Urban Forestry & Urban Greening 63 (2021) 127184

Contents lists available at ScienceDirect

Urban Forestry & Urban Greening

journal homepage: www.elsevier.com/locate/ufug

Species and season affect response of container-grown shade trees to pre-plant root modifications

Riley P. Rouse[a], Bert Cregg[a,b,*]

[a] Michigan State University, Department of Horticulture, 1066 Bogue St., East Lansing, MI, 48824, USA
[b] Michigan State University, Department of Forestry, 480 Wilson Rd., East Lansing, MI, 48824, USA

ARTICLE INFO

Handling Editor: A. Alessio Fini

Keywords:
Acer rubrum
Bare-rooting
Circling roots
Liriodendron tulipifera
Platanus x *acerifolia*
Shaving

ABSTRACT

Container-grown shade trees make up an increasing proportion of nursery stock, yet arborists and urban foresters are often concerned about root defects associated with trees grown in smooth-sided containers, such as circling roots, persisting in the landscape post-transplant. The objective of this study was to determine the effect of root modifications (shaving or bare-rooting) at planting on establishment, survival, and growth of container-grown *Acer rubrum* L. 'October Glory', *Liriodendron tulipifera* L. 'Fastigiatum', and *Platanus* x *acerifolia* (Aiton) Willd. 'Bloodgood'. Trees were planted on two dates (May and July) in 2018 and evaluated for two growing seasons. Modifying roots before planting resulted in increased occurrence of leaf scorch for *L. tulipifera* and *A. rubrum* trees. Nearly all trees bare-rooted before planting in July had severe die-back. Survival was excellent (>75 %) for all *A. rubrum* and *P.* x *acerifolia* trees planted in May regardless of treatment. Survival for *L. tulipifera* trees that were bare-rooted in May was 50 %; all *L. tulipifera* trees that were bare-rooted in July died. Bare-rooting increased predawn leaf water potential (Ψ_w) immediately after planting. However, Ψ_w did not differ among root treatments for the rest of 2018 and throughout 2019. This suggests that trees with modified root systems achieved a functional equilibrium by adjusting leaf area to reduce whole-tree water loss. Root biomass outside the original root-ball did not differ among root modification treatments two years post-transplant. However, bare-rooting reduced the proportion of circling roots compared to control trees for all species. Shaving root systems reduced circling roots compared to the control for *L. tulipifera* and *P.* x *acerifolia* trees. For practitioners interested in trialing these techniques, we advise performing root modifications in the dormant season and avoiding species known to be difficult to transplant bareroot.

1. Introduction

The sale of deciduous shade trees in the United States in 2014 exceeded half a billion dollars, and over 60 percent of those trees were grown in containers (United States Department of Agriculture, 2014). Container production offers a myriad of benefits for nursery growers: ability to maximize space during production and shipping, ability to grow on unproductive soil, uniform plant growth, ease of handling, and a longer seasonal market (Davidson et al., 2000; Gilman and Beeson, 1996; Harris and Gilman, 1991; Whitcomb, 2003). Arborists and homeowners benefit from the ease of handling of container-grown trees due to lightweight container substrate and compact root systems compared to traditional ball-and-burlap (B&B) stock. Several studies have compared the transplantability of B&B stock and container-grown trees and found that trees grown in containers generally exhibit less stress following transplant, because they retain the entirety of their original root system whereas B&B trees lose up to 95 % of roots during transplant (Gilman and Beeson, 1996; Harris and Gilman, 1991, 1993; Kozlowski and Davies, 1975; Mathers et al., 2005; Watson, 1985). The most commonly used nursery containers are smooth-sided black plastic (BP) containers. BP containers are lightweight, durable, well-suited for mechanization, and can be reused and recycled; however, they are often cited as a cause of inadequate or malformed root systems, specifically circling roots (Amoroso et al., 2010; Gilman et al., 1996, 2010a, b, c; O'Connor et al., 2018; Ruter, 1994). Circling roots persist in the landscape post-transplant (Grene, 1978) and can reduce root establishment and tree stability (Coutts, 1983; Gilman, 1994; Smiley, 2008; Smiley et al., 2014).

Despite advances in design of alternative containers (Appleton, 1993; Gilman et al., 2010a; O'Connor et al., 2018; Whitcomb, 1985), BP

---

* Corresponding author at: Michigan State University, Department of Horticulture, 1066 Bogue St., East Lansing, MI, 48824, USA.
E-mail address: cregg@msu.edu (B. Cregg).

https://doi.org/10.1016/j.ufug.2021.127184
Received 14 November 2020; Received in revised form 5 May 2021; Accepted 10 May 2021

containers remain the standard throughout the nursery industry. Some researchers and industry professionals recommend pruning circling roots prior to transplanting (Chalker-Scott, n.d.; Cotrone, 2019; Putnam, 2015), either during up-potting in the nursery or at time of transplant, to help minimize or eliminate root girdling and to stimulate root growth into backfill soil (Cregg and Ellison, 2018; Gilman et al., 2010b; Gilman and Wiese, 2012). Various root-ball modification techniques have been researched with the intent of reducing circling roots and promoting root growth (Arnold, 1996; Cregg and Ellison, 2018; Gilman et al., 2010c). Some recommendations include: 1) *slicing* roots by making a series of vertical slits in the root-ball to disrupt outer circling roots; 2) *teasing* apart and straightening circling roots; 3) *butterflying* the root system by slicing open the bottom of the root-ball and splaying the ends; and 4) *shaving* by removing the entire periphery and bottom of the root-ball using a saw or shovel. These techniques, however, have yielded mixed results for improving subsequent root growth and transplant success. Studies pertaining to mechanical root pruning of large container-grown trees include limited species and results are inconsistent or contradictory (Weicherding et al., 2007).

Another root modification technique that is increasingly promoted as a means of reducing and correcting root defects is *bare-rooting*, or removal of all container substrate, prior to transplant (Chalker-Scott, 2012a, b). Advocates of this technique note removal of the container substrate improves root-soil contact, ensures proper planting depth, and provides access to the root system's interior, allowing for the removal of all malformed roots (Appleton and Flott, 2009; Chalker-Scott and Stout, 2009). This practice is promoted largely based on anecdotal evidence, yet few, if any, studies have been published evaluating the response of large container-grown trees to bare-rooting when transplanting.

Based on preliminary data from Appleton and Flott (2009), bare-rooting and transplanting container-grown *Acer rubrum* and *Quercus phellos* L. trees in July (actively-growing) resulted in higher levels of tree mortality compared to bare-rooting and transplanting in March (dormancy) or October (entering dormancy). While there were no differences in caliper growth of *A. rubrum* trees one-year post-transplant, *Q. phellos* trees that were bare-rooted had less aboveground growth than control trees (Appleton and Flott, 2009). Similarly, Hummel et al. (2009) performed varying degrees of root disruption when transplanting 1 L *Pinus sylvestris* and *Pinus contorta* var. *contorta* trees to 19 L containers. They reported bare-rooting (washing or washing and pruning) reduced height growth compared to control trees for at least one year following treatment for both species. They also noted species differences in response to root treatments; bare-rooting resulted in mortality of half of the *P. contorta* trees while there was no mortality of *P. sylvestris* trees in the same treatment group (Hummel et al., 2009). Currently available guidelines on bare-rooting (Appleton, 2007; Chalker-Scott, 2012b, 2020) provide little guidance on differences in species responses or timing of planting. Moreover, nursery stock that is lifted bareroot is often sensitive to time of planting (Watson and Himelick, 2013), and many tree species do not transplant well bareroot (Buckstrup and Bassuk, 2009) due to low root growth potential, ability to rehydrate, and/or root carbohydrate status (Bates et al., 1994; Ellison et al., 2016).

In this study, we conducted two experiments to examine the response of three common species of container-grown trees to root modification treatments at different times in the growing season with the goal of improving transplant success. The root modification methods that we investigated included shaving the periphery of the root systems and two forms of bare-rooting, washing roots or using an airspade to remove container substrate; we included the latter bare-root method to determine if airspade use would expedite the bare-rooting process for large-scale tree plantings. The objectives of this research were to:

1. Evaluate the effect of shaving and bare-rooting (via washing or airspade) root-balls of container-grown trees on survival, growth, physiology, and root responses after transplanting
2. Determine if species vary in their responses to pre-plant root modifications
3. Determine if response to root modification varies with planting season.

2. Materials and methods

2.1. Plant materials

In spring 2016, we received 180 bareroot liners (3.2 cm caliper) from a commercial nursery (J. Frank Schmidt & Son Co., Boring, OR, USA). The shipment included 60 trees from each of three common landscape cultivars: *Acer rubrum* 'October Glory' (October Glory® red maple), *Liriodendron tulipifera* 'Fastigiatum' (columnar tulip poplar), and *Platanus* x *acerifolia* 'Bloodgood' (Bloodgood London planetree). The three species chosen are widely used in urban tree plantings. *P.* x *acerifolia* 'Bloodgood' was included in the study given its successful response to root shaving (Cregg and Ellison, 2018); *L. tulipfera* is a species know to be difficult to transplant bareroot (Buckstrup and Bassuk, 2009), and *A. rubrum* is an extremely common landscape tree species with dense root systems which are very susceptible to girdling roots in the landscape (Johnson and Hauer, 2000). We planted the liners, with root flare at grade, in a substrate of pine bark and peat moss (80:20; v:v) in #25 (104 L) BP containers (model GL10000, Nursery Supplies, Inc., Chambersburg, PA, USA). The trees were grown for two years in a pot-in-pot nursery at the Michigan State University (MSU) Horticulture Teaching and Research Center (HTRC) near East Lansing, MI, USA. During the nursery production cycle, trees were irrigated daily during the growing season (May to October) and top dressed with 400 g of controlled-release fertilizer (Osmocote® Plus 15-9-12, 5-6 month release, ICL Fertilizers – North America, St. Louis, MO, USA) each spring. The mean height of the trees at planting for *A. rubrum, L. tulipifera,* and *P.* x *acerifolia* were 3.4 m, 3.4 m, and 3.9 m, respectively.

2.2. Spring planting experiment

On 15 May 2018, 32 trees of each species (96 total) were selected at random from the pot-in-pot nursery to be transplanted to a field plot at the MSU HTRC. We collected 16 soil samples (0−30 cm depth) across the site, and the samples were analyzed by the MSU Soil and Plant Nutrient Laboratory for nutrient concentration (Table 1). Four additional soil samples were collected across the site to determine average bulk density (Table 1).

2.2.1. Experimental design and treatments

The experiment was installed as a 3 × 4 factorial of species (3) and root modification treatment (4) with eight replications (N = 8). Trees of each species were randomly assigned one of four root-ball modification treatments: 1) *Control* – nursery container removed and planted without root modification (Fig. 1A); 2) *Shave* – removal of the 3 cm periphery and bottom of the root-ball using a pruning saw (Fig. 1B); 3) *Bare-root*

Table 1
Soil description and soil nutrient concentration of the field site for both transplant studies.

Soil series[1]	Marlette fine sandy loam
Typical profile[1]	Ap – 0 to 23 cm: fine sandy loam B/E – 23 to 41 cm: clay loam Bt – 41 to 91 cm: clay loam C – 91 to 203 cm: loam
Bulk density	1.64 g cm^{-3}
Soil pH	7.1
Phosphorus	22 mg kg^{-1}
Potassium	85 mg kg^{-1}
Magnesium	218 mg kg^{-1}
Calcium	1357 mg kg^{-1}

[1] Source: USDA NRCS Web Soil Survey.

Fig. 1. Examples of root-ball treatments. A – Control treatment. B – Shave treatment. C – Bare-root treatment (prior to root pruning).

airspade – removal of all container substrate using compressed air flow from a pneumatic air excavation tool (Series 2000, AirSpade®, Chicopee, MA, USA) (Fig. 1C), then any obvious root deformations, such as kinked or girdling roots, were removed with hand pruners; 4) *Bare-root wash* – root-balls were soaked in water approximately 12 h prior to additional handling, then, the following day, all container substrate was removed using the stream of water from a garden hose before removing any obvious root deformations using hand pruners.

To facilitate transplanting, planting holes were dug using a 90 cm diameter tractor-mounted auger. For trees in the control and shave treatments, planting holes were dug to a depth of 0.5 m. For trees in the bare-root airspade and bare-root wash treatments, the holes were augured to a depth of 0.3 m because there was less overall volume to plant following removal of container substrate. All trees were planted at grade. The trees were transplanted to a plot at the MSU HTRC and were planted in six rows, 2.7 m on center. When planting bare-root airspade and bare-root wash trees, the root systems were “mudded in” by slowly adding water and backfill to the root-ball, then trees were maneuvered to eliminate excess air pockets in the soil. For all treatments, the planting holes were filled with unamended backfill, and the trees were watered immediately after planting. We mulched all trees with a ring (1.5 m diameter) of ground blonde pine wood mulch to a depth of 8 cm. All trees were provided with supplemental irrigation (9.5 L per tree) when weekly rainfall was less than 2.5 cm (monitored online via the MSU Hort Farm Enviroweather station [<https://enviroweather.msu.edu/weather.php?stn=msu>]) and no rain was predicted in the immediate (2–3 day) forecast; based on these criteria, we watered four times each growing season. We controlled weeds by hand weeding and applying glyphosate three times per growing season to the mulch rings using a backpack sprayer, using care to avoid application on the trunks of the trees.

2.3. *Summer planting experiment*

On 11 July 2018, an additional subset of 27 trees (nine trees of each cultivar) that were free of obvious defects were transplanted from the pot-in-pot nursery to a plot adjacent to the spring planting at the MSU HTRC.

2.3.1. *Experimental design and treatments*

The experiment was installed as a 3 × 3 factorial of species (3) and root modification treatment (3) with three replications (N = 3). Replication was lower for summer planting than for spring planting because we anticipated mortality might be higher following the summer plant and we wanted to minimize the potential loss of valuable trees. Nine trees of each species were randomly assigned to one of three root-ball modification treatments. We followed the same procedure to transplant the trees as in the spring planting experiment and included three of the four root modification treatments: 1) *control*, 2) *shave*, and 3) *bare-root wash*. The bare-root airspade treatment was not used in the summer planting experiment due to inadequate number of acceptable trees available from the nursery, and trees that were bare-rooted with the airspade had poor survival following the spring planting.

2.4. *Assessments*

2.4.1. *Installation time and root removal treatments*

Total installation time was measured for each individual tree. We recorded the time to perform root modification treatments (shaving or bare-rooting) plus time to complete the tree planting procedure. We collected roots from each tree as they were removed during the shaving or bare-rooting procedures. The roots were subsequently dried and weighed.

2.4.2. *Soil moisture*

We assessed volumetric soil moisture weekly during the first two growing seasons using a portable time domain reflectometer (TDR) soil moisture system (Trase System 1, Soilmoisture Equipment Corp., Goleta, CA, USA). TDR rods were installed approximately 30 cm from the westerly base of a subset of 20 *P.* x *acerifolia* trees. We assessed soil moisture on *P.* x *acerifolia* only due to time and resource constraints. Soil moisture was read at a depth of 0−45 cm in the backfill soil.

2.4.3. *Leaf scorch, tree survival, and growth*

All trees were scored, by the same observer, for percentage of leaf scorch using a qualitative rating system (0–4; 0 = 0–10 % of total leaves scorched; 1 = 11–25 % of total leaves scorched; 2 = 26–50 % of total leaves scorched; 3 = 51–80 % of total leaves scorched; and 4 = 81–100 % of total leaves scorched) on 25 July 2018 (Fig. 2). Trees rated ≥3 were classified as exhibiting “extreme scorch.” On 24 May 2019, one observer scored all trees for percentage of dieback using a qualitative rating system (0 = no dieback; 4 = complete dieback) to assess the dieback on all limbs including lateral branches.

In September 2018 and 2019, 20 leaves per tree were collected at random from throughout the crown of each tree to calculate mean leaf size. Leaf size of each sample was measured using a leaf area meter (LI-3100C, LI-COR, Inc., Lincoln, NE, USA), and the samples were subsequently dried and weighed. Mean leaf size was calculated as the sum of the sample leaf area ÷ 20.

We measured height and stem caliper of all trees at the beginning and end of the 2018 and 2019 growing seasons to calculate annual growth. Tree mortality was assessed in October 2018, April 2019, and September 2019.

2.4.4. *Water relations and gas exchange*

Predawn leaf water potential (Ψ_w) was assessed every two to three

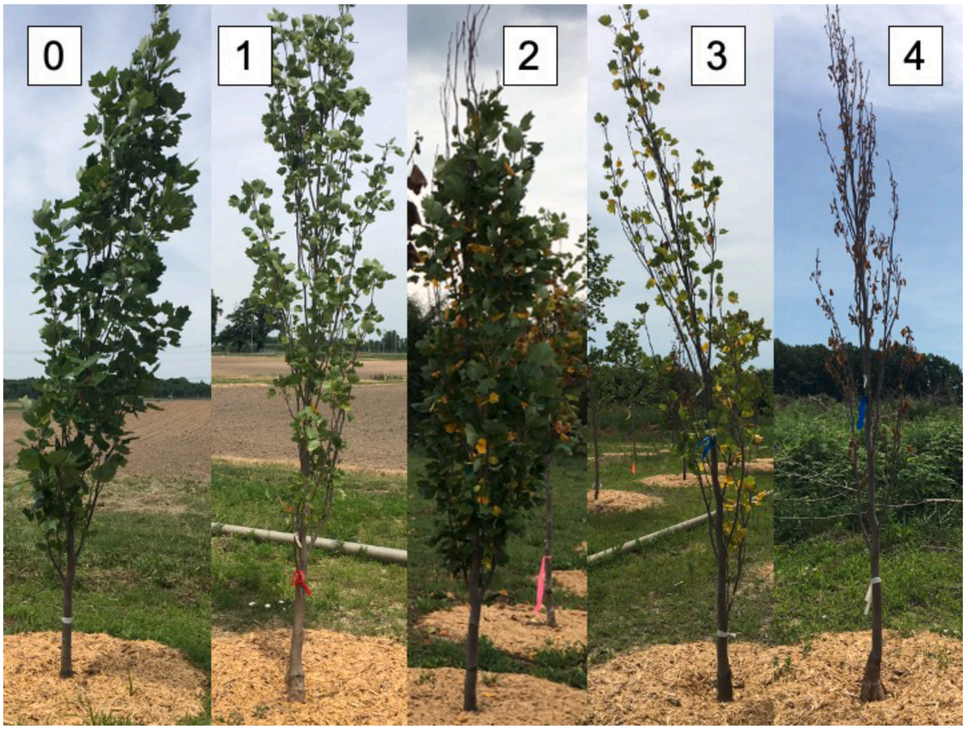

Fig. 2. Example representatives of the qualitative rating system based on percent of leaf scorch (shown for *L. tulipifera*). Left to right: 0 – 0-10 % of total leaves scorched; 1 – 11-25 % of total leaves scorched; 2 – 26-50 % of total leaves scorched; 3 – 51-80 % of total leaves scorched; and 4 – 81-100 % of total leaves scorched.

weeks during the 2018 and 2019 growing seasons using a portable pressure chamber (Model 1000, PMS Instrument Company, Albany, OR, USA). For the spring planting, leaf Ψ_w was measured on a subset of four of eight replications in order to balance logistics of the measurements and maintain sufficient replication for analyses. For the summer planting, leaf Ψ_w was measured on all living trees. Two fully-expanded leaves from mid-crown position were selected at random for each leaf Ψ_w measurement. The readings for both leaves were recorded and averaged.

We measured gas exchange on the same trees and dates that leaf Ψ_w was measured during the 2018 and 2019 growing seasons using a portable photosynthesis system (LI-6400XT, LI-COR, Inc., Lincoln, NE, USA) equipped with a 3 × 2-cm leaf chamber containing a red + blue light-emitting diode light source (LI-6400-02B). Gas exchange was measured twice on each date; once in late morning (between 0900 HR and 1200 HR) and once in early afternoon (between 1300 HR and 1500 HR). Net photosynthetic rate (P_n) was assessed on one east-facing, fully-expanded leaf from the mid-canopy. Environmental controls on the portable photosynthesis system were set to photosynthetic photon flux (*PPF*) $=1500$ mmol $m^{-2}s^{-1}$, reference CO_2 concentration $=400$ mmol mol^{-1}, and flow of air $=500$ mL min^{-1} during each measurement run.

2.4.5. Destructive harvest and root evaluation

In September 2019, we conducted a destructive harvest on a subset of four of the eight replications from the spring experiment excluding those lost to mortality (42 total trees). We did not harvest any trees from the summer planting due to mortality and limited replication. The aboveground portion of each tree was divided into three sections (leaves, branches, and trunk), and all portions were dried and weighed.

Following aboveground harvest, we excavated tree root systems using a 120 cm tractor-mounted tree spade. We removed all soil and remaining substrate from root systems using an air excavation tool (Series 2000, AirSpade®, Chicopee, MA, USA). Once soil was removed, excavated root systems were scored, by the same observer, for internal root defect rating (0–3; 0 = minimal defects, 3 = numerous defects) and for proportion of the periphery of the root-ball that had circling roots (% circling roots). Roots were trimmed from the root-ball and separated into two classes: 1) roots within the perceived outline of the original container (shave and control) or where root pruning had taken place (bare-root treatments) and 2) roots extending beyond the sides and bottom of the original root-ball (Fig. 3). Roots remaining in loose soil left by lifting the root-ball and roots remaining in the ground beyond the hole left by the tree spade were excavated with an airspade using a 20 min. timed search. These additional roots were collected and added to the roots in class 2 for each tree. All excavated roots were then rinsed with water and oven-dried before being further separated into two size classes, ≥ 6 mm in diameter or <6 mm, and weighed.

Fig. 3. Example excavated root system of *P.* x *acerifolia*; dashed line indicates perceived outline from the original nursery container.

2.4.6. *Statistical analysis*

Data were analyzed using SAS Version 9.2 software (SAS Institute Inc., Cary, NC, USA). PROC UNIVARIATE was used to test all variables for normality. For the spring planting, we conducted an analysis of variance (ANOVA) for a 3×4 factorial in a randomized complete block design (RDBD) with species and root treatment as main effects using PROC MIXED. For the summer planting, data were analyzed as a 3×3 factorial in an RCBD. For both experiments, block was considered a random factor and species and treatment were considered fixed factors Mean separation within species was performed using Tukey's Honestly Significant Difference (HSD) in the LSMEANS procedure of PROC GLIMMIX when species x root treatment interaction was significant. When modeling predawn leaf Ψ_w, data were logarithmically transformed to normalize residuals.

3. Results

3.1. *Weather and soil moisture*

Mean daily air temperatures during the growing seasons (mid-May to mid-October) were higher than average: 25.6 °C and 24.8 °C for 2018 and 2019, respectively. Total precipitation amounts during that time were 410 mm in 2018 and 369 mm in 2019. The seasonal rainfall deficit (rainfall – reference potential evapotranspiration) was similar for both study years: −125 mm and −122 mm in 2018 and 2019, respectively. 2018 was characterized by warm, dry weather in early summer, whereas 2019 was wet in early summer and dry later in the season.

Average volumetric soil moisture for 2018 and 2019 was 12.7 % and 8.6 %, respectively. Weekly volumetric soil moisture readings indicated consistent values throughout the 2018 growing season, ranging 9.7–14.1 %, while average soil moisture values in 2019 were highest (16.5 %) in late May then steadily decreased until average values stabilized around 5 % in mid-August.

3.2. *Planting time and roots removed*

Mean time to perform root modification and plant trees were averaged across both spring and summer planting experiments. The mean planting time for all control trees was 5 min. 44 s. Time to perform root modification treatments varied ($P < 0.001$) among species and root treatments with an interaction of species x root treatment. Overall, shaving added approximately 6 min to planting time. Bare-rooting with the airspade and bare-rooting by washing added approximately 25 and 50 min, respectively. *A. rubrum* trees had very dense root systems and took at least 60 % longer to bare-root than other species.

Total root biomass, biomass of roots ≥6 mm, and biomass of roots <6 mm removed when performing root modification treatments varied ($P < 0.01$) by species, root treatment, and their interaction when combined across spring and summer planting experiments. Trees in the control treatment had no root loss by nature of the treatment. The relative amount of root biomass removed varied among species (Table 2). Bare-rooting by airspade removed more ($P < 0.05$) root biomass ≥6 mm in diameter of *A. rubrum* trees compared to trees that had been shaved or unmodified (control). Shaving resulted in more ($P < 0.05$) total root and <6 mm root loss of *L. tulipifera* trees compared to bare-rooting by washing (Table 2). Root-ball modification (shaving, bare-root airspade, and bare-root washing) did not affect ($P > 0.05$) biomass of roots ≥6 mm of *P.* x *acerifolia* trees compared to the control (Table 2).

3.3. *Leaf scorch, tree survival, and growth*

In the spring planting, species, root treatment, and the interaction of species x root treatment affected ($P < 0.05$) mean scorch rating (0–4; 0 = no scorch, 4 = complete scorch). *L. tulipifera* trees subjected to bare-rooting consistently exhibited greater ($P < 0.05$) leaf scorch than control trees (Table 3). For *P.* x *acerifolia* and *A. rubrum* trees, those with modified root systems did not exhibit ($P > 0.05$) greater mean leaf scorch compared to control trees.

Bare-rooting by airspade and by washing increased ($P < 0.0001$) incidence of extreme leaf scorch (rating ≥ 3) of *L. tulipifera* trees following spring planting (Table 3). Species affected ($P < 0.05$) incidence of extreme leaf scorch; the percentage of *L. tulipifera* trees exhibiting extreme leaf scorch was consistently higher than *P.* x *acerifolia* or *A. rubrum* trees (Table 3). No *P.* x *acerifolia* trees showed extreme leaf scorch.

Mean leaf scorch ratings were generally higher for trees that were planted in July than those planted in May (Table 3). On 25 July 2018, approximately two weeks after transplant, 66.7 % of *A. rubrum* trees that were bare-rooted and 66.7 % of control trees exhibited extreme leaf scorch while 0% of shaved *A. rubrum* trees had extreme scorch (Table 3). For *L. tulipifera* trees, 100 % of those treated with bare-root wash, 66.67 % of control trees, and 33.3 % of shaved trees showed extreme leaf scorch. Only 33.3 % of *P.* x *acerifolia* control trees showed extreme leaf scorch compared to 66.7 % of bare-rooted trees and 100 % of shaved trees.

In the spring planting, species, root modification, and their interaction affected ($P < 0.001$) dieback condition rating (0 = no dieback; 4 = severe dieback) of trees following planting. Dieback was more severe ($P < 0.05$) for *L. tulipifera* trees in the bare-root airspade and bare-root wash treatments compared to the control. Among *P.* x *acerifolia* trees, dieback rating was higher ($P < 0.05$) for trees that were bare-rooted by washing compared to shave and control trees (Table 4). Root modification did not affect ($P > 0.05$) dieback rating of *A. rubrum* trees (Table 4). Following the summer planting, bare-rooting consistently resulted in a more severe ($P < 0.05$) stem dieback rating across species, and control trees had the lowest rating across species (Table 4).

Bare-rooting by washing reduced ($P < 0.05$) mean leaf size of *L. tulipifera* trees compared to control trees in 2018 and 2019. Bare-rooting via airspade also reduced leaf size, though it was not statistically significant due to smaller sample size as a result of tree mortality. Root treatment did not affect mean leaf size of *A. rubrum* or *P.* x *acerifolia*

Table 2
Mean dry weight (g) of roots (≥6 mm in diameter, <6 mm in diameter, and total root biomass) removed during root treatments of trees of three species subjected to four root modifications: control (no root modification), shave (outer 3 cm of roots removed), bare-root (BR)-airspade (all container substrate removed using an airspade, then root defects manually removed), or bare-root (BR)-wash (all container substrate removed using the stream of water from a garden hose, then root defects manually removed).

	A. rubrum			*L. tulipifera*			*P.* x *acerifolia*		
Root modification	≥6 mm (g)	<6 mm (g)	Total (g)	≥6 mm (g)	<6 mm (g)	Total (g)	≥6 mm (g)	<6 mm (g)	Total (g)
Control	0a	0a	0a	0a	0a	0a	0a	0a	0a
Shave	151b	424b	575b	133b	467c	600c	65a	229b	294b
BR-Airspade	249c	386b	635b	125b	361bc	486bc	66a	170ab	236b
BR-Wash	211bc	461b	672b	125b	273b	398b	68a	241b	309b

Note: Means shown are average of spring and summer plantings – n = 11. Means within a column followed by the same letter are not different at α = 0.05 level. Mean separation by Tukey's HSD.

Table 3

Mean scorch rating (0 to 4; 0 = no scorch, 4 = complete scorch) and percent of trees with extreme leaf scorch (rating ≥ 3) of three species subjected to four root modifications: control (no root modification), shave (outer 3 cm of roots removed), bare-root (BR)-airspade (all container substrate removed using an airspade, then root defects manually removed), or bare-root (BR)-wash (all container substrate removed using the stream of water from a garden hose, then root defects manually removed). The BR-airspade treatment was not included in the summer planting.

	Mean scorch rating					
	Spring Planting			Summer Planting		
	A. rubrum	*L. tulipifera*	*P.* x *acerifolia*	*A. rubrum*	*L. tulipifera*	*P.* x *acerifolia*
Control	0.63a	0.38a	0.25a	2.67a	2.33a	2.67a
Shave	0.25a	1.63ab	0.25a	2.00a	2.33a	3.33a
BR-Airspade	1.38a	3.75c	0.88a	.	.	.
BR-Wash	1.25a	2.50bc	1.13a	2.33a	3.67a	3.00a
	% with extreme scorch (rating ≥ 3)					
	Spring Planting			Summer Planting		
	A. rubrum	*L. tulipifera*	*P.* x *acerifolia*	*A. rubrum*	*L. tulipifera*	*P.* x *acerifolia*
Control	12.50a	0.00a	0.00a	66.67a	66.67a	33.33a
Shave	0.00a	37.50b	0.00a	0.00a	33.33a	100.00a
BR-Airspade	12.50a	87.50c	0.00a	.	.	.
BR-Wash	12.50a	37.50b	0.00a	66.67a	100.00a	66.67a

Note: n = 8 for Spring planting; n = 3 for Summer planting. Means within a column followed by the same letter are not different at α = 0.05 level. Mean separation by Tukey's HSD.

Table 4

Mean dieback rating (0 – no dieback; 4 – severe dieback) and 2018 and 2019 mean leaf size (cm^2) of trees of three species subjected to four root modifications: control (no root modification), shave (outer 3 cm of roots removed), bare-root (BR)-airspade (all container substrate removed using an airspade, then root defects manually removed), or bare-root (BR)-wash (all container substrate removed using the stream of water from a garden hose, then root defects manually removed) post-transplant. The BR-airspade treatment was not included in the summer planting.

		Spring Planting				Summer Planting		
	n	Mean dieback rating 2019	Mean leaf size (cm^2) 2018	Mean leaf size (cm^2) 2019	n	Mean dieback rating 2019	Mean leaf size (cm^2) 2018	Mean leaf size (cm^2) 2019
A. rubrum								
Control	7	1.0a	37.3a	36.3a	3	2.3a	16.5a	32.0a
Shave	8	0.0a	33.6a	32.7a	2	2.7a	18.1a	28.4a
BR - Airspade	7	1.1a	22.7a	31.7a	.	.	.	.
BR - Wash	7	0.8a	22.0a	28.6a	3	3.3a	14.1a	31.1a
L. tulipifera								
Control	8	0.4a	62.8	63.3	3	1.0a	55.8a	52.8a
Shave	5	1.8ab	53.6	56.2	3	1.0a	44.2ab	45.4a
BR - Airspade	1	3.9c	17.5*	44.8*	.	.	.	.
BR - Wash	4	2.9bc	27.2	44.9	1	4.0a	12.2b	.
P. x acerifolia								
Control	8	0.0a	46.9a	77.8a	3	1.3a	53.6a	82.2a
Shave	8	0.1a	65.0a	81.2a	2	2.3a	54.9a	72.9ab
BR - Airspade	8	1.0ab	52.1a	80.3a	.	.	.	.
BR - Wash	8	1.75b	51.5a	72.9a	2	3.0a	54.1a	50.3b

Means within a column followed by the same letter are not different at α = 0.05 level within each species. Mean separation by Tukey's HSD. *Root modification effect was significant at α = 0.05, however means did not separate under HSD.

Table 5

Overall survival (%) of trees of three species subjected to four root modifications: control (no root modification), shave (outer 3 cm of roots removed), bare-root (BR)-airspade (all container substrate removed using an airspade, then root defects manually removed), or bare-root (BR)-wash (all container substrate removed using the stream of water from a garden hose, then root defects manually removed) and overall survival (%) among root treatments two years post-transplant. The BR-airspade treatment was not included in the summer planting.

	Survival (%)					
	Spring Planting			Summer Planting		
	A. rubrum	*L. tulipifera*	*P.* x *acerifolia*	*A. rubrum*	*L. tulipifera*	*P.* x *acerifolia*
Control	75.0a	100.0a	100.0a	66.7a	100.0a	100.0a
Shave	100.0a	62.5ab	100.0a	33.3a	100.0a	66.7a
BR-Airspade	87.5a	12.5c	100.0a	.	.	.
BR-Wash	87.5a	50.0bc	100.0a	66.7a	0.0b	33.3a

Note: n = 8 for spring planting; n = 3 for summer planting. Means within a column followed by the same letter are not different at α = 0.05 level. Mean separation by Tukey's HSD.

trees (Table 4).

Tree growth was generally not affected in response to root treatments. Tree height was not affected ($P > 0.05$) by root treatments in either planting after two growing seasons. Following the spring planting, *A. rubrum* trees in the control group had greater ($P < 0.05$) mean caliper growth after two years in the landscape compared to those in the bare-root wash treatment. There were no other differences in caliper growth among species in either spring or summer planting (data not shown).

Root modification, species, and species x root modification interaction affected ($P < 0.05$) tree survival following spring planting. Mortality of *L. tulipifera* trees occurred in all root modification treatments, and only one of eight *L. tulipifera* trees that were bare-rooted with the airspade survived; no *L. tulipifera* trees in the control group died (Table 5). Survival of *P.* x *acerifolia* trees was 100 % for all treatments while survival of *A. rubrum* trees was variable (Table 5). Following summer planting, root modification decreased ($P < 0.05$) tree survival. Overall, 6 out of 9 trees that were bare-rooted died. All *L. tulipifera* trees that were bare-rooted died, while survival of *L. tulipifera* trees that had shaved or unmodified (control) root systems was 100 % (Table 5). Survival of *A. rubrum* trees was 66.67 % for both control and bare-rooted trees and was 33.33 % for trees with shaved root systems. For *P.* x *acerifolia* trees, 100 % of control, 66.67 % of shaved, and 33.33 % of bare-rooted trees survived.

3.4. *Water relations and gas exchange*

3.4.1. *Leaf water potential*

Predawn leaf Ψ_w responses were complex and reflected the effects of species, root treatment, date, and all 2-way interactions (Fig. 4). For all species, bare-rooting with an airspade reduced ($P < 0.05$) leaf Ψ_w on the measurement date two weeks after spring planting. For both *L. tulipifera* and *P.* x *acerifolia* trees, bare-rooting by washing also reduced ($P < 0.05$) predawn leaf Ψ_w following planting compared to trees with shaved root systems or untreated controls. *L. tulipifera* trees subjected to the bare-root airspade treatment were not sampled after July 2018 due to mortality. For the remainder of the 2018 season and the 2019 season leaf Ψ_w did not vary among treatments for either *A. rubrum* or *P.* x *acerifolia* trees (Fig. 4).

Predawn leaf Ψ_w varied ($P < 0.05$) among species in the summer planting. One week after planting, *A. rubrum* trees subjected to shaving had the highest values of predawn leaf Ψ_w, and the control trees had the lowest values ($P = 0.057$) (Fig. 4). Two weeks later, trees that were

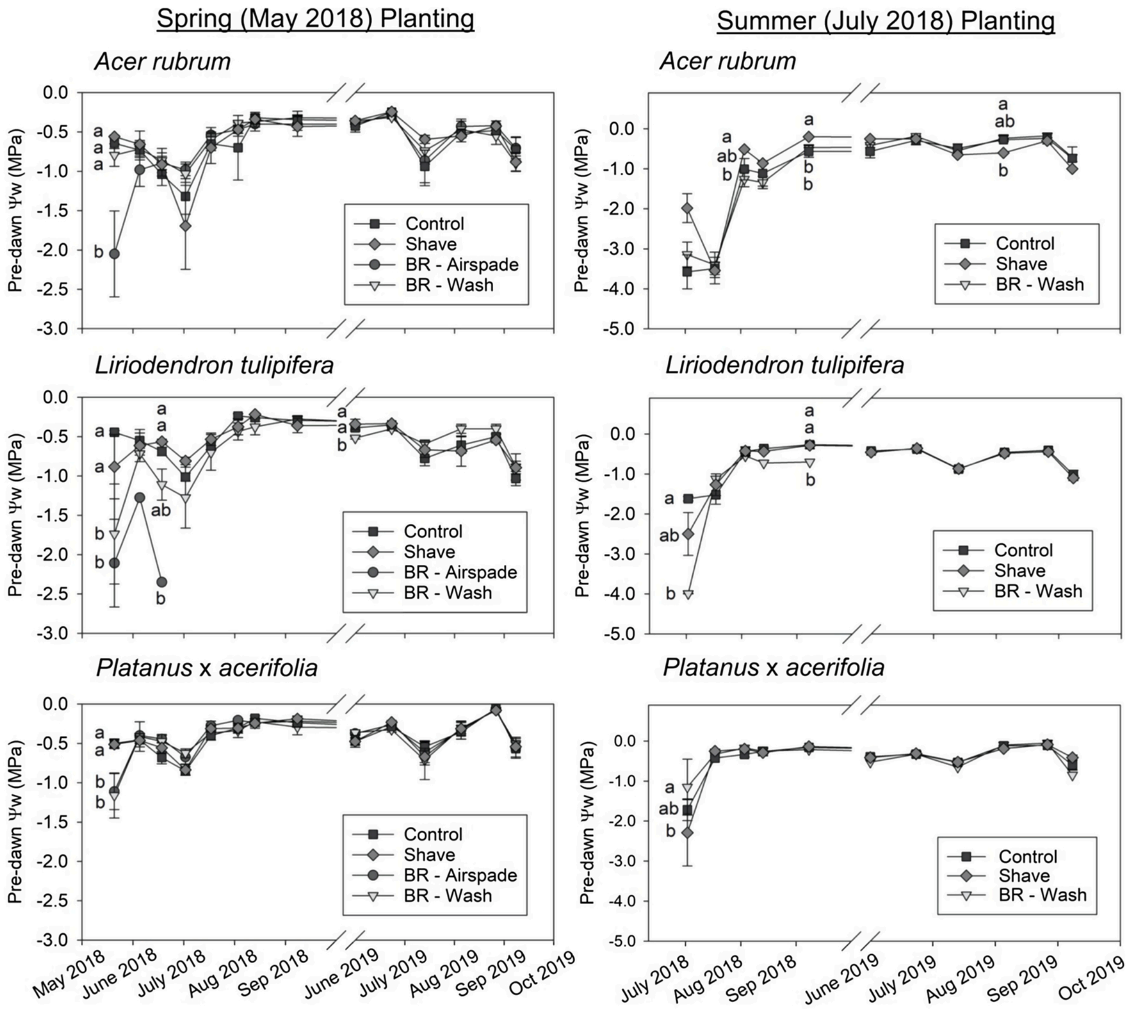

Fig. 4. Mean (± SE) predawn leaf Ψ_w of trees of three species subjected to four root modifications: control (no root modification), shave (outer 3 cm of roots removed), bare-root (BR)-airspade (all container substrate removed using an airspade, then root defects manually removed), or bare-root (BR)-wash (all container substrate removed using the stream of water from a garden hose, then root defects manually removed) post-transplant. Following the spring planting, *L. tulipifera* trees subjected to BR-airspade treatment were not sampled after July 2018 due to mortality. The BR-airspade treatment was not included in the summer planting. Note: For the spring planting, n = 8 for *A. rubrum* and *P.* x *acerifolia*; n is variable for *L. tulipifera*. For the summer planting, n is variable for all species due to tree mortality. Means within a species not followed by the same letter are significantly different at α = 0.05 level on a given measurement date. Mean separation by Tukey's HSD. On dates where no mean separation is indicated, means are not different.

shaved or bare-rooted had similar leaf Ψ_w values to the control trees (Fig. 4). At the end of 2018, leaf Ψ_w was highest ($P < 0.05$) for trees with shaved root systems, but this trend did not carry into 2019 (Fig. 4). Following planting, bare-rooting reduced ($P < 0.05$) leaf Ψ_w values of *L. tulipifera* trees compared to control trees (Fig. 4). *L. tulipifera* trees subjected to the bare-root wash treatment were not sampled after September 2018 due to mortality. Throughout 2019, shaved and control *L. tulipifera* trees had similar values (Fig. 4). *P.* x *acerifolia* trees had higher values of leaf Ψ_w compared with the other species. Immediately following planting, *P.* x *acerifolia* trees that were shaved had the lowest leaf Ψ_w values, and trees that were bare-rooted by washing had the highest values (Fig. 4). Except for the first measurement date post-transplant, *P.* x *acerifolia* trees had similar values of leaf Ψ_w across all root treatments (Fig. 4).

3.4.2. Net photosynthesis

Two weeks after planting in May, P_n was relatively low (generally <10 μmol $m^{-2}s^{-1}$) for all species through mid-July and then increased steadily through the rest of the growing season (Fig. 5). Root modification did not affect ($P > 0.05$) P_n, and values for P_n were similar for all root modification treatments within species (Fig. 5).

The effect of root modifications on P_n of summer-planted trees was not consistent between species. Bare-rooting reduced ($P < 0.05$) the rate of P_n of *A. rubrum* trees compared to controls at the end of 2018 and in June 2019 (Fig. 5). In August 2019, P_n was highest ($P < 0.05$) for *A. rubrum* trees that were bare-rooted (Fig. 5). Two weeks following planting, P_n was higher ($P < 0.05$) for *L. tulipifera* trees that were bare-rooted compared to trees with shaved or unmodified (control) root systems (Fig. 5). However, *L. tulipifera* trees subjected to the bare-rooting treatment were not sampled after September 2018 due to mortality. There were no differences in P_n for *L. tulipifera* trees in 2019 (Fig. 5). P_n of *P.* x *acerifolia* trees was consistently higher ($P < 0.05$) compared to other species. Immediately following planting, shaving increased ($P < 0.05$) P_n of *P.* x *acerifolia* trees; for the remainder of 2018 and 2019, there were no differences in P_n among treatments (Fig. 5).

3.5. Destructive harvest

3.5.1. Aboveground biomass

Approximately half, excluding those lost to mortality, of the spring-planted trees were subjected to a destructive harvest; trees in the summer planting were not included in harvest. Species and root modification affected ($P < 0.05$) all measures of aboveground biomass (leaf, branch, trunk, and total) two years post-transplant (Table 6). Total

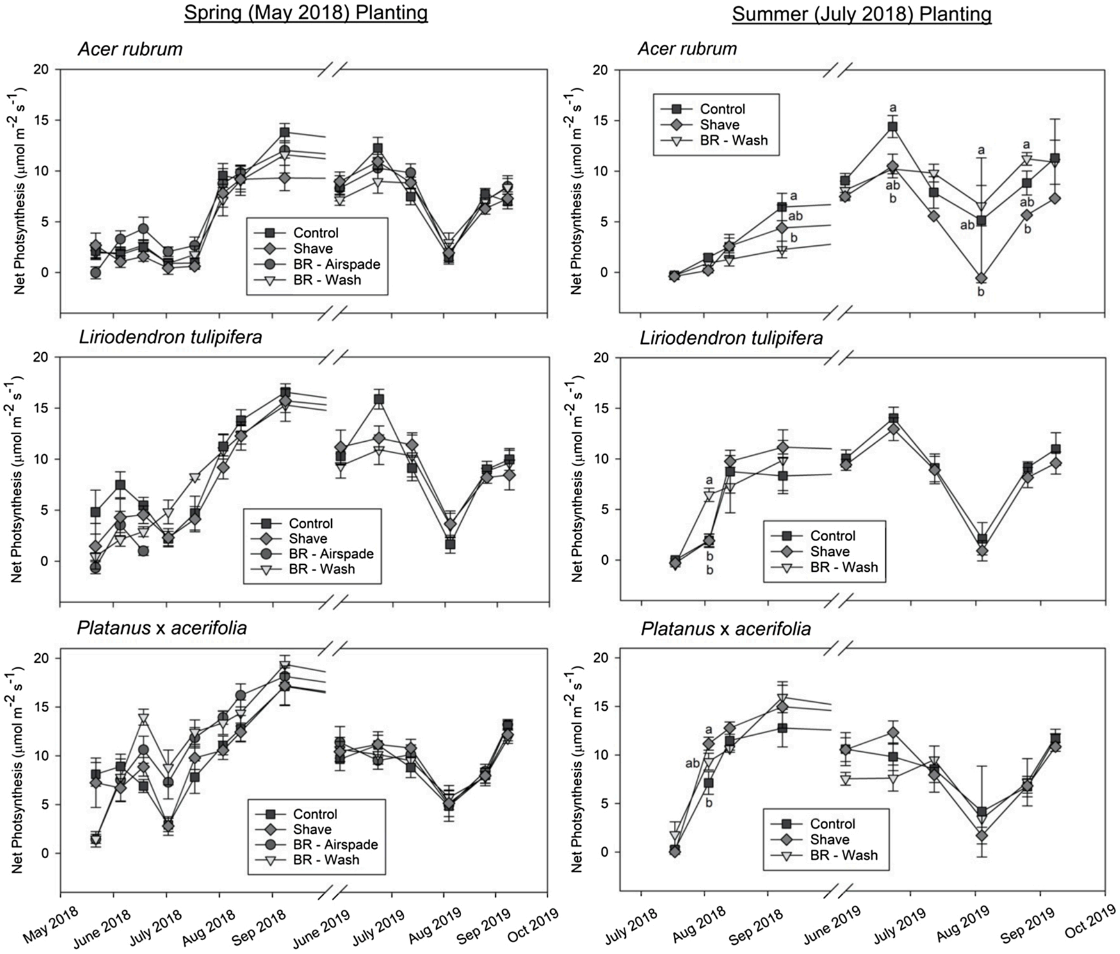

Fig. 5. Mean (± SE) net photosynthesis (μmol·$m^{-2}s^{-1}$) of trees of three species subjected to four root modifications: control (no root modification), shave (outer 3 cm of roots removed), bare-root (BR)-airspade (all container substrate removed using an airspade, then root defects manually removed), or bare-root (BR)-wash (all container substrate removed using the stream of water from a garden hose, then root defects manually removed) post-transplant. Following the spring planting, *L. tulipifera* trees subjected to BR-airspade treatment were not sampled after July 2018 due to mortality. The BR-airspade treatment was not included in the summer planting.

Note: For the spring planting, n = 8 for *A. rubrum* and *P.* x *acerifolia*; n is variable for *L. tulipifera*. For the summer planting, n is variable for all species. Means within a species not followed by the same letter are significantly different at $\alpha = 0.05$ level on a given measurement date. Mean separation by Tukey's HSD. On dates where no mean separation is indicated, means are not different.

Table 6
Mean aboveground biomass (g) of trees of three species from the spring planting subjected to four root modifications: control (no root modification), shave (outer 3 cm of roots removed), bare-root (BR)-airspade (all container substrate removed using an airspade, then root defects manually removed), or bare-root (BR)-wash (all container substrate removed using the stream of water from a garden hose, then root defects manually removed) two years post-transplant. *L. tulipifera* trees subjected to BR-airspade treatment were not harvested due to mortality.

	Aboveground Biomass			
	Leaf (g)	Branch (g)	Trunk (g)	Total (g)
A. rubrum				
Control	937.0a	1239.0a	2498.0a	4674.0a
Shave	698.4b	969.3ab	2018.0ab	3685.7b
BR-Airspade	560.3b	750.4b	1814.0b	3124.7b
BR-Wash	661.0b	772.2b	1851.0b	3284.2b
L. tulipifera				
Control	387.4a	973.0a	1786.3a	3146.7a
Shave	360.0a	946.7a	1586.6ab	2893.3ab
BR-Airspade	.	.	.	.
BR-Wash	224.7a	639.8a	1190.9b	2055.4b
P.* x *acerifolia				
Control	549.9a	1280.2a	2073.8a	3903.9a
Shave	488.2a	1045.4ab	2202.7a	3736.3a
BR-Airspade	401.0a	956.4ab	1787.4a	3144.8a
BR-Wash	351.4a	860.3b	1748.3a	2960.0a

Note: n = 4 for *A. rubrum* and *P.* x *acerifolia*; n = 4 for *L. tulipifera* trees in the control treatment; n = 3 for *L. tulipifera* trees subjected to shave and BR-wash treatments due to mortality. Means within species followed by the same letter are not different at α = 0.05 level within each species. Mean separation by Tukey's HSD.

aboveground biomass and leaf biomass of *A. rubrum* trees was higher ($P < 0.05$) for the control trees compared to those with root modification; bare-rooting (airspade and washing) reduced ($P < 0.05$) branch and trunk biomass of *A. rubrum* trees compared to the control (Table 6). Among *L. tulipifera* trees, bare-root washing reduced ($P < 0.05$) total aboveground biomass and trunk biomass compared to control trees (Table 6). *L. tulipifera* trees that were bare-rooted with the airspade were not included in the harvest due to mortality. Leaf and branch biomass among *L. tulipifera* trees were not affected by root treatment (Table 6). Root treatment did not affect ($P > 0.05$) total aboveground, leaf, or trunk biomass of *P.* x *acerifolia* trees; bare-root washing reduced ($P < 0.05$) stem biomass of *P.* x *acerifolia* trees (Table 6).

3.5.2. Root biomass and root quality

The effect of root modification on root growth and quality varied by species. Root modification treatments did not affect ($P > 0.05$) root biomass extending beyond the original root-ball (Table 7), though shaving and bare-rooting visibly improved lateral root spread following treatment (Fig. 6). *P.* x *acerifolia* trees that were bare-rooted or root-shaved had fewer ($P < 0.05$) internal root defects compared to control trees (Table 7), but root modifications did not improve internal root quality of *A. rubrum* and *L. tulipifera* trees. The bare-root airspade and bare-root wash treatments reduced the mean proportion of the root system with circling roots across all three species (Fig. 7). Shaving reduced circling roots of *L. tulipifera* and *P.* x *acerifolia* trees but not *A. rubrum* trees (Fig. 7).

4. Discussion

It is estimated that greater than 80 % of landscape plant problems originate from roots and surrounding soils (Watson and Himelick, 2013). Therefore, planting quality root systems is crucial for successful tree establishment, especially in urban settings where soil properties are often suboptimal. The need to plant large caliper trees is increasing as cities across the United States set goals to rapidly increase canopy cover (McPhearson et al., 2010; Nguyen et al., 2017), and some municipalities are grappling with canopy loss due to exotic pest outbreaks such as emerald ash borer (Kovacs et al., 2010). Life expectancy of an urban tree is as little as 7–11 years (Hilbert et al., 2019), yet tree survival is critical to attaining maximum ecosystem benefits provided by mature trees.

Table 7
Mean root biomass (g) and internal root defect rating (0 to 3; 0 = minimal defects, 3 = numerous defects) of trees of three species from the spring planting subjected to four root modifications: control (no root modification), shave (outer 3 cm of roots removed), bare-root (BR)-airspade (all container substrate removed using an airspade, then root defects manually removed), or bare-root (BR)-wash (all container substrate removed using the stream of water from a garden hose, then root defects manually removed) two years post-transplant. *L. tulipifera* trees subjected to BR-airspade treatment were not harvested due to mortality.

		Outside original root-ball			
	Inside original root-ball (g)	$\geq$ 6 mm (g)	< 6 mm (g)	Total (g)	Internal root defect rating
A. rubrum					
Control	4216.5a	176.5a	590.1a	766.6a	3.00a
Shave	3448.6ab	61.7a	422.6a	484.3a	3.00a
BR-Airspade	2202.3c	153.6a	429.5a	583.1a	2.50a
BR-Wash	2636.4bc	58.4a	468.4a	526.8a	2.75a
L. tulipifera					
Control	1448.0a	20.9a	259.8a	280.6a	3.00a
Shave	1405.2a	24.9a	277.9a	302.8a	2.00a
BR-Airspade	.	.	.	.	.
BR-Wash	1207.0a	3.5a	94.5a	98.0a	3.00a
P.* x *acerifolia					
Control	1612.4a	57.4a	171.4a	228.8a	2.25a
Shave	1373.1a	72.2a	173.8a	246.0a	0.75b
BR-Airspade	1188.1a	75.3a	166.9a	242.1a	1.50ab
BR-Wash	1013.7a	22.5a	241.1a	263.6a	1.00b

Note: n = 4 for *A. rubrum* and *P.* x *acerifolia*; n = 4 for *L. tulipifera* trees in the control treatment; n = 3 for *L. tulipifera* trees subjected to shave and BR-wash treatments due to mortality. Means within species followed by the same letter are not different at α = 0.05 level within each species. Mean separation by Tukey's HSD.

Survival of trees in response to root modifications was variable and dependent on species and season (Table 4). For both experiments, all but two trees (both *A. rubrum*) in the control group survived. Following planting in May, some *L. tulipifera* trees died in all root treatment groups, and bare-rooting using the airspade reduced survival of *L. tulipifera* trees compared to control trees. Conversely, there was no mortality among *P.* x *acerifolia* trees in any treatment group. There was no mortality among *A. rubrum* trees with shaved root systems, whereas at least one tree in each of the other treatment groups died. This suggests differences in the ability of various species to tolerate moderate to severe root modification. The degree to which each species can manage root severance and the physiological differences between species that allow higher tolerance of root loss compared to others is not completely understood, but species differences in root regeneration potential (Struve, 2009), root carbohydrate status, and/or desiccation tolerance (Bates et al., 1994; Ellison et al., 2016) likely play a role in transplantability and subsequent tree establishment.

The low survival of trees planted in July compared to those planted in May highlights the importance of time of year in planting success. Timing is an important factor in transplanting trees regardless of production method (Appleton and Flott, 2009; Buckstrup and Bassuk, 2009; Harris and Bassuk, 1994; Richardson-Calfee et al., 2010; Watson and Himelick, 1982). In general, cooler air temperatures in spring limit transpiration rates which allows trees to allocate stored carbohydrates to root production rather than photosynthetically active tissue. Trees

Fig. 6. Examples of root systems of three species from the spring planting subjected to four root modifications harvested two years after transplanting. Top to bottom: *A. rubrum*; *L. tulipifera; P.* x *acerifolia*. Left to right: Control – no root-ball modification prior to planting; Shave – outer 3 cm of roots removed prior to planting; Bare-root airspade – all container substrate removed using an airspade, then root defects manually removed prior to planting; Bare-root wash – all container substrate removed using the stream of water from a garden hose, then root defects manually removed prior to planting. *L. tulipifera* trees subjected to BR-airspade treatment were not harvested due to mortality.

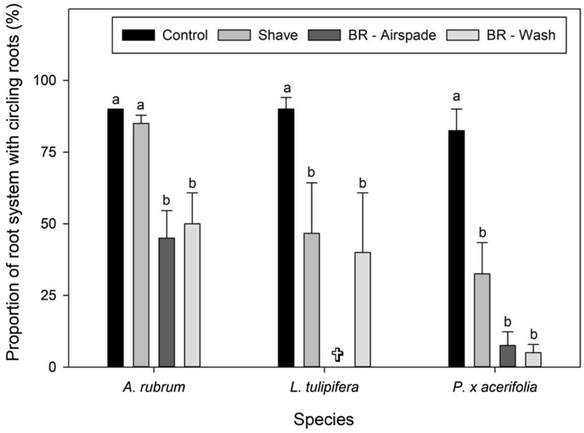

Fig. 7. Mean (± SE) proportion of the root-ball with circling roots (%) of trees of three species from the spring planting subjected to four root modifications: control (no root modification), shave (outer 3 cm of roots removed), bare-root (BR)-airspade (all container substrate removed using an airspade, then root defects manually removed), or bare-root (BR)-wash (all container substrate removed using the stream of water from a garden hose, then root defects manually removed) two years post-transplant. *L. tulipifera* trees subjected to BR-airspade treatment were not harvested due to mortality.
Note: n = 4 for *A. rubrum* and *P.* x *acerifolia*; n = 4 for *L. tulipifera* trees in the control treatment; n = 3 for *L. tulipifera* trees subjected to shave and BR-wash treatments due to mortality. Means within species followed by the same letter are not different at $\alpha = 0.05$ level within each species. Mean separation by Tukey's HSD.

planted in summer may require more irrigation compared to spring planting because the higher air temperatures result in increased water demand from a limited root system (Watson and Himelick, 2013), although in the current study mid-summer rainfall resulted in fairly consistent soil moisture levels across the 2018 growing season. Nonetheless, transplant season may be important when performing root modifications that result in root severance and reduction in fine, water-absorbing roots.

Providing supplemental irrigation is critical for post-transplant root growth (Barnett, 1986; Watson and Himelick, 2013), especially when transplanting trees from containers (Gilman, 2001; Yin et al., 2017). Still, species with low root growth potential may not benefit from additional irrigation if they cannot regenerate sufficient fine roots to facilitate water uptake. Regeneration of fine roots increases root hydraulic conductance which helps mitigate moisture stress (Jacobs et al., 2004; Yin et al., 2014). Because typical container substrate generally has low water retention, the removal of this media by bare-rooting reduces rapid water drainage out of the root zone of newly transplanted trees. Removal of container substrate improves root-soil contact which can further aid in water uptake, but bare-rooting also increases vulnerability of trees to desiccation (Bassuk & Buckstrup, 2009; Yin et al., 2017).

Lack of negative effect of root modification on predawn leaf Ψ_w, except immediately after planting, suggests that individual trees have the potential to achieve an equilibrium if they are able to survive the initial stresses associated with root loss and interruption of root-soil contact (Kjelgren and Cleveland, 1994; Watson and Himelick, 2013). After the first measurement date following transplant in May, trees across all species with modified root systems, regardless of the technique, had similar values of predawn leaf Ψ_w compared to control trees (except for *L. tulipifera* trees bare-rooted with an airspade that were unable to recover and died two months post-transplant). For trees planted in July, root modification did not affect values of predawn leaf Ψ_w, except immediately after transplanting Whole-plant responses such as reduced leaf area resulting from leaf scorch, stem dieback and reduced leaf size following root modification likely resulted in reduced whole-tree transpiration and conserved water. As Kjelgren and Cleveland (1994) note, this may explain the lack of differences in leaf-level gas exchange (P_n) in response to root modifications. The ability of trees to adapt and conserve water by reducing transpiring surface area reinforces the notion that if trees survive the initial period of transplant stress, they can achieve water status equilibrium (Benson et al., 2019; Kjelgren and Cleveland, 1994; Pallardy, 2008; Solfjeld and Hansen, 2004).

Root growth post-transplant is dependent on species and season (Arnold and Struve, 1989; Watson, 2004; Watson and Himelick, 2013). Some species are able to initiate root growth more quickly than others; for example, following transplant, *Acer saccharum* trees began root regeneration 4–6 weeks earlier than *Quercus rubra* trees depending on planting time (Harris et al., 2002).

Shaving and bare-rooting by washing reduced internal root defects of *P.* x *acerifolia* trees. Shaving also reduced root circling for *L. tulipifera* and *P.* x *acerifolia* trees. This result is consistent with other studies that have shown visual improvements of root system quality following shaving at transplant (Cregg and Ellison, 2018; Gilman et al., 2010c; Gilman and Wiese, 2012). Shaving did not reduce circling roots of *A. rubrum* trees, likely due to the nature of their dense, fibrous root systems. Bare-rooting with the airspade and bare-root washing reduced circling roots for all species. Root treatments, however, did not increase new root biomass extending beyond the original root-ball.

Modifying roots of container-grown trees at transplant has the potential to improve root establishment and ultimately tree longevity in urban and community forests, but clearly species and planting season need to be considered prior to making generalized recommendations (Buckstrup and Bassuk, 2000; Harris and Bassuk, 1994; Richardson-Calfee and Harris, 2005). Moreover, modifying roots can be laborious and may require specialized equipment. Time to perform the shave technique and finish tree planting was similar to the time required to plant the control for all species. Bare-rooting with the airspade and bare-rooting by washing added approximately 25 and 50 min, respectively, but the root modification techniques can likely be optimized with sufficient labor and equipment to remove container-substrate and prune out malformed roots. For example, in the current study we shaved root systems using handsaws, whereas some arborists and landscapers use power equipment (e.g., reciprocating saws) to shave roots. Gilman et al. (2010c) recommends root shaving in the landscape using a sharp digging shovel.

Supplemental research of root modification of container nursery stock with additional species is necessary, especially species known to be difficult to transplant (e.g., *Carpinus* spp., *Liriodendron tulipifera*, *Ostrya virginiana*, *Quercus alba*, *Taxodium distichum*). Since it is well documented that species differ with regard to root growth potential, carbohydrate status, and desiccation tolerance, future studies should aim to better understand which of these characteristics, or other morphological or physiological differences, affect transplantability of various species. Additional research will allow arborists to build an evidence-based framework of standard practices involving root modification techniques. Those interested in performing these root treatments are advised to start with species known to transplant easily bareroot – see Buckstrup and Bassuk (2009) for a list of species suitable for transplanting bareroot (hardiness zone 6). Due to high mortality in the summer experiment, we recommend performing root modifications in the dormant season, however, this recommendation largely negates the benefit of a longer transplanting window of container-grown trees compared to other stock types.

5. Conclusion

Response of trees to root modification differed among species and between planting dates. We found that use of root modification treatments at transplant reduced instance of root circling but did not increase root egress in the surrounding soil two years post-transplant. If additional precautions are taken to minimize moisture stress, trees with modified root systems can achieve a functional equilibrium. More studies are necessary before recommending these techniques for all shade tree species.

For practitioners interested in trialing shaving and/or bare-rooting container-grown trees, we advise performing root modification in the dormant season and avoiding species known to be difficult to transplant as bareroot stock. The root modification techniques may be ill advised for landscape professionals unless clients are comfortable with the aesthetic risks involved, such as leaf drop and stem dieback, following transplant.

Funding

This research was supported by USDA National Institute of Food and Agriculture, Hatch ProjectMICL02403 through Michigan State University AgBioResearch; Michigan's plant agriculture initiative, Project GREEEN grant GR18-040; the Michigan Agricultural and Rural Development Horticulture fund; and the J. Frank Schmidt Family Charitable Foundation.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

We gratefully acknowledge in-kind contributions from J. Frank Schmidt & Son, Co., Nursery Supplies, Inc., ICL Fertilizers, and Renewed Earth, Inc. Dr. Brad Rowe and Dr. Asia Dowtin provided helpful reviews of an earlier version of this manuscript. We thank Jay Andrews, Bill Chase, Mitchell Fox, and the MSU Horticulture Teaching and Research Center staff for assistance with tree installation, plot maintenance, and tree harvest. We acknowledge Linda Chalker-Scott for discussions on project design and on-site instruction on the bare-rooting technique. We thank Jerry Wahl and MSU Landscape Services for use of their Air-Spade®. We gratefully thank Dana Ellison-Smith, Becky Pobst, Alex Love, Kimberley Le, and Austin Wujkowski for field work assistance.

References

Amoroso, G., Frangi, P., Piatti, R., Ferrini, F., Fini, A., Faoro, M., 2010. Effect of container design on plant growth and root deformation of littleleaf linden and field elm. HortScience 45 (12), 1824–1829.

Appleton, B.L., 1993. Nursery production alternatives for reduction or elimination of circling tree roots. J. Arboric. 19 (6), 383–388.

Appleton, B.L., 2007. The bare root of the matter. Am. Nurseryman 205 (10), 41–42, 44–46.

Appleton, B., Flott, J., 2009. Bare root to bare root–coming full circle. In: Watson, G.W., Costello, L., Scharenbroch, B., Gilman, E. (Eds.), The Landscape Below Ground III: Proceedings of an International Workshop on Tree Root Development in Urban Soils. The International Society of Arboriculture, Champaign, IL, pp. 182–190.

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. Am. Soc. Hortic. Sci. 121 (2), 258–263.

Arnold, M.A., Struve, D.K., 1989. Green ash establishment following transplant. J. Am. Soc. Hortic. Sci. 114, 591–595.

Barnett, D., 1986. Root growth and water use by newly transplanted woody landscape plants. Public Garden: J. Am. Assoc. Bot. Gardens Arboreta 1 (2), 23–25.

Bates, R.M., Niemiera, A.X., Seiler, J.R., 1994. Cold storage method affects root and shoot water potential of bare-root hawthorn and maple trees. J. Environ. Hortic. 12 (4), 219–222.

Benson, A.R., Morgenroth, J., Koeser, A.K., 2019. The effects of root pruning on growth and physiology of two *Acer* species in New Zealand. Urban For. Urban Green. 38, 64–73.

Buckstrup, M.J., Bassuk, N.L., 2000. Transplanting success of balled-and-burlapped versus bare-root trees in the urban landscape. J. Arboric. 26 (6), 298–308.

Buckstrup, M.J., Bassuk, N.L., 2009. Creating the Urban Forest: the Bare Root Method. Cornell University, Ithaca, NY, USA, 16 pp.

Chalker-Scott, L., 2012a. Protecting Water Resources: Planting and Caring for Trees and Shrubs in Home Wetlands. Washington State University Extension Fact Sheet FS091E. https://www.whidbeycd.org/uploads/1/1/6/8/11683986/protecting_water_resources_-_planting__caring_for_trees__shrubs_in_home_wetlands.pdf.

Chalker-Scott, L., 2012b. Take It All Off! The Bare-root Method of Installing Trees and Shrubs [PowerPoint Slides]. SlideShare. https://www.slideshare.net/LindaCS/bare-root-primer.

Chalker-Scott, L., 2020. Root washing: why and how to wash roots. Fine Garden. 191, 22–24.

Chalker-Scott, L. (n.d.). You shouldn't Disturb the Rootball when Transplanting Trees and Shrubs. Washington State University Puyallup Research and Extension Center. https://s3.wp.wsu.edu/uploads/sites/403/2015/03/fragile-roots.pdf.

Chalker-Scott, L., Stout, T., 2009. Bare-rooting containerized materials: a comparison of installation techniques. In: Watson, G.W., Costello, L., Scharenbroch, B., Gilman, E. (Eds.), The Landscape Below Ground III: Proceedings of an International Workshop on Tree Root Development in Urban Soils. The International Society of Arboriculture, Champaign, IL, pp. 191–204.

Cotrone, V.C., 2019. Container Grown Trees and Shrubs – Fix Those Roots Before You Plant. PennState Extension. https://extension.psu.edu/container-grown-trees-and-shrubs-fix-those-roots-before-you-plant.

Coutts, M.P., 1983. Root architecture and tree stability. In: Atkinson, D., Bhat, K.K.S., Coutts, M.P., Mason, P.A., Read, D.J. (Eds.), Tree Root Systems and Their Mycorrhizas. Martinus Nijhoff/Dr. W. Junk Publishers, Dordrecht, The Netherlands, pp. 171–188.

Cregg, B., Ellison, D., 2018. Growth and establishment of container-grown London planetrees in response to mulch, root-ball treatment and fertilization. Urban For. Urban Green. 35, 139–147.

Davidson, H., Mecklenburg, R., Peterson, C., 2000. Nursery Management: Administration and Culture. Prentice Hall, Upper Saddle River, NJ.

Ellison, D.S., Schutzki, R., Nzokou, P., Cregg, B., 2016. Root growth potential, water relations and carbohydrate status of ash alternative species following pre-plant storage. Urban For. Urban Green. 18, 59–64.

Gilman, E.F., 1994. Establishing trees in the landscape. In: Neely, D., Watson, G.W. (Eds.), The Landscape Below Ground: Proceedings of an International Workshop on Tree Root Development in Urban Soils. International Society of Arboriculture, Champaign, IL, pp. 69–77.

Gilman, E.F., 2001. Effect of nursery production method, irrigation, and inoculation with mycorrhizae-forming fungi on establishment of *Quercus virginiana*. J. Arboric. 27 (1)), 30–39.

Gilman, E.F., Beeson Jr., R.C., 1996. Nursery production method affects root growth. J. Environ. Hortic. 14 (2), 88–91.

Gilman, E.F., Wiese, C., 2012. Root pruning at planting and planting depth in the nursery impact root system morphology and anchorage. Arboric. Urban For. 38 (5), 229–236.

Gilman, E.F., Yeager, T.H., Weigle, D., 1996. Fertilizer, irrigation and root ball slicing affects Burford holly growth after planting. J. Environ. Hortic. 14 (3), 105–110.

Gilman, E.F., Harchick, C., Paz, M., 2010a. Effect of container type on root form and growth of red maple. J. Environ. Hortic. 28 (1), 1–7.

Gilman, E.F., Harchick, C., Paz, M., 2010b. Effect of tree size, root pruning, and production method on establishment of *Quercus virginiana*. Arboric. Urban For. 36 (4), 183–190.

Gilman, E.F., Paz, M., Harchick, C., 2010c. Root ball shaving improves root systems on seven tree species in containers. J. Environ. Hortic. 28 (1), 13–18.

Grene, S., 1978. Root Deformations Reduce Root Growth and Stability. British Columbia Ministry of Forests/Canadian Forestry Service, pp. 150–155.

Harris, J.R., Bassuk, N.L., 1994. Seasonal effects on transplantability of scarlet oak, green ash, Turkish hazelnut and tree lilac. J. Arboric. 20 (6), 310–317.

Harris, J.R., Gilman, E.F., 1991. Production method affects growth and root regeneration of leyland cypress, laurel oak and slash pine. J. Arboric. 17 (3), 64–69.

Harris, J.R., Gilman, E.F., 1993. Production method affects growth and post-transplant establishment of ‘East Palatka’ holly. J. Am. Soc. Hortic. Sci. 118 (2), 194–200.

Harris, J.R., Fanelli, J., Thrift, P., 2002. Transplant timing affects early root system regeneration of sugar maple and northern red oak. HortScience 37 (6), 984–987.

Hilbert, D.R., Roman, L.A., Koeser, A.K., Vogt, J., van Doorn, N.S., 2019. Urban tree mortality: a literature review. Arboric. Urban For. 45 (5), 167–200.

Hummel, R.L., Evans, E., Riley, R., 2009. . Effect of mechanical root disruption at transplant on short- and longer-term growth and survival of scotch pine (*Pinus sylvestris*) and shore pine (*Pinus contorta* var. contorta). In: Watson, G.W., Costello, L., Scharenbroch, B., Gilman, E. (Eds.), The Landscape Below Ground III: Proceedings of an International Workshop on Tree Root Development in Urban Soils. The International Society of Arboriculture, Champaign, IL, pp. 211–221.

Jacobs, D.F., Rose, R., Haase, D.L., Alzugaray, P.O., 2004. Fertilization at planting impairs root system development and drought avoidance of Douglas-fir (*Pseudotsuga menziesii*) seedlings. Ann. For. Sci. 61 (7), 643–651.

Johnson, G.R., Hauer, R.J., 2000. A Practitioner’s Guide to Stem Girdling Roots of Trees: Impacts on Trees, Symptomology, and Prevention. BU–7501–S. University of Minnesota, Extension Service. https://hdl.handle.net/11299/49810.

Kjelgren, R., Cleveland, B., 1994. Growth and water relations of Kentucky coffee tree and silver maple following transplanting. J. Environ. Hortic. 12 (2), 96–99.

Kovacs, K.F., Haight, R.G., McCullough, D.G., Mercader, R.J., Siegert, N.W., Liebhold, A. M., 2010. Cost of potential emerald ash borer damage in U.S. communities, 2009–2019. Ecol. Econ. 69 (3), 569–578.

Kozlowski, T.T., Davies, W.J., 1975. Control of water balance in transplanting trees. J. Arboric. 1 (1), 1–10.

Mathers, H., Lowe, S., Struve, D., Scagel, C., 2005. Factors Altering Root Growth in Nursery Containers. Part 2: Media Decomposition and Chemical Properties. The Buckeye, pp. 15–18 (October).

McPhearson, P.T., Feller, M., Felson, A., Karty, R., Lu, J.W., Palmer, M.I., Wenskus, T., 2010. Assessing the effects of the urban forest restoration effort of MillionTreesNYC on the structure and functioning of New York City ecosystems. Cities Environ. (CATE) 3 (1), 57–78.

Nguyen, V.D., Roman, L.A., Locke, D.H., Mincey, S.K., Sanders, J.R., Fichman, E.S., Duran-Mitchell, M., Tobing, S.L., 2017. Branching out to residential lands: missions and strategies of five tree distribution programs in the US. Urban For. Urban Green. 22, 24–35.

O’Connor, A.S., Klett, J.E., Koski, A.J., 2018. Container type affects root development of Chanticleer® pear (*Pyrus calleryana* ‘Glen’s Form’) during landscape establishment. Arboric. Urban For. 44 (4), 165–173.

Pallardy, S.G., 2008. Physiology of Woody Plants, 3rd ed. Academic Press, Burlington, Massachusetts, USA.

Putnam, A.H., 2015. Florida Grades and Standards for Nursery Plants 2015. Florida Department of Agriculture and Consumer Services. https://www.fdacs.gov/ezs3download/download/60817/1267268/Media/Files/Plant-Industry-Files/Grades-and%20Standards/Grades%20and%20Standards%20FEB17%202017.1.pdf.

Richardson-Calfee, L.E., Harris, J.R., 2005. A review of the effects of transplant timing on landscape establishment of field-grown deciduous trees in temperate climates. HortTechnology 15 (1), 132–135.

Richardson-Calfee, L.E., Harris, J.R., Jones, R.H., Fanelli, J.K., 2010. Patterns of root production and mortality during transplant establishment of landscape-sized sugar maple. J. Am. Soc. Hortic. Sci. 135 (3), 203–211.

Ruter, J.M., 1994. Growth and landscape establishment of *Pyracantha* and *Juniperus* after application of paclobutrazol. HortScience 29 (11), 1318–1320.

Smiley, E.T., 2008. Root pruning and stability of young willow oak. Arboric. Urban For. 34 (2), 123–128.

Smiley, E.T., Holmes, L., Fraedrich, B.R., 2014. Pruning of buttress roots and stability changes of red maple (*Acer rubrum*). Arboric. Urban For. 40 (4), 230–236.

Solfjeld, I., Hansen, O.B., 2004. Post-transplant growth of five deciduous Nordic species as affected by transplanting date and root pruning. Urban For. Urban Green. 2 (3), 129–137.

Struve, D.K., 2009. Tree establishment: a review of some of the factors affecting transplant survival and establishment. J. Arboric. 35 (1), 10–13.

United States Department of Agriculture, 2014. 2012 Census of Horticultural Specialties. Washington, D.C., U.S..

Watson, G., 1985. Tree size affects root regeneration and top growth after transplanting. J. Arboric. 11 (2), 37–40.

Watson, G.W., 2004. Effect of transplanting and paclobutrazol on root growth of ‘Green Column’ black maple and ‘Summit’ green ash. J. Environ. Hortic. 22 (4), 209–212.

Watson, G.W., Himelick, E.B., 1982. Seasonal variation in root regeneration of transplanted trees. J. Arboric. 8 (12), 305–310.

Watson, G.W., Himelick, E.B., 2013. The Practical Science of Planting Trees. International Society of Arboriculture, Champaign, IL.

Weicherding, P.J., Giblin, C.P., Gillman, J.H., Hanson, D.L., Johnson, G.R., 2007. Mechanical root-disruption practices and their effect on circling roots of pot-bound *Tilia cordata* Mill. and *Salix alba* L. ‘Niobe’. Arboric. Urban For. 33 (1), 43–47.

Whitcomb, C.E., 1985. Innovations and the nursery industry. J. Environ. Hortic. 3 (1), 33–38.

Whitcomb, C.E., 2003. Plant Production in Containers II. Lacebark, Inc., Stillwater, OK.

Yin, J., Bassuk, N.L., Olberg, M.W., Bauerle, T.L., 2014. Fine root hydraulic conductance is related to post-transplant recovery of two *Quercus* tree species. J. Am. Soc. Hortic. Sci. 139 (6), 649–656.

Yin, J., Harper, R.W., Bassuk, N.L., 2017. Effects of tree production method and transplanting on root hydraulic conductance. J. Environ. Hortic. 35 (2), 79–83.