Research Report

Landscape Establishment for Baldcypress, Red Maple, and Chaste tree is Delayed for Trees Transplanted from Larger Containers[1]

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Abstract

With container-grown trees offered to the public in an increasing array of sizes, it is important to determine the effects of different sizes of container stock on transplant establishment. Clonal replicates of *Vitex agnus-castus*, *Acer rubrum* var. *drummondii*, and *Taxodium distichum* grown under common nursery conditions in five container sizes, 3.5, 11.7, 23.3, 97.8, or 175.0 L (#1, #3, #7, #25, or #45, respectively), were transplanted to a sandy clay loam field. Physiological stress was measured using xylem water potential and photosynthetic gas exchange rates. Height, trunk diameter, and canopy spread were monitored post-transplant for three growing seasons and root growth was sampled for the first two growing seasons. Trees of all three species from smaller-sized containers, 23.3 L (#7) or less, exhibited reduced transplant shock, decreased establishment time and increased growth rates in comparison to larger-sized containers, apart from increased mortality in 3.5 L (#1) *A. rubrum* and slower growth in 3.5 L (#1) *T. distichum* compared to those transplanted from 11.7 L (#3) or 23.3 L (#7) containers Reduced stress levels and increased growth rates corresponded in timing with greater change in root extension of smaller container-grown trees. At the end of three growing seasons, no statistical differences in height or trunk diameter were present for *V. agnus-castus* container sizes. With a modest wait, consumers may find that smaller container-grown trees will overcome transplant stress more quickly and exhibit growth rates that surpass those of larger container-grown trees.

Index words: *Acer rubrum, Taxodium distichum, Vitex agnus-castus,* container-grown trees, transplant shock, transplant establishment, photosynthesis, transpiration, water stress.

Species used in this study: Chaste tree **(***Vitex agnus-castus* L. [an unnamed white flowering clone]); red maple (*Acer rubrum* L. var. *dummondii* [Hook. & Arn. *ex* Nutt.] Sarg. 'Maroon'); bald cypress (*Taxodium distichum* (L.) Rich. [test clone TX8DD38]).

Significance to the Horticulture Industry

With a large array of container size stocks available for transplanting to landscapes or nursery fields as liners, it is important to determine times required for successful establishment of differing-sized container stock and the trade-offs associated with initial size and establishment requirements. The objective of the current study was to quantify post-transplant stress levels expressed among trees transplanted from a wide range of container sizes within three differing taxa during landscape establishment and to document the rapidity of establishment (recovery and resumed growth) among trees from the various container sizes within each species. This information will help to better inform the industry regarding relative advantages of different container sizes for nursery growers, landscape contractors and consumers relative to post-transplant establishment in the landscape. Results from this study indicate a more rapid establishment for all three species (chaste tree, red maple, bald cypress) when transplanted from 11.7 (#3) or 23.3 L (#7) containers compared to trees from 97.8 L (#25) or 175.0 L (#45) containers. Industry professionals and consumers must determine if the immediacy of aesthetic impacts in the landscape from installation of larger 97.8 L (#25) or 175.0 L (#45) containers outweigh the advantages of less expensive smaller size trees from 11.7 (#3) or 23.3 L (#7) containers which have more rapid establishment after transplanting.

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Introduction

Trees have become available in containers in a wide array of sizes, with commiserate variability in pricing. Debate continues over the relative merits of these different container sizes, which could in part be due to the appreciation landscape firms and homeowners have for the instant impact large trees can provide, such as greater aesthetic value of larger trees (Kalmbach and Kielbaso 1979, Schroeder 2006), greater biomass present to withstand environmental anomalies (Nowak et al. 2007), less potential for catastrophic accidental or malicious mechanical damage (Foster 1976, Parsons 2015, Watson and Himelick 2013), instant shade (Kalmbach and Kielbaso 1979, Schroeder 2006), and increase in property value (Behe et al. 2005, Maco and McPherson 2003). These larger trees cost more to grow and occupy a greater amount of nursery space, resulting in higher prices for consumers (Watson and Himelick 2013). Smaller container sizes are less expensive for consumers as nurseries expend less on materials, maintenance, inventory carrying costs and square footage of nursery space occupied to produce smaller trees. Plants grown in smaller container sizes, once transplanted to the field, have reduced transplant shock (Teskey and Hinckley 1986), are in a phase of growth more closely aligned with the exponential growth rate of young seedlings (Gilman and Beeson 1996), have been in containers for shorter times, often have been successively transplanted from smaller to larger containers fewer times, reducing the potential occurrence of circling root development by reducing the number of deflected or circling roots and providing better anchorage (Gilman and Kane 1990, Gilman et al. 2013), and their smaller size makes for easier handling and staking (Watson and Himelick 2013). Benefits and costs of varying container sizes have yet to be fully evaluated to determine which container size affords the most advantageous opportunity for consumers.

The landscape establishment period of a plant is of utmost importance to determining vitality, growth rates, and maintenance needs. There are several measures of transplant establishment: re-establishment of growth (Gilman 1997, Watson 1985), resumption of a pre-transplant shoot elongation rate (Struve and Joly 1992), restoration of shoot xylem water potential (Beeson 1994, Beeson and Gilman 1992, Gilman 1992), and/or a return to pre-transplant photosynthetic rates (Richardson 2002). Due to physiological stress, as well as loss of roots from mechanical damage and root deflection during nursery production, transplanted trees experience a phase after planting in which growth is significantly reduced or suspended (Gilman et al. 2013). Therefore, the re-establishment of shoot growth is highly dependent on the rate and extent of root elongation outside the original planted root ball. The potential for root elongation is affected by the length of the growing season, as well as maintaining adequate soil moisture (Gilman 1997). Reduced gas exchange occurs when too little water uptake causes stomatal closure, thus limiting CO_2 uptake (Federer and Gee 1976). Physiological stress occurs when decreased xylem water potential in leaves affects plant growth processes (Hsiao 1973). When restoration of stomatal conductance and minimum xylem water potential deficits are achieved, growth can resume. Differential watering regimes can also affect tree establishment. In an experiment conducted by Gilman (2004), trees from containers irrigated three times a week during establishment grew faster and resumed minimal water potential deficits more quickly leading to a faster establishment versus those trees watered once every ten days.

It is often generally accepted that smaller-sized planting stock establishes more quickly after transplanting than larger stock, but this may not always be the case (Struve 2009) and formal studies are limited. Struve et al. (2000) suggested that this perception might be due to the marketing of quick growing individuals at an early age in the nursery compared to surrounding plants in the block, essentially unintentionally marketing the more vigorous phenotypes as smaller size plants while less vigorous phenotypes remained in the nursery to be marketed at larger container sizes. Gilman et al. (2013, 2010) found that smaller trees established more quickly than larger trees, but only tested one species in each study and a maximum of four container sizes. Lambert et al. (2010) investigated three sizes of containers for three species during forest establishment conditions, but the largest size tested was a 23.3 L (#7) container and no information was provided relative to the genotypic background of the plants, nursery source or production regimes; thus genotype, size, nursery source, or differential nursery production regimes may have been confounded with container size responses. Robbins (2006) also tested field responses of seven liner sizes of *A. rubrum* up to a maximum of #7 (no L volume provided) containers and found the greatest percentage growth increases in trunk caliper of the trees from smaller of the tested container sizes (#3 and #5, no L volumes were provided). The objective of the current study was to quantify post-transplant stress levels expressed among trees transplanted from a wide range of container sizes within three differing taxa during landscape establishment and to document the rapidity of establishment (recovery and resumed growth) among trees from the various container sizes within each species.

Materials and Methods

Three taxa were selected to represent different niches of the landscape industry and to eliminate genetic variation within a species by using clonal materials. Clonal selections of *Vitex agnus-castus* L. (an unnamed white flowering clone), *Acer rubrum* L. var. *dummondii* (Hook. & Arn. *ex* Nutt.) Sarg. ‘Maroon’, and *Taxodium distichum* (L.) Rich. (test clone TX8DD38) were chosen due to the widespread use of these species in the southern United States nursery trade and their representation of differing classes of landscape trees. Tip cuttings, 8 to10 cm (3 to 4 in) long, of each clone were taken from container-grown stock plants developed and maintained in College Station, TX (lat. 30°37′45"N, long. 96°20′34” W). Basal ends of these cuttings were then dipped in a liquid rooting hormone (Dip n’ Grow® Inc., Clackamas, OR) containing indole-3-butyric acid (IBA): naphthalene acetic acid (NAA) at a 3:1 concentrate [2,500 mg·L^{-1} (2,500 ppm) IBA: 1,250 mg·L^{-1}

Table 1. **Height and trunk diameter sizes of *Acer rubrum* var. *drummondii* 'Maroon', *Vitex agnus-castus*, and *Taxodium distichum* at the end of nursery production in 3.4, 11.7, 23.3, 97.8, or 175 L (#1, 3, 7, 25, or 45, respectively) containers prior to transplanting to the field site for in-ground testing.**[z]

	Acer rubrum		*Taxodium distichum*		*Vitex agnus-castus*	
Container size (L)	**Mean trunk diameter (cm)**	**Mean height (cm)**	**Mean trunk diameter (cm)**	**Mean height (cm)**	**Mean canopy spread (cm)**	**Mean height (cm)**
3.5	—	—	0.4±0.1	37.0±6.1	55.5±9.8	54.7±7.9
11.7	0.9±0.1	114.3±10.9	0.8±0.1	52.2±5.0	73.2±4.0	76.8±8.1
23.3	1.7±0.2	188.0±15.6	1.4±0.1	105.3±6.5	119.0±9.5	135.5±23.4
97.8	4.1±0.1	348.5±20.6	3.3±0.2	194.2±8.2	224.7±19.6	200.8±14.5
175	5.5±0.3	411.7±22.5	4.6±0.3	245.5±8.1	274.5±33.2	266.2±19.6

[z] As presented in Garcia et al. (2016). Values within a column represent the mean of six observations ± standard errors; — = omitted from analysis due to lost replicates in the field; 2.54 cm = 1.0 in.

(1,250 ppm) NAA] to water ratio for 5 s. Cuttings were placed in 36 cm by 51 cm by 10 cm (14 in by 20 in by 4 in) deep flats (Kadon Corp., Dayton, OH) filled with coarse perlite (Sunshine Perlite #3 4cf SUGRPLITE, Sun Gro Horticulture Canada Ltd., Seba Beach, AB, Canada) on an intermittent mist bench. Intermittent mist was applied at 16 min intervals for 20 s durations using reverse osmosis water from 1 h before sunrise to 1 h after sunset. Rooted cuttings were then potted in 3.5 L (#1) black plastic pots (Nursery Supplies, Inc., Kissimmee, FL) containing Metro-Mix 700 media (Sun Gro Horticulture Canada Ltd., Vancouver, BC, Canada). As cuttings grew, plants were transplanted repeatedly to sequentially larger container sizes (11.7 L, 23.3 L, 97.8 L, and 175.0 L; #3, #7, #25, and #45, respectively) according to ANSI Z60.1 (American Nursery and Landscape Association, 2004) standards. This process was repeated with additional cuttings until nine uniform plants of each species were achieved in each 3.5 L (#1), 11.7 L (#3), 23.3 L (#7), 97.8 L (#25), and 175.0 L (#45) container size (Table 1). During production, trees were amended with 15-3.9-9.9 controlled-release fertilizer (Osmocote® Plus, Scotts Co., Marysville, OH) every six months at 6.53 $kg \cdot m^{-3}$ (11.0 $lb \cdot yd^{-3}$) and grown in a gravel-bottomed nursery. When all container sizes were obtained [dates and sequence of propagation were as described in detail in Garcia et al. (2016)], six trees of each size for each species were transported 3.5 km (2.1 mi) to a sandy clay loam (66% sand, 8% silt, 26% clay, 6.0 pH) field in June 2013. Trees were transplanted to the field in a completely randomized design with each species constituting a separate but concurrent experiment conducted in adjacent plots. Trunk diameters of all three species were within ANSI Z60.1 specifications for their respective container sizes (Table 1) at the time of transplant. Trees were transplanted at spacings of 6 m (20 ft) within rows by 7.3 m (24 ft) between rows with 4 rows of alternating seven to eight trees per row in each experiment. Transplanting procedures followed those specified in ANSI A300 (Accredited Standards Committee A300 2014) and Watson and Himelick (2013). Spaces between the rows were sown with bermudagrass [*Cynodon dactylon* (L.) Pers.] and mown to maintain a 7 to 15 cm (3 to 6 in) height. A 2-m (6.6 ft) wide within row strip was maintained turf and weed free using seasonal pre-emergence herbicides and spot application of glyphosate.

Water needs. Under each tree, two Dan PC Jet spray stakes with a 18.9 $L \cdot h^{-1}$ (5.0 GPH) flow (NaanDanJain Irrigation, Inc., Pasco, WA) were connected to a polyethylene round tubing irrigation system (The Toro Company, El Cajon, CA). Since it was reasonable to assume irrigation requirements would vary among species and container sizes, providing irrigation via a single irrigation system would likely result in systematically over or under irrigating certain species and container size combinations. Thus, irrigation was conducted on a species-by-species and container size-by-container size within species basis according to estimates of soil moisture tension levels. This resulted in five independent irrigation systems for each of the three species, 15 independent irrigation systems in total. Soil moisture levels were determined using 30.5 cm (12 in) soil moisture tensiometers (Spectrum Technologies, Inc., Aurora, IL) installed in the soil at the edge of the root ball at the transition zone between backfill soil and potting media. These were placed at one specimen of each container size of each species at a depth of approximately 20 cm (8 in). Trees were monitored daily during the first growing season and approximately three times per week thereafter. Water was applied when the tensiometer indicated -20 kPa (-0.2 Bar), a soil moisture tension empirically determined to be well below when water stress symptoms (wilting) began to occur on these species at this site, or less and continued until tensiometers returned to near 0 kPa (0 Bar) of tension. Length of irrigation events and flow rates were used to estimate required supplemental irrigation for each container size and species combination during the first three growing seasons after transplant.

Water stress and gas exchange rates. Maximal water stress was estimated at midday (1200 to 1400 hr) and the ability to recover from this midday water stress was estimated the subsequent pre-dawn (0400 to 0600 hr) by measuring xylem water potential. Xylem water potential (Ψ) of leaves was estimated using a portable nitrogen pressure chamber (PMS Model 610 pressure chamber system, PMS Instrument Co., Albany, OR). Base-line measurements were recorded in the nursery prior to transplanting. Measurements were recorded at two-week intervals for the first two months following transplanting, then once a month until the end of the first growing season (October 2013), followed by every three months for the second growing season. Photosynthetic gas exchange readings were assessed at the same intervals as water potential measurements by estimating net carbon assimilation rate and stomatal conductance using a portable photosynthesis system (model 6400XT, LI-COR, Inc., Lincoln, NE) equipped with a red/blue LED light source (model 6400-02B LED, LI-COR Inc.). Observations were determined utilizing leaves in the middle half of the tree height, which were healthy, fully expanded and located in full sun exposure. Sample CO_2 was set to 390 $mg \cdot L^{-1}$ (390 ppm) and irradiance was set to 1200 $\mu mol \cdot m^{-2} \cdot s^{-1}$.

Growth after transplanting. Measurements of shoot growth included: height from ground level to uppermost shoot tip, mean canopy spread calculated as the mean canopy width in two directions from widest point to widest point within and perpendicular to the rows, shoot extension of three branches per tree, and trunk diameter at 15 cm (6 in) above the soil surface. Trunk diameters measurements for *V. agnus-castus* followed ANSI Z60.1 (American Association of Nurseryman 2004) standards for multi-trunk trees dictating a sum of the three largest trunk diameters divided by two. Measurements were taken for each tree prior to transplanting in early June 2013 and then at the end of each growing season in October. Three additional trees from each container size and species were destructively harvested in June 2013 to determine initial biomasses at the end of nursery production prior to transplanting to the field, which were reported in Garcia et al. (2016).

Additionally, root growth following transplant was measured at the end of each of the first two growing seasons in October. A 1.5 m (4.9 ft) long by 0.5 m (1.6 ft) wide rectangular swath extending out from the edge of the initial root ball was excavated using a compressed air excavation tool (Air-Spade, GuardAir® Corp., Chicopee, MA) and extended until the longest root's length which originated in that swath was determined. Swaths were located at random on the north or south side (within rows) of three of the six transplanted trees within each species and container size combination. In the fall of the second growing season, the root growth on the opposite side of the tree from that sampled in the previous year was measured. This was done on the chance roots were damaged during the excavation process the year before. Counts of all roots extending beyond the original planted root ball and the length of the longest regenerated root were then recorded. Ratios comparing shoot height to root extension, trunk diameter to root extension, and canopy spread to root extension were calculated during the first two growing seasons.

Data analysis. An analysis of the variance in the data was analyzed using general linear models procedures in SAS 9.3 (SAS Institute Inc., Cary, NC) to determine the significance ($P \leq 0.05$) of interactions and main effects for each species independently. Where interactions were not significant, observations were pooled to test main effects. Means and standard errors were estimated using least-squares means procedures for significant ($P \leq 0.05$) effects to illustrate responses and variability at the measured intervals. When significant effects for continuous variables were found, stepwise polynomial regression analyses ($P \leq 0.05$) were used to elucidate trends and predict levels in between the measured data intervals.

Results and Discussion

Acer rubrum. The *A. rubrum* transplanted from 3.5 L (#1) containers were highly susceptible to herbivory by deer (*Odocoileus virginianus* Zimmermann) as signs of deer grazing were found on only transplanted 3.5 L (#1) *A. rubrum*. The presence of leaves closer to the ground on the smaller *A. rubrum* from 3.5 L (#1) containers exposed them to irrigation drift from the spray stakes resulting in some foliar necrosis due to the elevated sodium [193 $mg \cdot L^{-1}$ (193 ppm)] and total dissolved salt [544 $mg \cdot L^{-1}$ (544 ppm)] content in the municipal water in College Station, TX (City of College Station 2014). Four of the six *A. rubrum* replicates from 3.5 L (#1) containers died within the first month of transplant and the remaining two were consistently defoliated or had few leaves from which to sample during the first growing season. By the end of the first growing season, only one of the 3.5 L (#1) container-grown *A. rubrum* remained. Therefore, data collection and observations were omitted for the 3.5 L (#1) container-grown *A. rubrum*. Foliage of trees from other sizes of *A. rubrum* and the *T. distichum* trees were not exposed to foliar salts. Some of the lower leaves on *V. agnus-castus* were occasionally exposed to irrigation drift but exhibited no adverse symptoms of damage.

For *A. rubrum*, two-way interactions were significant for time after transplanting and container sizes for all measures except net carbon assimilation, season ending trunk diameter, and root extension (Table 2). Main effects of time were significant for all measured characteristics of *A. rubrum,* and the main effects of container size were significant for all characteristics except net carbon assimilation and stomatal conductance. In the figures, the first growing season in the field is represented by those observations occurring up to 150 days after transplant and the second growing season is represented by the readings after the first winter, 300 to 500 days after transplant (Fig. 1–6).

Midday water potentials for *A. rubrum* transplanted from 11.7 L (#3) and 23.3 L (#7) containers exhibited mild stress based on midday Ψ for the first three months after transplant, while those of trees transplanted from 97.8 L (#25) or 175 L (#45) containers exhibited more moderate to severe water deficits (Fig. 1A). However, by the final observation date of the first growing season and throughout the second growing season *A. rubrum* from all container sizes exhibited only modest midday Ψ stress (Fig. 1A). Drought stress sensitivity appeared to be a more immediate effect of transplant stress, even when soil moisture was available as irrigation was provided to maintain soil moisture tension at >-20 kPa (-0.2 Bar) throughout the study. Insufficient time for acclimation of plants to the more challenging conditions in the field compared to the nursery environment may explain part of the initial stress symptoms. Alternatively, the initial water deficit could be related to slower movement of water from higher bulk density soil to the low bulk density root ball once irrigation

Table 2. Partial analysis of variance for stress and growth measures of *Acer rubrum* var. *drummondii* 'Maroon', *Vitex agnus-castus*, and *Taxodium distichum* three years after transplant from five container sizes, 3.5, 11.7, 23.3, 97.8, or 175 L (#1, 3, 7, 25, or 45, respectively). Each species was treated as a separate, but concurrent, experiment and arranged in the field in a completely random design.[z]

Experiment	Effect	Mid-day Ψ	Pre-Dawn Ψ	Pn	Stomatal Conductance	End of season Trunk diameter	End of season Height	End of season Canopy spread	Root extension
Acer rubrum	Time	***	***	***	***	***	***	***	**
	Container size	***	***	ns	ns	***	***	***	***
	Time x container size	***	*	ns	*	ns	**	*	ns
Taxodium distichum	Time	***	***	***	***	***	***	***	***
	Container size	***	***	ns	ns	***	***	***	***
	Time x container size	ns	ns	ns	**	ns	*	ns	ns
Vitex agnus-castus	Time	***	***	***	***	***	***	***	***
	Container size	***	***	***	***	***	***	***	***
	Time x container size	***	**	ns	ns	ns	***	*	ns

[z]***, **, * indicate the effect is significant at $P \leq 0.001$, 0.01, or 0.05, respectively; ns = not significant at $P \leq 0.05$.

falling directly on the root ball was depleted for the transplanted trees, particularly those from larger containers. Although both the volume and surface area of planted root balls increases with increasing container volume, the ratio of volume of substrate to surface area of the planted root ball does not remain constant. The ratio of substrate to surface volume increases over three fold from 2.68 $cm^3 \cdot cm^{-2}$ (0.16 cubic in per square in) for the 3.5 L (#1) planted root balls to 9.55 $cm^3 \cdot cm^{-2}$ (0.58 cubic in per square in) for the 175 L (#45) root balls. This would mean that with a given rate of movement of water into or out of the planted root balls, the smaller planted root balls would likely dry or rewet more quickly than those from larger containers due to the greater surface area per unit volume of substrate within the smaller root balls. This could be an asset or liability depending upon whether it was during depletion of water from the planted root ball in dry soils or rewetting during an irrigation or precipitation event. There may be an optimal size of root ball that retains sufficient moisture during drought events, but is not so large as to hinder rewetting as soil moisture is restored.

Throughout the first growing season (Fig. 1A), the trees from all container sizes progressively exhibited reduced midday water stress following the initial peak stress

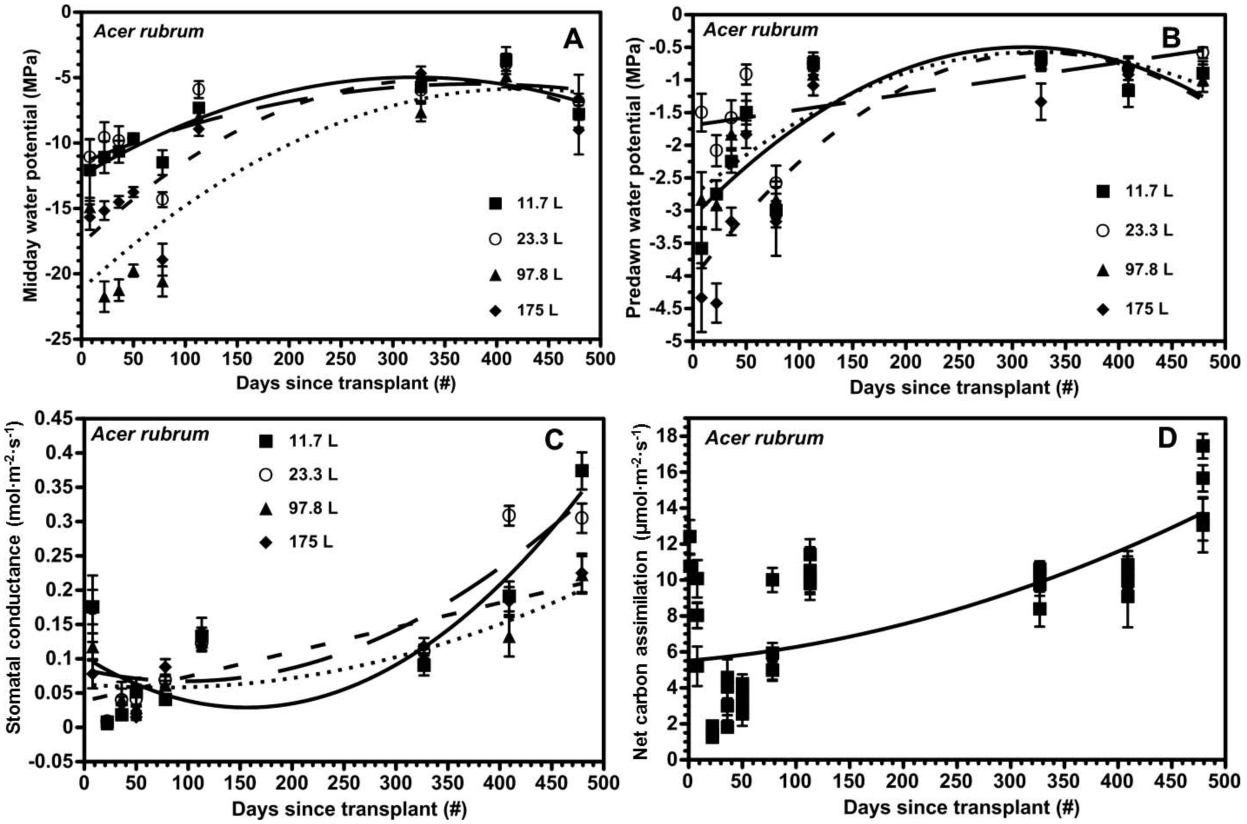

Fig. 1. Xylem water potential (Ψ) [A midday Ψ; B predawn Ψ] and photosynthetic gas exchange [C stomatal conductance; D net carbon assimilation] across container sizes of *Acer rubrum* grown in 11.7, 23.3, 97.8, or 175.0 L (#3, 7, 25 or 45, respectively) containers during the first two growing seasons after transplant to a field site in College Station, TX. Symbols represent mean ± standard errors of six observations.

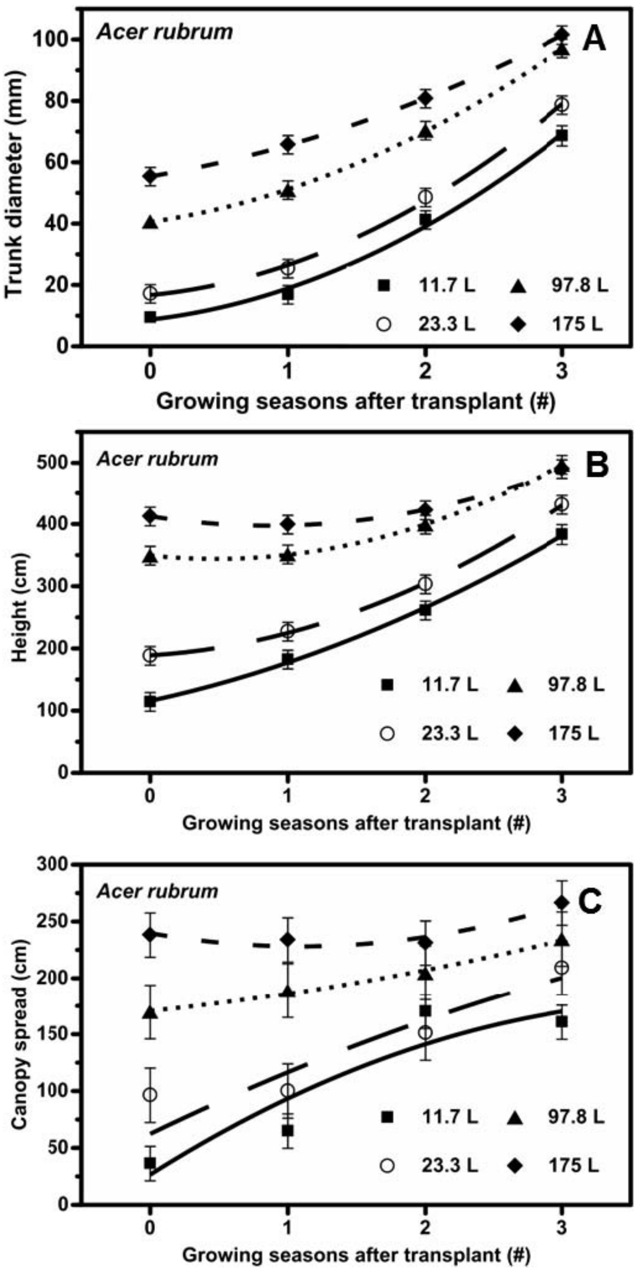

Fig. 2. **Shoot growth (A trunk diameter; B height; and C canopy spread) of *Acer rubrum* grown in 11.7, 23.3, 97.8, or 175.0 L (#3, 7, 25 or 45, respectively) containers during three growing seasons after transplant to a field site in College Station, TX. Symbols represent mean ± standard errors of six observations.**

immediately after transplanting. The exception occurred at the 78-day mark, which correlates with the hottest part of the first growing season (mean 38.3 C [101 F] over five days). During this period, trees from all container sizes experienced more negative water potentials followed by recovery with cool fall temperatures and rain at the 113th day after transplanting. Readings taken during the second growing season exhibit reduced midday water stress levels with measurements across all container-sized trees clustered tightly and varying by less than 5 MPa throughout the season. Overall trends show that during initial establishment the smaller 11.3 L (#3) and 23.3 L (#7) container-grown trees were less water stressed during the day when compared with larger 97.8 L (#25) and 175 L (#45) container-grown trees (Fig. 1A). Predawn xylem water potentials exhibited a similar trend of greater recovery from the previous day's midday water stress by 11.3 L (#3) and 23.3 L (#7) trees compared to those from 97.8 L (#25) and 175 L (#45) containers during the first two months after transplant (Fig. 1B). With the exception of the hottest part of the first summer following transplant (day 78) and first observation for 175 L (#45) trees of the second growing season, predawn recovery was similar among all container sizes of *A. rubrum* (Fig. 1B). Given similar responses among trees from the various container types from the end of the first growing season and throughout the second growing season, it would indicate that establishment was similar across container sizes from a water stress perspective in the second growing season (Fig. 1A and 1B).

Stomatal conductance of *A. rubrum* immediately following transplanting was moderately high in comparison to baseline nursery data for all container sizes followed one week later by a sudden decrease (Fig. 1C). This could represent the acclimation of stomata to the more demanding conditions in the field than the nursery. This follows reports of anisohydric plants in which stomatal closure is delayed to more severe water stress levels compared to milder Ψ (Mitchell et al. 2013, Savi et al. 2016). At 15 days following transplant, stomatal conductance (Fig. 1C) was close to 0 $mol{\cdot}m^{-2}{\cdot}s^{-1}$ in all container sizes, indicating gas exchange was inhibited and the trees were experiencing water stress, which was consistent with both more negative midday and predawn Ψ (Fig. 1A and 1B). Within a few weeks of transplanting, mean stomatal conductance of *A. rubrum* slowly increased, likely allowing water and carbon dioxide exchange to occur at higher levels, which is supported by the pattern of response in net carbon assimilation (Fig. 1D). Overall stomatal conductance continued to increase during the second growing season, particularly with *A. rubrum* from smaller 11.7 L (#3) and 23.3 L (#7) container sizes, allowing greater gas exchange to occur, which would be consistent with less comparative water stress in the second growing season (Fig. 1A and 1B). Across container sizes, net carbon assimilation rates of transplanted *A. rubrum* followed similar patterns as that of stomatal conductance with an initial drop, then consistent recovery through the latter part of the first growing season and throughout the second growing season (Fig. 1D).

Initial trunk diameters at transplant were within ANSI Z60.1 (American Association of Nurseryman 2004) container size standards (Table 1). Trees transplanted from all container sizes increased in trunk diameter across all three growing seasons compared to initial sizes of *A. rubrum* at transplant (Fig. 2A, Table 2). Trees from the smaller container sizes grew at such a rate that, by the end of the third growing season, only modest differences in diameter were apparent between trees from larger and smaller containers (Fig. 2A). At the end of the second growing season, trees from 11.7 L (#3) and 23.3 L (#7) containers were half the diameter of 175 L (#45) trees [40 mm to 80 mm (1.57 in to 3.15 in)] and by the end of the

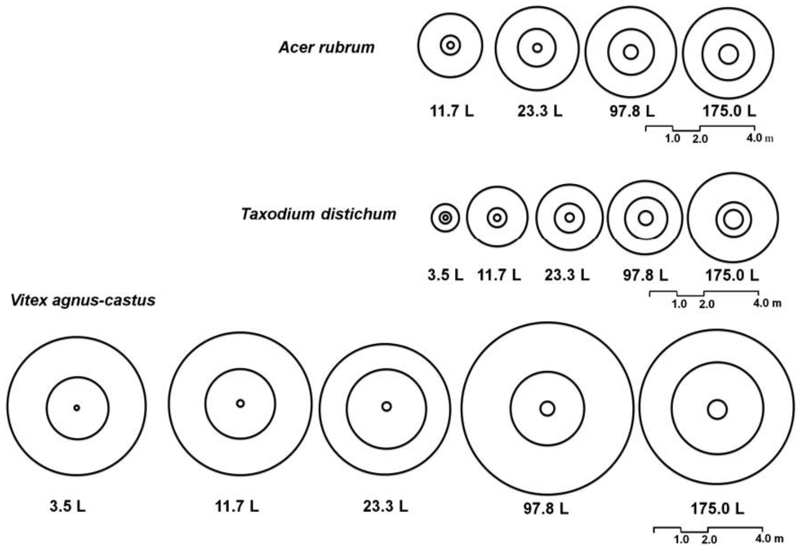

Fig. 3. Mean maximum root length (n=3) of *Acer rubrum*, *Taxodium distichum*, and *Vitex agnus-castus* at transplant (inner circles), end of the first growing season (middle circles), and end of the second growing season (outer circles) after transplant from either 3.5, 11.7, 23.3, 97.8, or 175.0 L (#1, 3, 7, 25, or 45, respectively) containers to a field site in College Station, TX.

third growing season were converging with the trunk diameters of the trees planted from much larger containers (Fig. 2A). Cumulative percentage change in growth after transplant was substantially greater with smaller 11.7 L (#3) and 23.3 L (#7) container-grown trees, increasing trunk diameter to approximately 4 and 3 times their initial diameters compared to *A. rubrum* from larger 97.8 L (#25) and 175 L (#45) containers, which increased in trunk

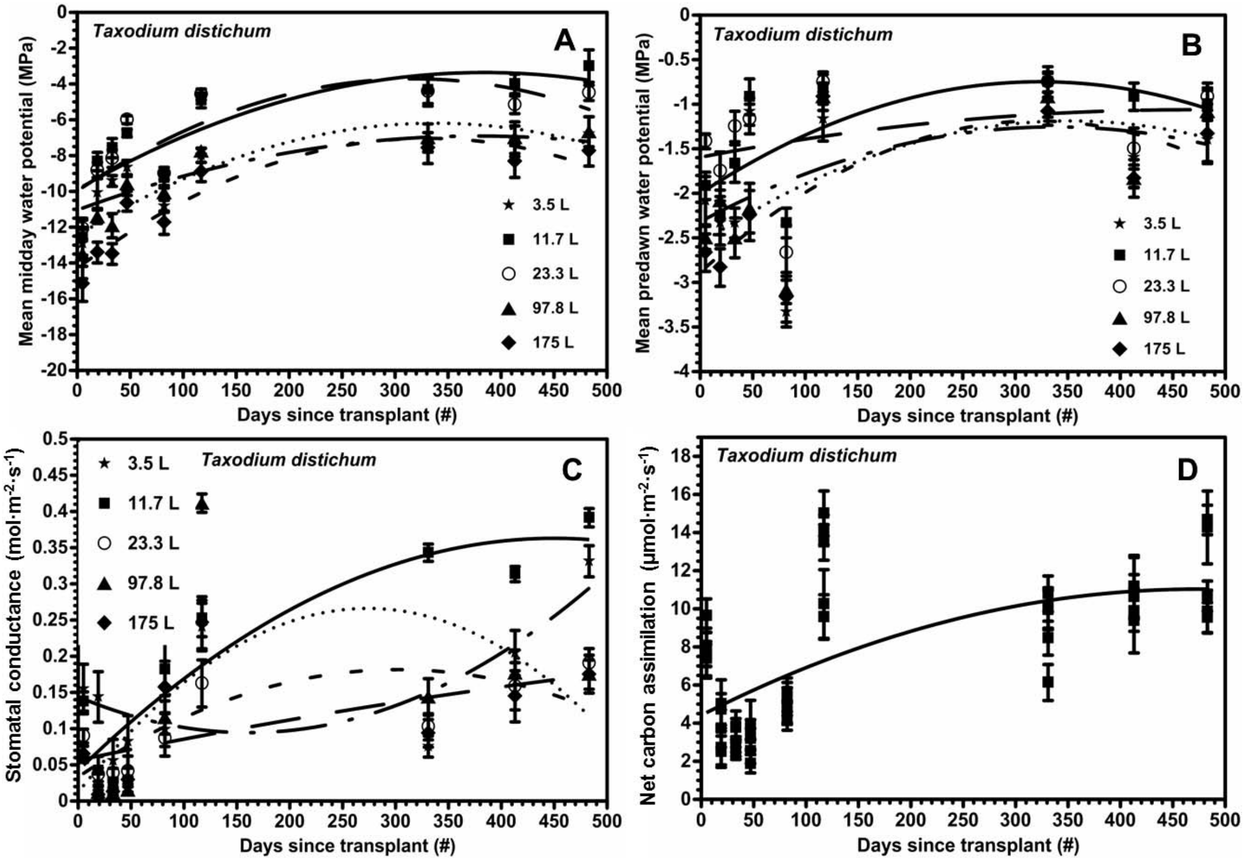

Fig. 4. Xylem water potential (Ψ) [A midday Ψ; B predawn Ψ] and photosynthetic gas exchange [C stomatal conductance; D net carbon assimilation] across container sizes of *Taxodium distichum* grown in 3.5, 11.7, 23.3, 97.8, or 175.0 L (#1, 3, 7, 25 or 45, respectively) containers during the first two growing seasons after transplant to a field site in College Station, TX. Symbols represent mean ± standard errors of six observations.

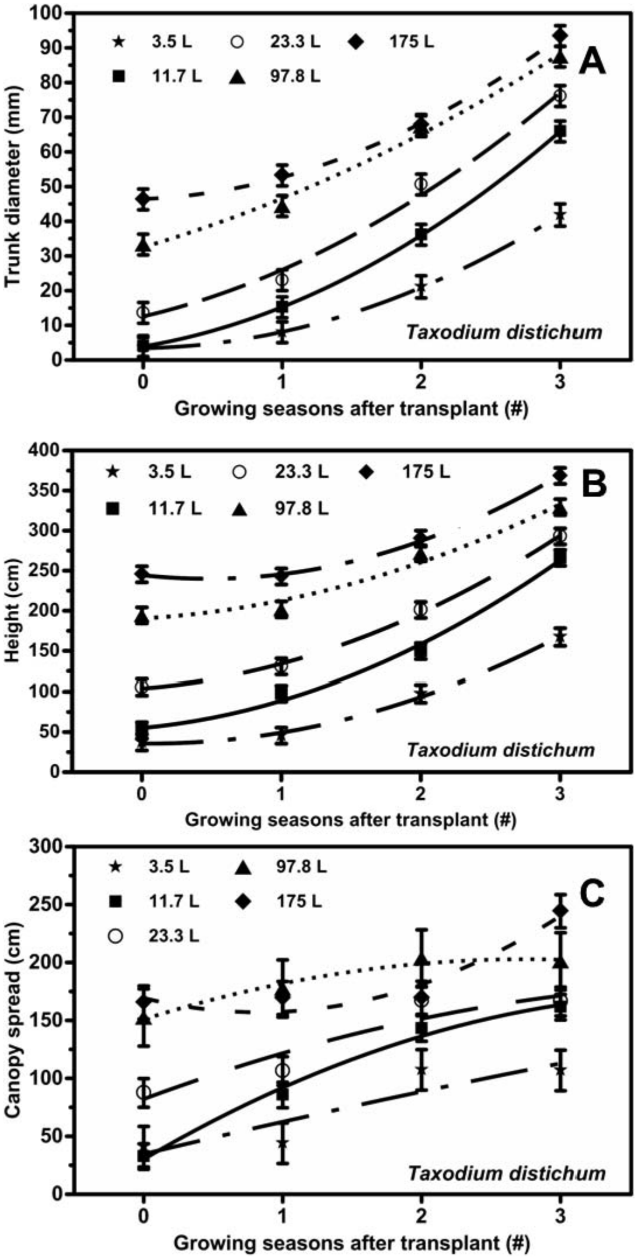

Fig. 5. Shoot growth (A trunk diameter; B height; and C canopy spread) of *Taxodium distichum* grown in 3.5, 11.7, 23.3, 97.8, or 175.0 L (#1, 3, 7, 25 or 45, respectively) containers during three growing seasons after transplant to a field site in College Station, TX. Symbols represent mean ± standard errors of six observations.

diameter by only about 2 to 2.5 times their initial diameters (Fig. 2A). This is in concurrence with findings of Robbins (2006) assessing the change in trunk diameter of field-grown red (*A. rubrum*) and freeman (*Acer* x *freemanii* A.E. Murray) maples from different liner sizes in which increase of trunk diameter was 223% and 445% for #5 (no L equivalents provided) and #3 container grown trees, respectively.

Height growth after transplant (Fig. 2B, Table 3) of *A. rubrum* responded similarly to that of trunk diameter growth. Trees from the 97.8 L (#25) and 175 L (#45) containers grew very little until the third growing season. Growth rates of trees from 11.3 L (#3) and 23.3 L (#7) containers remained steady and greater than larger container sizes from transplant through the third growing season (Fig. 2B). At the time of transplanting, *A. rubrum* from 97.8 L (#25) and 175 L (#45) containers were 200 to 300 cm (79 to 118 in) taller than those from 11.3 L (#3) or 23.3 L (#7) containers, but by the end of three growing seasons in the field the mean heights of trees from all container sizes were within 100 cm (39 in) of each other (Fig. 2 B). Mean increase in height was negligible for *A. rubrum* from larger container sizes during the first two growing seasons and was actually slightly negative during the first growing season for 175 L (#45) container-grown trees (Fig. 2B). This most likely was due to slight stress-induced dieback of branch tips on some trees. Canopy spread exhibited similar patterns of response as trunk diameter and canopy height, but was more variable (Fig. 2C). Mean differences in canopy spread of *A. rubrum* went from a five-fold spread between that of 11.7 L (#3) compared to that of the 175 L (#45) container grown trees to a two-fold spread after three growing seasons (Fig. 2C). Given the rapid rates of return to active trunk diameter, shoot height, and canopy spread growth of *A. rubrum* from 11.7 L (#3) and 23.3 L (#7) containers (Fig. 2A-C) and their reduced xylem water potentials (Fig. 1A-B) and recovered stomatal conductance (Fig. 1C), they were assumed to have fully established sometime late in the first or beginning of the second growing seasons. *Acer rubrum* transplanted from 97.8 L (#25) and 175 L (#45) containers did not appear to exhibit characteristics of establishment for resumption of strong shoot growth until the third season after transplant (Fig. 2). Struve et al. (2000) suggested that smaller trees may establish better because they grew to a marketable size and were harvested sooner, essentially selecting for more vigorous phenotypes compared to larger trees rather than being an inherent growth advantage of younger stock. However, given that all of the trees were clonal in this study and grown under the same nursery conditions with no selective harvesting among a group of plants occurring, the growth advantages can be attributed to the stock size rather than some unintentional selection of more vigorous individuals. Levinsson (2015) working with red oak [*Quercus rubra* (L.)] and sweet cherry (*Prunus avium* L.) found no relationship among chlorophyll fluorescence, shoot growth, or stem circumference in the nursery and post-transplant measures of establishment.

Root extension beyond the transplanted root ball was sampled at the end of the first and second growing seasons. During the first growing season, all *A. rubrum* averaged a 200% or greater change in root length compared to the initial length in the root ball (Fig. 3, Table 2); however, trees from 11.7 (#3), 97.8 (#25), and 175 L (#45) container-grown trees were slightly less vigorous in root growth than the 23.3 L (#7) trees. By the end of the second growing season, percentage change in root growth was greater in 11.7 L (#3) container-grown trees than the others. Thus cumulatively across both growing seasons, the trees from 11.7 L (#3) and 23.3 L (#7) containers extended their roots a greater percentage of their initial size than did the larger

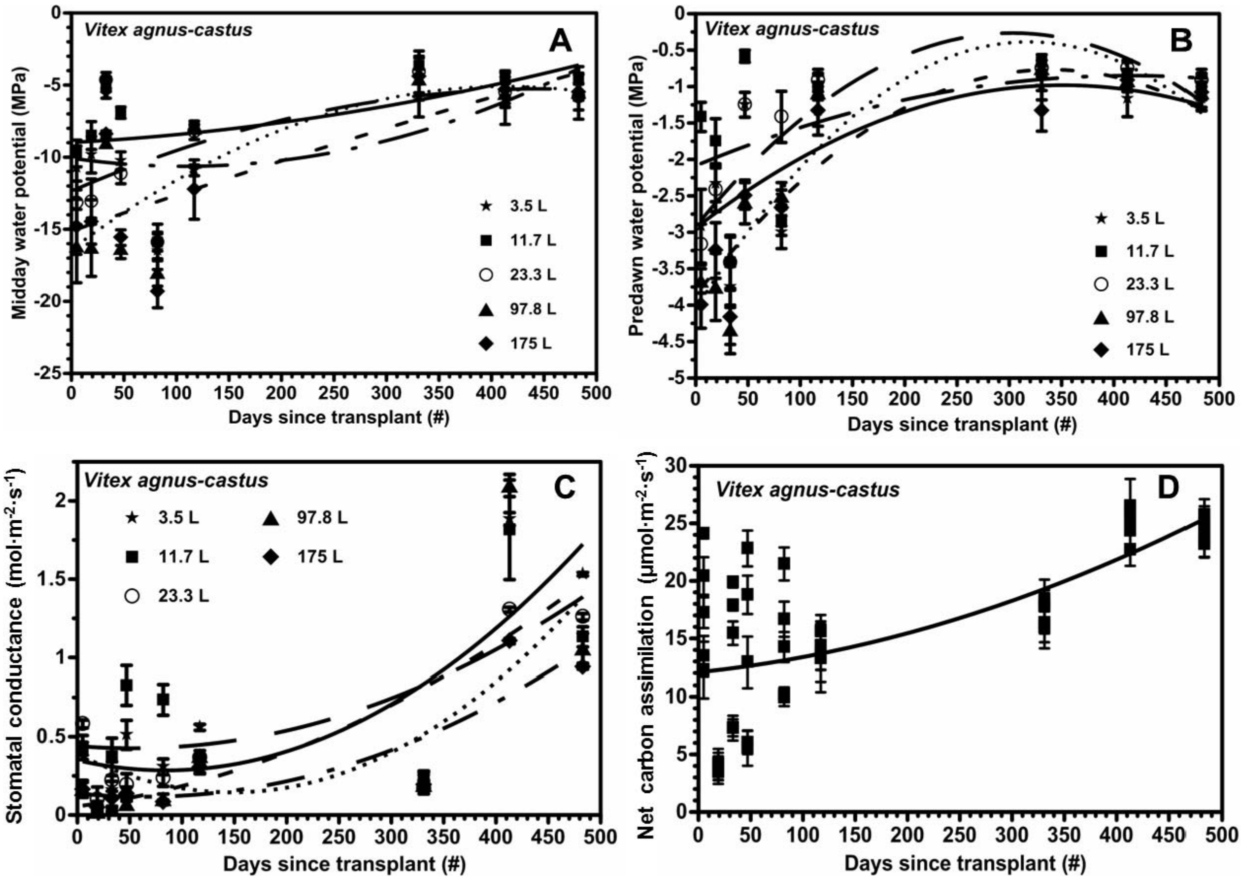

Fig. 6. Xylem water potential (Ψ) [A midday Ψ; B predawn Ψ] and photosynthetic gas exchange [C stomatal conductance; D net carbon assimilation] across container sizes of *Vitex agnus-castus* grown in 3.5, 11.7, 23.3, 97.8, or 175.0 L (#1, 3, 7, 25 or 45, respectively) containers during the first two growing seasons after transplant to a field site in College Station, TX. Symbols represent mean ± standard errors of six observations.

container-grown trees. This increased root extension (Fig. 3) mirrors increases in growth of the shoot system for both 11.7 L (#3) and 23.3 L (#7) container-grown trees in comparison to those from 97.8 L (#25) and 175 L (#45) containers (Fig. 2A-D). By the end of the first growing season, the length of the roots for 11.7 L (#3) trees were the same length as the initial 175 L (#45) tree root length. Roots of *A. rubrum* transplanted from 11.7 L (#3), 23.3 (#7), and 97.8 L (#25) containers all grew by approximately 90 cm (36 in) the second growing season, suggesting 90 cm (36 in) a season would be a norm for the climate, soil conditions, and irrigation on the site. Of note, by the end of the second growing season, root growth of *A. rubrum* grown in 23.3 L (#7) containers was nearly equal in spread to that of trees transplanted from 97.8 L (#25) and 175 L (#45) containers (Fig. 3), which correlates with shoot growth responses (Fig. 2). Differential rates of root extension of *A. rubrum* appeared to be most noticeable

Table 3. Effects of container size 3.5, 11.7, 23.3, 97.8, or 175 L (#1, 3, 7, 25, or 45, respectively) on ratios of root length to shoot height, trunk diameter, or canopy spread across the first two growing seasons after transplanting for *Vitex agnus-castus*, *Acer rubrum*, and *Taxodium distichum* on a sandy clay loam soil in College Station, TX; n = 6.^{z}

	Root length to shoot height			Root length to shoot height		Root length to trunk diameter			Root length to trunk diameter		Root length to canopy spread			Root length to canopy spread	
	(cm*cm^{-1})			[container size # (L)]		(cm*mm^{-1})			[container size # (L)]		(cm*cm^{-1})			[container size # (L)]	
Species	Mean	Max.	Min.^{y}	Max.	Min.^{x}	Mean	Max.	Min.^{y}	Max.	Min.^{x}	Mean	Max.	Min.^{y}	Max.	Min.^{x}
Acer rubrum	0.8	0.9	0.7^{ns}	23.3	11.7	5.3	7.5	3.8^{*}	23.3	175	1.4	1.9	1.2^{ns}	23.3	175
Taxodium distichum	1.0	1.2	0.9^{ns}	11.7	175	4.8	5.8	3.7^{ns}	23.3	175	1.2	1.3	1.0^{ns}	23.3	3.5
Vitex agnus- castus	2.0	2.2	1.8^{ns}	3.5	175	8.8	10.8	7.3^{ns}	3.5	97.8	1.9	2.2	1.7^{ns}	3.5	97.8 & 175

[z] ***, **, * indicate the effect is significant at $P \leq 0.001$, 0.01, or 0.05, respectively; ns = not significant at $P \leq 0.05$; na = not applicable.

[y] Mean of the ratio across container types; Max. = maximum ratio fora container size; Min. = minimum ratio for a container size; conversions to English units: 2.54 cm = 1 in., 25.4 mm = 1 in.

[x] Max. = container size in L of the maximum ratio, Min. = container size in L of the minimum ratio; 3.5 L, 11.7 L, 23.3 L, 97.8 L, and 175 L = #1, #3, #7, #25, and #45 containers, respectively.

during the first year of establishment and then become more uniform among container sizes during the second growing season (Fig. 2). The second growing season responses would be consistent with establishment models outlined in Watson (2004) and Watson and Himelick (2013) indicating that root elongation distance is often similar across various sizes of trees for a given genotype. When a tree is established, many roots will have grown a distance equal to approximately 3 times the distance from the trunk to the branch tips (Gilman, et al. 1998, Watson and Himelick 1982). Our results indicated that root length during the first two years post-transplant were less than this ration of 3:1 for height, trunk diameter, and canopy spread (Table 3); however, this may be a reflection of the growth habit of the trees, species variation in responses, variation in soil types or the more demanding site conditions in central Texas compared to locations in more mesic climates.

Taxodium distichum. Interactions among effects of time after transplant and container sizes were significant for only stomatal conductance and ending height of *T. distichum*, although main effects of time after transplant were significant for all remaining parameters presented (Table 2). Likewise, the main effects of container size were significant for all characteristics measured for *T. distichum* other than net carbon assimilation rates and stomatal conductance (Table 2). *Taxodium distichum* across all container sizes exhibited signs of drought stress within the first five days of transplant as indicated by midday and predawn Ψ values (Fig. 4A and 4B). For all container sizes of *T. distichum*, Ψ initially decreased then gradually became more positive, indicating less water stress, until the 84th day following transplant. At this point, all container sizes were affected by high summer temperatures (mean high of 38.3 C [101 F] over five days), as seen through elevated levels of water stress indicated by more negative predawn recovery (poor recovery from prior midday stress) (Fig. 4B and 4A). Otherwise, *T. distichum* transplanted from 11.7 L (#3) and 23.3 L (#7) containers exhibited the least negative midday Ψ (Fig. 4A) and recovered as well as or better than plants from any of the other container sizes during both the first and second growing seasons (Fig. 4B). Differential midday Ψ persisted among trees from the various container sizes throughout both growing seasons (Fig. 4A), but predawn recovery under these conditions was similar among all container sizes by the final observations of the first growing season and throughout most of the second growing season (Fig. 4B). The consistently milder midday stress symptoms exhibited by trees from 11.7 L (#3) and 23.3 L (#7) containers suggest that they were more fully established in comparison with the remaining trees.

Within the first week after transplanting, *T. distichum* from all container sizes had reduced photosynthetic gas exchange compared to initial rates at transplanting as evidenced by reduced stomatal conductance (Fig. 4C). Interestingly, trees increased stomatal conductance compared to initial rates after transplanting at approximately the 84th day following transplanting (Fig. 4C), which was associated with a peak in summer temperatures and presumably evaporative demand, and which also corresponded with a reduced capacity to recover from the previous day's water stress across all container sizes (Fig. 4B). Continued increase in stomatal conductance occurred through the end of the first growing season. Throughout the second growing season, *T. distichum* from 11.7 L (#3) containers diverged from the remaining trees demonstrating levels that might be expected when trees would be fully established (Fig. 4C). The *T. distichum* from 3.5 L (#1) containers had low stomatal conductance in the spring of the second year, but by autumn appeared to be trending toward establishment as well. Consistent with water potential data, the 97.8 L (#25) and 175 L (#45) trees continued to exhibit lower levels of stomatal conductance during the second growing season, indicating they were not yet established. These responses are consistent with the reports that *Taxodium distichum* is a relatively slow-growing tree (Wilhite and Toliver 1990). Of interest, while trees from 23.3 L (#7) containers appeared established according to midday and predawn Ψ by the end of the first growing season (Fig. 4A and 4B), stomatal conductance was not fully restored during the second growing season (Fig. 4C). Across container sizes, *T. distichum* exhibited an initial drop in net photosynthetic rates, which recovered to a high level with the cooler conditions of autumn (Fig. 4D) during the first growing season. Net carbon assimilation rates were similar to or greater than those reported by Bryan (2008) during establishment of *T. distichum* in four soil types. Across container sizes, net photosynthetic rates of *T. distichum* during the second growing season were similar to or greater than those seen at transplant and at the final fall observation of the first growing season (Fig. 4D).

All *T. distichum* trees grew in trunk diameter during the first three growing seasons after transplant (Fig. 5A, Table 2). Relative trunk diameter growth of *T. distichum* from the 97.8 L (#25) and 175 L (#45) containers occurred at a modest rate throughout the first three seasons after transplanting; however, trunk diameter growth of trees from 11.7 L (#3) and 23.3 L (#7) containers was more rapid and by the end of the third growing season, they had greatly narrowed the size gap with those *T. distichum* from 97.8 L (#25) and 175 L (#45) containers (Fig. 5A, Table 2). Although the growth rates of *T. distichum* from 2.5 L (#1) containers was greater during the first growing season than those from the largest two containers, their growth rates appeared to be slower in comparison to that of trees transplanted from 11.7 L (#3) or 23.3 L (#7) containers (Fig. 5A). Thus, there may be a lower threshold for *T. distichum* trees from smaller container sizes that are able to match with the growth rate of those from larger containers. By the end of the second year, the trees transplanted from 11.7 L (#3) containers ended with a trunk diameter of 3.6 cm (1.4 in), similar to the starting trunk diameter of 97.8 L (#25) trees (Fig. 5A). By the end of the second growing season, no statistical differences were present for trunk diameters of *T. distichum* from 97.8 L (#25) and 175 L (#45) containers (Fig. 5A).

Height growth (Fig. 5B, Table 3) for *T. distichum* was similar in pattern of response among trees from various container sizes as trunk diameter (Fig. 5A). However, overall changes in height were of a lesser magnitude for smaller container sizes. Final height growth during the first growing season for *T. distichum* after transplanting was very moderate for trees from smaller containers and essentially non-existent for *T. distichum* from larger 97.8 L (#25) and 175 L (#45) containers (Fig. 5B). Smaller container-sized trees, 3.5 (#1), 11.7 (#3), and 23.3 L (#7) increased in height proportionally more following transplant than larger container-sized trees (Fig. 5B). Given this height growth (Fig. 5B), in combination with the greater growth seen in the trunk diameter (Fig. 5A), establishment of the smaller container sizes appears to have occurred more rapidly and was likely completed by the end of the second growing season based on low levels of water stress (Fig. 4A and 4B) and resumption in shoot growth measures. Although small differences in size persist among *T. distichum* transplanted from the four larger size containers, only those transplanted from 3.5 L (#1) containers remained substantially smaller after three growing seasons (Fig. 5A and 5B). The inability of very small container-grown *T. distichum* to "catch up" as quickly as intermediate size transplants can likely be attributed to some of the same factors as discussed for *A. rubrum* survival when transplanted from 3.5 L (#1) containers. When transplanting *Pinus monticola* Douglas *ex* D. Don in forest plantings, Regan and Davis (2008) reported an advantage to trees from larger liner containers. Although their containers sizes were much smaller than those used in this study, their findings also suggest a lower limit to smaller trees establishing more rapidly than larger ones and suggesting optima may vary with planting conditions and intended uses. Canopy spread of *T. distichum* followed a generally similar pattern of responses as that of trunk diameter and height, but differences among trees from the various container sizes appeared to be persisting longer for the largest, 175 L (#45) and smallest, 3.5 L (#1) trees (Fig. 5 C). Slower establishment of *T. distichum* is consistent with its reputation as a slower growing tree species (Wilhite and Toliver 1990).

As with *A. rubrum*, root growth *of T. distichum* was assessed at the end of the first and second growing seasons. The first growing season, *T. distichum* from 23.3 L (#7) containers had a slightly larger percentage change in root elongation than the trees from the 175 L (#45) containers (Fig. 3, Table 2). The 11.7 L (#3) trees produced 83 cm (33 in) of root extension between the first and second growing seasons (Fig. 3). Overall, across both growing seasons, the 11.7 L (#3) and 23.3 L (#7) container-grown trees extended their roots a greater percentage of their initial size than did the 97.8 L (#25) and 175 L (#45) container-grown trees (Fig. 3). As with *A. rubrum,* the rate of root elongation appeared to vary among trees from different container sizes during the first growing season, but unlike *A. rubrum*, the rates of root elongation appeared to continue to vary among *T. distichum* from different container sizes in the second growing season (Fig. 3). Similar to differences in shoot growth of *T. distichum* among container types, the root elongation of 3.5 L (#1) container grown trees substantially lagged behind that of the other four container size trees.

Vitex agnus-castus. Interactions between time and container sizes were significant for mid-day and predawn Ψ, tree height, and canopy spread (Table 2). Main effects of time and container size were significant for all measured characteristics (Table 2). *Vitex agnus-castus* exhibited moderate levels of midday water stress immediately following transplanting in all container size trees as indicated by initial drop in midday Ψ, but was only present at modest levels for trees from the three smaller container sizes during the first couple of weeks after transplant (Fig. 6A). Recovery from these midday water stresses for *V. agnus-castus* was poor during the first two months after transplant for all except the 3.5 L (#1) and 11.7 L (#3) container-grown trees (Fig. 6B). At the 34th day following transplant, midday Ψ became less negative indicating less water stress for all container sizes (Fig. 6A). This could be explained by the wet soils and humid overcast conditions surrounding that date of data collection with a cumulative rainfall of 32.8 mm (1.3 in) over three days. As seen with *A. rubrum* and *T. distichum* on the 82nd day following transplant, *V. agnus-castus* exhibited high levels of water stress associated with elevated summer temperatures (mean 38.3 C [101 F] over five days). Midday Ψ fluctuated greatly over the first growing season, but trees from 3.5 L (#1) and 11.7 L (#3) containers tended to exhibit less severe midday Ψ deficits (Fig. 6A) and consistently recovered to less negative predawn Ψ (Fig. 6B) indicating greater recovery from the previous midday water stress for these treatments. Trees from all five container sizes appeared to be recovering fully from the previous day's water stress by the final observation of the first growing season (Fig. 6B). In the second growing season, midday Ψ were consistent over all three seasonal sample dates with *V. agnus-castus* from all five container sizes experiencing only mild midday water stresses and showing strong predawn recovery from the previous days' water deficits (Fig. 6A and 6B). Overall, *V. agnus-castus* transplanted from the 3.5 L (#1) and 11.7 L (#3) containers recovered from water related stress most rapidly, suggesting more rapid establishment than trees from larger containers.

Mean stomatal conductance at five days following transplant was reduced compared to that at initial transplanting for all container sizes, and by seven days later, conductance was almost zero for all container sizes (Fig. 6C). Gradual increases in stomatal conductance occurred for trees from most container sizes over the remainder of the first growing season, but recovered most quickly for 3.5 L (#1) and 11.7 L (#3) container grown trees (Fig. 6C). The second growing season stomatal conductance of *V. agnus-castus* began at a low rate, perhaps due to the succulent state of newly expanding shoots; however, stomatal conductance recovered strongly in the subsequent observations and was greater than during the first growing season for trees from all container sizes (Fig. 6C). Rapid avoidance (Fig. 6A) and recovery from water deficits (Fig. 6B) as well as recovery of stomatal conductance (Fig. 6C) are consistent with rapid resumption of shoot growth (Fig. 7) and rapid root elongation (Fig. 3). The overall pattern of photosynthesis of *V. agnus-castus*

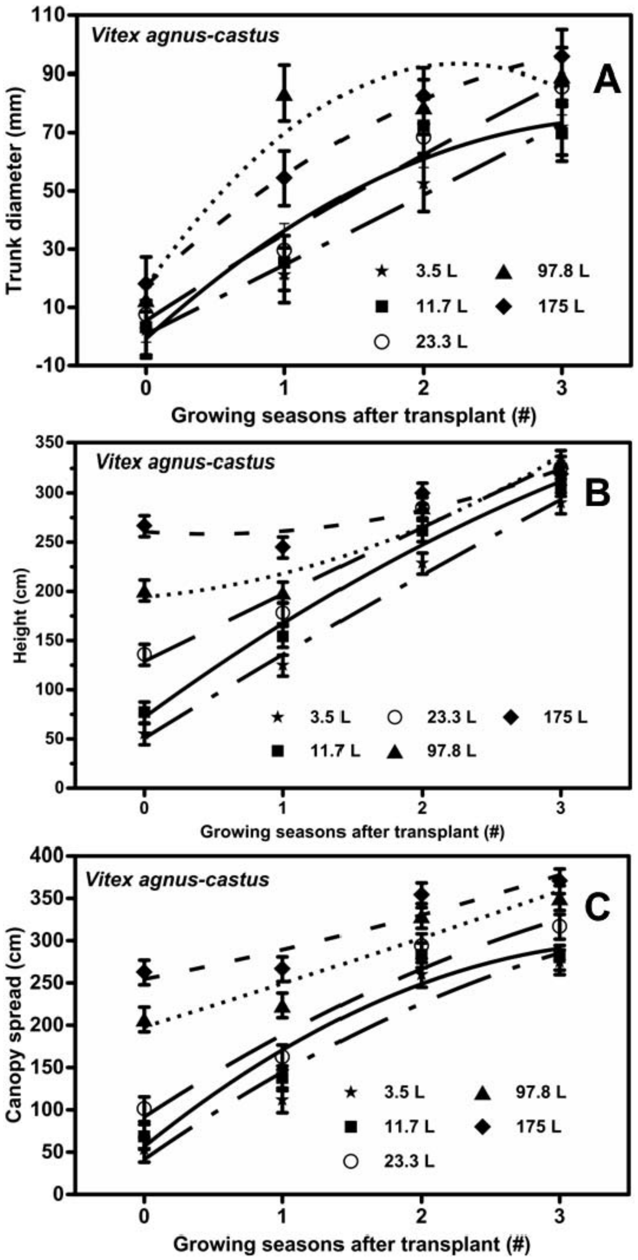

Fig. 7. Shoot growth (A trunk diameter; B height; and C canopy spread) of *Vitex agnus-castus* grown in 3.5, 11.7, 23.3, 97.8, or 175.0 L (#1, 3, 7, 25 or 45, respectively) containers during three growing seasons after transplant to a field site in College Station, TX. Symbols represent mean ± standard errors of six observations.

followed a generally similar response as that of stomatal conductance (Fig. 6D). After an initial drop to very low levels, photosynthetic rates recovered in a sporadic fashion during the first growing season and then recovered to what would be considered high rates for most tree species during the second growing season (Fig. 6D), considerably above the magnitudes of net carbon assimilation measured in *A. rubrum* (Fig. 1D) or *T. distichum* (Fig. 4D). These rates would be high even in comparison to typical tree saplings (Thomas and Winner 2002), suggesting *V. agnus-castus* is capable of rapid carbon assimilation. High photosynthetic rates would be consistent with the generally rapid growth rates exhibited by *V. agnus-castus* transplanted from most container sizes (Fig. 7, Table 2).

Growth was substantial for *V. agnus-castus* from small to medium-sized containers, with very little differences occurring in final trunk diameters at the end of the second growing season for trees originating from 11.7 L (#3) to 175 L (#45) containers (Fig. 7A, Table 2). Strong growth rates were present for trunk diameter of *V. agnus-castus* in all three growing seasons, particularly for those trees transplanted from the smaller 3.5 (#1), 11.7 (#3), and 23.3 L (#7) containers (Fig. 7A). In fact the *V. agnus-castus* transplanted from 3.5 L (#1) containers were nearly the same size by the end of the second growing season as those from 175 L (#45) containers at the end of the first growing season in the field (Fig. 7A). Cumulative percentage change in trunk growth of *V. agnus-castus* was substantial with smaller 3.5 (#1), 11.7 (#3), and 23.3 L (#7) container trees increasing trunk diameter by approximately ten times the initial diameter (Fig. 7A). Smaller changes in trunk diameter were recorded for 97.8 (#25), and 175 L (#45) trees, but these were still substantial. Similar patterns, although at a reduced rate, were observed for season ending height (Fig. 7B) for *V. agnus-castus*. During the first growing season, final height for trees from 97.8 L (#25) and 175 L (#45) containers was similar to or less than that at transplant indicating some slight terminal dieback due to transplant stress. Recovered growth during the second growing season brought cumulative growth across both seasons to less than 50% change in height for trees from 97.8 (#25) and 175 L (#45) containers. Conversely, trees from 3.5 (#1), 11.7 (#3), and 23.3 L (#7) containers increased in height by more than 100% with trees from 3.5 L (#1) containers increasing at approximately 325%. Ending heights for the first growing season of all *V. agnus-castus* were within 71 cm (28 in) of each other after two growing seasons, with trees from 3.5 L (#1) containers the only ones to lag statistically (Fig. 7B). By the end of the third growing season no statistical differences in height were present among trees from all five container sizes (Fig. 7B). Given the increase of the trunk diameter and height (Fig. 7A and 7B), all container sizes of *V. agnus-castus*, except perhaps 97.8 (#25) and 175 L (#45) containers, were likely becoming well established early in the first growing season. Canopy spread (Fig. 7E, Table 3) followed the same patterns of growth as trunk diameter and height with only small differences among *V. agnus-castus* transplanted from all five container sizes persisting by the end of the second and third growing seasons. Rapid establishment of *V. agnus-castus* is consistent with reports of it being a fast-growing tree in landscape settings (Arnold 2008, Welch 2008). *Vitex agnus-castus* has also been found to be very tolerant of other transplant stresses, such as suboptimal planting depths (Arnold et al. 2007).

Mean root lengths show that *V. agnus-castus* from all container sizes extended roots into the surrounding soil by at least 100 cm (39 in) the first growing season (Fig. 3). Cumulatively, the roots of *V. agnus-castus* extended large distances away from the initial root ball by the end of the second growing season, even crossing with neighboring tree roots planted 6 m (20 ft) away (Fig. 3). This may

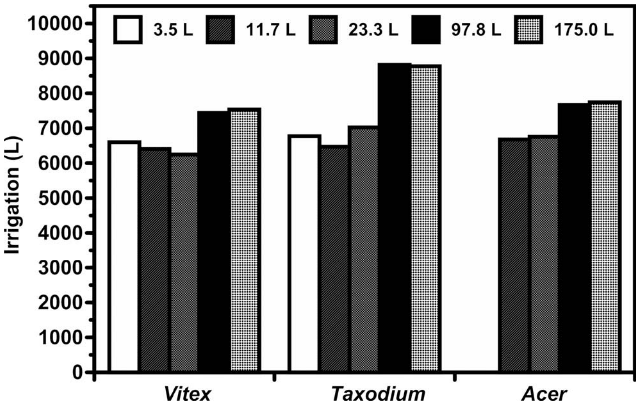

Fig. 8. **Cumulative supplemental irrigation applied per tree over the first three growing seasons after transplanting from 3.5 L, 11.7 L, 23.3 L, 97.8 L, or 175.0 L (#1, 3, 7, 25 or 45, respectively) containers for *Acer rubrum*, *Taxodium distichum*, and *Vitex agnus-castus* on a sandy loam soil in College Station, TX.**

provide insight into the sometimes erratic responses reported in soil fertility or applied fertilizer trials if treatment units are not widely separated spatially to eliminate potential overlapping root zones. Overlapping root zones and rapid increases in size of trees from smaller containers may have contributed to the relatively small cumulative growing season differences in supplemental irrigation required among the five container sizes within a species observed in this study (Fig. 8). Percentage change in root length compared to the diameter of the original planted root ball was greatest in *V. agnus-castus* from smaller container sizes, 3.5 (#1), 11.7 (#3), and 23.3 L (#7) (Fig. 3). When graphically represented, it is easy to see that the maximum root extension of *Vitex agnus-castus* was similar among trees from the various container sizes by the end of the second growing season (Fig. 3). The old adage that by the time trees are established, many roots will have grown a distance equal to approximately 3 times the distance from the trunk to the branch tips (Gilman et al. 1998, Watson and Himelick 1982) appears to have some merit for trees with a rounded canopy such as *V. agnus-castus* (Table 3), but may be less predictive for more narrow upright growers such as *A. rubrum* or *T. distichum* (Table 3). This would also likely be dependent on the propensity for a species to have a taproot versus fibrous root system and of course the depth of topsoil or presence of pans influencing vertical versus horizontal root growth. Under experimental field growing conditions across container sizes, root length to canopy spread ranged from a ratio of 1.2 $\mathrm{cm{\cdot}cm^{-1}}$ (0.47 $\mathrm{in{\cdot}in^{-1}}$) for *T. distichum,* the most upright growing of the three species, to 1.9 $\mathrm{cm{\cdot}cm^{-1}}$ (0.75 $\mathrm{in{\cdot}in^{-1}}$) for *V. agnus-castus,* which has the most rounded spreading growth habit (Table 3). In comparing root extension (mean maximum length) to shoot height, trunk diameter, and canopy spread, it was interesting to note that across the first two years the only ratio that was statistically significant in differences among container types for any of the three species was with root length to trunk diameter (Table 3). The ratio of root length to trunk diameter differed between the trees from the 23.3 L (#7) containers, which had greater root elongation per unit of trunk diameter than the trees from the 175 L (#45) containers (Table 3). In all cases the greatest numerical ratio of root length to shoot measure was observed for trees transplanted from one of the three smallest container sizes, while the smallest ratios were in all but two cases from the 175 L (#45) transplanted trees (Table 3). The two other smallest ratios were from 97.8 L (#25) transplanted *V. agnus-castus* for root length to trunk diameter and the 3.5 L (#1) transplanted *T. distichum* for root length to canopy spread (Table 3). It is also noteworthy that the ratios were mostly within a two-fold range for a given measure across species.

Our observations of species differences in response to container sizes is consistent with prior reports. Lambert et al. (2010) while studying the use of #1, #3, and #7 (no metric equivalents were provided) container-grown *T. distichum*, *A. rubrum* and *Pinus palustris* Mill. for ecological restoration projects, found that *T. distichum* and *A. rubrum* trees transplanted from #3 containers were of a similar size and had similar survival as those from #7 containers. However, they also concluded that with *P. palustris* it may be more advantageous to use trees from #7 containers (Lambert et al. 2010). Unfortunately, in Lambert et al. (2010), no information on genotypic origins of the stock, nursery source or nursery growing conditions were provided, so the impact of genotypic variation and nursery production conditions on differential container size and species performance are unknown. Our findings are also consistent with Robbins (2006) findings of the greatest growth rates for *A. rubrum* and *A.* x *freemanii* with trees transplanted from #3 and #5 containers.

Although the timing of responses varied among the three species tested, overall patterns of effects of container sizes on transplant establishment were remarkably similar. The most rapid establishment in most cases occurred with 11.7 L (#3) or 23.3 L (#7) containers for all three species both in terms of physiological responses (Fig. 1, 4, and 6) or general shoot (Fig. 2, 5, and 7) and root (Fig. 3) parameters. In general, establishment of larger 97.8 L (#25) and 175 L (#45) containers lagged substantially behind that of smaller containers for all three species. Shoot growth parameters of trees of all three species transplanted from 97.8 L (#25) or 175 L (#45) containers did not manifest resumption of rapid shoot growth until the second or third growing season (Fig. 2, 5 and 7). Establishment of the smallest container size trees, 3.5 L (#1), was less consistent among species, with *V. agnus-castus* establishing very rapidly in contrast with *A. rubrum,* which exhibited high mortality. Transplant establishment of *V. agnus-castus* was very rapid with smaller sizes exhibiting signs of full physiological recovery to pre-transplant levels within a couple of months of transplant and substantial growth resumed by the end of the first growing season. *Taxodium distichum* appeared to be the slowest of the three species to establish, with physiological differences among container sizes persisting through the second growing season (Fig. 4) and shoot growth differences through the third growing season (Fig. 5).

Root extension paralleled shoot growth responses, with smaller container sizes initially growing more rapidly but then appearing to converge on a similar root extension as larger containers during the second growing season. Ratios expressing root elongation to shoot height, trunk diameter, and canopy spread were remarkably similar within a species and growth parameter and only tended to vary cumulatively across the first two growing seasons within a parameter by about a 2.0 to 2.5 fold spread (Table 3). Root growth extended on average from 1.2 to 1.9 times the canopy spread across the three species, somewhat less extension than the approximately 3 times distance from the trunk to the branch tips suggested by others (Gilman et al. 1998, Watson and Himelick 1982), but these ratios may well be dependent upon soil conditions, local climatic conditions, growth habit of the trees, or other species specific characteristics.

All three taxa ultimately exhibited less stress symptoms and recovered more quickly when transplanted from the smaller container sizes, with the exceptions of 3.5 L (#1) container size for *A. rubrum* and *T. distichum*. This confirms observations comparing two sizes of containers in studies by Gilman et al. (2010) with *A. rubrum* and *Quercus virginiana* Mill. on a sandy, well-drained soil. Gilman et al. (2010) found that *Q. virginiana* 'SNDL' (PP#12015, Cathedral Oak®) transplanted from 57 L containers (probably equivalent to about a #15 container) established more rapidly than those transplanted from 170 L (similar to our #45) containers. Robbins (2006) results with *A. rubrum* and *A.* x *freemanii* were also consistent with the current work. Our results suggest that if a nurseryman, landscape client or consumer is willing to wait just a few years for the end results, substantial financial savings might be garnered by planting less expensive, smaller-sized container stock. However, to do this, clients will need to balance this gain against foregoing other benefits of larger planting stock such as greater aesthetic value of larger trees (Kalmbach and Kielbaso 1979, Schroeder 2006), greater biomass present to withstand environmental anomalies (Nowak et al. 2007), less potential for catastrophic accidental or malicious mechanical damage (Foster 1976, Parsons 2015, Watson and Himelick 2013), instant shade (Kalmbach and Kielbaso 1979, Schroeder 2006), and an increase in property value (Behe et al. 2005, Maco and McPherson 2003). Large urban trees are reported to reduce particulate matter by 7% to 24% in their immediate vicinity and may cool the air temperature by as much as 2 C (3.6 F) (Kinver 2016). Ecosystem services such as these may be greater initially with larger transplanted trees than smaller ones. An economic analysis quantifying the potential magnitude of economic values of transplanted trees at transplant and subsequently over time in the landscape associated with container size would greatly assist in assessing these tradeoffs.

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