IMPROVING ESTABLISHMENT OF CONTAINER-GROWN DECIDUOUS SHADE TREES

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ABSTRACT

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Container-grown shade trees make up an increasing proportion of nursery stock, yet arborists report concerns about root defects associated with smooth-sided containers, such as circling roots, persisting in the landscape post-transplant. We conducted two field experiments to examine the response of three species (October Glory® red maple, columnar tulip poplar, and 'Bloodgood' London planetree) of container-grown trees to root modification treatments (shaving and bare-rooting) at different times in the growing season with the goal of improving root system development and transplant success. Root modification increased leaf scorch for tulip poplar and red maple trees. Nearly all trees bare-rooted in July had severe die-back. Survival was excellent for all red maples and planetrees planted in May. Survival for tulip poplar trees that were bare-rooted in May was 50%; all tulip poplars that were bare-rooted in July died. Bare-rooting increased tree stress immediately after planting, however, leaf water potential values for the rest of 2018 and throughout 2019 suggest that water status of trees with modified root systems achieved an equilibrium by reducing whole-tree water loss as functional leaf area was reduced. 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 reduced circling roots compared to control trees for tulip poplar and planetrees. 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 (e.g., oaks, hackberry, tulip poplar).

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CHAPTER ONE

LITERATURE REVIEW

Importance of the problem

The annual sale of deciduous shade trees in the United States exceeds $550 million (United States Department of Agriculture, 2014). The top states for nursery production of deciduous shade trees, as measured by total number of operations, are Florida, Oregon, and North Carolina; Michigan ranks 11th. Thirteen percent of all nursery stock sold in 2014 were deciduous shade trees, and 60% of those trees were grown in containers (United States Department of Agriculture, 2014).

Container production allows nursery growers to maximize space during production and shipping of plant material. Container production can occur on unproductive soils that are unsuitable for field-grown materials. Arborists and homeowners benefit when planting container-grown trees because of their easy handling, light-weight, and relatively long planting window compared to traditional ball-and-burlap (B&B) production (Davidson et al., 2000; Gilman & Beeson, 1996; Harris & Bassuk, 1993; Harris & Gilman, 1991; Richardson-Calfee et al., 2008; Whitcomb, 2003). Bareroot stock is also light-weight and is less expensive than container-grown stock, however, bareroot trees are extremely vulnerable to desiccation when handling prior to planting. In addition, container trees retain the entirety of their root system, whereas B&B and bareroot trees may experience significant root loss in the digging process (Buckstrup & Bassuk, 2009). However, containers provide limited volume for root growth, and trees grown in containers can develop malformed roots as a result.

The most commonly used nursery containers are smooth-sided black plastic containers, yet these are often cited as a cause of inadequate root systems, specifically circling roots (Amoroso et al., 2010; Gilman & Beeson, 1996; Gilman et al., 2010a, b, c; Ruter, 1994). Circling roots on the periphery of root systems reduce root egress in the surrounding soil and therefore decrease stability of the tree (Coutts, 1983; Gilman & Masters, 2010; Nichols & Alm, 1983). Root deformation from the container persists post-transplant in the landscape, and poor root architecture can lead to delayed establishment and eventual tree failure (Flemer, 1982; Gilman & Masters, 2010; Johnson & Hauer, 2000; Zahreddine et al., 2004). In addition to this safety risk related to tree instability (Coutts, 1983; Gilman, 1994; Smiley, 2008; Smiley et al., 2014), circling roots near the soil surface also have the potential to become stem girdling roots (SGRs).

During the lifespan of the tree, the trunk and roots continue to increase in diameter, and circling outer roots can become SGRs. SGRs restrict radial trunk growth and compress sapwood (Hudler & Beale, 1981). This compression disrupts the tree's vascular system and can effectively choke the tree by reducing water conductance and transport of photosynthates (Hudler & Beale, 1981; Johnson & Hauer, 2000). For more detailed information regarding SGRs, see Johnson & Hauer, 2000.

To minimize instance of circling roots and SGRs, it is crucial to improve root system quality whether in the nursery or at time of transplant. High quality root systems are those with shallow, symmetrical lateral-spreading coarse roots with prolific fine roots (O'Connor et al., 2018; Watson, 1987). Trees with high quality roots are better suited to tolerate moisture stress and are likely to establish faster compared to trees with poor root systems (Johnson & Hauer, 2000; Struve et al., 1989; Watson, 1986; Watson, 1987).

Factors influencing transplant success and establishment of landscape trees

Transplanting trees from the nursery to the landscape induces stress responses of trees for a period of time which is referred to as transplant shock. Transplant shock is cited as 1) a condition of distress from injuries, depletion, and impaired functions, 2) a process of recovery, and/or 3) a period of adaptation to a new environment (Rietveld, 1989; Struve, 2009). The term colloquially refers to the numerous stresses occurring in newly transplanted trees. Tree establishment has been defined as re-establishment of the tree height-to-root spread ratio (Gilman, 1997; Watson, 1985), resumption of a pre-transplant growth rate (Struve & Joly, 1992; Watson & Himelick, 2013), and/or restoration of shoot xylem water potential relative to un-transplanted control trees (Beeson, 1994; Beeson & Gilman, 1992; Gilman, 1992). Various factors influence the ability of a tree to become established after transplanting, such as: adequate soil moisture (Struve, 2009), climatic factors such as length of the growing season and soil temperatures (Tryon & Chapin, 1983; Watson, 1985; Watson, 2004), species selection (Arnold & Struve, 1989; Watson, 2004), tree size (Gilman et al., 1998; Gilman & Masters, 2010; Lauderdale et al., 1995; Litzow & Pellet, 1982; Struve, 2009; Watson, 1985), and production method (Gilman et al., 2010b; Yin et al., 2017).

Climate

Root growth after transplanting is affected by soil temperatures and length of the growing season (Bevington & Castle, 1985; Pregitzer et al., 2000). Optimum temperatures for root growth range from 18°C to 32°C, depending on the species (Martin & Ingram, 1991; Rohsler, 1982; Wong et al., 1971), however, roots can continue to grow, at a reduced rate, in much colder temperatures (Lyr & Hoffman, 1967). In the temperate climate of the upper Midwest, roots will grow slower and trees will take longer to become established than in climates where the soils are warm year-round (Gilman, 1997).

Adequate soil moisture is also required for root growth. Low soil water content can slow fine root growth up to 90% (Barnett, 1986; Meier & Leuschner, 2008; Olesinski et al., 2011). Water-absorbing root tips rapidly mature and decrease water uptake under drought-stress conditions (Bilan, 1974), and water uptake is slowed until new root tips are produced (Watson et al., 2014). The proper time of year to transplant varies among tree species and is related to seasonality (Watson & Himelick, 2013).

Tree size

Another factor influencing tree establishment is tree size. Smaller caliper trees establish more quickly than larger trees (Gilman, 2010a, b; Struve et al., 2009; Watson, 1985), potentially due to reduced vigor from prior nursery handling of large trees (Struve, 2009). Overall, the rate of root growth of both small and large trees is similar (Watson & Himelick, 2013), but distance that roots must extend to reach pre-transplant lengths is much further for larger trees. For example, Struve et al. (2000) found the mortality rate of 7.6-10.2 cm caliper trees to be higher than that of 3.8-5.1 cm caliper trees post-transplant; however, the surviving larger trees had faster caliper growth rates than the smaller trees.

Species

Species vary in their response to transplanting (Buckstrup & Bassuk, 2000, Buckstrup & Bassuk 2009; Curtis, 2010; Ellison et al., 2016; Struve, 2009). This is likely due to differences in rate of root regeneration, carbohydrate status, and/or desiccation tolerance (Bates et al., 2014; Ellison et al., 2016; Harris et al., 2002; Ritchie & Dunlap, 1980; Struve, 2009), though the reported findings are inconsistent. Following transplant, *Acer saccharum* trees began root regeneration 4-6 weeks earlier than *Quercus rubra* trees depending on planting time, but root growth rate was not found to be related to transplantability (Harris et al., 2002). Abod and Webster (1991) found new root growth of *Betula pendula* (difficult to transplant) occurred sooner following transplant compared to *Tilia cordata* (easy to transplant); fine roots were found to be the main reservoir of carbohydrates for *B. pendula* trees whereas coarse roots were more important to *T. cordata* trees (Abod & Webster, 1991). Ellison et al. (2016) suggests that low root growth potential may be the cause of poor transplanting success of *Quercus* spp., however, poor establishment of *Celtis occidentalis* trees may be related to a combination of low root growth potential, poor carbohydrate status, and desiccation.

With regard to root morphology, species with fibrous root systems are easier to transplant than coarse-rooted species (Fare et al., 1985; Harris & Bassuk, 1994) because there is greater root-soil contact (Harris & Bassuk, 1994) and they tend to have more intact root tips which increases the root regeneration potential (Struve, 2009). Species with a natural taproot are acknowledged to be difficult to transplant, though this is likely due to a combination of factors and not the taproot system alone (Watson & Himelick, 2013).

Tolerance of transplanting may also depend on the native environment of the species. For example, bottomland species, such as *Acer rubrum* or *Fraxinus pennsylvanica*, may be more tolerant of deep planting because they are well adapted to having roots covered by layers of sediment (Arnold et al., 2005; Gilman & Harchick, 2008; Harris & Day, 2010; Watson & Himelick, 2013; Wells et al., 2006).

Nursery production method

Digging and lifting field-grown trees results in loss of both coarse and fine roots and slow aboveground growth (Gilman & Beeson, 1996; Gilman & Yeager, 1987; Watson & Sydnor, 1987). Compared to field-grown trees, container-grown trees retain the entirety of their root system when transplanted, however, roots deflect when they contact the bottom or side of containers, which disrupts root development. Normal, radially spreading roots do not develop as well with defective roots present, so establishment and anchorage can be hindered (Gilman & Masters, 2010; Watson & Himelick, 2013). For a more detailed review of the influence of nursery production methods on subsequent tree survival, see Allen et al., 2017.

Approaches to improving quality of container-grown nursery stock

A myriad of new container types are being tested with the intention of eliminating lateral root deflection and other root defects. Several manufacturers produce containers that are alternatives to standard black plastic containers (Appleton, 1993; Whitcomb, 1985). Motivations for container innovation include ease of use, sustainability, and/or the desire to eliminate root defects on container-grown stock. Fabric containers are becoming increasingly common and have been found to reduce root defects because they effectively “air prune” roots (Gilman, 2001; Marler & Willis, 1996; Marshall & Gilman, 1998; Privett & Hummel, 1992). Air pruning of roots occurs when a root tip reaches a pocket of air; the air causes tip desiccation and allows the root to branch (Davis & Whitcomb, 1975; Hathaway & Whitcomb, 1977).

Gilman et al. (2010a) reported that caliper growth of *Acer rubrum* L. ‘Florida Flame’ grown in #3 smooth-sided containers was not different compared to seven types of air-pruning containers in the production nursery; however, 100% of trees grown in smooth-sided containers exhibited visible root defects while defects were reduced for trees grown in various air-pruning containers (Air-Pot™, Fanntum Pot, Jackpot™, and RootBuilder®). Similarly, O’Connor et al. (2018) compared growth of *Pyrus calleryana* 'Glen's Form' (Chanticleer®) produced in three different nursery container types: black plastic, Root Pouch® (fabric), and Smart Pot® (fabric), over three growing seasons post-transplant. Container type did not affect above-ground growth for all three growing seasons, however, trees grown in alternative fabric containers had a greater percentage of total root growth extending beyond the original root ball compared to the black plastic containers (O’Connor et al., 2018).

Copper hydroxide-lined containers are also used as a form of chemical root pruning as the roots are stunted on contact with the side of the container (Appleton, 1993; Struve et al., 1994). These copper-treated containers may increase lateral root growth compared to smooth-sided containers, but reports are limited to small containers, and findings are inconsistent (Smith et al., 1992). Struve (1993) reported that copper-treated containers produced fewer circling roots for four tree species (*Quercus rubra* L., *Q. coccinea* Muenchh., *Liquidambar styraciflura* L., and *Acer rubrum* L. 'Autumn Flame') grown in copper-treated containers compared to non-treated containers; however, following planting, the copper treatment in the nursery may not always result in better root growth (Brass et al., 1996; Struve, 1993), and not all species respond well to copper treatments (Beeson & Newton, 1992).

Planting practices to improve transplant success of container-grown landscape trees

Proper planting depth

Several studies have suggested that proper planting depth is a key factor influencing successful establishment of trees (Arnold et al., 2005; Arnold et al., 2007; Gilman & Harchick, 2008; Harris & Day, 2010; Watson & Hewitt, 2012; Wells et al., 2006). If trees are planted below grade with the root collar buried, they often have less stability and can form adventitious roots that can become SGRs (Johnson & Hauer, 2000). Browne and Tilt (1992) reported reductions in height growth following one growing season for *Pinus virginiana* and *Cornus florida* planted below grade. Deep planting of *Acer rubrum* and *Prunus* x *yedoensis* resulted in decreased survival, decreased SPAD chlorophyll content, and increased girdling root development (Wells et al., 2006). Similarly, Arnold et al. (2007) determined that planting below grade by as little as 7.6 cm for both seed and cutting-propagated container-grown stock correlated with adverse effects on survival and growth rates for trees from the five diverse taxa included in the study.

Conversely, Gilman and Grabosky (2004) reported that planting depth of *Quercus virginiana* did not impact plant water stress after transplanting into sandy soil. Bryan et al. (2010) found that planting 7.6 cm below grade had no effect on growth or survival of *Taxodium distichum*, yet in the same study, they reported decreased survival and reductions in stem caliper growth and height of *Platanus occidentalis* when planted at the same depth.

Mechanical root modification

Manual disruption of the root systems of container-grown trees has been acknowledged as a standard arboricultural practice for decades (Flemer, 1982; Gouin, 1984; Holmes, 1984), however, these recommendations are based on limited studies and anecdotal evidence. Scientific-based research regarding the various root modification techniques provide scarce data and contradictory findings (Blessing & Dana, 1987; Corley, 1984).

In the nursery, it is increasingly recommended in best management practice guides that roots of the smaller liners be root pruned when trees are shifted into larger containers (Gilman & Kempf, 2009; Gilman et al., 2015; Gilman et al., 2016; Halter & Chanway, 1993). Due to limited rooting volume, when trees remain in containers for extended periods, they may become pot-bound. It is thought that if roots are not modified before up-potting, the imprint of the smaller container, and any malformed roots within, will remain even as new root growth initiates. In a container nursery, manual root pruning of individual plants when repotting has been found to reduce circling roots. Starting with the liner, root-balls should be inspected at each shift to a larger container. Shaving, or manually removing of the periphery and bottom, of *Acer rubrum* trees when transplanted from #3 nursery containers to #15 containers decreased circling roots, improved the root rating (more straight roots compared to the untreated control), and increased the root egress (Gilman et al., 2010b).

Some researchers and industry professionals recommend that circling roots be pruned at time of transplant to help minimize or eliminate stem or root girdling and to stimulate root growth into the backfill. Various root ball modification techniques have been researched with the intent of reducing circling roots and promoting root growth. Some recommendations include: 1) *slicing* roots by making a series of vertical slits on the periphery of the root ball to disrupt outer circling roots; 2) *teasing* apart and straightening circling roots; 3) slicing open the bottom of the root-ball and splaying the ends, often referred to as '*butterflying*'; or 4) removing the entire periphery and bottom of the root ball using a saw, often referred to as '*shaving*'. The techniques, however, have yielded mixed results for improving transplant success.

Dr. Ed Gilman, professor emeritus at University of Florida, and research associates, have pioneered most of the recent studies regarding the use of these root modification techniques due to their success with shaving and slicing root-balls. These methodologies have been adopted and referenced in county extension bulletins and planting standards for some states, including California and Florida, as best management practices when planting container-grown stock (Cotrone, 2009; Kempf & Gilman, 2011; Putnam, 2015). Studies pertaining to mechanical root pruning of large container-grown trees include limited species and results are inconsistent or contradictory.

Gilman and Wiese (2012) report increased root egress into surrounding soils and reduction of circling roots in response to root disruption by slicing or shaving container-grown *Quercus virginiana* trees after one growing season. Similarly, *Platanus* x *acerifolia* 'Bloodgood' trees that were subjected to shaving and teasing had greater root egress and fewer circling roots compared to control trees two years post-transplant (Cregg & Ellison, 2018). Weicherding et al. (2007), however, reported no differences in new root growth of *Tilia cordata* and *Salix alba* trees subjected to teasing, slicing, and butterflying 14 months post-transplant. Ellyard (1984) compared root and shoot development of *Eucalyptus mannifera* subsp. *maculosa* and *E. polyanthemos* trees grown in 0.5 L and 4 L black polythene bags, respectively, with root systems subjected to teasing, removal of the bottom 25 mm of roots with a knife, and vertical slicing in addition to removal of the bottom 25 mm of roots. Six months post-transplant, root modification inhibited shoot growth of *E. polyanthemos* trees, however, there was no effect of root modification on shoot growth for either species when measured one and a half years after transplant. Following two growing seasons, vertical slicing virtually eliminated circling roots for trees of both species; removal of the bottom of the root-ball decreased root circling of *E. mannifera* subsp. *maculosa* trees compared to the unmodified controls. Teasing was not effective at reducing root circling compared to control trees (Ellyard, 1984).

Another frequently recommended technique for root correction is bare-rooting, or removing all container substrate, at time of transplant. This practice is recommended by social media sites (The Garden Professors Facebook page) and popular press outlets (Chalker-Scott, 2020) despite the absence of evidence-based supporting information.

Most of the concern with root defects is related to the circling roots on the periphery of the root-ball and root deformation at the soil surface, but roots on the interior of the root system can also be malformed. Interior defects of container-grown trees, likely caused by imprints from smaller nursery containers (Gilman et al., 2015; Gilman et al., 2016; Halter & Chanway, 1993), can only be accessed if container media is removed. The removal of container substrate also ensures proper planting depth and enhances root-soil contact (Appleton & Flott, 2009; Chalker-Scott & Stout, 2009). Few studies have been conducted to evaluate responses of large container-grown trees to bare-rooting at time of transplant.

To investigate the effects of species and time of year on success of bare-rooted trees, Appleton and Flott (2009) bare-rooted container-grown and field-grown *Acer rubrum* and *Quercus phellos* L. trees using a pressure washer or by soaking the root-balls in March, July, or October (*Q. phellos* only) 2007. After one year, there were no differences in survival or caliper growth of *A. rubrum* trees that were bare-rooted compared to the control regardless of planting time (March or July) or production method (Appleton & Flott, 2009). They found that most *Q. phellos* trees that were bare-rooted in March (regardless of bare-root method or production method) survived and had similar caliper growth to controls; nearly half of the *Q. phellos* trees bare-rooted in July died – field-grown *Q. phellos* had better survival than container-grown and *Q. phellos* that were bare-rooted by soaking had better survival than those that were pressure washed (Appleton & Flott, 2009). *Q. phellos* trees planted in November had slightly higher survival than those planted in July. Additional systematic studies are necessary to increase our understanding of responses of large container-grown trees to bare-rooting.

Soil amendments

Several soil amendments are marketed to aid in tree establishment including biostimulants, mycorrhizal inoculants, and mulch. Amendments to soil are used to increase soil quality by adding organic matter, increasing soil water holding capacity, and/or facilitating water uptake by the tree's roots.

Biostimulants are products marketed to reduce transplant stress. Biostimulants refer to proprietary products, generally mixtures of hormones, humates, and/or manures, marketed to reduce the effects of plant stress (Watson & Himelick, 2013). Several sugar and organic products have been evaluated, and studies show limited or no benefits to root or shoot growth of trees and high variability in species responses (Abbey & Rathier, 2005; Barnes & Percival, 2006; Fraser & Percival, 2003; Gilman, 2004; Schulte & Whitcomb, 1975).

Mycorrhizal inoculation is an example of soil amendment. Symbiotic mycorrhizal fungi can form a network of hyphae around fine roots; this association can increase water uptake during drought. Studies of tree responses to mycorrhizal inoculation have produced mixed results (Abbey & Rathier, 2005; Ferrini & Nicese, 2002; Gilman, 2001; Wiseman & Wells, 2009). Under drought stress conditions, symbiotic mycorrhizae aid roots in acquisition of water by extending the root surface (Bethlenfalvay et al., 1988; Ruiz-Lozano et al., 1995). Leaf water potential of *Carica papaya* L. var. Solo in containers following a water stress treatment was higher for those inoculated with an arbuscular mycorrhizal fungus than the non-inoculated trees, indicating that water stress was more severe for the non-inoculated trees (Cruz et al., 2000). Appleton et al. (2003), however, found no measurable growth benefits to *Acer rubrum, Quercus palustris,* or *Q. phellos* as a result of inoculation with a commercial mycorrhizal fungal product. Similarly, Gilman (2001) found no effect of inoculation of *Q. virginiana* on transplant stress, growth, or survival after two growing seasons. Inoculation with mycorrhizal fungi is beneficial to trees in soils lacking appropriate fungi, but often these symbiotic fungi are already present in urban soils (Wiseman & Wells, 2005).

Another soil amendment marketed to retain soil nutrients and water is Biochar. Biochar, a proprietary charcoal, is promoted to increase soil fertility by modifying physical and chemical soil properties. A 2014 meta-analysis of woody plant responses to biochar indicates potential for increases in growth, but the responses are more pronounced in tropical and boreal species than in temperate species and the majority of the references were container studies opposed to field studies (Thomas & Gale, 2015). The addition of biochar as a soil amendment to transplanted

Samanea saman trees increased caliper growth compared to the unamended control, but the root:shoot ratio was adversely affected (Ghosh et al., 2015).

Mulch is frequently cited to improve plant performance in response to increased soil moisture, moderated soil temperatures, and reduced weed competition (Chalker-Scott, 2007; Cregg & Schutzki, 2009; Watson et al., 2014). Cregg and Ellison (2018) reported that ground pine bark mulch increased predawn leaf water potential of *Platanus* x *acerifolia* 'Bloodgood' for two measurement dates; additionally, they found that mulch increased soil moisture and total stem caliper and height growth compared to the trees that were not mulched. Gilman and Grabosky (2004), however, found that mulch did not affect stem xylem potential or growth of B&B transplanted *Quercus virginana* Mill. trees.

Tree growth regulators

Tree growth regulators (TGRs) are often used by arborists to reduce shoot elongation to provide a compact canopy and to increase pruning cycles of trees under utility lines. A commonly used TGR is paclobutrazol (PBZ). PBZ is a heterocyclic triazole compound. Reduction in shoot growth by PBZ is caused by blocking cytochrome P450 dependent reactions in the mevalonic acid pathway (Hedden & Graebe, 1985). This effectively inhibits gibberellin synthesis; gibberellins regulate cell elongation in plants. Application of PBZ creates a more compact canopy which is useful for tree planting near overhead utilities because the pruning cycle by electric utility companies can be increased. The Environmental Protection Agency has approved its use as a soil injection or basal drench application.

McLoughlin (2000) lists over 50 tree species reported in the literature to respond to PBZ treatment with reduced shoot growth, but the amount of shoot growth reduction in trees ranges from 20 to 90 percent. Ranney et al. (1989) found, under well-watered conditions, PBZ reduced mean growth rate of *Prunus avium* x *pseudocerasus* by 71 percent compared to the control; they also reported that when water was withheld from container-grown *Prunus avium* x *pseudocerasus* whips, the control trees reached a predawn water potential of -2.0 MPa (a level of stress that could induce wilting) after 22 days without irrigation while the trees that received a soil applied PBZ treatment never decreased below -0.6 MPa predawn water potential. PBZ can reduce plant water use and minimize water stress, yet Watson and Hewitt (2017), reported no significant effect of PBZ application on crown growth of young *Fraxinus pennsylvanica*, *Acer nigrum, A. saccharum*, or mature *Quercus macrocarpa* or *Q. alba* trees.

TGRs may also increase synthesis of abscisic acid (ABA), known as the stress hormone, which plays a role in stomatal regulation and plant water relations. Physiological responses elicited by trees treated with PBZ include reduced gibberellin and sterol biosynthesis, increased chlorophyll content, altered carbohydrate status, and delayed senescence; these responses are often extrapolated to denote an increase in stress tolerance (Watson & Himelick, 2013). The application of PBZ to trees can aid in improving establishment as a result of reductions in internode length and subsequent increase in root growth and root:shoot ratio. PBZ may also aid in disease resistance and can effectively improve tree fruit color and quality (Wani et al., 2011).

Irrigation

Potentially more crucial than appropriate planting specifications is proper aftercare, namely irrigation. Following planting, water is often the limiting factor of tree growth (Watson & Himelick, 2013). Low root hydraulic conductance and reduced root-soil contact of newly planted container trees can cause embolisms and cavitation in the xylem and further reduce water conductance (Bréda et al., 1993; Jackson & Grace, 1994; Wilson & Jackson, 2006). Water availability varies by season, so irrigation requirements depend on time of transplant, however, adequate soil moisture must be maintained in the landscape to encourage root regeneration, (Gilman et al., 2003; Krizek & Dubik, 1987; Larson & Whitmore, 1970; Marshall & Gilman, 1997), root elongation potential (Bevington & Castle, 1985; Larson & Whitmore, 1970; Struve, 1990), and subsequent establishment. Trees are more vigorous when steps to mitigate moisture stress are taken; consequently, the trees are more resilient to other biotic or abiotic stressors (Johnson & Hauer, 2000; Roppolo & Miller, 2001).

Summary

Nursery production methods, mechanical root modification, and soil amendments are important factors influencing establishment success and survivability of landscape trees after transplanting. Various novel approaches have been recommended to reduce root defects for container-grown trees. Techniques that result in increased root regeneration and root egress, increased root:shoot ratio, and decreased water stress should have merit and success; however, more information is needed regarding species-specific responses before recommending the aforementioned root modification techniques for transplanting all container-grown trees.

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CHAPTER TWO

IMPROVING ESTABLISHMENT OF CONTAINER-GROWN DECIDUOUS SHADE TREES

Abstract

Container-grown shade trees make up an increasing proportion of nursery stock, yet arborists report concerns 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 at planting on establishment, survival, and growth of container grown October Glory® red maple, columnar tulip poplar, and 'Bloodgood' London planetree. Modifying roots before planting increased leaf scorch for tulip poplar and red maple trees. Nearly all trees bare-rooted before planting in July had severe die-back. Survival was excellent for all red maples and planetrees planted in May regardless of treatment. Survival for tulip poplar trees that were bare-rooted in May was 50%; all tulip poplars that were bare-rooted in July died. Bare-rooting increased tree stress immediately after planting, however, leaf water potential values for the rest of 2018 and throughout 2019 suggest that water status of trees with modified root systems achieved an equilibrium by reducing whole-tree water loss as functional leaf area was reduced. 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 reduced circling roots compared to control trees for tulip poplar and planetrees. 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 (e.g., oaks, hackberry, tulip poplar).

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 & Beeson, 1996; Harris & 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 transplant shock, the overall state of 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 (Kozlowski & Davies, 1975; Gilman & Beeson, 1996; Harris & Gilman, 1991, 1993; 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; Gilman et al., 2010a, b, c; O'Connor, 2018; Ruter, 1994). Circling roots persist in the landscape post-transplant (Grene, 1978) and can reduce stability of the tree (Coutts, 1983; Gilman 1994; Smiley, 2008; Smiley et al., 2014).

Manufacturers have developed various alternative nursery containers, such as fabric bags (Whitcomb, 1985) and other air-pruning containers (Appleton, 1993), that can reduce circling roots (Gilman et al., 2010a) and improve post-planting root growth (O'Connor, 2018). Despite the advances in alternative container design, BP 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 (Cregg & Ellison, 2018) and to stimulate root growth into backfill soil (Gilman et al., 2010b). Various root ball modification techniques have been researched with the intent of reducing circling roots and promoting root growth. 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. The techniques, however, have yielded mixed results for improving subsequent root growth and transplant success.

Root disruption by slicing or shaving reduced circling roots and increased root egress into the landscape of container-grown *Quercus virginiana* trees after one growing season (Gilman & Wiese, 2012). Similarly, Cregg and Ellison (2018) measured root egress and proportion of root ball with circling roots of *Platanus* x *acerifolia* 'Bloodgood' trees that were subjected to shaving and teasing treatments and found that both teasing and shaving increased root egress into the backfill and significantly decreased the proportion of the root ball with circling roots two growing seasons after transplant. Conversely, Weicherding et al. (2007) found no differences in new root growth of *Tilia cordata* and *Salix alba* trees subjected to teasing, slicing, and butterflying 14 months post-transplant. Studies pertaining to mechanical root pruning of large container-grown trees include limited species and results are inconsistent or contradictory.

Another increasingly recommended root modification technique is "*bare-rooting*", or removal of all container substrate, prior to transplant. 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 any malformed roots (Appleton & Flott, 2009; Chalker-Scott & Stout, 2009). This practice is repeatedly promoted based on anecdotal evidence, yet no studies have been published evaluating the response of large container-grown trees to bare-rooting at 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, there were differences in aboveground growth of *Q. phellos* trees (Appleton & Flott, 2009). Currently available guidelines on bare-rooting (Appleton, 2007; Chalker-Scott, 2012; Chalker-Scott, 2020) provide little guidance on differences in species responses or timing of planting. However, nursery stock that is lifted bareroot is often sensitive to time of planting (Watson & Himelick, 2013), and many tree species do not transplant well bareroot (Buckstrup & Bassuk, 2009) due to low root growth potential, ability to rehydrate, and/or carbohydrate status (Bates et al., 1994; Ellison et al., 2016).

In this study, we conducted two experiments to examine the response of three species of container-grown trees to root modification treatments at different times in the growing season with the goal of improving transplant success. The objectives of this research were to:

1. Evaluate the effect of shaving and bare-rooting 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 modification
3. Determine if response to root modification varies with time of planting.

Materials and methods

Plant materials

In spring 2016, we received 180 bareroot liners (3.2 cm caliper, lightly branched whips) from a commercial nursery (J. Frank Schmidt & Son Co., Boring, OR, USA). The shipment included 60 trees from each of three common landscape species: October Glory® red maple (*Acer rubrum* 'October Glory'), columnar tulip poplar (*Liriodendron tulipifera* 'Fastigiatum'), and Bloodgood London planetree (*Platanus* x *acerifolia* 'Bloodgood'). We planted the trees, 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. In May 2018, we selected 41 trees of each cultivar (123 trees total) that were free from obvious defects for two transplanting studies (Table 1).

Experiment 1: Spring planting

In 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 soil samples (0-30 cm depth) from the site, and the samples were analyzed by the MSU Soil and Plant Nutrient

Laboratory for nutrient analysis (Table 2). Additional soil samples were collected across the site to determine average bulk density (Table 2).

The experiment was installed as a 3 x 4 factorial of species (3) and root modification treatments (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 airspade* – removal of all container substrate using compressed air flow from a pneumatic air spade (Series 2000, AirSpade®, Chicopee, MA, USA) (Fig. 2A and Fig. 2B), 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 hours prior to additional handling (Fig. 2C), then, the following day, all container substrate was removed using a stream of water from a garden hose (Fig. 2D) before removing any obvious root deformations using hand pruners.

To facilitate transplanting, planting holes were dug using a 90 cm diameter tractor-mounted auger to a depth of 0.5 m for both the control and shave treatments; for the bare-root airspade and bare-root wash treatments, the holes were augured to a depth of 0.3 m. The trees were transplanted to a field block at the MSU HTRC and were planted in six rows, 2.7 m on center. When planting trees in bare-root airspade and bare-root wash treatments, the root systems were "mudded in" by slowly adding water and backfill to the root-ball, and the tree was maneuvered to eliminate excess air pockets in the soil. For all treatments, the planting holes were backfilled 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 (Fig. 3). 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. 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.

Experiment 2: Summer planting

In 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 Experiment 1 at the MSU HTRC.

The experiment was installed as a 3 x 3 factorial of species (3) and root-ball modification treatment (3) with three replications (N=3). Nine trees of each species were randomly assigned one of three root-ball modification treatments. We followed the same procedure to transplant the trees as in Experiment 1 and included three of the four root modification treatments: control, shave, and bare-root wash. The bare-root airspade treatment was eliminated due to lack of acceptable trees available from the nursery, and trees in this treatment had poor survival in Experiment 1.

Assessments

<u>Installation time and root removal treatments</u>

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.

Soil moisture

We assessed volumetric soil moisture weekly during the first two growing seasons using a portable time domain reflectometer soil moisture system (Trase System 1, Soilmoisture Equipment Corp., Goleta, CA, USA). Soil moisture was monitored at 0-30 cm depth in the backfill soil, approximately 30 cm from the base of the tree on a subset of 20 London planetrees from Experiment 1 and 2, including all root modification treatments.

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 to 4; 0 = no scorch, 4 = complete scorch) on June 14, July 25, and September 21, 2018 (Fig. 4). Trees rated ≥3 were classified as exhibiting "extreme scorch."

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 height was measured using a height pole. Stem caliper was measured 15 cm above the graft union, and we marked the measurement point on each tree with an indelible marker in order to re-measure at the same point. Stem caliper was measured in two perpendicular directions using a digital caliper and calculated as a geometric mean. On May 24, 2019, using a height pole, we measured the highest point where leaves flushed in order to calculate stem dieback in relation to 2018 final height growth; on the same date, one observer scored all trees for percentage of dieback using a qualitative rating system (0 = no dieback; 4 = complete dieback) to quantify the dieback on all limbs including lateral branches. Tree mortality was assessed in October 2018, April 2019, and September 2019.

In September 2018 and 2019, 20 leaves per tree were collected at random from throughout each tree crown 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 sample leaf size ÷ 20.

Water relations and gas exchange

Predawn leaf water potential (Ψ_w) was assessed every 2 to 3 weeks during the 2018 and 2019 growing seasons using a portable pressure chamber (Model 1000, PMS Instrument Company, Albany, OR, USA). For Experiment 1, leaf Ψ_w was measured on a subset of four of the eight blocks (even replications) in order to balance logistics of the measurements and maintain sufficient replication for analyses. For Experiment 2, 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.

The same trees were used when measuring gas exchange for Experiment 1 and Experiment 2. We measured gas exchange on the same 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 x 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. Gas exchange was measured on clear days [photosynthetic photon flux (*PPF*) > 1500 $mmol \cdot m^{-2} s^{-1}$] using a CO_2 concentration at 400 $mmol \cdot mol^{-1}$ and flow of air at 500 $mL \cdot min^{-1}$ during each measurement run. We recorded the measurement values after the readings had stabilized on the system's real-time graphics screen.

Nutrition and phenology

On July 19, 2018, SPAD chlorophyll content was measured on a subset of trees (even replications) and recorded as an average of five leaves per tree using a portable chlorophyll meter (SPAD-502, Konica Minolta, Inc., Osaka, Japan). On July 16, 2019, the same procedure was used to measure SPAD chlorophyll content of all living trees.

For all living trees in Experiment 1, we collected 5 leaves per tree for foliar nutrient analysis on September 19, 2019. Leaf samples were pooled by species x root treatment combinations and were sent to a commercial analytical laboratory (Waters Agricultural Laboratories, Inc., Camilla, GA, USA).

On April 30, 2019, terminal buds were observed and scored for developmental stage (Fig. 5) based on routinely used standard scores for assessing bud burst (0 to 4; 0 = bud is quiescent and protected by scales, 4 = one leaf is completely out of the bud) (Derory et al., 2006; Ducousso et al., 1996; Scotti-Saintagne et al., 2004).

Destructive harvest and root evaluation

In September 2019, we conducted a destructive harvest on a subset of four replications of trees (even replications), excluding those lost to mortality, from Experiment 1 (42 total trees). We did not harvest any trees from Experiment 2 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 the root systems using an airspade. Once soil was removed, excavated root systems were scored, by the same observer, for internal root defects (0 to 3; 0 = minimal defects, 3 = numerous defects) and for percent of circling roots. Roots were trimmed from the root-ball and separated into two classes: 1) roots within the perceived outline of the original container root-ball (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. 6). Roots remaining in loose soil left by lifting the root-ball and roots in the surrounding soil in the ground beyond the hole left by the tree spade were excavated with an airspade using a 20 min timed search method and were added to the roots in class 2. All excavated roots were then rinsed with water and oven-dried before being further separated into coarse (≥6 mm) or fine (<6 mm) roots and weighed.

Statistical analysis

Data were analyzed using SAS Version 9.2 software (SAS Institute Inc., Cary, NC, USA). PROC UNIVARAITE was used to test all variables for normality. PROC MIXED was used to conduct analysis of variance (ANOVA) for all variables. Mean separation was performed using Tukey's HSD in the LSMEANS prompt of PROC GLIMMIX. When modeling predawn leaf Ψ_w, data was logarithmically transformed to normalize residuals.

Results

Weather and soil moisture

Maximum daily air temperatures during the growing seasons (May to October) were higher than average: 34.4ºC and 33.5ºC 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 (Fig. 7). 2018 was characterized by warm, dry weather in early summer, whereas 2019 was wet in early summer and dry later in the season (Fig. 7).

Average volumetric soil moisture was 28.2% and 22.5% for 2018 and 2019, respectively (data not shown). Weekly volumetric soil moisture readings at 0-30 cm depth indicated consistent values throughout the 2018 growing season, ranging 24.1-30.1%, while average soil moisture values in 2019 were highest (33.5%) in late May then steadily decreased until average values stabilized around 17% in mid-August.

Planting time and roots removed

Time to perform root modification treatments varied (P<0.001) among species and root treatments and there was 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 (Table 3). *A. rubrum* trees took at least 30% longer for root modifications and planting than the other species (Table 3).

Total root biomass, coarse (≥6 mm) root biomass, and fine (<6 mm) root biomass removed when performing root modification treatment prior to transplant was affected (P<0.05) by species, root treatment, and their interaction. Trees in the control treatment had no root loss by nature of the treatment. The relative amount of root biomass removed was not consistent between species (Table 4). Bare-rooting with an airspade and bare-rooting by washing resulted in greater (P<0.05) coarse root biomass loss compared to the shave treatment (Table 4). Bare-rooting by airspade removed more (P<0.05) coarse root biomass of *A. rubrum* trees compared to trees that had been shaved or unmodified (control). Shaving resulted in more (P<0.05) fine and total root loss of *L. tulipifera* trees compared to bare-rooting by washing (Table 4). Root-ball modification (shaving, bare-rooting by airspade, and bare-rooting by washing) did not affect (P>0.05) coarse root biomass of *P.* x *acerifolia* trees compared to the control (Table 4).

Experiment 1: Spring Results

Leaf scorch, tree survival, and growth

For all measurement dates, root treatment and the interaction of species x root treatment affected (P<0.05) mean scorch rating (0 to 4; 0 = no scorch, 4 = complete scorch); species affected (P<0.05) mean scorch rating on July 25 and September 21, 2018. For all species, shaving did not increase (P>0.05) mean levels of leaf scorch compared to control trees (Table 5). By July 25, 2018, there were no differences of degree of mean leaf scorch between root treatments of *P*. x *acerifolia* trees (Table 5). *L. tulipifera* trees subjected to bare-rooting by washing consistently exhibited greater leaf scorch than other root treatments (Table 5). On September 21, 2018, no *A. rubrum* trees with shaved root systems exhibited leaf scorch (Table 5).

Bare-rooting by airspade and by washing increased (P<0.0001) incidence of extreme leaf scorch (rating ≥ 3) of *L. tulipifera* and *P*. x *acerifolia* trees (Table 5). 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 5). When measured on June 14, 2018, bare-rooting by airspade and bare-rooting by washing increased (P<0.05) incidence of extreme leaf scorch of *P*. x *acerifolia* trees compared to the control and those in the shave treatment; on July 25 and September 21, no *P*. x *acerifolia* trees had extreme leaf scorch (Table 5).

Root modification, species, and the species x root modification interaction affected (P<0.05) tree survival. Mortality of *L. tulipifera* trees occurred for all root treatments, and only one of eight *L. tulipifera* trees that were bare-rooting with the airspade survived (Fig. 8). Among

A. rubrum trees, survival was 87.5% or greater for all treatments. Survival of *P.* x *acerifolia* trees was 100% for all treatments (Fig. 8).

After two growing seasons, bare-rooting by washing reduced (P<0.05) caliper growth of *A. rubrum* trees compared to the control; there were no differences in caliper growth among other species (Table 6). Mean height growth following two growing seasons was not (P>0.05) affected by root treatment.

Root modification did not affect (P<0.05) dieback condition rating (0 = no dieback; 4 = severe dieback) of *A. rubrum* trees (data not shown). Dieback was more severe (P<0.05) for *L. tulipifera* trees that were bare-rooted using an airspade or by washing 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 the trees that were shaved and the controls (data not shown).

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* trees (data not shown).

Water relations and gas exchange

Predawn leaf Ψ_w responses were complex and reflected the effects of species, root treatment, and date and their interactions (Fig. 9). For all species, bare-rooting trees with an airspade reduced (P<0.05) leaf Ψ_w immediately following 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 the trees that had shaved root systems or the 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 there were no significant differences for leaf Ψ_w for either *A. rubrum* or *P.* x *acerifolia* (Fig. 9).

Immediately following planting, 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. 10). 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. 10).

<u>Nutrition and phenology</u>

Mean SPAD chlorophyll index differed by species on both measurement dates (Table 7). In July 2018, there were no differences in SPAD among *A. rubrum* trees (Table 7). Bare-rooting by washing *L. tulipifera* trees reduced (P<0.05) SPAD compared to trees with shaved or unmodified (control) root systems (Table 7); *L. tulipifera* trees subjected to bare-rooting by airspade were not sampled due to mortality. Bare-rooting by washing increased (P<0.05) SPAD of *P.* x *acerifolia* trees (Table 7).

In July 2019, bare-rooting via airspade and washing reduced (P<0.05) mean SPAD of *A. rubrum* trees compared to trees with unmodified (control) root systems (Table 7). Bare-rooting by washing reduced (P<0.05) mean SPAD chlorophyll index of *L. tulipifera* trees (Table 7). There were no differences in mean SPAD among *P.* x *acerifolia* trees (Table 7).

Timing of bud burst in 2019 was affected (P<0.01) by species, root modification, and the interaction of species x root modification (data not shown). Among *A. rubrum* trees, trees that were bare-rooted with the airspade broke bud earlier (P<0.05) compared to shaved trees, but they were not different (P>0.05) than the control trees or those that were bare-rooted by washing. Developmental bud burst stage of *L. tulipifera* trees did not differ among root modifications (P>0.05), but shoot development of control trees was more advanced than those that had root modification. *P*. x *acerifolia* trees that were shaved or unmodified (control) broke bud earlier ($P<0.05$) than the trees that had been bare-rooted (airspade and wash).

Aboveground biomass

Species and root modification affected ($P<0.05$) total, leaf, stem, and trunk biomass two years post-transplant (Fig. 11). Total 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 by airspade and washing reduced ($P<0.05$) stem and trunk biomass of *A. rubrum* trees compared to the control (Fig. 11). Among *L. tulipifera* trees, bare-rooting by washing reduced ($P<0.05$) total aboveground biomass and trunk biomass compared to control trees (Fig. 11). *L. tulipifera* trees that were bare-rooted with the airspade were not included in the harvest due to mortality. Leaf and stem biomass among *L. tulipifera* trees were not affected by root treatment (Fig. 11). Root treatment did not affect ($P>0.05$) total aboveground, leaf, or trunk biomass of *P*. x *acerifolia* trees; bare-rooting by washing reduced ($P<0.05$) stem biomass of *P*. x *acerifolia* trees (Fig. 11).

Root biomass and root quality

The effect of root modification varied by species. Root modification treatments did not affect ($P>0.05$) root biomass extending beyond the original root-ball (Table 8), though shaving and bare-rooting visibly improved lateral root spread (Fig. 12). Bare-rooting and shaving reduced ($P<0.05$) internal root defects of *P*. x *acerifolia* trees compared to control trees (Table 8), but root modifications did not improve internal root quality of *A. rubrum* and *L. tulipifera* trees. Bare-rooting by airspade and washing reduced the mean proportion of the root system with circling roots across all three species, and shaving reduced circling roots of *L. tulipifera* and *P*. x *acerifolia* but not for *A. rubrum* (Fig. 13).

Experiment 2: Summer Results

<u>Leaf scorch, tree survival, and growth</u>

Mean leaf scorch ratings (0 to 4; 0 = no scorch, 4 = complete scorch) were generally higher for trees that were planted in July than those planted in May. All but one of the trees that were bare-rooted in July exhibited extreme scorch (rating ≥3) by the September measurement date (Table 9). *L. tulipifera* trees that were bare-rooted had a higher (P<0.05) scorch rating than trees in which root systems were shaved; there were no other differences among root modification treatments for all species (Table 9).

On July 25, 2018, approximately two weeks after transplant, 66.67% of *A. rubrum* trees that were bare-rooted and 66.67% of control trees exhibited extreme leaf scorch while 0% of shaved *A. rubrum* trees had extreme scorch (Table 9). For *L. tulipifera* trees, 100% of those treated with bare-root wash, 66.67% of control trees, and 33.33% of shaved trees showed extreme leaf scorch (Table 9). Only 33.33% of *P.* x *acerifolia* control trees showed extreme leaf scorch compared to 66.67% of bare-rooted trees and 100% of shaved trees (Table 9). On September 21, 2018, incidence of extreme leaf scorch of *P.* x *acerifolia* control trees had dropped to 0% and to 33.33% of shaved trees; 66.67% *P.* x *acerifolia* trees that had been bare-rooted still had levels of extreme leaf scorch (Table 9). Among *A. rubrum* trees, on the September measurement date, 66.67% of controls, 33.33% of shaved trees, and 100% of bare-root wash trees showed extreme leaf scorch (Table 9).

Root modification affected (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 10). 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 (Table 10). Survival of *P.* x *acerifolia* trees was 100% for control trees, 66.67% for those that were shaved, and 33.33% for bare-rooted trees (Table 10).

There were no differences (P>0.05) in stem caliper or height growth after two years (data not shown). Bare-rooting consistently resulted in a more severe (P<0.05) stem dieback rating (0 – no dieback; 4 – severe dieback) across species, and control trees had the lowest rating across species (Table 11). Bare-rooting reduced mean leaf size of *L. tulipfera* (2018) and *P.* x *acerifolia* trees compared to control trees (Table 11).

Water relations and gas exchange

Predawn leaf Ψ_w varied (P<0.05) among species. Immediately following planting, *A. rubrum* trees subjected to shaving had the highest values of predawn leaf Ψ_w, and the control trees had the lowest values, though values were not different at P<0.05 level (Fig. 14). Two weeks later, trees that were shaved or bare-rooted had similar leaf Ψ_w values to the control trees (Fig. 14). 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. 14). Following planting, bare-rooting reduced (P<0.05) leaf Ψ_w values of *L. tulipifera* trees compared to control trees (Fig. 14). *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. 14). *P.* x *acerifolia* trees had higher values of leaf Ψ_w than 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 reported the highest values (Fig. 14). Except for the first measurement date post-transplant, *P.* x *acerifolia* trees had similar values of leaf Ψ_w across all root treatments (Fig. 14).

The effect of root modification on P_n were not consistent between species. Bare-rooting reduced (P<0.05) rate of P_n of *A. rubrum* trees compared to the control at the end of the 2018 and in June 2019 (Fig. 15). In August 2019, P_n was highest (P<0.05) for *A. rubrum* trees that were bare-rooted (Fig. 15). 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. 15). 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. 15). P_n of *P.* x *acerifolia* trees were 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. 15).

Discussion

This research was conducted to evaluate root modification techniques that are commonly recommended to reduce root defects and increase transplant success of container-grown landscape trees. If it is recognized that greater than 80% of landscape plant problems originate from roots and surrounding soils (Watson & Himelick, 2013), planting quality root systems is crucial for successful tree establishment, especially in urban settings where soil properties are often less than desirable. The need to plant large caliper trees is increasing as cities across the US set goals to rapidly increase canopy cover (McPhearson et al., 2011; 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., 2009). 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 trees at maturity.

Survival of trees in response to root modification was variable and dependent on species and timing. For both experiments, all but two trees (both *A. rubrum*) in the control group survived. Following planting in May (Expt. 1), 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 one tree in each of the control, bare-root airspade, and bare-root wash 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 warrants continued research; species differences in root regeneration potential (Struve, 2009), root carbohydrate status, and/or desiccation tolerance (Bates et al., 2014; Ellison et al., 2016) likely play a role in transplantability and subsequent tree establishment.

The increased mortality of trees planted in July (Expt. 2) compared to those planted in May highlights the importance of time of year in planting success. Timing is an important factor in transplanting trees from all production methods (Appleton & Flott, 2009; Bassuk & Buckstrup, 2009; Harris & Bassuk, 1994; Watson & Himelick, 1982). In general, spring planting provides cooler air temperatures and greater available soil moisture that is more conducive to root growth compared to summer planting. Trees planted in summer require more irrigation compared to spring planting because the higher air temperatures result in increased water demand from a limited root system (Watson & Himelick, 2013). Transplant time may be especially important when performing root modifications that result in root severance and reduction in fine, water-absorbing roots.

Providing supplemental irrigation is critical for root growth post-transplant (Barnett, 1986; Watson & 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 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 container substrate generally has low water retention, the removal of this media by bare-rooting reduces rapids 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 the tree to desiccation (Bassuk & Buckstrup, 2009; Yin et al., 2017).

After the first measurement date following transplant in May, trees across all species with shaved and bare-rooted root systems, regardless of bare-root 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. Lack of negative effect of root modification on predawn leaf Ψ_w values suggest 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 & Cleveland, 1994; Watson & Himelick, 2013). Whole-plant responses such as leaf scorch, stem dieback, and reduction in mean leaf size following root modification likely resulted in reduced whole-tree transpiration and conserved water. This may explain the lack of differences in P_n in response to root modifications. P_n was similar across root treatments on a leaf area basis, but that does not equate to whole-tree photosynthesis due to reduced leaf size. The ability to adapt and conserve water by reducing surface area of photosynthetically active tissue reinforces the notion that if trees survive the initial period of transplant shock, they can achieve water status equilibrium (Benson et al., 2019; Kjelgren & Cleveland, 1994; Pallardy, 2008; Solfjeld & Hansen, 2004).

Root growth post-transplant is dependent on species and timing. Some species are able to initiate root growth more quickly than others; following transplant, *A. saccharum* trees began root regeneration 4-6 weeks earlier than *Q. 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 & Ellison, 2018; Gilman et al., 2010b; Gilman & 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 by washing reduced circling roots for all species. Root treatments, however, did not increase new root biomass extending beyond the original root-ball.

The concept of performing root modifications at transplant to improve root systems of container-grown trees has merit, and municipalities and homeowners will greatly benefit from increased longevity of urban trees if instance of girdling roots can be reduced. The techniques, however, are laborious and require specialized equipment. Time to perform the shave technique and finish tree planting was similar to the time required for the control planting method for all species. Bare-rooting with the airspade and bare-rooting by washing added approximately 25 and 50 min, respectively, but the techniques can likely be optimized with sufficient labor and equipment to remove container-substrate and prune out malformed roots.

Supplemental research of root modification of container nursery stock with additional species is necessary, especially species known to have difficultly transplanting (e.g., *Carpinus* spp., *Liriodendron tulipifera*, *Ostrya virginiana*, *Quercus alba*, *Taxodium distichum*). Since it is well established 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 scientific 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 complete list of species suitable for transplanting bareroot (hardiness zone 6). Due to high summer mortality, 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.

Conclusion

This research evaluated the use of shaving and bare-rooting on container-grown shade trees. Response of trees to root modification differed among species and between planting dates. We found that 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 an equilibrium. More studies are necessary before recommending these techniques for all trees.

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 hired landscape professionals unless the client is comfortable with the risks involved (dropping leaves, stem dieback) following transplant.

APPENDIX

Table 1. Mean (± SE) height and caliper of three species of container-grown trees at the start of Experiment 1 and Experiment 2.

	Experiment 1 (spring planting)		Experiment 2 (summer planting)	
Species	Height (m)	Stem caliper (mm)	Height (m)	Stem caliper (mm)
A. rubrum	3.4 (0.3)	48.0 (2.7)	3.4 (0.2)	50.4 (3.5)
L. tulipifera	3.4 (0.2)	51.3 (4.4)	3.5 (0.2)	57.1 (4.7)
P. x *acerifolia*	3.9 (0.2)	45.1 (3.4)	4.1 (0.2)	49.6 (3.4)

Table 2. Soil description and soil nutrient concentration of the field site used for both transplant studies. [1]Source: USDA NRCS Web Soil Survey.

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}

Table 3. Mean total time (min) to perform root modification treatments and complete planting 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). Means within a column followed by the same letter are not different at $P<0.05$ level. Mean separation by Tukey's HSD.

Root modification	Total root treatment and planting time (min)		
	A. rubrum	*L. tulipifera*	*P.* x *acerifolia*
Control	6.8a	4.7a	5.7a
Shave	17.1a	12.1a	11.4ab
BR-Airspade	43.3b	24.6b	23.5b
BR-Wash	71.7c	48.0c	44.5c

Table 4. Mean weight (g) of roots removed during root modification at planting 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). Means within a column followed by the same letter are not different at P<0.05 level. Mean separation by Tukey's HSD.

	A. rubrum			*L. tulipifera*			*P.* x *acerifolia*		
Root modification	Coarse (g)	Fine (g)	Total (g)	Coarse (g)	Fine (g)	Total (g)	Coarse (g)	Fine (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

Table 5. Mean scorch rating (0 to 4; 0 = no scorch, 4 = complete scorch) and percent of trees with extreme leaf scorch (rating ≥ 3) 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) on three measurement days in 2018. Means within date x species followed by the same letter are not different at $P<0.05$ level. Mean separation by Tukey's HSD.

	Mean scorch			**% with extreme scorch (rating ≥ 3)**		
June 14	*A. rubrum*	*L. tulipifera*	*P.* x *acerifolia*	*A. rubrum*	*L. tulipifera*	*P.* x *acerifolia*
Control	1.13a	0.38a	0.88a	0.0a	0.0a	0.0a
Shave	1.25a	1.50ab	0.88a	0.0a	37.5ab	0.0a
BR-Airspade	2.25a	3.25c	1.75ab	25.0a	75.0b	25.0ab
BR-Wash	2.00a	2.50bc	2.88b	37.5a	50.0b	50.0b
July 25	*A. rubrum*	*L. tulipifera*	*P.* x *acerifolia*	*A. rubrum*	*L. tulipifera*	*P.* x *acerifolia*
Control	0.63a	0.38a	0.25a	12.5a	0.0a	0.0a
Shave	0.25a	1.63ab	0.25a	0.0a	37.5a	0.0a
BR-Airspade	1.38a	3.75c	0.88a	12.5a	87.5b	0.0a
BR-Wash	1.25a	2.50bc	1.13a	12.5a	37.5a	0.0a
Sept. 21	*A. rubrum*	*L. tulipifera*	*P.* x *acerifolia*	*A. rubrum*	*L. tulipifera*	*P.* x *acerifolia*
Control	0.50ab	0.38a	0.25a	12.5a	0.0a	0.0a
Shave	0.00a	1.63ab	0.13a	0.0a	37.5ab	0.0a
BR-Airspade	1.75b	3.63c	0.63a	37.5a	87.5c	0.0a
BR-Wash	1.75b	2.88bc	1.38a	25.0a	62.5bc	0.0a

Table 6. Mean caliper (mm) and height (m) growth 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) two years post-transplant. Means within a column followed by the same letter are not different at $P<0.05$ level. Mean separation by Tukey's HSD.

	A. rubrum		*L. tulipifera*		*P.* x *acerifolia*	
Root modification	Caliper Growth (mm)	Height Growth (m)	Caliper Growth (mm)	Height Growth (m)	Caliper Growth (mm)	Height Growth (m)
Control	15.7a	0.148a	18.2a	0.161a	12.7a	0.175a
Shave	12.9a	0.138a	15.8a	0.128a	14.7a	0.193a
BR-Airspade	10.8a	-0.026a	12.3a	0.240a	13.6a	0.175a
BR-Wash	9.6b	0.001a	12.4a	0.072a	13.0a	0.209a

Table 7. Mean SPAD chlorophyll index 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) on July 19, 2018 and July 16, 2019. *L. tulipifera* trees subjected to BR-airspade treatment were not sampled due to mortality. Means within a species x date not followed by the same letter are significantly different at $P<0.05$ level. Mean separation by Tukey's HSD.

	Mean SPAD		
July 19, 2018	*A. rubrum*	*L. tulipifera*	*P.* x *acerifolia*
Control	28.3a	37.6a	29.7b
Shave	27.4a	36.1a	30.5ab
BR-Airspade	29.1a	NA	33.4ab
BR-Wash	27.5a	29.9b	35.5a
July 16, 2019	*A. rubrum*	*L. tulipifera*	*P.* x *acerifolia*
Control	29.2a	37.1a	26.5a
Shave	26.3ab	34.4ab	26.0a
BR-Airspade	24.5b	NA	25.8a
BR-Wash	24.0b	32.5b	24.6a

Table 8. Mean root biomass (g) and internal root defect rating (0 to 3; 0 = minimal defects, 3 = numerous defects) 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) two years post-transplant. *L. tulipifera* trees subjected to BR-airspade treatment were not harvested due to mortality. Means within species followed by the same letter are not different at $P<0.05$ level. Mean separation by Tukey's HSD.

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

Table 9. Mean scorch rating (0 to 4; 0 = no scorch, 4 = complete scorch) and percent of trees with extreme leaf scorch (rating ≥ 3) of trees of three species subjected to three root modifications: control (no root modification), shave (outer 3 cm of roots removed), or bare-root (BR) wash (all container substrate removed using the stream of water from a garden hose, then root defects manually removed) on two measurement days in 2018. Means within date x species followed by the same letter are not different at P<0.05 level. Mean separation by Tukey's HSD.

	Mean scorch			**% with extreme scorch (rating ≥ 3)**		
July 25	*A. rubrum*	*L. tulipifera*	*P.* x *acerifolia*	*A. rubrum*	*L. tulipifera*	*P.* x *acerifolia*
Control	2.67a	2.33a	2.67a	66.67	66.67	33.33
Shave	2.00a	2.33a	3.33a	0.00	33.33	100.00
BR-Wash	2.33a	3.67a	3.00a	66.67	100.00	66.67
Sept. 21	*A. rubrum*	*L. tulipifera*	*P.* x *acerifolia*	*A. rubrum*	*L. tulipifera*	*P.* x *acerifolia*
Control	2.33a	2.00ab	1.00a	66.67	33.33	0.00
Shave	2.33a	1.33a	2.33a	33.33	0.00	33.33
BR-Wash	3.00a	3.67b	2.67a	100.00	100.00	66.67

Table 10. Mean survival (%) of trees of three species subjected to three root modifications: control (no root modification), shave (outer 3 cm of roots 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.

	% survival			
	A. rubrum	*L. tulipifera*	*P.* x *acerifolia*	Overall
Control	66.7	100.0	100.0	88.9
Shave	33.3	100.0	66.7	66.7
BR-Wash	66.7	0.0	33.3	33.3

Table 11. 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 three root modifications: control (no root modification), shave (outer 3 cm of roots 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. Means within columns followed by the same letter are not different at P<0.05 level. Mean separation by Tukey's HSD.

	Mean dieback rating	Mean leaf size (cm^2) 2018	Mean leaf size (cm^2) 2019
A. rubrum			
Control	2.33	16.47a	33.74a
Shave	2.67	18.03a	31.98a
BR-Wash	3.33	14.09a	32.87a
L. tulipifera			
Control	1.00	55.83a	52.83a
Shave	1.00	44.20ab	45.42a
BR-Wash	4.00	12.22b	NA
P.* x *acerifolia			
Control	1.33	53.59a	82.23a
Shave	2.33	54.85a	74.64ab
BR-Wash	3.00	54.09a	50.26b

Figure 1. Examples of root-ball treatments. A – Control treatment. B – Shave treatment.

Figure 2. Examples of root-ball treatments. A – Bare-root airspade treatment. B – Root-ball following removal of container substrate. C – Soaking root-balls for bare-root wash treatment. D – Bare-root wash treatment.

Figure 3. Field planting following Experiment 1 installation.

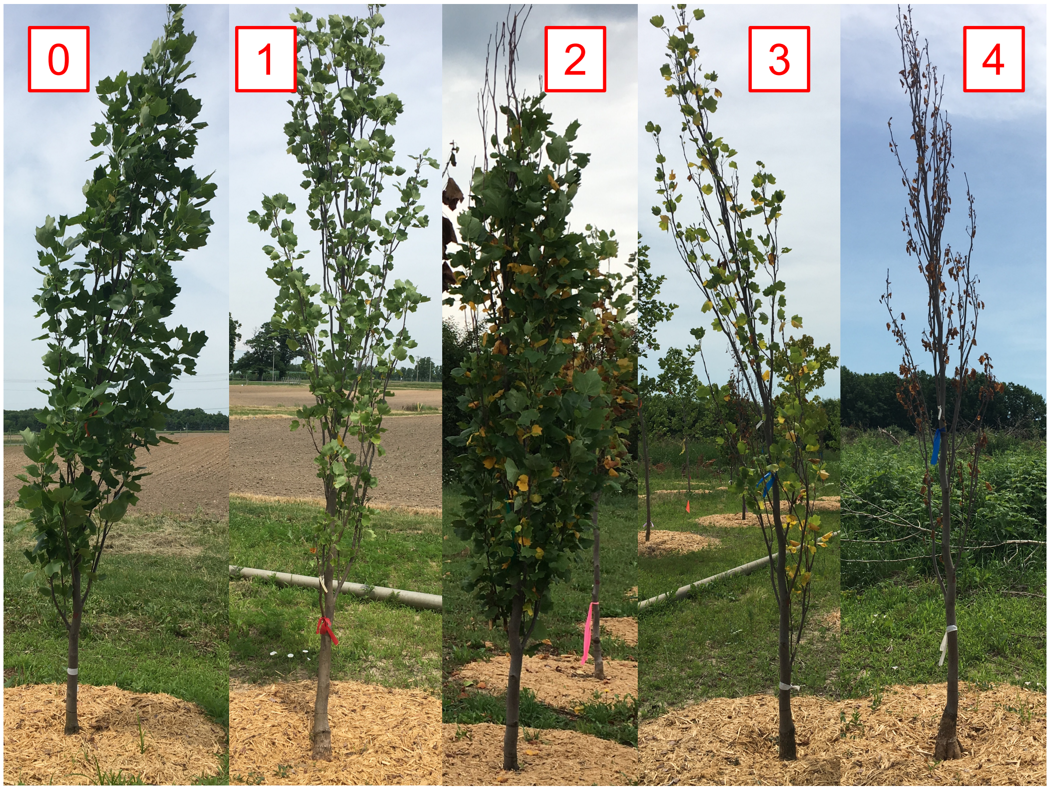

Figure 4. Example representatives of the qualitative rating system based on percent of leaf scorch (shown on *L. tulipifera*). Left to right: 0 – 0-10% of total leaves scorched; 1 – 11-25% of total leaves scorched; 2 – 26-50% of total leaves scorched; 3 – 51-80% of total leaves scorched; and 4 – 81-100%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

Figure 5. Example representatives of stages of bud development (shown in *L. tulipifera*). Stage 0, bud is quiescent and protected by scales; Stage 1, swelling bud; Stage 2, opening of the bud has occurred; Stage 3, leaves have grown; Stage 4, one leaf (at least) is completely out of the bud.

Figure 6. Example excavated root system of *Platanus* x *acerifolia*; dashed line indicates perceived outline from the original nursery container.

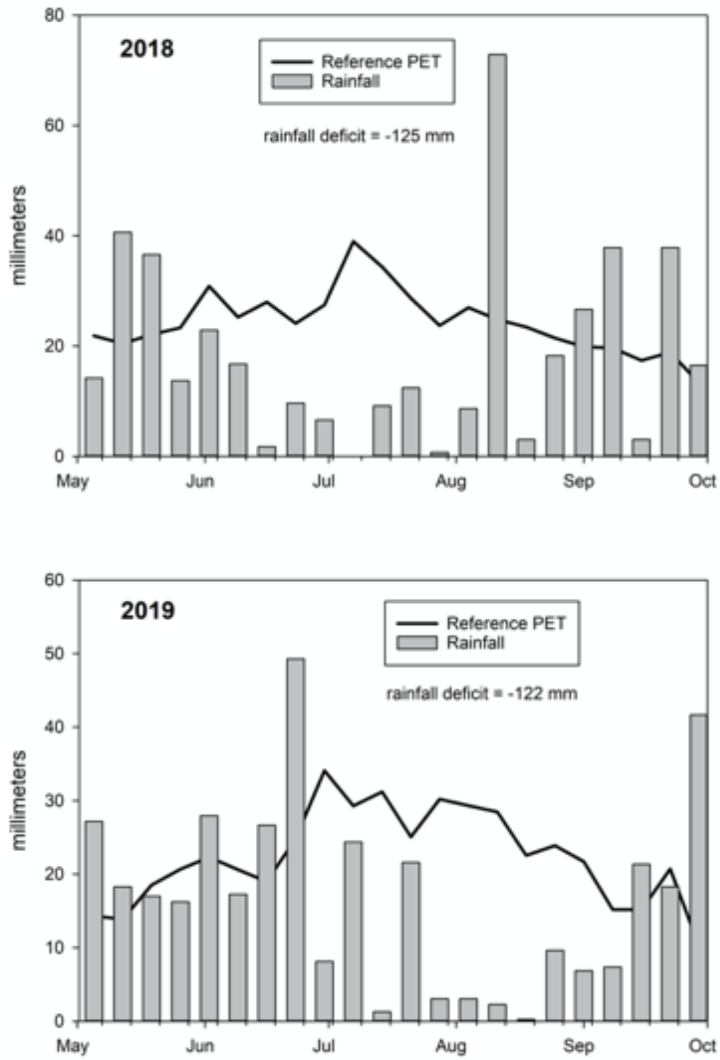

Figure 7. Weekly precipitation and reference potential evapotranspiration (ref PET) recorded at MSU HTRC, 2018-2019. Rainfall deficit calculated as cumulative precipitation – ref PET. Source: MSU Enviroweather (https://enviroweather.msu.edu/).

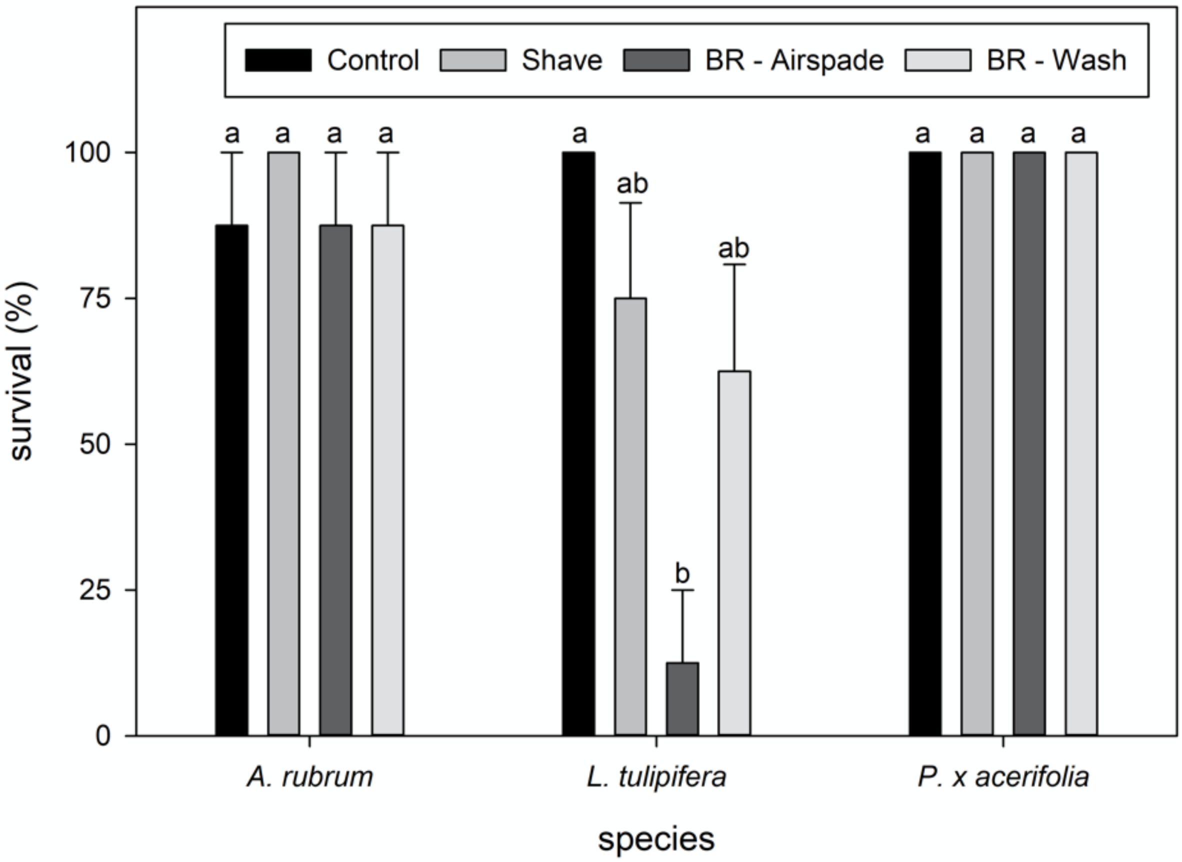

Figure 8. Mean (± SE) survival (%) of trees of three species subjected to four root modifications: control (no root modification), shave (outer 3 cm of roots removed), bare-root (BR)-airspade (all container substrate removed using an airspade, then root defects manually removed), or bare-root (BR)-wash (all container substrate removed using the stream of water from a garden hose, then root defects manually removed). Means within a species followed by the same letter are not different at $P<0.05$ level. Mean separation by Tukey's HSD.

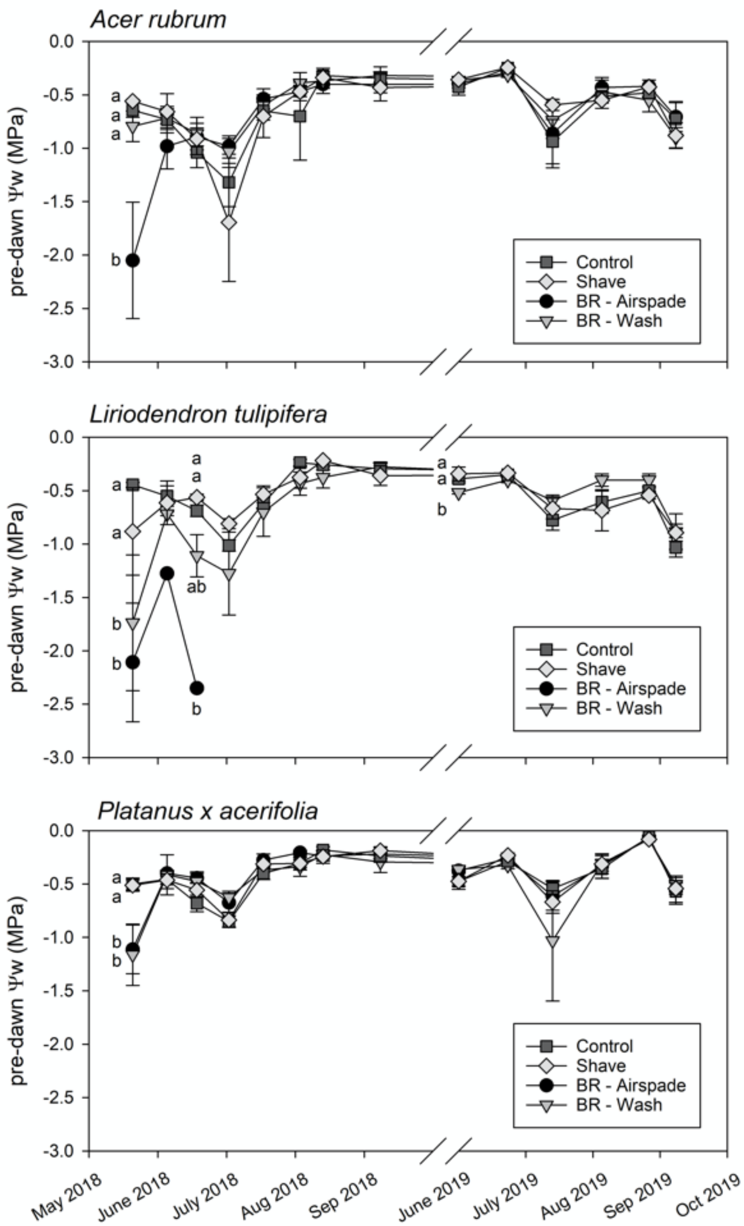

Figure 9. Mean (± SE) predawn leaf Ψ_w of trees of three species subjected to four root modifications: control (no root modification), shave (outer 3 cm of roots removed), bare-root (BR)-airspade (all container substrate removed using an airspade, then root defects manually removed), or bare-root (BR)-wash (all container substrate removed using the stream of water from a garden hose, then root defects manually removed) post-transplant. *L. tulipifera* trees subjected to BR-airspade treatment were not sampled after July 2018 due to mortality. Means within a species not followed by the same letter are significantly different at *P*<0.05 level. Mean separation by Tukey's HSD. On dates where no mean separation is indicated, means are not different.

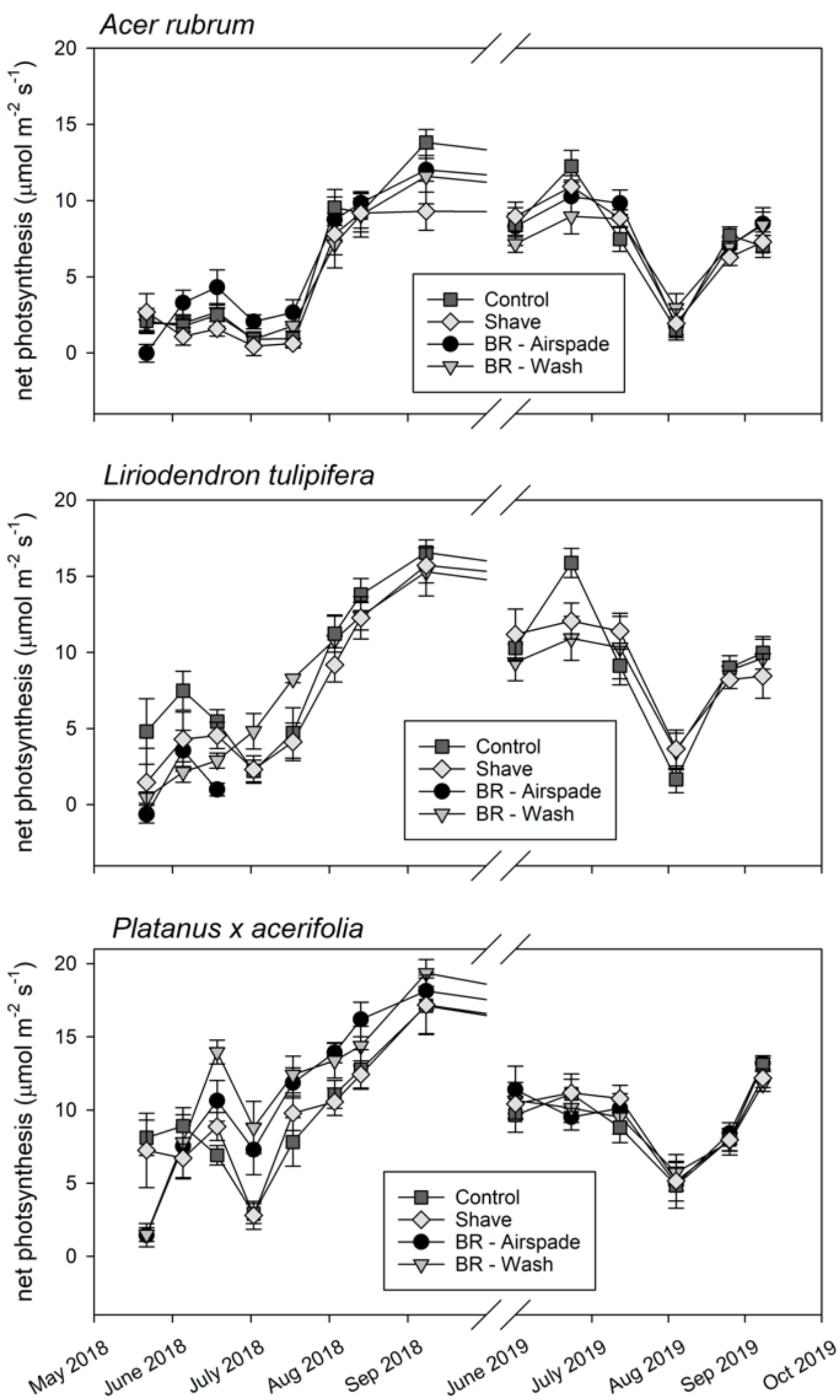

Figure 10. Mean (± SE) net photosynthesis (μmol m^{-2}s^{-1}) of trees of three species subjected to four root modifications: control (no root modification), shave (outer 3 cm of roots removed), bare-root (BR)-airspade (all container substrate removed using an airspade, then root defects manually removed), 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. *L. tulipifera* trees subjected to BR-airspade treatment were not sampled after July 2018 due to mortality.

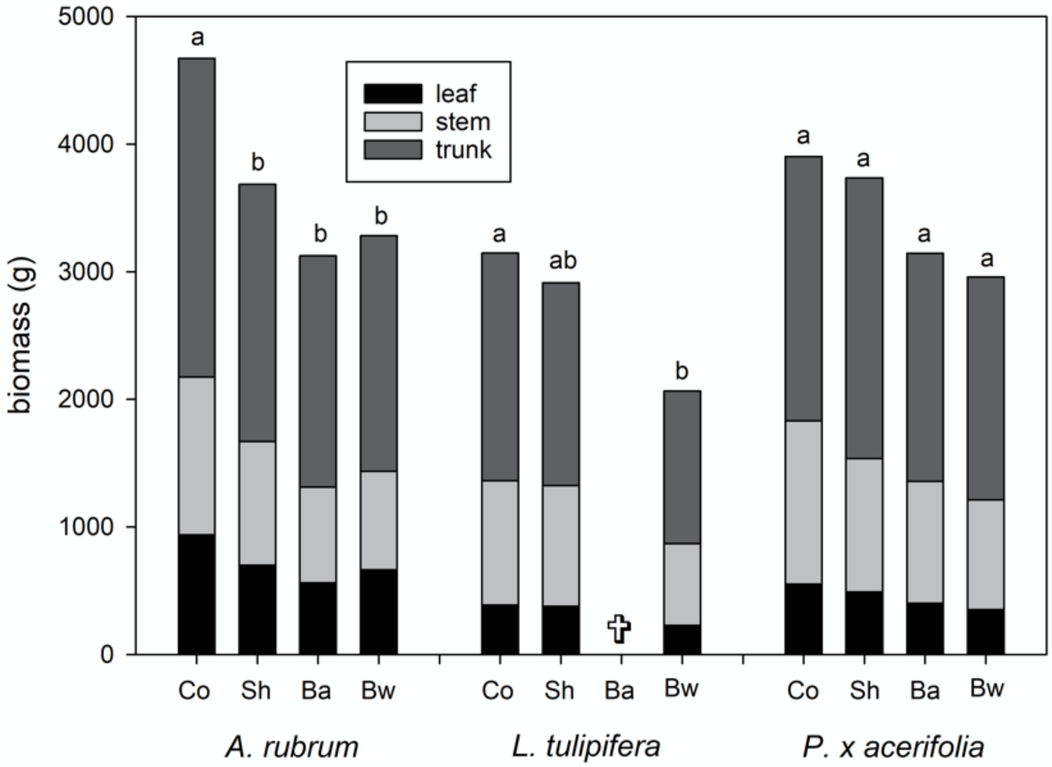

Figure 11. Mean aboveground biomass (g) of trees of three species subjected to four root modifications: control (no root modification), shave (outer 3 cm of roots removed), bare-root (BR)-airspade (all container substrate removed using an airspade, then root defects manually removed), or bare-root (BR)-wash (all container substrate removed using the stream of water from a garden hose, then root defects manually removed) two years post-transplant. Means within a species not followed by the same letter are significantly different at $P<0.05$ level. Mean separation by Tukey's HSD.

Figure 12. Examples of root systems of trees of three species subjected to four root modifications harvested two years after transplanting. Top to bottom: *Acer rubrum*; *Liriodendron tulipifera*; *Platanus* x *acerifolia*. Left to right: a) Control – no root-ball modification prior to planting; b) Shave – outer 3 cm of roots removed prior to planting; c) Bare-root airspade – all container substrate removed using an airspade, then root defects manually removed prior to planting; d) Bare-root wash – all container substrate removed using the stream of water from a garden hose, then root defects manually removed prior to planting.

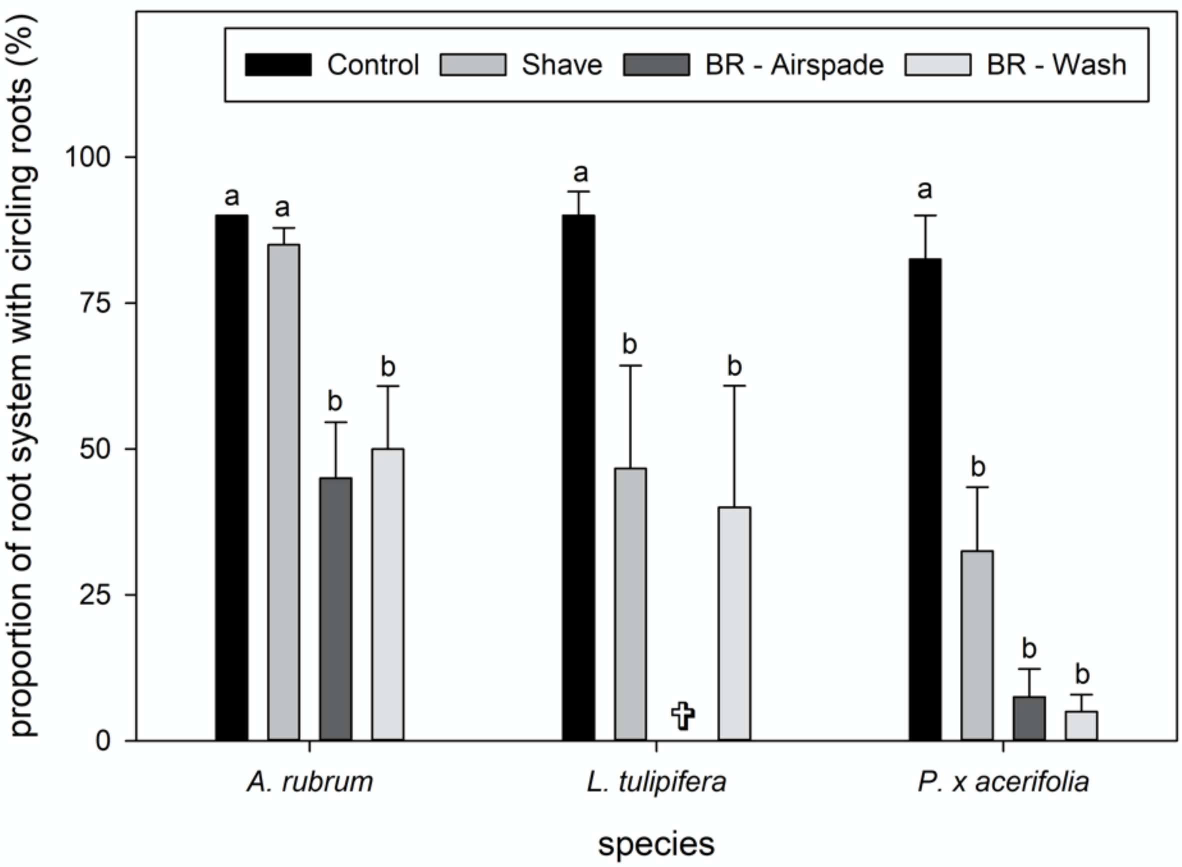

Figure 13. Mean (± SE) proportion of the root-ball with circling roots (%) of trees of three species subjected to four root modifications: control (no root modification), shave (outer 3 cm of roots removed), bare-root (BR)-airspade (all container substrate removed using an airspade, then root defects 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) two years post-transplant. *L. tulipifera* trees subjected to BR-airspade treatment were not harvested due to mortality. Means within species followed by the same letter are not different at $P<0.05$ level. Mean separation by Tukey's HSD.

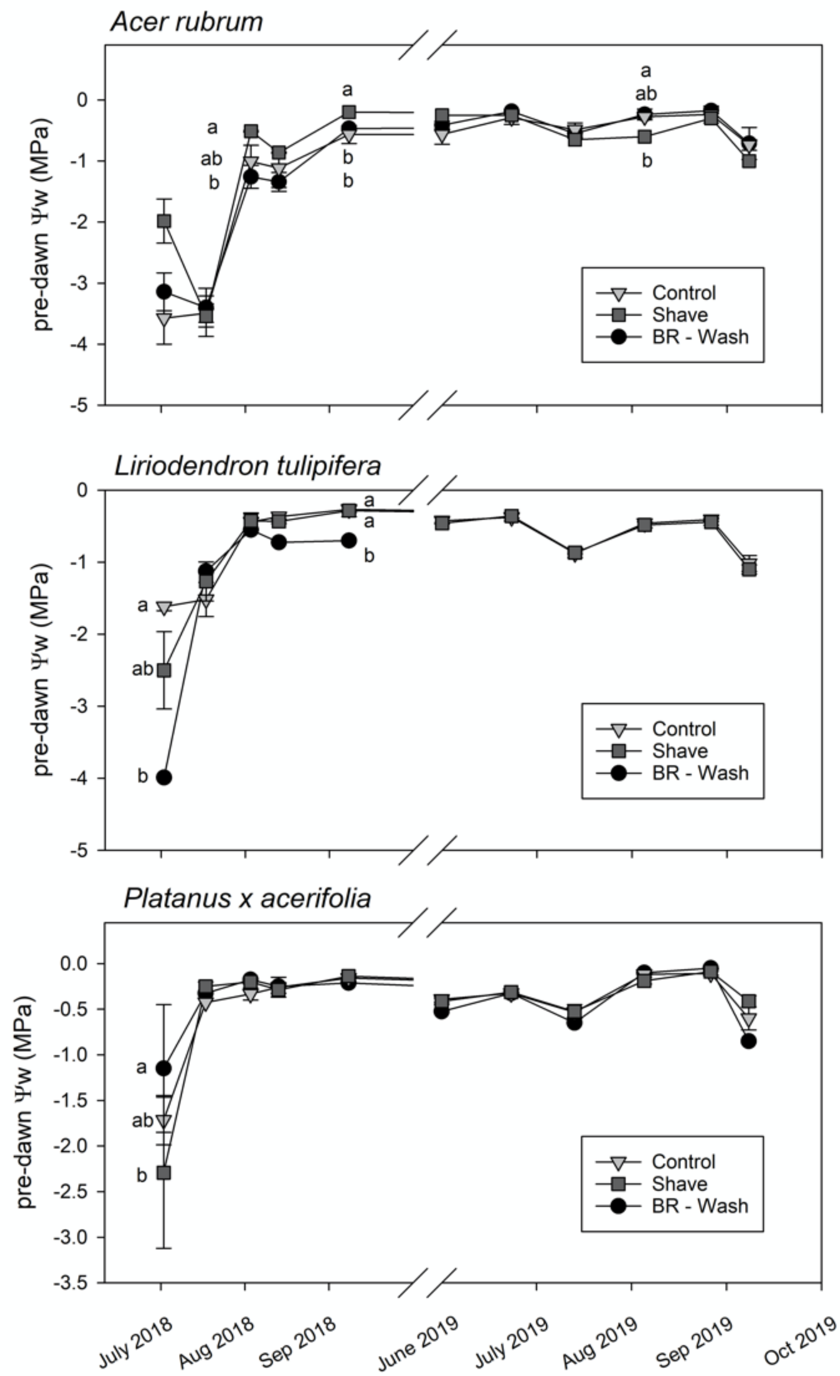

Figure 14. Mean (± SE) predawn leaf Ψ_w of trees of three species subjected to three root modifications: control (no root modification), shave (outer 3 cm of roots removed), or bare-root (BR)-wash (all container substrate removed using the stream of water from a garden hose, then root defects manually removed) post-transplant. Means within a species followed by the same letter are not significantly different at $P<0.05$ level. Mean separation by Tukey's HSD.

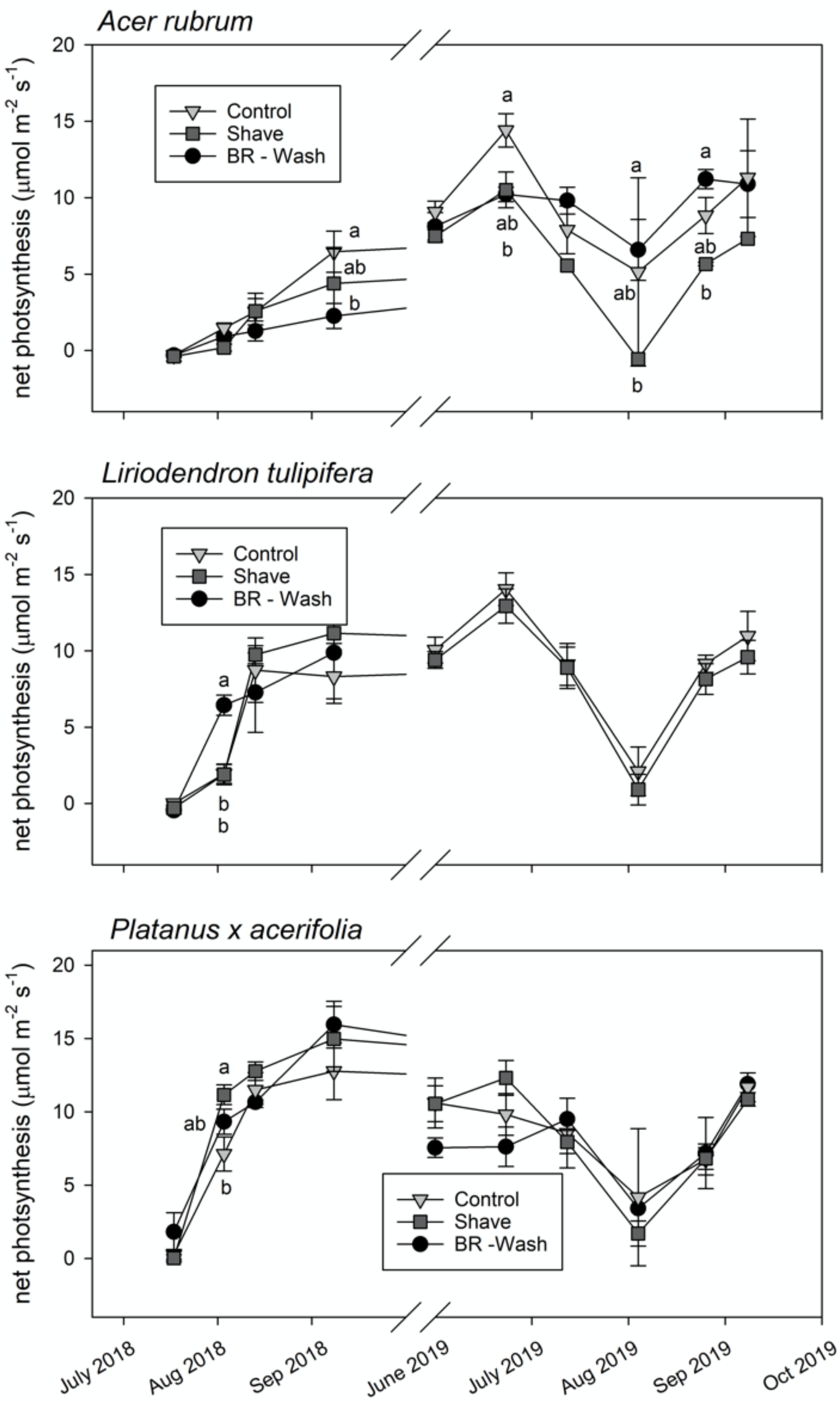

Figure 15. Mean (± SE) net photosynthesis (μmol $m^{-2}s^{-1}$) of trees of three species subjected to three root modifications: control (no root modification), shave (outer 3 cm of roots removed), or bare-root (BR)-wash (all container substrate removed using the stream of water from a garden hose, then root defects manually removed) post-transplant. Means within a species not followed by the same letter are significantly different at *P*<0.05 level. Mean separation by Tukey's HSD.

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