roots to a soil depth of 122 cm, which might explain why bending stress required to pull trees was similar for all planting depth and irrigation treatments. However, trees planted deeper had deeper roots measured 115 cm horizontally from trunk. Root cross-sectional area (CSA) 20–30 and 40–50 cm deep was positively correlated with bending stress six growing seasons after planting. Trees planted deep had some roots that ascended toward soil surface at a steeper angle than trees planted shallow, and had a deeper root flare and more roots growing over the flare that could potentially form stem girdling roots. Diameter of roots over the flare was not impacted by planting depth; however, trees irrigated for the duration of the study had more roots over main flare roots than trees not irrigated. Irrigation increased root number (>5 mm diameter) in the top 30 cm soil profile. Irrigation had no impact on any other measured root parameter. Trees planted deeper settled down below soil surface more than shallow planted trees.

Introduction

Reasons suggested for planting trees below grade in field soil include increased stability (Lyons et al., 1983), increased moisture retention for establishing trees (VanderSchaaf and South, 2003), simpler mechanical planting of forestry plots (Slocum and Maki, 1956; Harrington and Howell, 1998), reduced damage from herbicide (Reighard et al., 1985), reduced sprouting, and hiding the graft union on grafted trees (Watson and Hewitt, 2005). However, more recent studies have contradicted some of these concepts. For example, Sparks (2005) found that after 3 years, weakly developed lateral or brace roots on deeply planted *Carya illinoinensis* (Wangenh.) trees resulted in increased tilting or blowing over during a hurricane. Gilman and Grabosky (2004) showed that deeply planted trees can become more stressed (had reduced xylem turgor pressure) in the months after planting than those planted shallow. Arnold et al. (2007) showed deeply planted container grown trees had reduced survival compared to those planted shallow. In contrast, Day and Harris (2008) found no planting depth impact on survival or trunk growth in well drained silt loam soil first five years after planting from containers; however, there were more stem girdling roots on deeply planted trees. Broschat (1995) found that both growth and survival were lower when *Phoenix roebelinii* O'Brien palms were planted deeply.

Planting deeply into containers may be more problematic than planting deeply into field soil because roots in containers are deflected down, around, up, and back toward the trunk by the container wall (Gilman et al., 2010b). In several instances, roots grew tangent to and touched or became embedded into the trunk buried by soil. Wells et al. (2006) found that roots growing tangent to and touching the trunk can lead to tree death on *Prunus serrulata* Lindl. 'Kwanzan' seven years after planting. Roots growing over the flare close to the trunk from deep planted landscape sized trees in clay soil (Wells et al., 2006) may also result from deflection by compacted sides of planting holes (Zisa et al., 1980; Gilman et al., 1987) typical of urban soils. It is not clear if this occurs in other soil types.

Roots of nursery sized trees are likely to grow out and away from the trunk on trees planted into field soil (Hewitt and Watson, 2009)

* Corresponding author.
E-mail address: egilman@ufl.edu (E.F. Gilman).

1618-8667/$ – see front matter © 2010 Elsevier GmbH. All rights reserved.
doi:10.1016/j.ufug.2010.09.005

because there is no container wall to deflect them back over the flare. Another contributing factor that encourages roots on young trees to grow down and radially away from the trunk is the cultivated soil common to many field nurseries. Small seedlings planted from certain containers can be less stable than natural regenerated trees due to container-induced root deflections (Lindstrom and Rune, 1999). Landscape sized trees planted from 170 L containers were poorly anchored compared to trees transplanted from field soil (Gilman and Masters, 2010). However, long term research is needed on planting depth effects on root growth and tree stability in sandy soils. This study was designed to measure growth and lateral stability of 95 L container grown trees planted at various depths under two irrigation regimes into sandy landscape soil.

Materials and methods

Planting, cultural practices, and experimental design

Seventy-five acorn propagated *Quercus virginiana* Mill. in 10 L containers (20 cm top diameter × 24 cm tall) were planted October 2001 into 95 L smooth sided black plastic containers (58 cm top diameter × 46 cm tall) at University of Florida Great Southern Tree Conference demonstration site in Alachua County, Florida (USDA hardiness zone 8b). The point where the top-most root emerged from trunk (referred to as the root flare) was positioned at the surface of 95 L container substrate. A small amount of substrate and roots was removed from the top surface of some 10 L container root balls to position flare appropriately. Trees were pruned in the container nursery twice annually to a central dominant leader. All branches were removed from the lower 1.4 m of trunk June 2003. Forty-eight trees in 95 L containers closest to mean caliper for the group of 75 trees were planted into Millhopper fine sand (loamy, silicaceous, hyperthermic Grossarenic *Paleudults*) with less than 2% organic matter June 10–14, 2003 on 3 m centers about 100 m away from where trees were grown in containers.

Holes were hand dug with straight sides and flat bottoms 10–15 cm wider than root balls, adjusted to appropriate depth described below, and tamped by foot evenly around bottom of planting hole. Root ball sides were sliced with a hand pruner top to bottom in four places about 2.5 cm deep into substrate. Substrate and roots were removed with a hand pruner from the top edge surface of the 95 L root ball by cutting the edge on a 45° angle about 3–5 cm into substrate. Once root ball was placed in planting hole at the assigned depth a 15 cm wide volume of soil at the edge of hole was loosened and pushed into the hole. The rest of the hole was filled with soil that came out of the planting hole. Water was added to settle backfill soil and soil was packed firmly with a person's foot. No berm or water ring was constructed around the root balls.

The 48 trees were arranged in a randomized complete block design (4 planting depths × 2 irrigation treatments randomized within each of six blocks). There were two replicates of each planting depth in each block for a total of eight trees per block. Trees were installed at each of four planting depths with the root flare either 5 cm above grade, 0–2.5 cm below grade, 10 cm below grade, or 18 cm below grade. Each combination of planting depth and irrigation was randomly assigned to the eight trees in each block. Half of the trees in each block (one of each planting depth) were irrigated regularly to maintain vitality the first four months after planting (regular irrigation) and half were irrigated only enough to keep them from dying (survival irrigation). Irrigation was delivered through two bubbler emitters (model Shrubbler 360°; Antelco, Longwood, FL) installed on the surface of the root ball in the north and south directions.

Irrigation was applied primarily to the root ball surface; a small amount landed on landscape soil beyond root ball. Regular irrigation comprised the following: 18 L three times weekly for two weeks then 3.8 L every other day through March 2004, then every third day through May 2005, then every other day through April 2008. This irrigation program simulated a frequently irrigated managed landscape typical of the region. Survival irrigation was 18 L three times weekly for two weeks, 18 L on 7/11/03, rainfall of 2.5 cm 7/14/03, 18 L 7/18/03 then no irrigation. Periodic summer showers typical of the climate had begun about the time trees were planted June 2003 into landscape. More irrigation detail for the first four months after planting can be found in Gilman and Grabosky (2004). Beginning March 2004, irrigation was delivered through two spray emitters so water landed in a 1.5 m diameter circle around the trunk.

Hardwood chips from local line clearance operations 8 cm deep were added to landscape soil around trees in a 2.4 m × 3.0 m rectangular area and kept weed free with periodic Glyphosate application. Mulch rested against the top 5 cm of root ball side on trees installed 5 cm above grade; about 3.0 cm covered root ball top surface. Approximately 8 cm mulch covered root ball surface on other planting depth treatments. Mulch was replenished to these original depths summer 2005. Mulch treatment was similar to procedures routinely conducted in landscapes in the USA. Trees were subsequently pruned to maintain 1.5 m clearance under the lowest branches. Trees were fertilized in a 1.5 m diameter circle centered on trunk with 16–4–8 (N–P–K) three times in 2004 with 272 g and 3 times in 2005 with 544 g. In 2006, trees were fertilized with 544 g in March and July, and then with 814 g in October. In 2007, trees were fertilized with 544 g in March and 814 g in July and October and at the same rate in April 2008.

Data collection

Trunk diameter 15 cm from ground (caliper) and tree height were measured at planting and at the end of each subsequent growing season in October through 2007. Two stakes were driven into the soil just beyond the edge of the planting hole directly opposite one another so they lined up with trunk. Top of stakes were about 8 cm above mulch surface. A string was tightened between tops of the two stakes at planting and trunk was marked where string touched the trunk. String was again stretched in October 2007 between stakes to determine if trees had settled or sunk down into the soil. There was no soil-induced change in position of the stakes since soil never freezes at the site.

All 48 tree trunks were pulled in the 210° Azimuth (from north) July 2008 to evaluate lateral stability. An inclinometer (model N4; Rieker Inc., Aston, PA) was mounted to a fabricated steel plate (5.1 cm × 7.6 cm), and plate secured to trunk base 15 cm from soil surface which was above the swollen flare. A 3629 kg capacity load cell (SSM-AF-8000; Interface Inc., Scottsdale, AZ) was placed inline with a pulling cable attached to trunk an average of 30 cm above lowest main branch. Distance between inclinometer and trunk pulling point was recorded on each tree. Trunks were pulled so cable was parallel to ground. The cable was pulled at a rate of 2 cm s^{-1} until inclinometer tilted 5° relative to its non-deformed (non-loaded) shape, and then cable was let slack. Trunk angle was recorded during the pull and immediately after cable went slack; angle immediately after cable went slack was referred to as resting angle and was compared with initial non-loaded angle to evaluate if tree permanently tilted in the soil.

Load cell and inclinometer measurements during pulling tests were sampled at 2 Hz using a 16-bit data acquisition system (National Instruments Corporation, Austin, TX) and displayed and archived in real-time on a laptop running LabView software (v: 7.0; National Instruments, Austin, TX). Trunk bending stress at position of inclinometer was calculated as: (pulling force × distance from pulling point to inclinometer × trunk radius

Table 1
Root mat rating and characteristics of the root flare by planting depth and irrigation treatment.

Planting depth	Root mat rating (1–10)[a]	Depth to root flare (mm)[b]	No. of roots >5 mm diameter over root flare	Average diameter of roots >5 mm over flare (mm)	No. of adventitious roots	Average diameter of adventitious roots (mm)	Straight root rating[c]
5-cm above	3.0 b[d]	46 b	3.3 b	19 a	0 b	0 b	3.3 ab
Even	2.8 b	10 c	5.5 a	16 a	0 b	0 b	3.6 a
10-cm below	4.8 a	−66 b	6.2 a	16 a	1.0 a	10.4 ab	2.8 ab
18-cm below	5.8 a	−170 a	7.3 a	13 a	1.2 a	17.4 a	2.2 b

Irrigation	Root mat rating (1–10)[a]	Depth to root flare (mm)[b]	No. of roots >5 mm diameter over root flare	Average diameter of roots >5 mm over flare (mm)	No. of adventitious roots	Average diameter of adventitious roots (mm)	Straight root rating[c]
Yes	5.2 a	−43 a	6.6 a	17 a	0.2 b	1.0 b	3.0 a
No	2.9 b	−48 a	4.5 b	15 a	0.9 a	12.9 a	3.0 a

[a] 1 = no small roots matted over root flare; 10 = dense mat of roots over root flare.
[b] A positive number indicates above soil surface; a negative number below soil surface.
[c] Straight root rating: 1 = most large roots grew into landscape soil from roots deflected by the 95 L container; 5 = most large roots grew more-or-less straight not influenced by container wall.
[d] Means in a column with a different letter are statistically different at $p < 0.05$. Based on 12 trees per treatment for planting depth, and 24 trees per treatment for irrigation.

at inclinometer)/($0.25\pi \times$ trunk radius^4) after James and Kane (2008). Bending moment at position of inclinometer was calculated as force x distance from pulling point to inclinometer. Trunk radius was calculated by halving diameter measured with a diameter tape.

Trees were dug in summer 2009 with a 2.3 m diameter tree spade (4-bladed spade; Caretree Nursery Equipment, Hilliard, OH) and washed of soil to characterize root systems. Digging with the spade was an efficient method of harvesting a uniform soil volume. Root balls were turned up-side-down and the periphery gently washed of soil. Root measurements were collected just inside of the root ball periphery. Measurements included the depth and diameter of roots >5 mm diameter, and total root cross-sectional area (CSA) of the ten largest roots in the upper 61 cm of soil profile. In the 61–122 cm profile, measurements included the diameter and CSA of the ten largest roots. Azimuth north compass direction between trunk and cut root (for roots >5 mm diameter) was recorded in the top 30 cm soil profile and used to divide root CSA into the leeward (toward winch) and windward (away from winch) quadrants relative to trunk pulling direction. Distance between the top surface of the top most root at the root flare and the soil surface was recorded, as was a root mat rating on all trees. Root mat rating was a visual estimate of density or amount of roots of any diameter over the largest dominant roots in the root flare where 1 = few roots and 10 = many roots. This rating was used because some trees had hundreds of roots growing over the flare making measurement impractical.

Maximum angle relative to soil surface of any 15 cm long segment of the 5 largest diameter roots growing up toward soil surface was recorded on each tree. Number of adventitious roots was recorded for each tree as well as number of roots >5 mm and >10 mm diameter growing over dominant main roots in the flare. Roots were considered adventitious if they grew more-or-less straight from the trunk, not from existing roots deflected by the 95 L nursery container. Root balls were evaluated in the following manner: 1 = most roots grew from roots deflected by 95 L nursery container wall to 5 = most roots grew more-or-less straight from the trunk or from a straight root segment prior to deflection by container wall. Percentage of root CSA that was in the largest root, in the largest + the second largest, largest + second largest + third largest, and so on in the 10 largest roots was calculated for each tree.

Statistical analysis

Root mat ratings and root counts were analyzed as a Poisson distribution using PROC GENMOD as a two way ANOVA (main effects planting depth and irrigation) in a randomized complete block design. Percents were square root arcsine transformed prior to analysis; however, non-transformed percents were shown in figures. All other data was analyzed using PROC GLM as a two way ANOVA in a randomized complete block design. Duncan's multiple range test was used to separate means. Coefficients of quadratic equations relating percentage of root CSA in the ten largest roots to root number were compared between treatments using pair-wise comparisons of least square means adjusted for multiple comparisons using Tukeys. Pearson's correlation coefficient was used to test correlation between trunk bending stress and root CSA at various soil depth profiles. PROC GLM was used to calculate linear and quadratic coefficients predicting trunk bending stress from trunk diameter and root CSA. Means were considered significant at $p < 0.05$ unless indicated.

Results

There were no interactions between planting depth and irrigation so only main effects are discussed. Landscape planting depth did not impact trunk caliper (mean = 167 mm) or tree height (7.2 m), or caliper (108 mm) or height (4.1 m) increase during the first five growing seasons following installation (data not shown). Irrigation resulted in trees that had 10 mm larger trunk caliper (171 mm, $p < 0.05$) than trees not irrigated (161 mm, data not shown); however irrigation did not impact tree height or height increase. Trunk bending stress (10.1, 16.8, 24.6 MPa) and trunk bending moment (6.1, 10.2, 13.6 kN m) required to tilt tree trunk to 1°, 2°, and 5° from non-deformed starting position, respectively, were not impacted by planting depth. Irrigation treatment had no impact on trunk bending stress or bending moment to tilt trees (data not shown). Planting depth and irrigation did not impact trunk resting angle following pulling to 5°.

Root matting and number of roots >5 mm diameter growing over main roots in the root flare increased with planting depth and irrigation (Table 1). Mean diameter of roots >5 mm diameter (16 mm) growing over flare roots was not impacted by planting depth. Distance between top of root flare and soil surface (i.e. depth of root flare) increased with planting depth but was not impacted by irrigation (Table 1). Number and diameter of adventitious roots increased with planting depth but decreased with irrigation (Table 1). Straight root rating decreased with planting depth but was not impacted by irrigation (Table 1). Irrigation did not impact mean diameter of roots >5 mm diameter growing over root flare (Table 1), number of roots >10 mm diameter growing over the flare (2.8), diameter of largest ten roots in the 0–61 cm deep soil profile (35 mm), diameter

Table 2
Characteristics of the ten largest diameter roots in the top and bottom half of root balls, angle of ascending roots, and tree settlement by planting depth treatment averaged across irrigation treatments.

Planting depth	Diameter of largest 10 roots from top 61 cm of soil (mm)	Average depth of largest 10 roots from top 61 cm of soil (mm)	Diameter of largest 10 roots 61–122 cm depth of soil (mm)	Total root cross-sectional area[a] (mm^2)	Angle of largest 5 ascending roots	Tree settlement[b] (mm)
5-cm above	35 a	259 bc[c]	24 a	16,206 a	15 c	2.8 a
Even	37 a	206 c	24 a	17,912 a	22 bc	−9.0 b
10-cm below	36 a	328 b	26 a	17,752 a	25 b	−15.3 b
18-cm below	34 a	406 a	31 a	19,565 a	36 a	−14.0 b

[a] Total root cross-sectional area (CSA) of the ten largest roots in top 61 cm of soil plus CSA of ten largest in 61–122 cm soil depth.
[b] A positive number indicates tree shifted up relative to original planting position; a negative number indicates sinking into the landscape soil.
[c] Means of 12 trees per treatment in a column with a different letter are statistically different at $p < 0.05$.

of the ten largest roots in the 61–122 cm deep soil profile (26 mm), angle from horizontal of the five largest roots measured at any depth (up toward soil surface at mean angle of 24° from horizontal), or tree settlement after planting (data not shown).

Planting depth had no impact on mean diameter of the ten largest roots in the 0–61 cm deep soil profile or the 61–122 cm deep soil profile (Table 2). However, mean depth of the ten largest roots in the top 61 cm increased with planting depth. The five largest ascending roots grew up at a steeper angle as planting depth increased. Tree settlement or subsidence into the soil during the five growing seasons following planting increased with planting depth. Planting depth (Table 2) and irrigation (data not shown) had no impact on root CSA.

Quadratic and linear coefficients for the best fit least squares line relating percentage of root CSA in the ten largest roots to root number was similar among planting depths and irrigation treatments (data not shown). Fig. 1 shows this relationship for all 48 trees including all planting depths and irrigation treatments together. Approximately 25% of total root CSA in the ten largest roots was contained in the largest root, 35% in the largest two roots, 50% in the largest three, and so on.

Number of roots and root CSA (of the ten largest) in upper soil profiles (0–10, 10–20, 20–30 cm depth ranges) was greater on shallow planted trees (5 cm above and even) than on trees planted deeper (10 and 18 cm below, Fig. 2). Number of roots and root CSA (of the ten largest) in deeper soil profiles (40–50 and 50–60 cm depth range) was generally greater for deeply planted trees (10 and 18 cm below) than for trees planted shallow. Planting depth did not impact number of roots or root CSA at the 30–40 cm depth range. Roots >5 mm diameter in the top 30 cm soil profile were evenly distributed among the four cardinal directions for all planting depths except for trees planted 10 cm below grade (Fig. 3). Irrigation increased root number (>5 mm diameter) in the top 30 cm soil profile from 17.3 to 20.9 averaged across planting depths (data not shown).

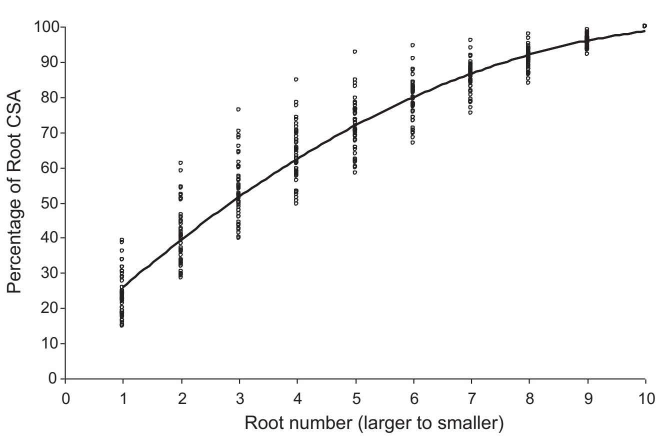

Fig. 1. Percentage of root CSA on the tree in the largest root (1), in the largest + the second largest (2), largest + second largest + third largest (3), and so on, in the 10 largest roots. Root CSA = sum of CSA in the largest ten roots (0–122 cm soil profile). Percentage of root CSA = 10.91 + 15.58 (root number) − 0.68 (root number)^2; $R^2 = 0.94$, intercept and slope $p < 0.0001$.

Root CSA at 20–30 cm deep and 40–50 cm deep (Table 3) was correlated with trunk bending stress; root CSA at other depth ranges was not correlated with bending stress (data not shown). Root CSA 20–30 cm deep in the leeward quadrant and 40–50 cm deep in the windward quadrant was also correlated with trunk bending stress to 1° and 2° tilt but not for the 5° tilt (Table 3). Bending stress was not correlated with root CSA in the ten largest roots or root CSA at any other soil depth (Table 3). Bending stress was not correlated with the sum of all root diameters (roots >5 mm diameter) on the tree or the sum of root diameter in any soil depth range (data not shown).

Trunk bending moment to 1°, 2°, and 5° trunk tilt was correlated with trunk diameter and root CSA in top 61 cm soil profile across all four planting depths and two irrigation treatments according to the following equations:

(1) Moment (kN m) to 1° tilt=
  a. 1.09 trunk diameter (cm) − 13.62; $r^2 = 57\%$, $p > 0.0001$, $n = 48$.
  b. 1.13 trunk diameter (cm) + 0.0005 root CSA (20–30 cm soil depth) − 13.7; $R^2 = 65\%$, $p < 0.0005$, $n = 48$.
(2) Moment (kN m) to 2° tilt=
  a. 1.57 trunk diameter (cm) − 18.96; $r^2 = 64\%$, $p < 0.0001$, $n = 48$.
  b. 1.77 trunk diameter (cm) + 0.0004 root CSA (20–30 cm soil depth) − 20.7; $R^2 = 67\%$, $p < 0.01$, $n = 48$.
(3) Moment (kN m) to 5° tilt=
  a. 1.73 trunk diameter (cm) − 17.73; $r^2 = 68\%$, $p < 0.0001$, $n = 48$.
  b. 2.02 trunk diameter (cm) + 0.0006 root CSA (20–30 cm soil depth) − 20.9; R^2, 71%, $p < 0.007$, $n = 48$.

Discussion

Planting depth had no impact on trunk or height growth in the five growing seasons following planting or on bending stress required to pull trunks to a given angle six growing seasons after planting. However, in agreement with Day and Harris (2008) increasing planting depth corresponded to more roots (>5 mm diameter) growing over main roots of the flare (Table 1) because it placed main roots deep in the soil profile. Deep flare roots provided an opportunity for roots of the excavated tree and roots of nearby trees in the test plot to grow close to the soil surface over main flare roots. Shallow roots growing tangent to trunk over main roots have been associated with reduced health on some trees (Giblin et al., 2005; Wells et al., 2006). Wells et al. (2006) and Day and Harris (2008) also found more potential stem girdling roots as planting depth increased in landscape soil.

Roots >5 mm diameter grew over main roots in the root flare even when flare was positioned 5 cm above surrounding landscape soil at planting (Table 1). On the shallowest planted trees, this likely

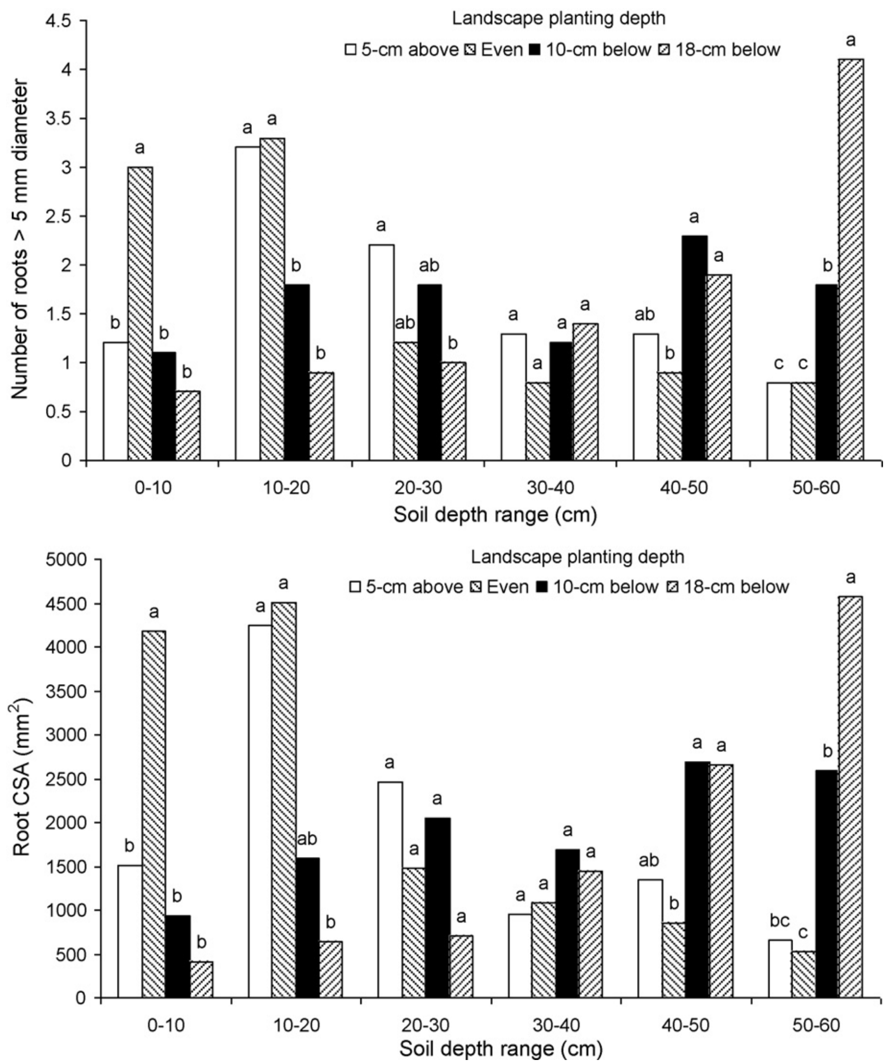

Fig. 2. Number of roots (of the ten largest) and root CSA (of the ten largest) in the 0–61 cm soil profile at increasing soil depths averaged across irrigation treatments five growing seasons after planting at four landscape depths. Means of 12 trees per treatment in a soil depth range with a different letter are significantly different at $p < 0.05$.

resulted from roots growing across the top of the root ball under and in the thin (3.0 cm) mulch layer placed there at planting. On deep planted trees, roots grew in the soil and in the 8 cm thick mulch layer placed over the root ball at planting. Despite significant relationship between planting depth and number of roots (>5 mm diameter) growing over flare, there was a great deal of variability around means (Table 1). For example, three trees planted 10 and 18 cm deep had less than three roots growing over the flare; one tree planted 18 cm deep had no roots over flare. In other words, increased planting depth did not assure that roots grew over flare; it simply increased the likelihood. Planting 5 cm above grade did not prevent roots from growing over the flare; it simply reduced the likelihood.

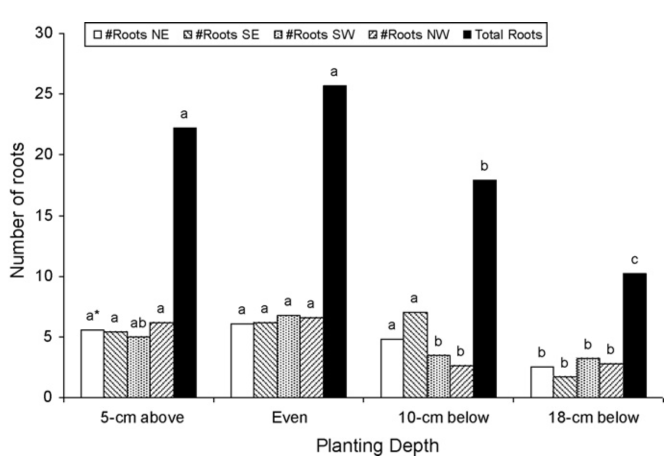

Fig. 3. Number of roots >5 mm diameter in top 30 cm of landscape soil for four planting depths averaged across irrigation treatments five growing seasons after planting. Means of 12 trees per treatment within a compass direction with different letters are significantly different at $p < 0.05$.

Gilman et al. (2010a) also found that roots of three taxa in containers grew over the flare when the root ball surface was planted even with substrate at each shift to larger containers. This emphasizes the importance of implementing root management at planting and post planting when installing trees that were in a container for any portion of the propagation process, and when using mulch over the root ball of trees planted from any production method. Root growth over the flare is less likely if no mulch is placed over the root ball, and Gilman and Grabosky (2004) showed that eliminating mulch from the root ball surface had no negative impact on tree water stress and survival the first few months after planting.

Despite abundance of roots growing over the flare in response to deep planting (Table 1) roots produced after planting did not appear to embed into the trunk or main roots in six growing seasons after planting. Roots growing over the flare that were embedded into the trunk and main flare roots appeared to result from deflection by

Table 3
Root attributes correlated with trunk bending stress[a] during trunk pulling five growing seasons after planting at four planting depths[b].

Root attributes	Trunk bending stress[a] when trunk was pulled to		
	1° from vertical[c]	2° from vertical	5° from vertical
	Pearson's correlation coefficient[d]		
Root CSA in the 10 largest roots in top 61 cm	NS	NS	NS
Root CSA in the 20 largest roots in top 122 cm	NS	0.32	NS
Root CSA[e] 20–30 mm depth	0.49	0.36	0.47
Root CSA[e] 40–50 mm depth	0.33	0.41	NS
Root CSA[e] 20–30 mm depth leeward 1/4[f]	0.39	0.33	NS
Root CSA[e] 40–50 mm depth windward 1/4[g]	0.30	0.39	NS

[a] Trunk bending stress = (pulling force × length × trunk radius)/(0.25π × trunk radius^4).
[b] Data from all trees was pooled since planting depth had no impact on bending stress.
[c] Vertical indicates the non-deformed (non-loaded) trunk starting position just prior to pulling.
[d] Significantly correlated at $p < 0.05$; NS indicates not significant at $p < 0.05$.
[e] All roots >5 mm diameter. No other 10-cm depth range (from 0 to 61 cm) was significant.
[f] Roots in the 90° section toward pulling winch.
[g] Roots in the 90° section opposite pulling winch.

container walls during nursery production prior to landscape planting. Some of these roots were entirely embedded into the trunk, and they circled more than half the trunk circumference. Apparently, removing all roots and substrate from the top outer edge of the 95 L root ball at planting as described in methods was not effective at removing all container-induced root defects. Defects remained further inside the root ball as a result of deflection by a smaller container size (10 L) because these were not removed at planting. Many roots that were near the edge of the 95 L container at planting were more than 10 cm diameter six growing seasons later (data not shown). A more aggressive treatment such as shaving off the entire outside periphery of the root ball at each shift to a larger container size has been shown effective at removing most container induced defects (Gilman et al., 2010c). Teasing and cutting roots growing over main roots in the root ball at planting may also be required to fully remove defects.

There was no corresponding increase in stability from deeper rooting that occurred on trees planted deeply (Fig. 2). In contrast, Day and Harris (2008) observed roots in a silt loam soil gradually rising as they grew away from the root ball ultimately resulting in similar root distributions among planting depths. Perhaps the silt loam soil type forced more roots closer to soil surface due to lower soil oxygen content, as Gilman et al. (1987) showed, than the current study in sandy soil where most roots remained deep on deeply planted trees. Deeper root systems on deep planted trees occurred despite an increase in ascending root angle with planting depth (Table 2). Most of the five largest ascending roots originated from the top several cm of the root ball sides. Some increase in ascending angle might have resulted from tree settlement that occurred during establishment, especially in trees planted 10 and 18 cm deep (Table 2). Trunk settlement probably resulted from original root ball components (bark and peat) decomposing, and the root ball or root system sinking down into landscape soil. Perhaps the added mass of mulch and soil over the root ball encouraged more settlement on deep planted trees. If this occurred when roots were young and small in diameter then some lateral roots may have broken or been pulled back through the soil toward the trunk during a wind event. A 30 m s^{-1} tropical storm occurred in the region 14 months after planting; trees appeared to have sunken during this storm. This root injury could have caused a redirection of some roots up toward the soil surface.

Roots growing up toward soil surface in response to deep planting were described decades ago on very small nursery liner stock. For example, Carvell and Kulow (1964) found an upper layer of superficial roots had formed on *Pinus strobus* L. trees planted from small propagation-sized containers 15 cm below grade. Lyons et al. (1983) found that after 2 years, *Malus domestica* Mill. was less likely to be shaken loose by wind when planted at the same depth as they were in the nursery than when planted as much as 20 cm deeper. All cited studies above were conducted in moist temperate climates. In contrast, deep planting in drier climates increased survival by reducing irrigation needs of very young liner stock planted from small containers (Dreesen and Fenchel, 2008). It is not clear whether this difference in response was due to climate, tree age, species, soil type, or some other factor.

It might be tempting to recommend planting deeply near sidewalks to minimize risk of sidewalk damage because there is some evidence in the current study that deep planting (especially 18 cm deep, Table 1) reduced number and CSA of roots in the top soil profile in this soil type. However, deep planting has risks including increased formation of stem girdling roots (Table 1 and Wells et al., 2006) and reduced survival of certain species in the first few years after planting (Gilman and Grabosky, 2004; Wells et al., 2006; Arnold et al., 2007). In addition, there is evidence that roots in soil types with more silt or clay content are redirected toward the soil surface in response to planting deeply indicating that deep planting would not result in a deeper root system (Day and Harris, 2008). Compacted layers (base, subbase, and/or subgrade) under sidewalks could also direct roots to more shallow profiles by encouraging root growth on top of the subbase under the concrete or asphalt surface.

A higher straight root rating and increase in shallow root number and CSA (Table 1) for trees planted 5 cm higher than or even with surrounding landscape soil may have resulted from increased water stress (reduced xylem potential) on deeply planted trees in the months after planting (Gilman and Grabosky, 2004; Arnold et al., 2007). Gilman and Grabosky (2004) suggested that rain and irrigation was intercepted by soil and mulch placed over the root ball on deeply planted trees resulting in a drier root ball. Shallow roots were missing on deeply planted trees perhaps due to root damage that occurred from the reduced moisture in the upper part of the root ball. This could have encouraged roots deeper in the root ball to grow into landscape soil instead of the damaged shallower roots. As a result, roots positioned at the bottom of the root ball may have been in contact with landscape soil that retained more moisture.

Trunk bending moment was positively correlated with a combination of trunk diameter and root CSA (Eqs. (1)–(3)); however, root number and root CSA in the top 20 cm of soil profile were not correlated with trunk bending stress required to tilt trunks. Instead, root CSA deeper in the profile (20–30 and 40–50 cm) correlated positively with trunk bending stress (Table 3). This might indicate that trees (such as oaks used in this study) of this size capable of growing deep roots in this soil type could remain stable immediately after roots in the top 20 cm were severed. This might help guide specifications for root severing near sidewalks and curbs. Smiley (2009) showed that surface roots on young *Quercus phellos* L. could be cut in a clay soil a distance from the trunk equal to 5 times the trunk diameter with little reduction in tree stability. Presence of sinker roots growing down from horizontal roots likely accounted for stability of these trees. Data from the current study supports this in sandy soil since anchorage appears largely due to roots deeper than 20 cm measured 1.15 m from trunk (Table 3). Dupuy et al. (2005) also found that deep roots increased anchorage on sand soils. Mickovski and Ennos (2002) reported that surface roots in clay loam contributed little to anchorage so long as deep roots could develop. Surface roots contribute most to anchorage by spreading out more and growing to a large diameter in soils that promote mostly shallow root systems due to soil compaction or high water tables (Coutts, 1983, 1986). Trees with shallow roots resulting from soil conditions, or those not capable of generating abundant deep roots such as *Acer* (Gilman and Kane, 1990), may not be as stable as trees with deeper roots following root severing. Much more research in this area is required to draw conclusions about anchorage or stability in different urban soil types.

Irrigation significantly increased number of roots and root mat rating over the root flare (Table 1), but had no impact on any other measured root parameter including root depth, diameter, or total CSA. Since roots growing over the flare can lead to stem girdling roots (Wells et al., 2006) irrigation should not be applied over the root ball or near the trunk for a prolonged period. Irrigation treatment in the current study did not impact tree height growth and had a negligible (10 mm over 5 growing seasons) impact on trunk caliper. Others also showed that irrigation after trees were established in temperate Florida (Beeson and Gilman, 1995; Gilman et al., 2002, 2003) and other climates (Fabiano et al., 1995) had a negligible impact on growth. Marshall and Gilman (1997) showed irrigation treatment had no impact on root systems of live oak transplanted to landscape soil from a field nursery, but increased root number from container-planted trees in first three years after planting. Irrigation over the root ball clearly enhances survival after planting with little impact on growth or root system development once trees are established. Irrigation close to the trunk should be discontinued once trees become established to reduce likelihood of stem girdling root formation.

Percentage of root CSA in the largest ten roots (Fig. 1) was very similar to several other species grown in different soil types and planted from much smaller containers (Coutts, 1983; Gilman and Kane, 1990). This supports the hypothesis of similarity in basal root form among many tree species (Eis, 1974) even when trees are planted from 95 L containers as in the current study. Long term implications of modified root form close to the trunk induced by growing trees in containers or transplanted from field nurseries are unknown and should be studied in more detail to better understand root attributes associated with tree stability in urban landscapes.

Acknowledgements

Thanks to the Greatsoutherntreeconference.org, McIntire Stennis project NJ17312, and John-Eleanor Kuser Faculty Scholar endowment for providing partial funding for this project.

References

Arnold, M.A., McDonald, G.V., Bryan, B.L., Denny, G.C., Watson, W.T., Lombardini, L., 2007. Below-grade planting adversely affects survival and growth of tree species from five different families. Arboriculture and Urban Forestry 33, 64–69.

Beeson Jr., R.C., Gilman, E.F., 1995. Irrigation and fertilizer placement affect root and canopy growth of trees produced in in-ground fabric containers. Journal of Environmental Horticulture 13, 133–136.

Broschat, T., 1995. Planting depth affects root growth and nutrient content on transplanted pygmy date palms. HortScience 30, 1031–1032.

Carvell, K.L., Kulow, D.L., 1964. Planting depth affects survival and growth of eastern white pine. Journal of Forestry 62, 735–736.

Coutts, M.P., 1983. Development of the structural root system of Sitka spruce. Forestry 56, 1–16.

Coutts, M.P., 1986. Components of tree stability in Sitka spruce on peaty gley soil. Forestry 59, 173–197.

Day, S.D., Harris, J.R., 2008. Growth, survival, and root system morphology of deeply planted *Corylus colurna* 7 years after transplanting and the effects of root collar excavation. Urban Forestry and Urban Greening 7, 119–128.

Dreesen, D.R., Fenchel, G.A., 2008. Deep-planting methods that require minimal or no irrigation to establish riparian trees and shrubs in the southwest. Journal Soil and Water Conservation 63, 129a–133a.

Dupuy, L., Fourcaud, T., Stokes, A., 2005. A numerical investigation into the influence of soil type and root architecture on tree anchorage. Plant and Soil 278, 119–134.

Eis, S., 1974. Root system morphology of western hemlock, western red cedar, and Douglas-fir. Canadian Journal of Forest Research 4, 28–38.

Fabiano, A., Madeira, M., Steen, E., Katterer, T., Ribeiro, C., Araujo, C., 1995. Development of root biomass in a *Eucalyptus globulus* plantation under different water and nutrient regimes. Plant and Soil 168–169, 215–223.

Giblin, C., Gillman, J., Hanson, D., Johnson, G.R., Weicherding, P., 2005. The effect of soil depth on the long-term health and frequency of storm damage to trees in the upper midwest. In: Watson, G. (Ed.), Trees and Planting: Getting the Roots Right. Morton Arboretum, Lisle, IL, pp. 33–39.

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

Gilman, E.F., Grabosky, J., 2004. Mulch and planting depth affect live oak establishment. Journal of Arboriculture 30, 311–317.

Gilman, E.F., Harchick, C., Paz, M., 2010a. Planting depth affects root form of three shade tree cultivars in containers. Arboriculture and Urban Forestry 36, 132–139.

Gilman, E.F., Kane, M.E., 1990. Root growth of red maple following planting from containers. HortScience 25, 527–528.

Gilman, E.F., Leone, I.A., Flower, F.B., 1987. Effect of soil compaction and oxygen content on vertical and horizontal root distribution. Journal of Environmental Horticulture 5, 33–36.

Gilman, E.F., Masters, F., 2010. Effect of tree size, root pruning and production method on root growth and lateral stability of *Quercus virginiana*. Arboriculture and Urban Forestry 36, 281–291.

Gilman, E.F., Paz, M., Harchick, C., 2010b. Effect of container type on root form of red maple. Journal of Environmental Horticulture 28, 1–7.

Gilman, E.F., Paz, M., Harchick, C., 2010c. Root ball shaving improves root systems on seven species in containers. Journal of Environmental Horticulture 28, 13–18.

Gilman, E.F., Stodola, A., Marshall, M.D., 2002. Root pruning but not irrigation in the nursery affects live oak root balls and digging survival. Journal of Environmental Horticulture 20, 122–126.

James, K., Kane, B., 2008. Precision digital instruments to measure dynamic wind loads on trees during storms. Agriculture and Forest Meteorology 148, 1055–1062.

Harrington, T.B., Howell, K.D., 1998. Planting cost, survival, and growth one to three years after establishing loblolly pine seedlings with straight, deformed, or pruned taproots. New Forests 15, 193–204.

Hewitt, A., Watson, G.W., 2009. Bare root liner production can alter tree root architecture. Journal of Environmental Horticulture 27, 99–104.

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

Lyons Jr., C.G., Byers, R.E., Yoder, K.S., 1983. Influence of planting depth on growth and anchorage of young 'Delicious' apple trees. HortScience 18, 923–924.

Marshall, M.D., Gilman, E.F., 1997. Production method and irrigation affect root morphology of live oak. Journal of Environmental Horticulture 15, 84–87.

Mickovski, S.B., Ennos, A.R., 2002. A morphological and mechanical study of the root systems of suppressed crown Scots pine *Pinus sylvestris*. Trees 16, 264–280.

Reighard, G.L., Howe, G., Hanover, J.W., 1985. Effects of chemical weed control and seedling planting depth on survival and growth of aspen. Tree Planter's Notes 36, 3–7.

Slocum, G.K., Maki, T.E., 1956. Some effects of depth of planting upon loblolly pine in the North Carolina piedmont. Journal of Forestry 54, 21–25.

Sparks, D., 2005. Tree setting depth affects wind resistance in pecan. Journal of American Pomology Society 59, 134–140.

Smiley, E.T., 2009. Root pruning and stability of young willow oak. Arboriculture and Urban Forestry 34, 123–128.

VanderSchaaf, C.L., South, D.B., 2003. Effect of planting depth on growth of open-rooted *Pinus elliotii* and *Pinus taeda* seedlings in the United States. Southern African Forestry Journal 198, 63–73.

Watson, G.W., Hewitt, A., 2005. Distinguishing between root system architecture changes and planting too deep. In: Watson, G. (Ed.), Trees and Planting: Getting the Roots Right. Morton Arboretum, Lisle, IL, pp. 1–5.

Wells, C., Townsend, C.E.K.S., Caldwell, J.D., Ham, D.L., Sherwood, M., Smiley, E.T., 2006. Effects of planting depth on landscape tree survival and girdling root formation. Arboriculture and Urban Forestry 32, 305–311.

Zisa, R., Halverson, H.G., Stout, B.B., 1980. Establishment and early growth of conifers on compact soils in urban areas. USDA Forest Service Research Paper NE No. 451.