POST-- TRANSPLANT ESTABLISHMENT AND ECONOMIC VALUE OF THREE TREE SPECIES FROM FIVE CONTAINER SIZES

A Thesis

by

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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 transplant on different size container stock. Transplant shock is a condition of physiological stress, which is a normal consequence of transplanting plants into conditions less favorable than those in the nursery. Clonal replicates of *Vitex agnus-castus* L., *Acer rubrum* L. var. *drummondii* (Hook. & Arn. *ex* Nutt.) Sarg., and *Taxodium distichum* (L.) Rich. were grown under common conditions in each of five container sizes #1, 3, 7, 25, or 45 (3.5, 11.7, 23.3 97.8, or 175.0 L, respectively) to minimize residual differences during production. Beginning June 2013, six trees of each container size and species were transplanted to a sandy clay loam field in College Station, Texas. To determine the extent of transplant shock, physiological stress was assessed through xylem water potentials and photosynthetic gas exchange rates. Changes in shoot growth of each tree were calculated along with root growth for two growing seasons. Utilizing industry standards, the initial costs of materials and labor were then compared with the size of trees two years post-transplant to determine return on investment for each container size.

Responses observed in *A. rubrum* and *V. agnus-castus* indicted growth increased exponentially in #3 and #7 container-grown trees. *Taxodium distichum* recovered at much slower rates, with less rapid although still vigorous growth in #3 and #7 container-grown trees. Data indicates all trees in #3 and #7 containers experienced less severe water stresses and required less time to return to normal transpiration rates than trees grown in other containers. The reduced stress levels and increased growth rates correlated with greater percent changes found in root lengths of smaller container-grown trees. Economic analysis after two growing seasons indicated a greater increase in value for #3 and #7 container-grown trees versus losses in value for some #45 container-grown trees. In comparison with trees from larger containers, trees from smaller size containers exhibited reduced transplant shock, decreased establishment time and increased growth rates, thus creating a quicker return on investment for trees transplanted from the smaller container sizes.

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CHAPTER I

INTRODUCTION AND LITERATURE REVIEW

Nurseries over the years have produced trees in larger and larger container sizes (Arnold, 2004; Watson, 2004), and even large box stores, such as Walmart, Lowe's, and Home Depot, now sell trees in up to 100-gallon containers. While debate continues over the relative merits of different container sizes (Watson, 2004), this could in part be due to the appreciation landscape industries 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 accidental or malicious mechanical damage (Watson and Himelick, 2013), instant shade (Kalmbach and Kielbaso, 1979; Schroeder, 2006), and increase in property value (Maco and McPherson, 2003). However, 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 and square footage to produce smaller trees. Smaller container sizes, once transplanted to the field, reportedly have reduced transplant shock (Watson, 2004), are in a phase of growth more closely aligned with the exponential growth rate of young seedlings (Gilman and Dehgan, 1996), have been in containers for shorter times and have been upcanned (sequentially transplanted to larger containers) fewer times potentially reducing the chances of circling root development (Gilman and Kane, 1990), and their smaller size makes for easier handling and staking (Watson and Himelick, 2013). The 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. This leads to the question: How much time is required to establish various size container-grown trees in the landscape?

Although container size establishment has been considered by several sources (Gilman et al., 1998, 2010; Gilman and Masters, 2010; Lambert et al., 2010; Struve 2009), extensive research has yet to be conducted as is proposed herein. With trees being offered to the public in an ever increasing array of sizes, it is important to determine the times required for successful establishment of differing size stock and the trade-offs associated with initial size and establishment requirements. It is often generally accepted that smaller size planting stock establishes more quickly after transplanting than larger stock (Struve, 2009). Gilman et al. (2010) also found that smaller trees established more quickly than larger trees, but only tested two sizes, which would not permit the development of predictive regression curves for establishment times or other factors. Lambert et al. (2010) investigated three sizes of containers for three species in forestry conditions, but no information was provided relative to the genotypic background of the plants, so size may have been confounded with genotypes. The three genera studied were selected to represent different niches of the landscape industry and to eliminate genetic variation by using clonal materials. Clonal selections of *Vitex agnus-castus*, *Acer rubrum* var. *dummondii,* and *Taxodium distichum* were chosen due to their wide spread use in our regional nursery trade and their representation of a variety of classes of landscape trees.

1.1 Tree Background

Vitex agnus-castus is a small multi-stem ornamental tree, almost shrub-like, known for its hardiness and attractive flowers. *Vitex* L. is a genus of 250 species distributed throughout the world (Dutta, 1970). Introduced to the United States in 1570, *V. agnus-castus* is used ornamentally as a shrub border or as a small specimen tree (Gilman and Watson, 1994). This species generally grows in humid habitats like stream banks and valleys, mostly on sandy soils, perched alluvial soils, and rocky areas. As a Mediterranean native, *V. agnus-castus* prefers warm, sunny habitats (Dogan, 2008). Though it is drought tolerant once established, it will grow faster with supplemental water, especially during initial transplant (Welch, 2008). Propagation is from cuttings in summer or winter (Welch, 2008). Although detailed research is lacking, *Vitex* seems to grow tap and lateral root systems with abundant fine roots (Long et al., 2012). The unnamed clone to be used in this study was selected for a profusion of large branched panicles of clear white flowers compared to the bluish or purplish colors of the species types.

Acer rubrum is one of the most abundant and widespread trees in North America (Hutnick and Yawney, 1961). *Acer rubrum* does very well in a wide range of soil types, with varying textures, moisture, soil pH, and elevation, probably more so than any other forest tree in North America (Hepting, 1971). While it can occur in rather extreme moisture conditions, both very wet and quite dry, its ideal conditions are in moderately well drained, moist sites at low or intermediate elevations (Walters and Yawney, 1990). Its ability to thrive in a large number of habitats is largely due to an ability to produce roots to suit its site from a young age. In wet locations, red maple seedlings produce short taproots with long and developed lateral roots, while on dry sites they develop long taproots with significantly shorter laterals (Hutnick and Yawney, 1961). The roots are primarily horizontal, however, forming in the upper 25 cm of soil. Mature trees have woody roots up to 25 m long (Lyford and Wilson, 1964). They are very tolerant of waterlogging conditions, with one study showing that 60 days of flooding caused no leaf damage (Hosner and Boyce, 1962). At the same time, they are tolerant of drought due to their ability to stop growing under dry conditions by then producing a second growth flush when conditions later improve, even if growth has stopped for 2 weeks (Walters and Yawney, 1990). *Acer rubrum* is considered difficult to propagate from cuttings, however through the use of rooting hormones and appropriate media, successful propagation can be achieved (Hartmann et al., 2011). *Acer rubrum* var. *drummondii* represents a more southern and southwestern ecotype thought to be more heat and high pH soil tolerant than the species type (Arnold, 2008). The clone 'Maroon' to be used in this study is a selection by Dr. Edward McWilliams and Mr. Lynn Lowrey that produces attractive red fruit and flowers in abundance.

Finally, *Taxodium distichum*, commonly known as baldcypress, is a tall, deciduous coniferous tree dominant in lowland river flood plains and swamps of the Southeastern United States (Wilhite and Toliver, 1990). *Taxodium distichum* can grow across a wide climatic range, due to its ability to handle a range of rainfall conditions

(Little, 1971). The most favorable soil characteristics vary but are typically fertile, fine textured, alluvial soils, allowing for effective drainage (Fowells, 1965). *Taxodium distichum* has a relatively high salt tolerance in comparison with other landscape trees (Denny, 2007). Allen et al. (1996) noted salt tolerance in *Taxodium* is probably due to relative ability to “exclude ions or effectively compartmentalize them in cell vacuoles”, citing a higher concentration of Na and Cl ions in the leaves of less tolerant genotypes. *Taxodium distichum* can establish on seasonally inundated fluvial sediment due to its ability to thrive in anaerobic, saline soil conditions (Wilhite and Toliver, 1990). Baldcypress seedlings develop a taproot (Williston et al., 1980), which can be maintained through maturity (Swanson, 1965). Older, naturally seeded baldcypress in swamps develop several descending roots that provide anchorage, and numerous lateral roots from which arise peculiar conical structures known as "knees" (Harlow et. al, 2001). However, small knees have been observed on many trees not subjected to flooding (Brown, 1981) and it is not uncommon for *T. distichum* to produce knees in built environments.

1.2 Transplant and Transplant Shock

Improper planting has a profound effect on tree survival, health, and longevity. Up to 50% loss of trees within the first five years of planting is not uncommon due to problems that originate below ground in the soil and root system (Watson and Himelick, 2013). Preparation for transplanting is the first step to establishing a healthy tree. For trees grown in containers, the planting hole should be no deeper than the root ball. Higher mortality and slower growth often result from trees with root systems planted deeper than optimal (Arnold et al., 2005). Structural roots should be placed just below the surface on well-drained soils (Watson and Himelick, 2013), or on heavy soils at or slightly above grade (Arnold et al., 2005, 2007). The hole should be dug about 30 cm wider than the root ball and the sides of the hole broken down with a spade to widen the hole near the surface where root growth will be most rapid (Watson and Himelick, 2013). Though many containers have been developed to prevent roots from circling around the interior of the containers, it is common practice to disrupt these circling roots by making several vertical cuts on the outside of the root ball prior to transplanting and to disrupt or remove matted roots at the bottom of the container (Harris et al., 2004). Without disruption, root growth of container-transplanted trees was one-quarter that of field-grown trees and resulted in reduced tree stability (Gilman et al., 2010). After placing the tree at the correct depth, the tree should be held in place while loose soil is added around the root ball. Watering immediately after transplanting helps the tree to counter stress as well as to settle the added soil (Watson, 1986). A slightly raised ring of soil surrounding the edge of the root ball will also help to create a basin that can be filled with water.

Transplant shock is a condition of distress from injuries, depletion of nutrients, and impaired functions; a process of recovery; and a period of adaptation to a new environment (Rietveld, 1989). Stress is a normal consequence of handling, moving, and planting plants into a less favorable field or landscape environment than those experienced in the nursery. Transplant shock is exacerbated by root system loss during transplant, which results in a decrease in the tree’s ability to absorb water and mineral nutrients, and causes the loss of stored compounds already present in the tree (Watson and Sydnor, 1987). Transplant shock will persist until root regeneration begins. There are two types of root regeneration: elongation of existing root tips and initiation of adventitious roots and their subsequent elongation (Stone and Shubert, 1959). Overcoming transplant shock is largely dependent on the rate of elongation of existing roots, which is independent of the season of the year and occurs whenever soil moisture and temperatures permit (Struve, 2009). Root elongation is also inhibited in compacted soils and is made worse by the combination of soil compaction and low soil moisture content (Bennie, 1991). Stress caused by soil moisture deficit reduces root elongation and increases the effects of transplant shock. Transplanted trees often become drought stressed soon after planting, as the soil volume accessed by roots of a naturally established tree can be more than ten-fold that of a transplanted tree of the same shoot size (Burdett, 1990). Plant nutrient uptake is decreased under drought stress due to reduced transpiration (Yambao and O'Toole, 1984) and impaired active transport and membrane permeability (Hsiao, 1973) resulting in reduced water absorption. Nutrient uptake from the soil is also closely linked to soil moisture conditions. A decrease in soil moisture reduces the diffusion rate of nutrients from the soil towards the root surface (Marais and Weirsma, 1975). Drought stress following transplanting can be further exacerbated by poor acclimatization to the field environment (Rowe, 1964). In the nursery, trees are within close proximity of each other, sheltering each other from wind and are irrigated more frequently than when moved into the field (Watson, 1996).

1.3 Establishment

The establishment period of a plant is of utmost importance to determining vitality, growth rates, and maintenance needs. There are several measures of plant establishment: re-establishment of growth (Watson, 1985; Gilman, 1997), 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 loss of roots from mechanical damage as well as physiological stresses, transplanted trees frequently experience a phase after planting in which growth is significantly reduced or suspended. Therefore, the re-establishment of shoot growth is most 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). Stress associated with reduced gas exchange occurs when too little water causes stomatal closure, thus limiting CO_2 uptake (Federer and Gee, 1976). Reduction of transpiration as stomata close during drought stress may also elevate leaf temperatures due to reduced evapotranspiration (Taiz and Zeiger, 2010). Plant growth is affected by loss of turgor pressure within the cells (Green and Cummins, 1974). When restoration of stomatal conductance and xylem water potential is achieved, growth can resume. In an experiment conducted by Gilman (2004), trees from containers irrigated three times a week during establishment grew faster and resumed water potentials quicker leading to a faster establishment versus those trees watered once every ten days with equivalent water volumes. Photosynthesis is one of the most basic measures of plant productivity. In order to reduce water loss, trees close their stomata, thus decreasing photosynthetic rates during initial transplant establishment (Hsiao, 1973). Therefore, as an indicator of future growth, photosynthetic rates return to normal as trees begin to establish (Richardson, 2002).

1.4 Cost Analysis

The value of a tree, defined as its monetary worth, is based on people's perception of the tree (Cullen, 2000). Arborists use several methods to develop a fair and reasonable estimate of the value of individual trees (Council of Tree and Landscape Appraisers, 2000; Cullen, 2005; Watson, 2002). The cost approach is widely used today and assumes that value equals the cost of production (Cullen, 2002). It assumes that the benefits inherent in a tree can be reproduced by replacing the tree and therefore, replacement cost is an indication of value (Cullen, 2000). Replacement cost is depreciated to reflect differences in the benefits that would flow from an "idealized" replacement compared with the older and imperfect appraised tree. The depreciated replacement cost method uses tree size, species, condition, and location factors to determine tree value (McPherson, 2007). The income approach measures value as the future use of a tree such as in fruit or nut production (The Appraisal Institute, 2000). In the absence of products, another approach could be based on the present value of future benefits the tree is likely to produce (Council of Tree and Landscape Appraisers, 2000). A number of benefits and their monetized values can be calculated for a tree in the landscape. Some benefits that have proven to improve the value of the tree are energy savings (McPherson and Simpson, 1999), atmospheric carbon dioxide (CO_2) reductions

(McPherson et al., 2003), stormwater runoff reductions (Xiao et al., 2000), and aesthetics (Anderson and Cordell, 1988). Quantifying and totaling these benefits over time can provide an idea of a tree's projected value, but are difficult to determine accurately, thus replacement costs are the typical value method assigned to most landscape trees.

CHAPTER II

EFFECTS OF CONTAINER SIZE ON LANDSCAPE ESTABLISHMENT OF THREE TREE SPECIES

With trees being offered to the public in an ever-increasing array of container sizes, it is important to determine the times required for successful establishment of differing size container stock and the trade-offs associated with initial size and establishment requirements.

While debate continues over the relative merits of different container sizes, this could in part be due to the appreciation landscape industries 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 accidental or malicious mechanical damage (Watson and Himelick, 2013), instant shade (Kalmbach and Kielbaso, 1979; Schroeder, 2006), and increase in property value (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 and square footage to produce smaller trees. Smaller container sizes, once transplanted to the field, have reduced transplant shock (Watson, 2004), are in a phase of growth more closely aligned with the exponential growth rate of young seedlings (Gilman and Dehgan, 1996), have been in containers for shorter times and have been upcanned fewer times potentially reducing the chance of circling root development (Gilman and Kane, 1990), and their smaller size makes for easier handling and staking (Watson and Himelick, 2013). The 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.

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It is often generally accepted that smaller size planting stock establishes more quickly after transplanting than larger stock (Struve, 2009), but formal studies are limited. Gilman et al. (2010) also found that smaller trees established more quickly than larger trees, but only tested two sizes, which would not permit the development of predictive regression curves for establishment times or other factors. Lambert et al. (2010) investigated three sizes of containers for three species in forestry conditions, but no information was provided relative to the genotypic background of the plants, so size may have been confounded with genotypes.

The objective of the current study was to identify initial stress expressed by three taxa among container sizes during landscape establishment and the amount of time each planting required to achieve establishment (recovery and resumed growth).

2.1 Materials and Methods

The three genera we used were selected to represent different niches of the landscape industry and to eliminate genetic variation 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. (unnamed test code clone TX8DD38) were chosen due to the widespread use of these species in the southern regional nursery trade and their representation of a variety of classes of landscape trees. Tip cuttings, 8-10 cm long, of each clone were taken from containerized stock plants developed and maintained in College Station, TX. The basal end of these cuttings was then dipped in a liquid rooting hormone (Dip n' Grow® Inc., Clackamas, OR) containing indolebutyric acid (IBA) / naphthalene acetic acid (NAA) at a 3:1 concentrate (2,500 ppm IBA/ 1,250 ppm NAA) to water ratio for 5 seconds. Cuttings were placed in 36 cm x 51 cm x 10 cm deep flats (Kadon Corp., Dayton, OH) filled with course 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 to larger container sizes (11.7 L, 23.3 L, 97.8 L, and 175.0 L) according to ANSI Z60.1 (American Association of Nurserymen, 2004) standards and the process began again with additional cuttings until nine 3.5 L (#1), 11.7 L (#3), 23.3 L (#7), 97.8 L (#25), and 175.0 L (#45) plants of each species was achieved. These trees were amended with 15N -3.9P-9.9K controlled release fertilizer (Osmocote® Plus, Scotts Co., Marysville, OH) every six months at 6.53 kg•m^3 and grown in a gravel-bottom nursery in College Station, TX (lat. 30°37'45"N, long. 96°20'34" W). When all container sizes were obtained, six trees of each size for each species were transported 3.5 km to a sandy clay loam (66% sand, 8% silt, 26% clay, 6.0 pH) field in College Station, TX (lat. 30˚37'45"N, long. 96˚20'34" W) in June 2013. The trees were transplanted into the ground in a completely randomized design with each species being a separate but concurrent experiment at spacing of 6 m within rows x 7.3 m between rows with 4 rows of alternating seven to eight trees per row in each experiment. Each tree was transplanted into a hole as specified by general practice procedures, ANSI A300 (Accredited Standards Committee A300, 2014), and "The Practical Science of Planting Trees" (Watson and Himelick, 2013). Under each tree, two Dan PC Jet spray stakes with a 5.0 GPH flow (NaanDanJain Irrigation, Inc., Pasco, WA) were connected to a polyethylene round tubing irrigation system (The Toro Company, El Cajon, CA). Irrigation was laid on a species by species and container size by container size within species basis. A 30.5 cm (12") soil moisture tensiometer (Spectrum Technologies, Inc., Aurora, IL) was installed at the edge of the root ball for one specimen of each container size of each species at a depth of approximately 20 cm.

2.1.1 Water Stress and Photosynthetic Rates

Water stress was determined through midday (1200 to 1400 hr) and pre-dawn (1600 to 1800 hr) xylem water potential readings (MPa). The leaf water potential (Ψ_L) method was utilized by detaching the leaf at the petiole for each reading, then inserting it into a nitrogen pressure chamber (PMS Model 610 pressure chamber system, PMS Instrument Company, Albany, OR). Selected leaves were healthy, fully expanded with no insect holes and located in full sun exposure. Measurements were recorded at two-week intervals for the first two months following transplant, then once a month until the end of the first growing season (October 2013), followed by every three months for the following growing season. Photosynthetic gas exchange readings were assessed at the same intervals as water potential measurements. These readings were comprised of the photosynthetic rate (μmol CO_2 $m^{-2}s^{-1}$) and stomatal conductance (mol H_2O $m^{-2}s^{-1}$) of the plant (LI-6400XT Portable Photosynthesis System, LI-COR, Inc., Lincoln, NE). Readings were determined utilizing leaves in the middle half of the tree, which were healthy, fully expanded with no insect holes and located in full sun exposure. Sample CO_2 was set to 490 ppm and light was set to 1200 nm.

2.1.2 Water Needs

Irrigation was conducted on a species-by-species and container size-by-container size within species basis according to soil moisture levels. This resulted in five independent irrigation systems for each of the three species. The soil moisture levels were determined using 30.5 cm (12”) soil moisture tensiometers (Spectrum Technologies, Inc., Aurora, IL) installed at the edge of the root ball of one specimen of each container size of each species at a depth of approximately 20 cm. Water was applied when the tensiometer showed -20 kPa (a soil moisture tension empirically determined to be when transplant stress symptoms began to occur on these species) until it returned to “Wet” or <1 kPa of tension. A log was kept for each species and container size combination based on the liters per hour applied as governed by the tensiometer measurements. These data were then compiled with the natural rainfall for each month in order to determine total water needs of each tree.

2.1.3 Growth

In order to determine growth over time and as a function of the individual tree, percent change in growth was employed. Measurements included: height from ground level to leaf tip, canopy width in two directions from widest point to widest point within and perpendicular to the rows, shoot extension of three branches, and trunk diameter at 15 cm above the soil surface. Trunk diameters for *Vitex agnus-castus* followed ANSI Z60.1 (American Association of Nurseryman, 2004) regulations dictating a sum of the three largest trunk diameters divided by two (cm). Measurements were taken for each tree prior to transplant in early June 2013 and then at the end of each growing season in October. Using the differences in measurements, percent change was calculated and statistically analyzed. Three additional trees from each container size and species were destructively harvested in June 2013 to determine initial shoot and root biomasses prior to transplanting.

Additionally, root growth following transplant was measured at the end of each growing season in October. A 1.5 m x 0.5 m swath extending out from the edge of the root ball to the length of the longest root was excavated using a compressed air excavation tool (Air-Spade, GuardAir® Corp., Chicopee, MA). Swaths were located at random on the north or south sides of half of the trees within each species and container size combination. In fall of the second growing season, the root growth on the opposite side of the tree was measured. Root counts and length of the longest regenerated root were then recorded.

Data were analyzed with statistical software (JMP 2009 and SAS 9.3, SAS Institute Inc., Cary, NC) using ANOVA 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. When significant effects were found, regression analyses were used to determine significant differences ($P \leq 0.05$) among levels of quantitative data. Means were compared using least-squares means procedures for discreet data with significant effects.

2.2 Results and Discussion

2.2.1 *Acer rubrum*

Pre-transplant dry masses confirmed significant differences between initial container-grown tree size trees (Table 2.1). Smaller container sizes had smaller masses while larger container sizes had greater masses. Pre-transplant stress measures provided a baseline with which to compare transplant shock effects (Table 2.2).

The #1 *A. rubrum* were highly susceptible to herbivory, environmental changes, and salt damage from irrigation spray stakes. Four of the six samples died within the first month of transplant and the remaining two were consistently leaf bare or had few leaves from which to sample. By the end of the first growing season, only one #1 container grown tree remained. Therefore, data collection and observations were omitted for the #1 container-grown *A. rubrum* as is reflected in the findings below.

Midday water potential for *A. rubrum* at the 8th day following transplant remained similar for all container sizes (Fig. 2.1). These more negative readings indicate higher levels of drought stress than found in subsequent measurements. Drought stress sensitivity appears to be a more immediate effect of transplant stress, even when soil moisture is available. Perhaps this initial dip is related to poor movement of water from higher bulk density soil to the low bulk density root ball once irrigation falling directly on the rootball is depleted. Fifteen days after planting, midday water potentials began to diverge and differences among the trees grown in different containers became apparent. Of note, the 45-gallon container trees demonstrated reduced water stress at midday compared to 25-gallon container trees despite their larger biomass. Throughout the first growing season, represented in the left cluster of points (Fig. 2.1), the trees progressively exhibited reduced midday water stress following the initial peak stress immediately after transplanting. The exception occurs 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 transplant. Readings taken during the second year exhibit reduced water stress levels with measurements across all container size trees clustered tightly and varying by less than 5 MPa throughout the season. Overall trends show the smaller container-grown trees (#3 and #7 gallon) were less water stressed when compared with larger container-grown trees (#25 and #45 gallon) (Fig. 2.1).

Table 2.1. Root and shoot dry masses for *Acer rubrum* grown in various sized containers at the end of nursery production.

Container size	Root dry mass (g)	Shoot dry mass (g)	Root: shoot ratio ($g \cdot g^{-1}$)
#3	40.83 ± 7.09[z]	49.30 ± 23.60	0.91 ± 0.30
#7	66.37 ± 20.38	77.23 ± 32.04	1.04 ± 0.67
#25	1782.00 ± 179.45	2237.70 ± 14.76	0.80 ± 0.08
#45	4280.73 ± 184.83	4031.83 ± 138.96	1.06 ± 0.03

[z] Values represent means ± standard errors of 3 observations.

Table 2.2. *Acer rubrum* pre-transplant stress measures for each container size taken in nursery.

Container size	Mid-day (MPa)	Pre-dawn (MPa)	Stomatal conductance (mol H_2O m^{-2} s^{-1})	Net photosynthesis (μmol CO_2 m^{-2} s^{-1})
#3	-9.00 ± 1.18[z]	-1.67 ± 0.88	5.12 ± 2.87	0.05 ± 0.03
#7	-14.25 ± 2.66	-2.17 ± 0.75	9.02 ± 3.68	0.08 ± 0.05
#25	-9.75 ± 1.75	-2.08 ± 0.58	10.75 ± 1.60	0.12 ± 0.02
#45	-17.00 ± 2.72	-2.08 ± 0.86	12.40 ± 2.29	0.16 ± 0.07

[z] Values represent means ± standard errors of 3 observations.

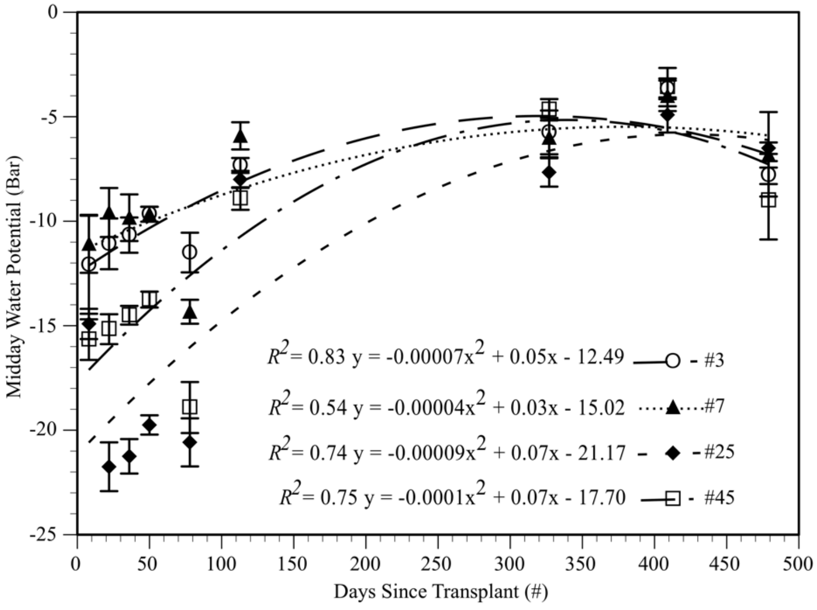

Fig. 2.1. Interactions among container sizes (#3, #7, #25, and #45) and days since transplant for mean midday water potentials of *Acer rubrum*. Symbols represent means (± standard errors) of n=6. Regressions are based on means and are presented when significant at $P \leq 0.05$.

Recovery of water stress during pre-dawn hours was measured beginning at the 8th day after transplant. Readings for container sizes were more variable at the 8th day than in subsequent readings (Fig. 2.2). Water stress recovery improved over the following 37 days until the 78th day at which point season high temperatures were recorded, impacting the ability of *A. rubrum* to recover from the previous day's water deficits. During the second growing season, measurements indicate a tighter cluster of data for all container size trees as well as minor seasonal effects through spring, summer, and fall. Overall, #7 container-grown trees demonstrated a better recovery of water stress than other container-grown trees with #45 container-grown trees demonstrating the poorest recovery.

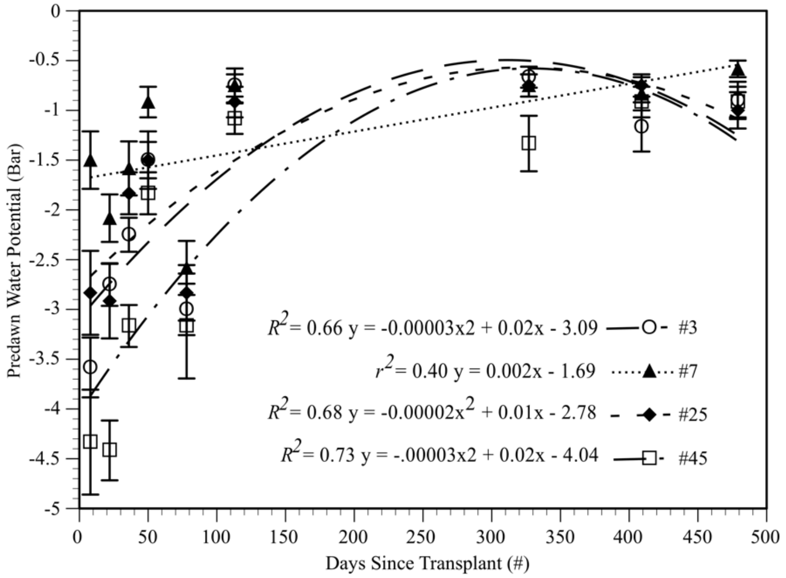

Fig. 2.2. Interactions among container sizes (#3, #7, #25, and #45) and days since transplant for mean predawn water potentials of *Acer rubrum*. Symbols represent means (± standard errors) of n=6. Regressions are based on means and are presented when significant at *P*≤0.05.

Stomatal conductance of *A. rubrum* immediately following transplant was high for all container sizes followed one week later by a sudden decrease (Fig. 2.3). This aligns with research suggesting stomatal conductance is a delayed transplant stress mechanism (Guehl et al., 1989). At fifteen days following transplant, stomatal conductance was close to 0 mol·m^{-2}·s^{-1} in all container sizes indicating gas exchange was inhibited and the plant was experiencing water stress. Throughout the following readings for the first season, mean stomatal conductance increased likely allowing water and carbon dioxide exchange to occur at higher levels. In the second growing season, there was a small decrease in stomatal conductance during the spring, which could be due to the succulent nature of new leaves. Overall, stomatal conductance continued to increase over time with the smaller container sizes (#3 and #7 gallons) tending to allow greater gas exchange to occur which would be consistent with less comparative water stress.

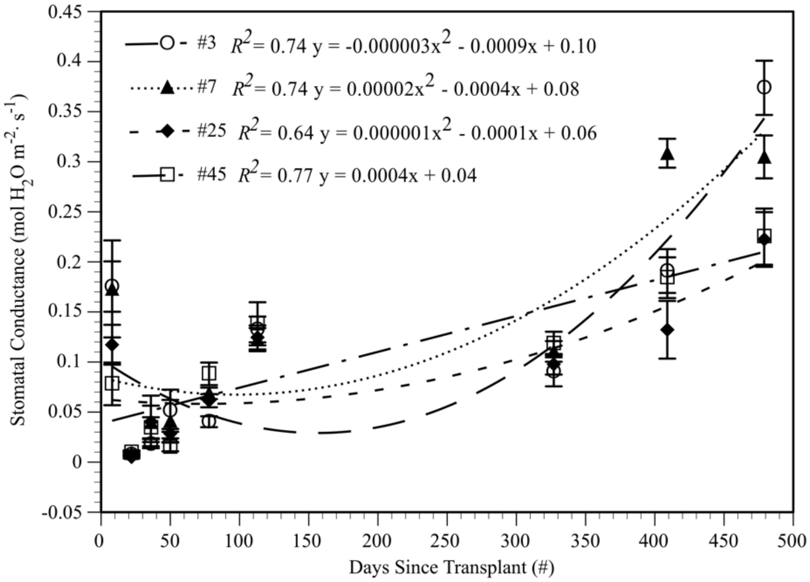

Fig. 2.3. Interactions among container sizes (#3, #7, #25, and #45) and days since transplant for mean stomatal conductance of *Acer rubrum*. Symbols represent means (± standard error) of n=6. Regressions are based on means and are presented when significant at $P \leq 0.05$.

Photosynthetic rates of *A. rubrum* remained relatively high following transplant for all container sizes (Fig. 2.4). A decrease in net photosynthesis was not seen until 22 d following transplant, at which point photosynthetic rates were at their lowest throughout the experiment. This decrease in net photosynthesis correlated with a decrease in stomatal conductance (Fig. 2.3) and an increase in water stress (Fig 2.1). Photosynthetic rates recovered during the remainder of the first growing season and did not appear to be affected by environmental temperatures in comparison to water potentials (Fig. 2.1 and 2.2). During the second growing season, photosynthetic rates resumed at similar levels as seen immediately following transplant and at the end of the first growing season. During the fall readings of the second growing season, photosynthetic rates peaked. No significant correlation was found for container sizes, but readings through time were significant with an R^2= 0.48.

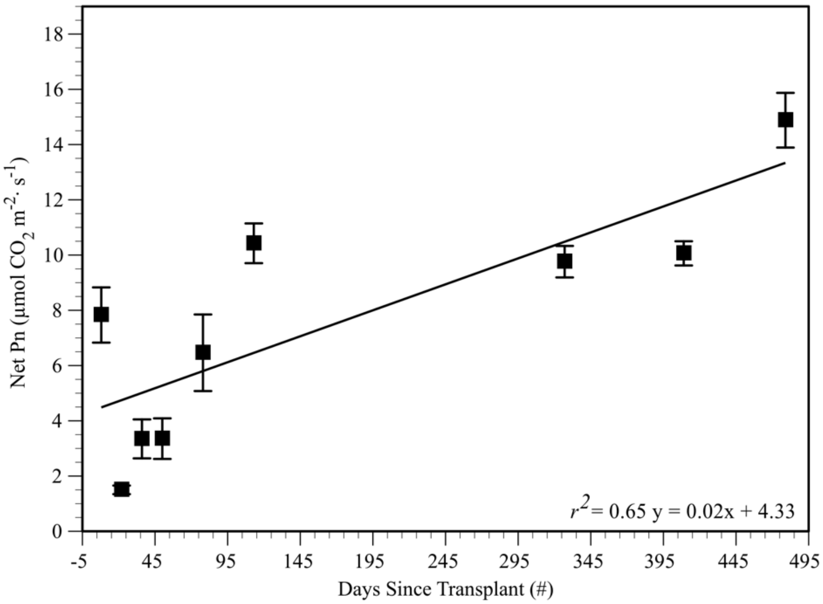

Fig. 2.4. Main effects on photosynthetic rates of *Acer rubrum* across all container sizes since days from transplant. Symbols represent means (± standard error) of n=6. Regressions are based on means and are presented when significant at $P \leq 0.05$.

Initial trunk diameters were within ANSI Z60.1 (American Association of Nurseryman, 2004) container size standards (Table 2.3). Percent change in growth during the first growing season was greater in the smaller container sizes (#3 and #7 gallon) than in the larger container sizes (#25 and #45), which demonstrated close to zero percent change (Fig. 2.5). During the second growing season growth increased particularly in the #3 container-grown trees. Cumulative percent change in growth was highly significant with smaller container-grown trees (#3 and #7) increasing trunk diameter by approximately 350 and 200 times initial diameter, respectively.

Table 2.3. ANZI Z60.1 container class regulations by height and caliper.

Types 1 & 2 shade trees		Types 3 & 4 small upright and spreading trees		Shrub form and multistem trees*		
Minimum plant size (height/ caliper)	Maximum plant size (height/ caliper)	Minimum plant size (height/ caliper)	Maximum plant size (height/ caliper)	Minimum plant size (height)	Maximum plant size (height)	Container Class (#)
12 in.[z]	4 ft.	12 in.	3 ft.	N/A	N/A	1
2 ft.	6 ft.	18 in.	4 ft.	N/A	N/A	2
3 ft.	6 ft.	2 ½ ft.	6 ft./ 1 in.	2 ft.	5 ft.	3
4 ft.	7 ft.	4 ft.	7 ft./ 1 ¼ in.	3 ft.	6 ft.	5
5 ft.	8 ft./1 ¼ in.	5 ft.	1 ½ in.	4 ft.	7 ft.	7
6 ft.	1 ½ in.	6 ft./ ¾ in.	1 ¾ in.	5 ft.	8 ft.	10
8 ft./ ¾ in.	2 in.	1 in.	2 in.	6 ft.	10 ft.	15
1 in.	2 ½ in.	1 ¼ in.	2 ½ in.	7 ft.	12 ft.	20
1 ¼ in.	3 in.	1 ½ in.	3 in.	8 ft.	14 ft.	25
1 ¾ in.	3 ½ in.	2 in.	3 ½ in.	10 ft.	16 ft.	45
2 in.	4 in.	2 ½ in.	4 in.	12 ft.	18 ft.	65
2 ½ in.	5 in.	3 in.	5 in.	14 ft.	20 ft.	95/100

[z] ANZI Z60.1 standards are presented in American units, conversions to S.I. units: 1 in = 2.54 cm, 1 ft = 0.305 m.

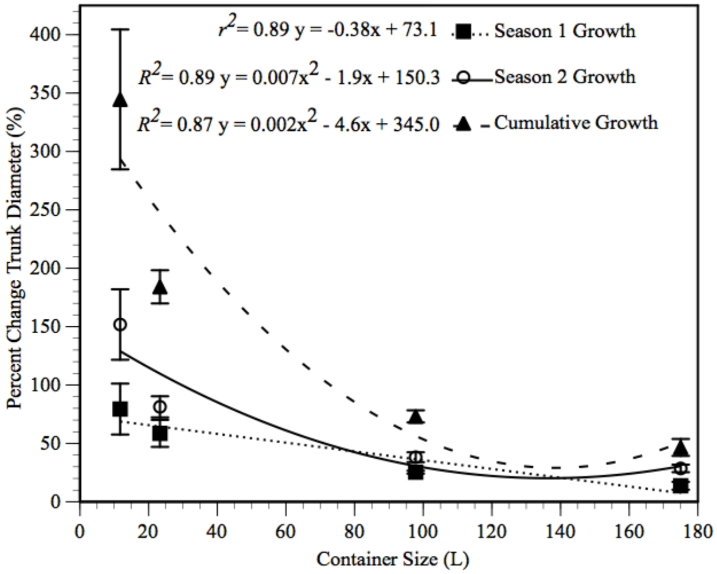

Fig. 2.5. Mean percent change in trunk diameter of *A. rubrum,* mean percent change in trunk diameter by container size (#3, #7, #25, and #45) over two growing seasons and the cumulative percent change. Symbols represent means (± standard error) of n=6. Regressions are based on means and are presented when significant at $P \leq 0.05$.

At the end of the second growing season, #3 and #7 trees were half the diameter of #45 trees at approximately 40 mm to 80 mm (Table 2.4). However, given starting trunk diameters of 9.3 mm and 17.1 mm, the increase over two growing seasons for #3 and #7 indicates establishment and return to normal growth.

Table 2.4. *Acer rubrum* mean trunk diameter by growing season and container size.

Container size	Initial (mm)	Season 1 (mm)	Season 2 (mm)
#3	9.34 ± 0.48[z]	16.75 ± 2.32	41.15 ± 5.51
#7	17.05 ± 0.63	27.27 ± 2.73	48.47 ± 3.19
#25	40.61 ± 0.34	50.90 ± 0.62	70.28 ± 1.97
#45	55.24 ± 1.13	62.68 ± 1.35	80.71 ± 3.36

[z] Values represent means ± standard error of 6 observations.

Similar results were seen for percent change in height of *A. rubrum*. The #3 container-grown trees had a large amount of growth during the first season followed by slightly less during the second growing season (Fig. 2.6). The #7 container-grown trees demonstrated the reverse with a greater growth during the second growing season than the first. Overall, percent change in height was more pronounced in trees transplanted from smaller containers (#3 and #7) over both growing seasons than those from larger container sizes (#25 and #45). Increase in height was negligible for *A. rubrum* from larger container sizes and in fact was slightly negative during the first growing season for the #45 container-grown trees, most likely due to slight stress induced dieback of branches. This is more evident when analyzing the mean height of the #45 trees, as an 11 cm decrease occurred between the initial height and the end of the first growing season (Table 2.5). In the second growing season the #45 trees increased 22 cm, indicating some recovery from transplant stress; the #3 and #7 increased by 79 cm and 71 cm, respectively. Given this growth, in combination with the greater growth seen in the trunk diameter (Table 2.4), establishment of the smaller container sizes during the first growing season was assumed.

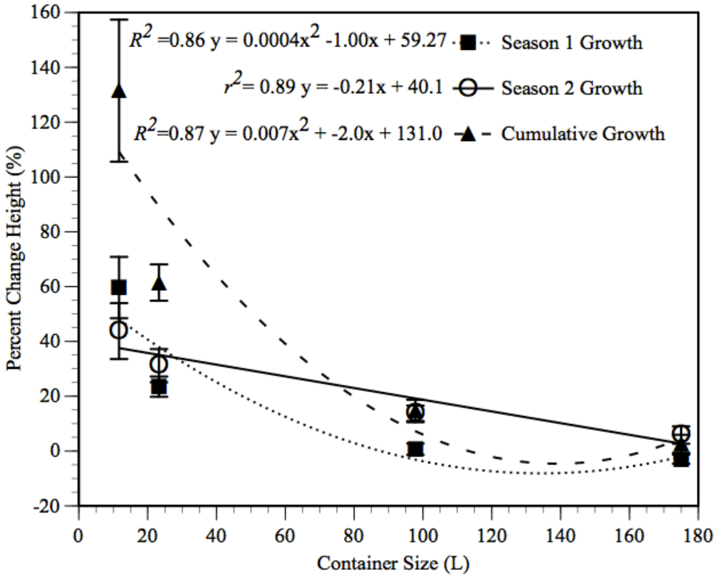

Fig. 2.6. Mean percent change in height of *A. rubrum* by container size over two growing seasons and the cumulative percent change. Symbols represent means (± standard error) of n=6. Regressions are based on means and are presented when significant at $P \leq 0.05$.

Table 2.5. *Acer rubrum* mean height by growing season and container size.

Container size	Initial (cm)	Season 1 (cm)	Season 2 (cm)
#3	114.33 ± 4.43[z]	182.03 ± 13.98	261.2 ± 25.26
#7	188 ± 6.35	232.00 ± 10.05	303.11 ± 14.47
#25	348.5 ± 8.4	350.97 ± 11.43	398.78 ± 13.46
#45	411.67 ± 9.2	399.22 ± 9.76	422.06 ± 13.37

[z] Numbers represent means (± standard error) of n=6.

For *A. rubrum*, sampling of root extension away from the root ball occurred during the first and second growing seasons. During the first growing season, all trees demonstrated no less than 200% change in root growth, however #3 container-grown trees were less vigorous than the #7 as well as #25 and #45 container-grown trees. Yet, in the second growing season, percent change in root growth was greater in #3 container-grown trees than the others. Overall, across both growing seasons, the #3 and #7 container-grown trees extended their roots a greater percentage of initial size than did the larger container-grown trees. This root extension mirrors the percent increase in growth of the shoot system for both #3 and #7 container-grown trees (Fig. 2.5 and 2.6). It is understood that root growth is a function of the size of the tree; therefore the increase in mean root length by container size is reasonable (Fig. 2.7). Of interest is the increase from the initial transplant through the first growing season to the second growing season for #3 trees. By the end of the first growing season, the length of the roots for #3 trees was the same length as the initial #45 trees, furthermore, second growing season root length was 89 cm, greater than either the first growing season or second growing season for #45. The #3, #7, and #25 trees all grew by approximately 90 cm the second growing season, suggesting 90 cm a season would be a norm (Table 2.6). Interestingly, by the end of the second growing season, root growth of the *A. rubrum* grown in #7 containers was nearly equal in spread to that of trees transplanted from #25 and #45 containers (Fig. 2.8).

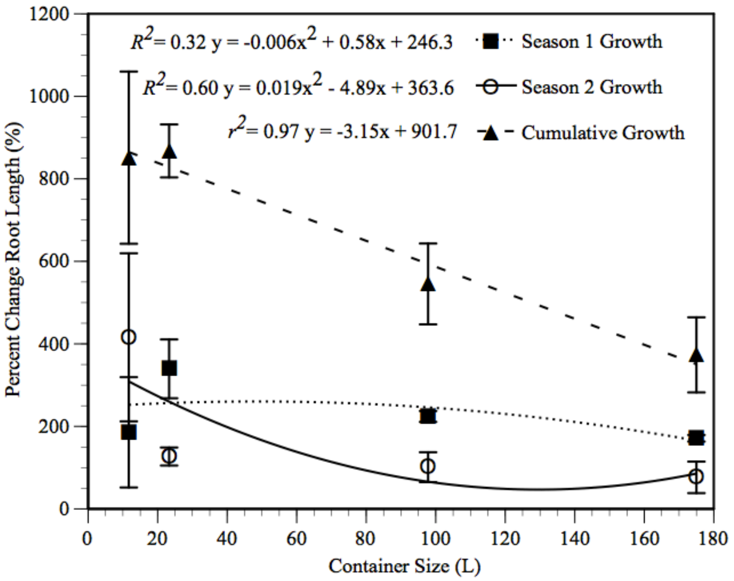

Fig. 2.7. Mean percent change in root length for *A. rubrum* by container size (#3, #7, #25, and #45) over two growing seasons and the cumulative percent change. Symbols represent means (± standard errors) of n=6. Regressions are based on means and are presented when significant at $P \leq 0.05$.

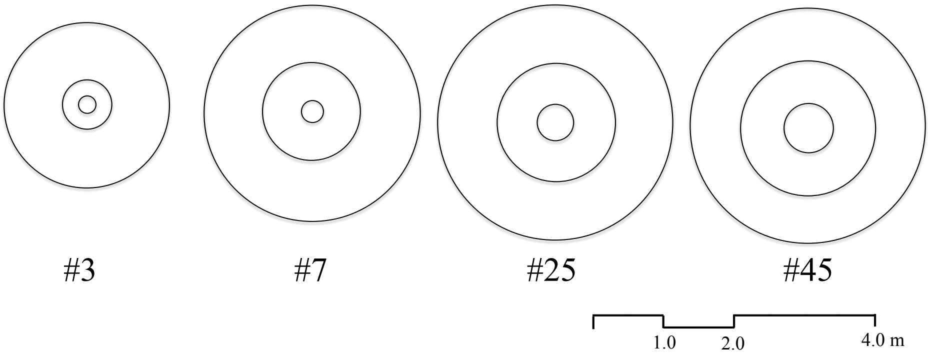

Fig. 2.8. *Acer rubrum* mean root length by container size (#3, #7, #25, and #45) from initial (inner circle) to season one (middle circle) to season two (outer circle). Symbols represent means of n=3.

Table 2.6. *Acer rubrum* mean root length by growing season.

Container size	Initial (cm)	Season 1 (cm)	Season 2 (cm)
#3	13.35[y]	38.13±17.85[z]	127.00±27.86
#7	17.15	75.37±12.23	165.95±11.01
#25	27.95	90.57±3.69	180.34±27.40
#45	38.10	103.30±3.040	180.34±34.67

[y] Indicates initial diameter of the planted rootball from the various container sizes.

[z] Values represent means ± standard errors of 3 observations.

Acer rubrum, across all four container sizes, exhibited transplant stress during the first growing season based on water stress (Fig. 2.1 and 2.2), stomatal conductance (Fig. 2.3), and photosynthetic rates (Fig. 2.4). However in the second growing season, trees from #3 and #7 containers resumed regular activity and growth. The #25 container size appears to be near establishment while those from #45 containers still exhibit signs of lingering transplant stress, such as reduced growth rates (Table 2.4, 2.5, and 2.6). *Acer rubrum* grown in #3 and #7 containers additionally displayed large increases in trunk diameter following transplant, ending at half the trunk diameter of the #45 container-grown trees. Height was increased by a greater percentage in the #3 and #7 container-grown trees than the larger container sizes. Finally, it was found that trees from smaller container sizes (#3 and #7) extended their root system a further distance, proportionally, than did those from larger container sizes. This root extension could explain the greater growth rates and decreased stress measured with the transplanted smaller container-grown trees.

2.2.2 Taxodium distichum

Pre-transplant dry masses confirm significant differences among initial container-grown tree sizes (Table 2.7). Pre-transplant stress measures provided a baseline to understand transplant shock effects (Table 2.8).

Taxodium distichum across all container sizes showed signs of drought stress within the first five days of transplant as indicated by the water potential values (Fig. 2.9). Water potentials for all container sizes then gradually became more positive until the 84th day following transplant at which point all container sizes were affected by hot summer temperatures (mean 38.3°C [101°F] over five days), becoming more water stressed (Fig. 2.9). The elevated temperatures had a greater influence on trees from #3 and #7 containers than the other container-grown trees. All trees recovered with the fall weather. Beginning in the second growing season, mid-day water potentials indicated #3 and #7 container-grown trees were established in comparison with the remaining trees.

Table 2.7. Root and shoot dry masses for *Taxodum distichum* grown in various sized containers at the end of nursery production.

Container size	Root dry weight (g)	Shoot dry weight (g)	Root: shoot ratio ($g \cdot g^{-1}$)
#1	1.33 ± 0.12^z	2.13 ± 0.42	0.65 ± 0.16
#3	6.17 ± 0.83	13.40 ± 1.55	0.46 ± 0.07
#7	298.97 ± 113.14	200.10 ± 17.80	1.47 ± 0.47
#25	463.07 ± 518.19	864.13 ± 383.17	0.93 ± 1.34
#45	744.37 ± 185.89	2035.50 ± 157.80	0.36 ± 0.06

^{z}Values represent means ± standard errors of 3 observations.

Table 2.8. *Taxodium distichum* pre-transplant stress measures for each container size taken in nursery.

Container size	Mid-day (MPa)	Pre-dawn (MPa)	Stomatal conductance (mol H_2O m^{-2} s^{-1})	Net photosynthesis (µmol CO_2 m^{-2} s^{-1})
#1	-15.83 ± 0.98[z]	-6.42 ± 1.02	10.60 ± 3.39	0.08 ± 0.04
#3	-11.25 ± 1.04	-4.33 ± 0.68	11.67 ± 6.50	0.12 ± 0.08
#7	-15.33 ± 1.94	-7.17 ± 1.86	4.59 ± 2.75	0.07 ± 0.04
#25	-17.83 ± 2.27	-7.42 ± 1.46	5.18 ± 1.31	0.04 ± 0.02
#45	-17.92 ± 0.66	-9.08 ± 1.02	3.72 ± 1.84	0.04 ± 0.04

[z]Values represent means ± standard errors of 6 observations.

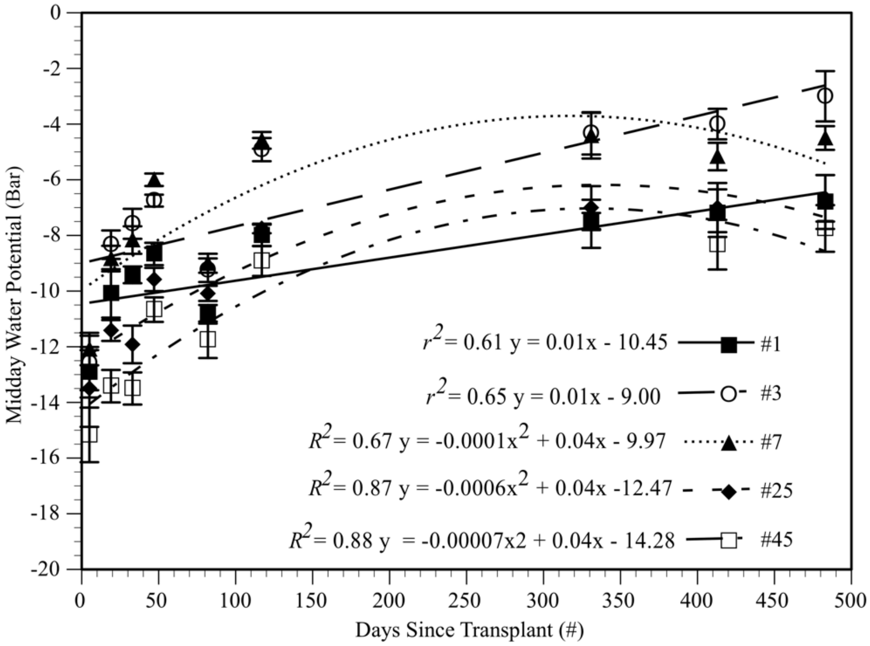

Fig. 2.9. Interactions among container sizes (#1, #3, #7, #25, and #45) and time since transplant in days for mean midday water potentials of *Taxodium distichum*. Symbols represent means (± standard error) of n=6. Regressions are based on means and are presented when significant at $P \leq 0.05$.

Pre-dawn recovery of water stress was more variable among container sizes immediately following transplant. At 12 days following transplant, predawn water potential in plants of all container sizes, except #25, became more negative indicating plants could not recover from water stress as effectively (Fig. 2.10). The #25 container transplanted trees exhibited this decrease in recovery seven days later. Following the drop, plants in all container sizes began to recover more efficiently with the exception of the 84th day following transplant, which correlated with elevated August temperatures. At the beginning of the second growing season, pre-dawn water potentials were similar to levels seen at the end of the first growing season. However, *T. distichum* exhibited decreased water potentials measured during summer, correlating with high temperatures. Trees recovered once again in the fall months with onset of cooler temperatures and greater rainfall. Overall, the #7 container-grown trees were consistent in their reaction to water stress and appeared to recover better than the larger container sizes. The #3 container-grown trees were similar in performance, corroborating mid-day water potential values (Fig. 2.9).

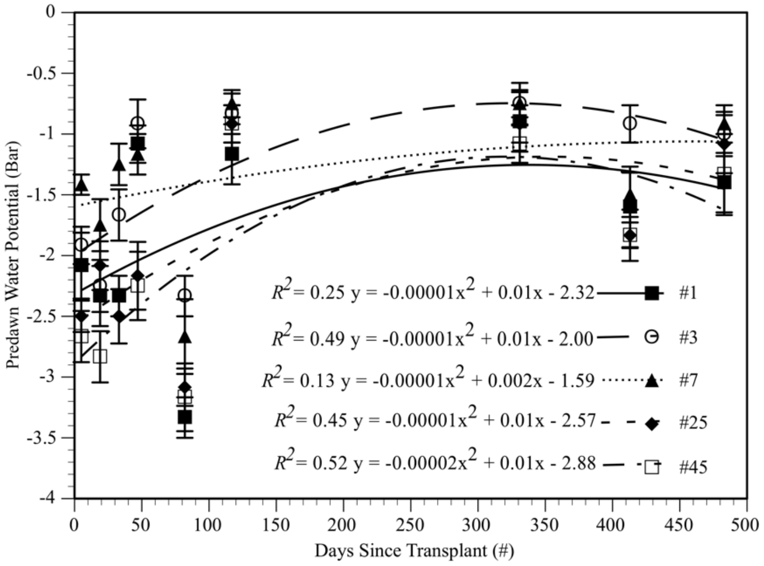

Fig. 2.10. Interactions among container sizes (#1, #3, #7, #25, and #45) and time since transplant in days for mean predawn water potentials for *Taxodium distichum*. Symbols represent means (± standard errors) of n=6. Regressions are based on means and are presented when significant at $P \leq 0.05$.

Trees from all container sizes restricted gas flow through reduced stomatal conductance following transplant. Of note, trees increased stomatal conductance around the 84th day following transplant, which is associated with a peak in summer temperatures as well as a decrease in water potential within all container sizes. Continued increase in stomatal conductance occurred through the end of the first growing season. Inexplicably, #25 container-grown trees' means did not follow the pattern for the 120th day following transplant (Fig. 2.11). Beginning in the second growing season, #3 trees diverged from the remaining trees demonstrating levels expected when trees would be fully established. The #1 trees had low stomatal conductance in the spring of the second year, but by fall appeared to be trending toward establishment as well. Consistent with mid-day and pre-dawn water potential data, the #25 and #45 trees continued to experience environmental stress indicating they were not yet established (Fig. 2.9 and 2.10). This would fit with the reports that *Taxodium distichum* is a slow growing tree (Wilhite and Toliver, 1990). Of interest, #7 trees, while established according to mid-day and pre-dawn water potentials, were not fully established according to stomatal conductance data from the second growing season. Instead, stomatal conductance was lowered in the spring than at the end of the first growing season. Increases in conductance over the season were minor resulting in ending stomatal conductance equivalent to the previous growing season’s ending rate.

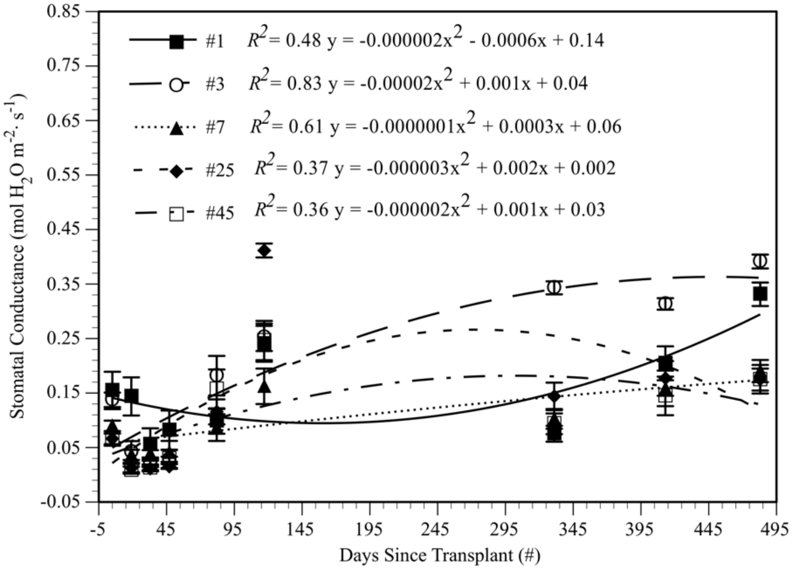

Fig. 2.11. Interactions among container sizes (#1, #3, #7, #25, and #45) and time since transplant in days for mean stomatal conductance for *Taxodium distichum*. Symbols represent means (± standard errors) of n=6. Regressions are based on means and are presented when significant at $P\leq0.05$.

Photosynthetic rates of *T. distichum* were not different among container sizes, but the main effects of time after transplant has an effect (R^2= 0.44) (Fig. 2.12). Photosynthetic rates of *T. distichum* remained relatively high following transplant in all container sizes. This could be due to stored mineral nutrients from the nursery and internal water reserves that allowed continuance of photosynthesis despite elevated stress conditions. A decrease in net photosynthesis is seen at 12 d following transplant, correlating with a decrease in stomatal conductance. Photosynthetic rates continue to remain low through the growing season until cooler temperatures of autumn when photosynthesis of trees from all container sizes increase by approximately two fold. Photosynthetic rates appear to be more directly influenced by water potentials (Fig. 2.9 and 2.10) than seasonal factors, as indicated by data through the 84th day following transplant. During the second growing season, photosynthetic rates resumed at lower levels compared to the end of the first growing season, yet increased to comparable levels by fall. The initial low levels of the second growing season suggest trees had not established by the beginning of the second growing season. These lower photosynthetic rates could also be due to restricted stomatal conductance (Fig. 2.11).

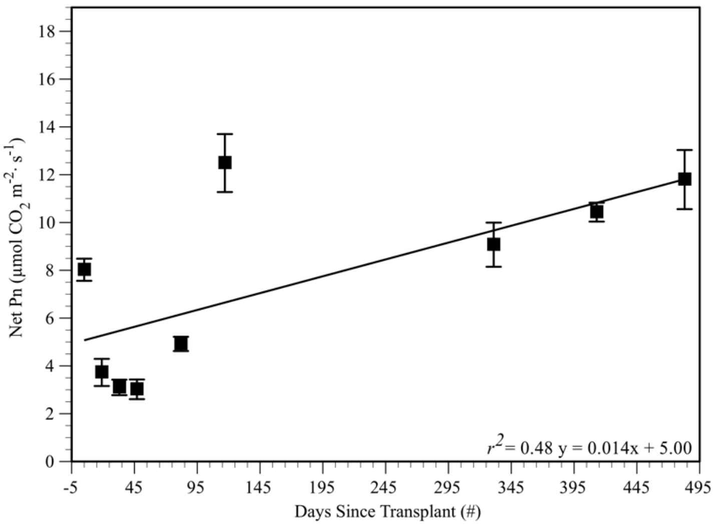

Fig. 2.12. Main effect of time since transplant in days across container sizes (#1, #3, #7, #25, and #45) for mean photosynthetic rates of *Taxodium distichum*. Symbols represent means (± standard errors) of n=6. Regressions are based on means and are presented when significant at $P \leq 0.05$.

Percent change in trunk diameter of *T. distichum* was not significant ($P \leq 0.05$) among container sizes for the first growing season. Despite high stress conditions (Fig. 2.9, 2.10, 2.11, and 2.12) during the second growing season, percentage change in trunk diameter was greater than in the first growing season for the #1, #7, and #25 trees (Fig. 2.13). The #45 trees maintained close to zero percent change in trunk diameter across the two-year growing period, while #1 and #3 trees had significant increases in trunk diameter. The #3 trees displayed a mean of 850% change in diameter over two growing seasons. The #3 container-grown trees ended with a trunk diameter of 36.1 mm, equivalent to the starting trunk diameter of #25 trees (Table 2.9.). Also, #7 container-grown trees ended with a trunk diameter of 50.6 mm, greater than the starting trunk diameter of #45 trees. The ending trunk diameters of #25 and #45 were equivalent at 67 mm.

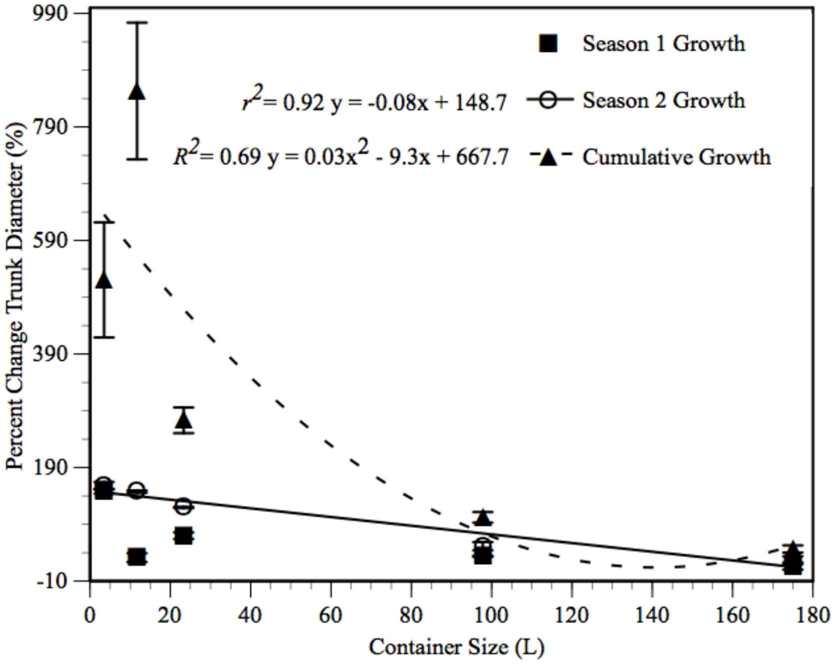

Fig. 2.13. Mean percent change in trunk diameter by container sizes (#1, #3, #7, #25, and #45) over two growing seasons and the cumulative percent change for *Taxodium distichum*. Symbols represent means (± standard errors) of n=6. Regressions are based on means and are presented when significant at $P \leq 0.05$.

Table 2.9. *Taxodium distichum* mean trunk diameter by growing season and container size.

Container size	Initial (mm)	Season 1 (mm)	Season 2 (mm)
#1	3.48 ± 0.58 [z]	7.96 ± 0.86	21.13 ± 3.3
#3	3.98 ± 0.36	15.14 ± 1.58	36.07 ± 2.54
#7	13.57 ± 0.3	22.98 ± 0.42	50.58 ± 3.1
#25	33.27 ± 0.94	44.42 ± 1.02	67.33 ± 3.85
#45	46.32 ± 1.15	53.11 ± 2.19	67.73 ± 2.69

[z] Values represent means ± standard errors of 6 observations.

Percent change in height for *T. distichum* was similar in pattern to percent change in trunk diameter (Fig. 2.13) however overall changes were of a lesser magnitude. The first growing season was once again insignificant (Fig. 2.14.). The #45 trees demonstrated a very slight negative percent change in height during the first growing season indicating some dieback of limbs; however it was not statistically different than that of trees from other containers during the first growing season. The presence of dieback is documented when analyzing the mean height of the trees from #45 containers, as a 3 cm mean decrease occurred between the initial height and the first growing season (Table 2.10). While in the second growing season the trees from the #45 containers increased 47 cm, indicating some recovery from transplant stress, although the #1 and #3 trees increased by 52 cm and the #7 and #25 trees increased by 71 cm. Smaller container size trees (#1, #3, and #7) increased in height more so than larger container size trees (Fig. 2.14). Given this growth, in combination with the greater growth seen in the trunk diameter (Table 2.9) and height (Table 2.10), establishment of the smaller container sizes appears to have occurred more rapidly and was completed by the end of the second growing season. However, they remained substantially smaller in canopy size than the trees from larger containers after two growing seasons.

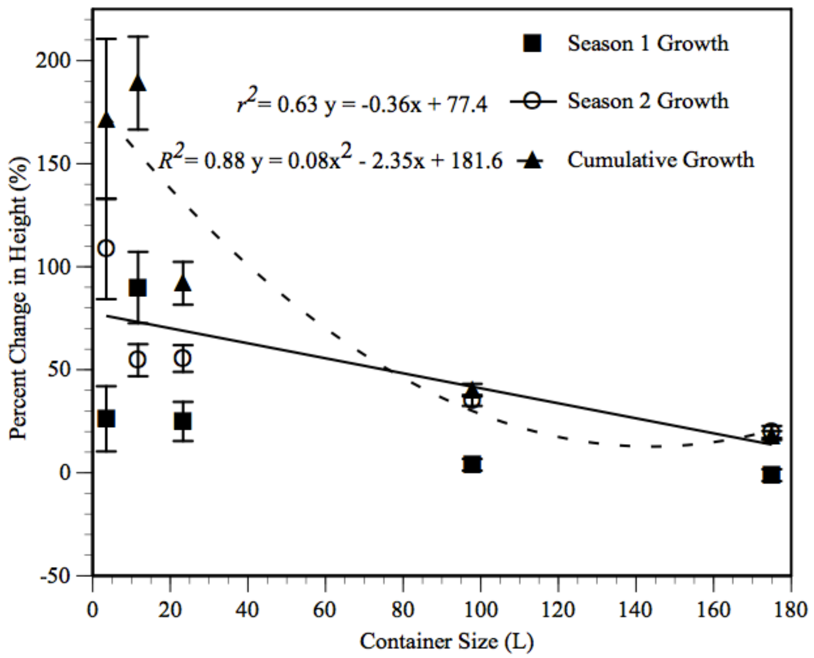

Fig. 2.14. Mean percent change in height by container sizes (#1, #3, #7, #25, and #45) over two growing seasons and the cumulative percent change for *Taxodium distichum*. Symbols represent means (± standard errors) of n=6. Regressions are based on means and are presented when significant at *P*≤0.05.

Table 2.10. *Taxodium distichum* mean height by growing season and container size.

Container size	Initial (cm)	Season 1 (cm)	Season 2 (cm)
#1	37.00 ± 2.50^z	45.3 ± 3.74	97.54 ± 10.79
#3	52.17 ± 2.06	97.78 ± 7.22	149.86 ± 10.57
#7	105.33 ± 2.64	130.82 ± 8.34	201.08 ± 7.05
#25	194.17 ± 3.34	201.5 ± 5.44	271.78 ± 5.68
#45	245.5 ± 3.31	242.57 ± 7.56	289.98 ± 8.07

^{z}Values represent means ± standard errors of 6 observations.

At the end of the first and second growing seasons, analysis of the extension of the roots extending away from the root ball was conducted. The first growing season, trees from #7 and #25 containers had a larger percentage change than the trees from the #1 or #45 containers (Fig. 2.15). Although trees from #3 and #25 containers had similar extension in the first growing season, the second growing season trees from #3 containers produced three times the percent change in root length compared to those from #25 containers (Fig. 2.15). The #3 trees produced 83 cm of growth between the first and second growing seasons, greater than #1, #7, and #25 trees (Table 2.11). Overall, across both growing seasons, the #3 and #7 container-grown trees extended their roots a greater percent of their initial size than did the #1, #25, and #45 container-grown trees. Cumulative percent change in root length was similar among trees from #1, #25, and #45 containers. A discrepancy exists between the rate of change for root length of #1 trees and the shoot growth of #1 trees (Fig. 2.14). However, root extension is consistent with the percent increase in growth of the shoot system for #3 container-grown trees (Fig. 2.13 and 2.14). Since root growth is a function of the size of the tree, a general increase in root length from #1 to #45 is not unexpected (Fig. 2.16). The difference in tree size associated with different container stock were still apparent for root growth of *T. distichum* and are easily visualized in Fig. 2.16. This is in contrast to the apparent "catching up" of intermediate sizes of *A. rubrum* with larger containers and the much less noticeable differences in root growth from trees of various sizes for *V. agnus-castus*.

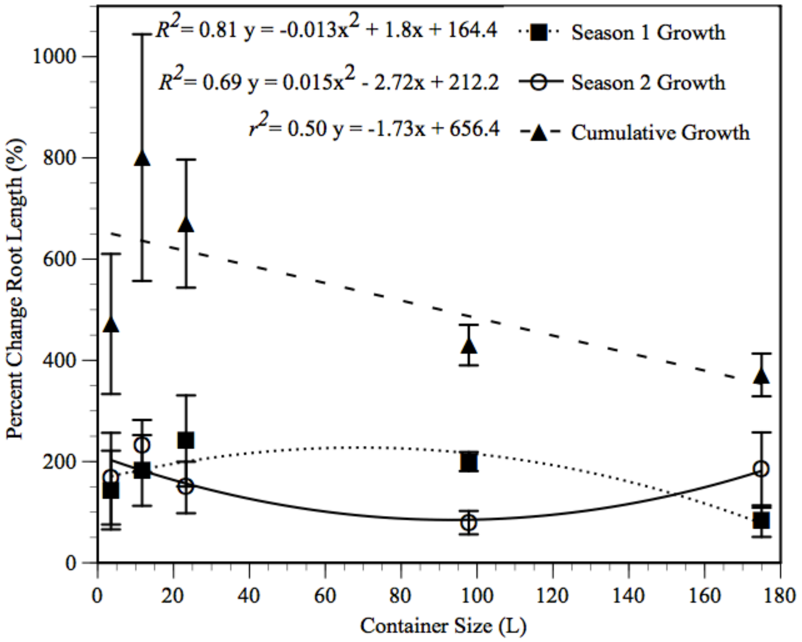

Fig. 2.15. Mean percent change in root length by container size (#1, #3, #7, #25, and #45) over two growing seasons and the cumulative percent change for *Taxodium distichum*. Symbols represent means (± standard errors) of n=6. Regressions are based on means and are presented when significant at $P \leq 0.05$.

Table 2.11. *Taxodium distichum* mean root length by growing season and container size.

Container size	Initial (cm)	Season 1 (cm)	Season 2 (cm)
#1	9.55 ^{z}	23.27 ± 7.43	54.61 ± 13.22
#3	13.35	37.70 ± 9.33	120.23 ± 32.54
#7	17.15	58.43 ± 15.44	132.08 ± 21.70
#25	27.95	83.83 ± 5.27	148.17 ± 11.20
#45	38.10	69.43 ± 11.87	179.49 ± 16.09

^{z}Values represent means ± standard errors of 3 observations.

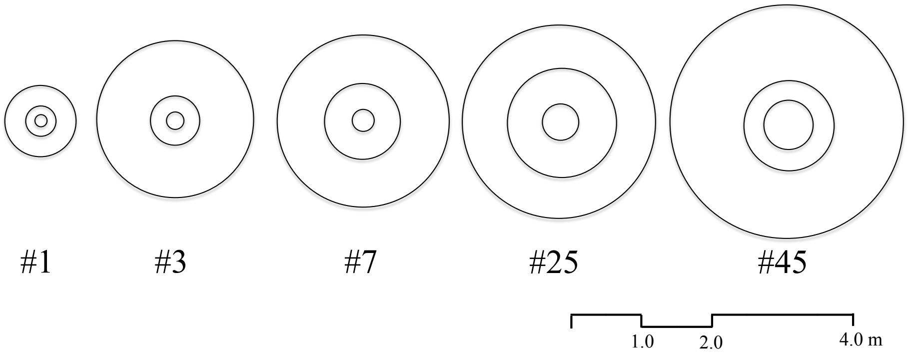

Fig. 2.16. *Taxodium distichum* proportional mean root length by container size (#1, #3, #7, #25, and #45) from initial (inner circle) to season one (middle circle) to season two (outer circle). Symbols represent means of n=3.

Across all five container sizes, *T. distichum*, across all five container sizes, exhibited transplant stress reactions during the first growing season based on water stress, stomatal conductance, and photosynthetic rates. However, in the second growing season, while #3 container trees resumed regular activity and growth, none of the *T. distichum* appeared to be fully established. Given their slower rate of growth, this could explain delayed establishment and growth. Trunk diameters increased more so in #3 container-grown trees, but were still relatively low across all container sizes. Similar observations were found with the height of each container size as both #1 and #3 container-grown trees increased height by over 100% of their initial transplant size at the end of the second growing season, but relative differences among trees from the various container sizes were still easily discernable. As with *A. rubrum*, the growth and stress reactions of the trees appear to be associated with the root growth. While #3 and #7 container-grown trees increased their root growth by large percentages, there remain apparently different levels of growth still identifiable among container sizes.

2.2.3 Vitex agnus-castus

Pre-transplant dry mass readings confirmed differences among initial container-grown tree sizes (Table 2.12). Pre-transplant stress measures provided a baseline to understand transplant shock effects (Table 2.13).

Vitex agnus-castus showed high levels of water stress immediately following transplant in all container size trees as indicated by strongly negative midday water potentials (Fig. 2.17). At the 34th day following transplant, trees became less negative indicating less water stress for all container sizes (Fig. 2.17). This could be explained by the wet conditions surrounding the date of data collection with a cumulative rainfall of 32.8 mm over three days. Again at the 82nd day following transplant, trees exhibited high levels of water stress associated with elevated summer temperatures (mean 38.3°C [101°F] over five days). Midday water potentials fluctuated greatly over the first growing season; however, in the second growing season midday water potentials were consistent over all three sample dates. Slightly depressed fall values could be related to early leaf senescence in *V.agnus-castus* trees during autumn 2014. Overall, trends indicated #3 trees best adjusted to water related stress and established quickly.

Table 2.12. Root and shoot dry masses of *Vitex agnus-castus* grown in various sized containers at the end of nursery production.

Container size	Root dry mass (g)	Shoot dry mass (g)	Root: shoot ratio $(g \cdot g^{-1})$
#1	15.77 ± 6.31[z]	13.83 ± 6.99	1.20 ± 0.18
#3	26.40 ± 3.64	42.27 ± 7.34	0.63 ± 0.03
#7	151.70 ± 39.22	257.43 ± 42.84	0.58 ± 0.08
#25	2144.97 ± 402.90	1598.23 ± 82.28	1.34 ± 0.18
#45	4946.10 ± 189.60	3008.1 ± 78.58	1.64 ± 0.07

[z] Values represent means ± standard errors of 3 observations.

Table 2.13. *Vitex agnus-castus* pre-transplant stress measures for each container size (n=6) taken in nursery.

Container size	Mid-day (MPa)	Pre-dawn (MPa)	Stomatal conductance (mol H_2O m^{-2} s^{-1})	Net photosynthesis (μmol CO_2 m^{-2} s^{-1})
#1	-2.50 ± 1.05[z]	-1.75 ± 0.76	2.55 ± 2.43	0.02 ± 0.02
#3	-2.58 ± 0.80	-1.67 ± 0.52	5.78 ± 1.47	0.04 ± 0.01
#7	-1.83 ± 0.41	-1.42 ± 0.38	5.27 ± 0.78	0.05 ± 0.01
#25	-2.33 ± 0.68	-1.50 ± 0.55	7.35 ± 2.10	0.07 ± 0.04
#45	-4.58 ± 0.92	-2.33 ± 0.82	7.32 ± 1.85	0.22 ± 0.39

[z] Values represent means ± standard errors of 6 observations.

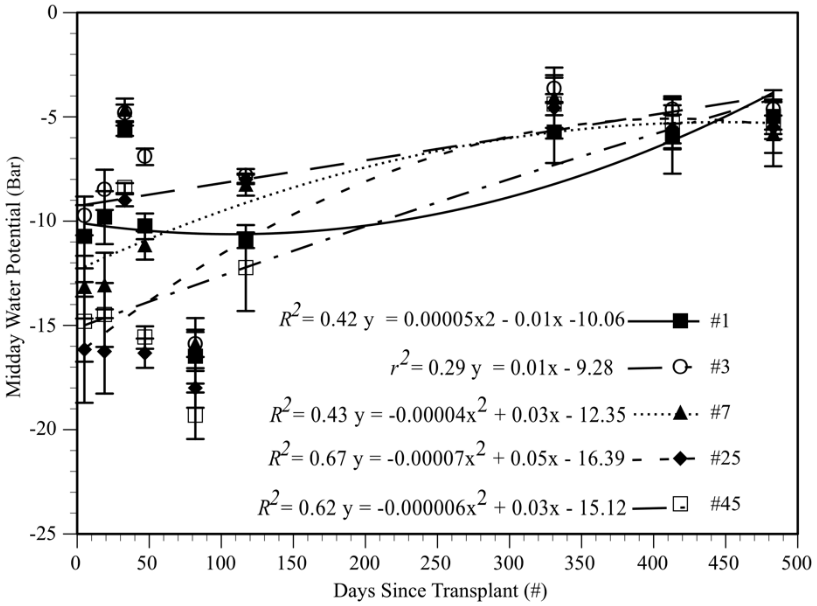

Fig. 2.17. Interaction among container sizes (#1, #3, #7, #25, and #45) and time since transplant in days for mean midday water potentials for *Vitex agnus-castus*. Symbols represent means (± standard errors) of n=6. Regressions are based on means and are presented when significant at *P*≤0.05.

Pre-dawn recovery of *V. agnus-castus* from the prior day's water stress immediately following transplant was less negative for the #3 trees followed by #1 and #7 trees versus the remaining container size trees (Fig. 2.18). At the 34th day following transplant, recovery from water stress was less efficient for all container size trees. All trees resumed recovery at the subsequent measurement with #3 trees once again recovering best followed by trees from #1 and #7 containers. At the 82nd day from transplant, pre-dawn water potentials for all trees, except those from #7 containers, became more negative likely due to the higher daytime temperatures. At the end of the first growing season, all trees demonstrated relatively little pre-dawn water stress, recovering by >7 bar from mid-day readings. The second growing season, *V. agnus-*

castus showed consistent readings across all container size trees. Averaged across both seasons, the #3 and #7 trees showed greater recovery from water stress than #25 and #45 trees although this could be in part due to their lower mid-day water potentials (Fig. 2.17).

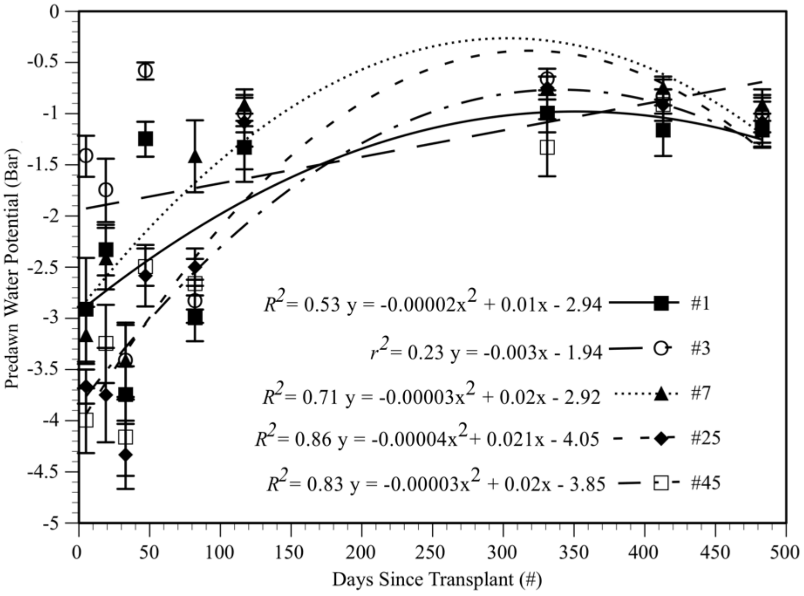

Fig. 2.18. Interaction among container sizes (#1, #3, #7, #25, and #45) and time since transplant in days for mean predawn water potentials for *Vitex agnus-castus*. Symbols represent means (± standard errors) of n=6. Regressions are based on means and are presented when significant at $P \leq 0.05$.

Mean stomatal conductance five days following transplant was reduced for all container sizes. However, seven days later, gas exchange was almost zero for all container sizes (Fig. 2.19). This is consistent with research indicating reduced stomatal conductance is delayed following transplant (Guehl et al., 1989). Gradual increase in stomatal conductance occurs over the following readings, with some decline associated with high temperature summer readings at the 82nd day following transplant. The second growing season stomatal conductance begins at a reduced rate. Stomatal conductance recovered in the subsequent readings. Over both growing seasons, #3 and #1 trees maintained high gas exchange rates. This is consistent with lower water stress levels (Fig. 2.17 and 2.18).

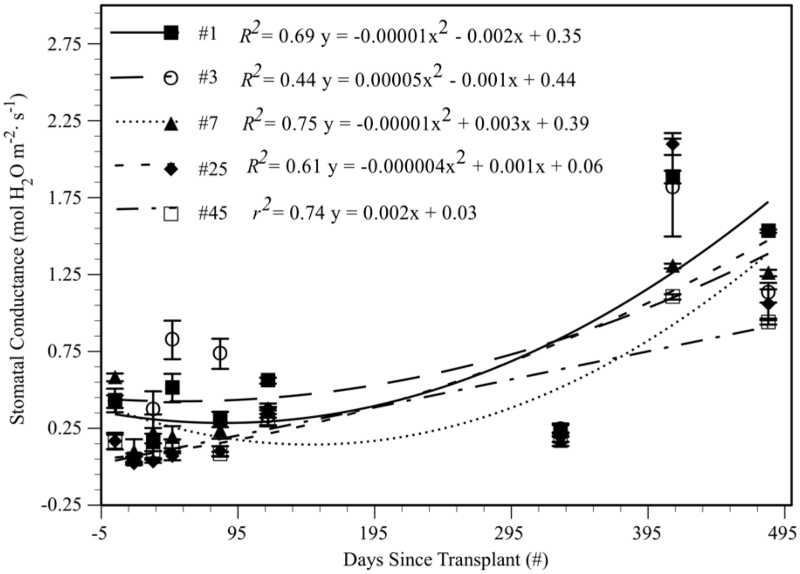

Fig. 2.19. Interaction among container sizes (#1, #3, #7, #25, and #45) and time since transplant in days for mean stomatal conductance for *Vitex agnus-castus*. Symbols represent means (± standard errors) of n=6. Regressions are based on means and are presented when significant at $P \leq 0.05$.

Differences in photosynthetic rates for *V. agnus-castus* were not significant ($P \leq 0.05$) across container size but were significant across time (Fig. 2.20). Photosynthetic rates are highly variable in the first 95 days following transplant. At 12 days following transplant, however, all trees showed significantly lower photosynthetic rates (Fig. 2.20), consistent with reduced stomatal conductance (Fig. 2.19). By the end of the first growing season, photosynthetic rates become consistent across container sizes and reduce likely due to decreased growth and leaf senescence in autumn (Sams and Flore, 1983). Photosynthetic rates resumed at similar levels in the second growing season and continue to increase to consistently elevated levels in summer and fall of the second season. Given the high photosynthetic rates and close groupings, this would suggest establishment of all container-grown trees by midway through the second growing season.

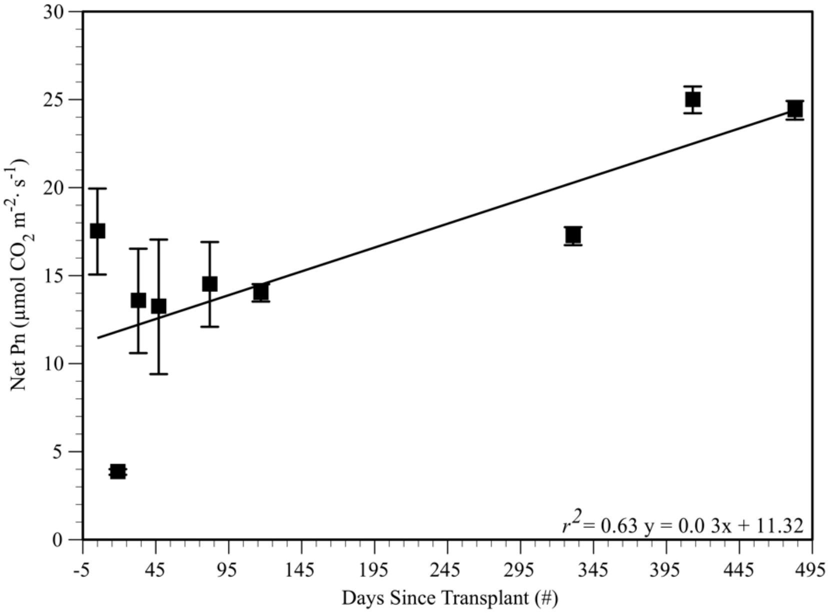

Fig. 2.20. Main effects of photosynthetic rates across all container sizes by time since transplant in days for mean midday water potentials of *Vitex agnus-castus*. Symbols represent means (± standard errors) of n=6. Regressions are based on means and are presented when significant at *P*≤0.05.

Initial trunk diameters were based on ANSI Z60.1 (American Association of Nurseryman, 2004) container size standards at transplant. Percent changes in trunk diameter during the first growing season and second growing season were greater in *V. agnus-castus* from smaller container sizes (#1 and #3) than from the larger container sizes (#7, #25, and #45) (Fig 2.21). For #1 and #3 container-grown trees, the first growing season percent change in diameter was greater than the second growing season. Percent change was similar for the first and second growing seasons in #7, #25, and #45. Cumulative percent change in trunk growth of *V. agnus-castus* was substantial with smaller container trees (#3 and #7) increasing truck diameter by approximately 12 times the initial diameter. Smaller changes in trunk diameter were recorded for #7, #25, and #45 trees. Mean trunk diameters increased for all container sizes, but more so for the #3 trees. The #3 trees ending trunk diameter was 72.2 mm, which was greater than the ending diameters of #7 trees and very similar to #25 trees (Table 2.14). Ending trunk diameters of #1, #3, and #7 in *V. agnus-castus* were all greater than the starting diameter for the #45 trees. Trunk diameters approximately doubled in growth for trees from the smaller container sizes (#1, #3, and #7) from the first growing season to the second growing season, for example, #1 trees increased by 18 mm during the first growing season and 31 mm the second.

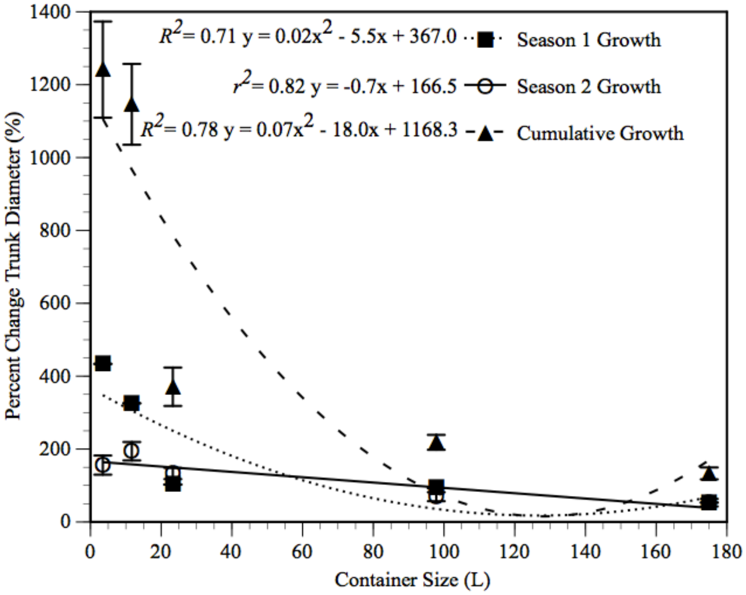

Fig. 2.21. Mean percent change in trunk diameter for *Vitex agnus-castus* by container size (#1, #3, #7, #25, and #45) over two growing seasons and the cumulative percent change. Symbols represent means (± standard errors) of n=6. Regressions are based on means and are presented when significant at $P \leq 0.05$.

Table 2.14. *Vitex agnus-castus* mean trunk diameter by growing season by container size.

Container size	Initial (mm)	Season 1 (mm)	Season 2 (mm)
#1	3.95 ± 0.19^z	21.02 ± 1.63	52.31 ± 4.57
#3	5.91 ± 0.44	25.13 ± 2.37	72.2 ± 5.48
#7	14.7 ± 0.69	29.41 ± 1.92	67.69 ± 4.59
#25	25.11 ± 1.92	47.07 ± 2.39	78.83 ± 4.4
#45	35.81 ± 1.89	54.26 ± 1.19	82.45 ± 3.92

^{z}Values represent means ± standard errors of 6 observations.

Similar patterns of change in height growth were found as in the percent change in trunk diameter for *V. agnus-castus*. Percent change in height was greater during the first growing season than the second growing season for #1 and #3 trees but reversed for the #7, #25, and #45 trees (Fig. 2.22). During the first growing season, percent change in height was less than zero for #25 and #45 trees indicating some 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 #25 and #45 trees. Conversely, #1, #3, and #7 trees increased in height by more than 100% with #1 trees increasing at approximately 325%. The increase in height from the initial to the end of the first growing season was exponential by container size, with #1 increasing in height more than the larger container sizes. The second growing season, this increase slows to become more linear. Ending heights for all *V. agnus-castus* were within 71 mm of each other after two growing seasons (Table 2.15.). Given the increase of the trunk diameter and height (Fig. 2.21 and 2.22) all container sizes of *V. agnus-castus* were likely established early in the first growing season.

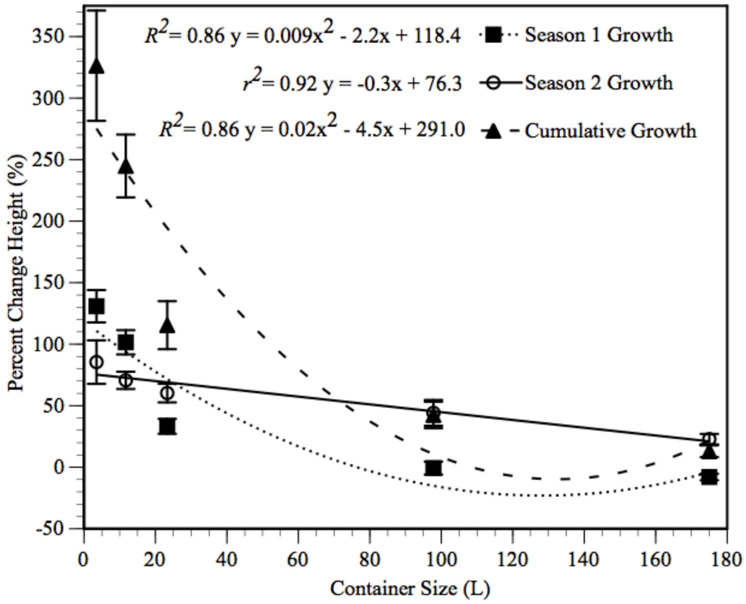

Fig. 2.22. Mean percent change in height by container size (#1, #3, #7, #25, and #45) over two growing seasons and the cumulative percent change for *Vitex agnus-castus*. Symbols represent means (± standard errors) of n=6. Regressions are based on means and are presented when significant at $P \leq 0.05$.

Table 2.15. *Vitex agnus-castus* mean height by growing season.

Container size	Initial (mm)	Season 1 (mm)	Season 2 (mm)
#1	54.7 ± 3.2[z]	124.5 ± 4.2	228.2 ± 17.0
#3	76.8 ± 3.3	153.7 ± 4.8	261.2 ± 9.2
#7	135.5 ± 9.6	177.8 ± 4.6	284.5 ± 13.3
#25	200.8 ± 5.9	198.6 ± 9.5	285.3 ± 21.1
#45	266.2 ± 8.0	244.3 ± 5.8	299.3 ± 8.9

[z] Values represent means ± standard errors of 6 observations.

Vitex agnus-castus is a reportedly fast growing tree (Arnold, 2008; Welch, 2008), which could explain the high percent change in root length during the first growing season. Of note is the low percent change in root length during the second growing season, which is close to zero in #7 and #45 trees (Fig. 2.23). While percent change was low, due to the large amount of growth the first growing season, mean root lengths show that trees from all container sizes extended roots into the surrounding soil by at least 100 cm (Table 2.16). Cumulatively, the roots of *V. agnus-castus* extended large distances away from the initial root ball, even crossing with neighboring tree roots planted 6 m away. Percent change in root length was greatest in the smaller container sizes, #1, #3, and #7. Visually represented it is easy to see that the root systems of *Vitex agnus-castus* are similar (Fig. 2.24). The #1 and #3 container tree roots were very similar in growth to the #45 and outperformed the #7 trees.

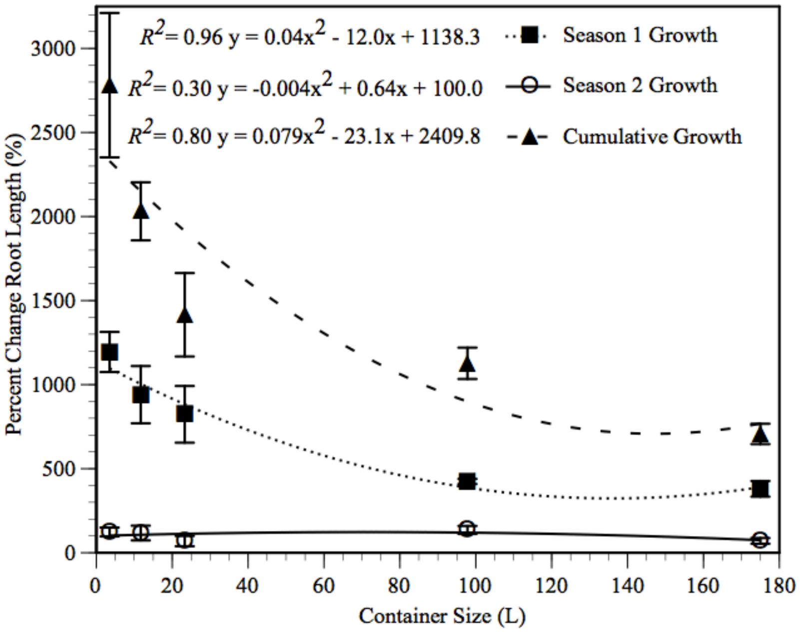

Fig. 2.23. Mean percent change in root length by container sizes (#1, #3, #7, #25, and #45) over two growing seasons and the cumulative percent change for *Vitex agnus-castus*. Symbols represent means (± standard errors) of n=6. Regressions are based on means and are presented when significant at $P \leq 0.05$.

Table 2.16. *Vitex agnus-castus* mean root length by growing season by container size. Numbers represent means (± standard errors) of n=3.

Container size	Initial (cm)	Season 1 (cm)	Season 2 (cm)
#1	9.55[y]	123.6 ± 11.39[z]	275.17 ± 41.02[z]
#3	13.35	138.87 ± 22.72	284.48 ± 23.05
#7	17.15	158.33 ± 28.93	259.93 ± 42.56
#25	27.95	146.43 ± 4.23	342.9 ± 26.07
#45	38.10	182.87 ± 17.79	307.34 ± 23.05

[y] Values in this column represent the original diameter of the planted rootballs which did not vary within a container size.

[z] Values within this column represent means ± standard errors of 3 observations.

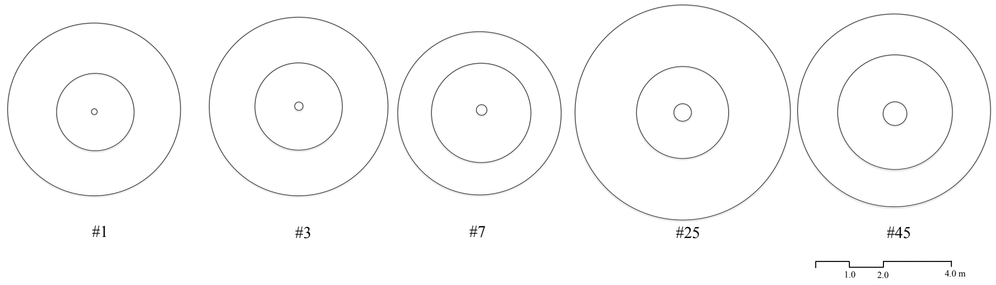

Fig. 2.24. *Vitex agnus-castus* mean root length by container size (#1, #3, #7, #25, and #45) from initial (inner circle) to season one (middle circle) to season two (outer circle). Symbols represent means of n=3.

Vitex agnus-castus is a reportedly fast growing tree (Arnold, 2008; Welch, 2008), which could explain why, across trees from all five container sizes, mild transplant stress reactions occurred during the first growing season. In the second growing season, all container trees resumed regular activity and growth. Given the growth of the trees and their stress measures during the second growing season, it would appear all container sizes were established during the second growing season. However, #1 and #3 trees showed faster recovery during the first growing season with the result that by the end of the second growing season they were able to "catch up" to the #7, #25, and #45 container-grown trees. This "catch up" occurred due to the large percent changes in trunk diameter and height. Additionally, the high percent change in root length during the first growing season helps to explain the reduced stress levels, quick establishment, and large percent change in growth that occurred in the *V. agnus-castus*. This is consistent with reports that smaller size stock responds with rapid growth responses similar to the early seedling stages of development in trees (Gilman and Dehgan, 1996), even when they are cutting derived plants.

CHAPTER III

ECONOMIC COST ANALYSIS OF THE IMPACT OF CONTAINER SIZE

Nurseries over the years have produced trees in larger and larger container sizes (Arnold, 2004; Watson, 2004). Retail garden centers and even large box stores, such as Walmart, Lowe's, and Home Depot, that now sell trees in up to 100-gallon containers. While debate continues over the relative merits of different container sizes (Watson, 2004), this could in part be due to the appreciation landscape industries 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 accidental or malicious mechanical damage (Watson and Himelick, 2013), instant shade (Kalmbach and Kielbaso, 1979; Schroeder, 2006), and increase in property value (Maco and McPherson, 2003). However, these larger trees cost more to grow and occupy a greater amount of nursery space per tree over longer time frames resulting in higher costs of production for growers and higher prices for consumers (Watson and Himelick, 2013). Smaller container sizes are ultimately less expensive for consumers as nurseries expend less materials, maintenance, and square footage to produce smaller trees. Also, smaller container sizes, once transplanted to the field, have been reported to experience reduced transplant shock (Watson, 2004), are in a phase of growth more closely aligned with the exponential growth rate of young seedlings (Gilman and Dehgan, 1996), have been in containers for shorter times and have been upcanned fewer times potentially reducing the chance of circling root development (Gilman and Kane, 1990), and their smaller size makes for easier handling and staking (Watson and Himelick, 2013). The 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 value of a tree, defined as its monetary worth, is based on people's perception of the tree (Cullen, 2000). Arborists use several methods to develop a fair and reasonable estimate of the value of individual trees (Council of Tree & Landscape Appraisers, 2000; Cullen, 2005; Watson, 2002). The cost approach is widely used today and assumes that value equals the cost of production (Cullen, 2002). It assumes that benefits inherent in a tree can be reproduced by replacing the tree and therefore, replacement cost is an indication of value (Cullen, 2000). Replacement cost is depreciated to reflect differences in the benefits that flow from an "idealized" replacement compared with the older and imperfect appraised tree. The depreciated replacement cost method uses tree size, species, condition, and location factors to determine tree value (McPherson, 2007).

The income approach measures value as the future use of a tree such as in fruit or nut production (The Appraisal Institute, 2000). In the absence of such products, the income approach could be based on the present value of future economic, environmental, and health-well being monetary benefits the tree is likely to produce (Council of Tree & Landscape Appraisers, 2000). For example, benefits that have proven to improve the value of the tree, including energy savings (McPherson and

Simpson, 1999), atmospheric carbon dioxide reductions (McPherson et al., 2003), storm water runoff reductions (Xiao et al., 2000), and aesthetics (Anderson and Cordell, 1988). Quantifying and totaling these benefits over time can provide an idea of a tree's projected value, but require data outside the scope of this project, thus a deviation of the replacement cost method was utilized within this study.

The objective of the current research was to determine the initial and replacement cost value of five different container sizes in three tree species at transplant and after two growing seasons in the landscape.

3.1 Materials and Methods

In analyzing the impact container size has on the value of the tree, the establishment cost of the tree was calculated and then compared to the replacement cost of the tree after two growing seasons. Using the difference, it was then possible to see the net value for each container size tree over time. The three taxa we utilized were selected to represent different niches of the landscape industry. Selections of *Vitex agnus-castus* L., *Acer rubrum* L. var. *dummondii* (Hook. & Arn. *ex* Nutt.) Sarg., and *Taxodium distichum* (L.) Rich. were chosen due to their wide spread use in the southern nursery trade and their representation of a variety of classes of landscape trees. Additionally, five container sizes, 3.5L (#1), 11.7L (#3), 23.3L (#7), 97.8L (#25), and 175.0L (#45), were selected as demonstrative of a range of typical container sizes purchased in the landscape trade. Clonal selections of these trees grown using as similar inputs as possible were transplanted and monitored over the course of two growing seasons in a sandy clay loam (66% sand, 8% silt, 26% clay, 6.0 pH) field in College Station, TX (lat. 30˚37'45"N, long. 96˚20'34" W) beginning June 2013.

3.1.1 Initial Costs

In order to analyze the cost of the various sizes of the containerized trees, data were collected from 185 different nurseries located across 21 states. Nurseries were contacted and requested for wholesale prices of all container sizes available in *Acer rubrum* 'Summer Red' or 'Red Sunset', *Taxodium distichum*, and *Vitex agnus-castus* 'Shoals Creek'. Although not all nurseries carried all sizes of each species, data from a minimum of twelve nurseries were acquired for each species and container size combination.

Labor and installation costs are included in analyzing the initial cost of a tree. RSMeans is the industry standard source for accurate and expert information on materials, labor, and construction costs (Reed Business Information, Norcross, GA). RSMeans has been adopted over time as the industry standard, thus labor and materials costs were determined utilizing this information. Labor and installation both by hand and using machinery were compiled for each container size from the RSMeans data. Additionally, twelve companies for each container size were contacted and asked to contribute their installation costs to corroborate the data from RSMeans benchmarks.

Finally, maintenance costs were determined by using maintenance records during the two growing seasons for each container size and species. These records were then compared to RSMeans for projected maintenance costs per container size over time.

Maintenance included such practices as fertilizing, weeding, pest control, pruning, and watering.

3.1.2 Equivalent Costs

To determine the equivalent costs at the end of two growing seasons, data were collected from the locally grown trees after two growing seasons. Final height and caliper in October 2014 were utilized to determine ANSIZ60.1 (American Association of Nurseryman, 2004) container size approximations. Utilizing the ending container sizes, prices were designated from the mean prices obtained from wholesale growers. Additionally, cost of installation and maintenance were extrapolated for the ending container size of each tree. By subtracting the ending container size collective costs from the beginning container size collective costs it was possible to see a net gain or loss in value over two growing seasons.

Data were analyzed using statistical software (JMP 2009 and SAS 9.3, SAS Institute Inc., Cary, NC) using ANOVA to determine the significance of interactions and main effects for each species independently. Where interactions were significant, Student's t-test was used to compute individual pairwise comparisons between initial and ending values. When significant effects were found, a paired t-test comparison was used to indicate values that are significantly different ($P \leq 0.05$).

3.2 Results and Discussion

3.2.1 Initial Costs

Prices for a range of commercial container production were obtained. Similar price trends existed for all three species (Fig 3.1). Costs begin close to zero for the #1 container-grown trees and then slowly increase in price until the #15 container-grown trees. Immediately after reaching the #15 container-grown tree stage, the wholesale price per tree increases at a much greater rate. While *V. agnus-castus* is slightly less expensive in the smaller container-grown trees, it becomes much more expensive in the larger container-grown trees than the other two species. The change in slope at the #15 point would indicate that #15 is the price point at which nursery growers must increase the prices at a higher rate to offset extra supplies, labor, and inventory carrying costs required to maintain larger container sizes. Similar trends are observed with the costs to transplant each container-grown tree (Fig. 3.2). The cost to transplant increases gradually with each container size. The #15 container size trees indicate another breaking point as the cost to transplant by hand is more cost-efficient than by machinery until this point. In the following #25 and #45 trees, machinery would be necessary to efficiently transplant these trees. Additionally, the #45 container trees are eight times more expensive to transplant than #1 container trees.

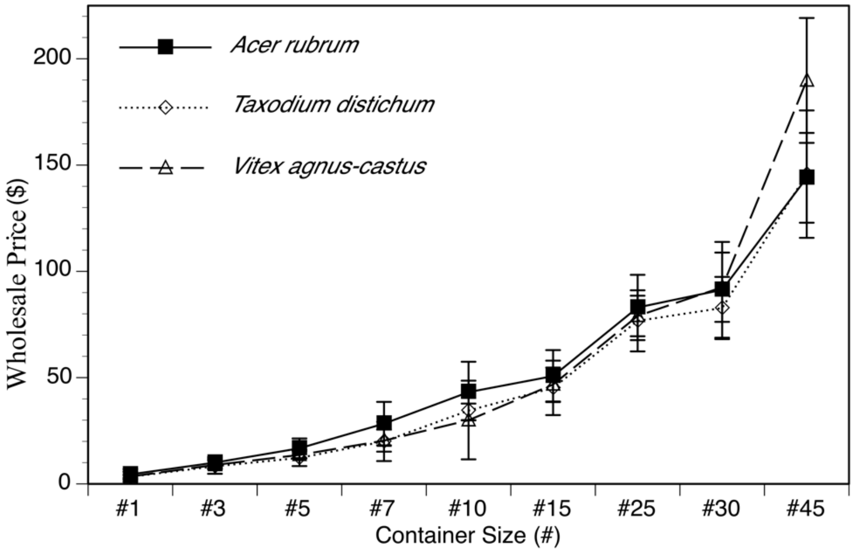

Fig. 3.1. Mean wholesale prices of container sizes for three tree species (*A. rubrum*, *T. distichum*, and *V. agnus-castus*) in 2013 where n≥12.

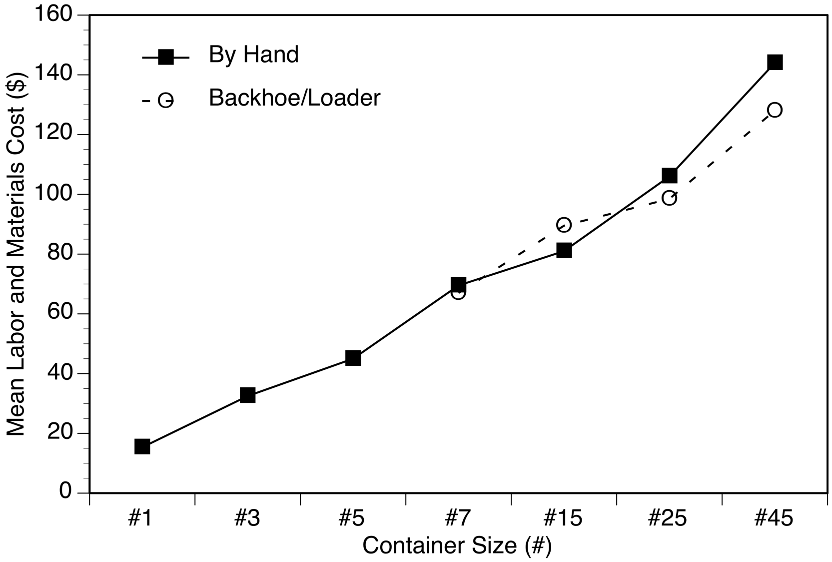

Fig. 3.2. Mean labor and materials cost for installation of various container sizes in 2013 (excluding wholesale cost of tree).

The maintenance costs for each container size were determined using general practices tree owners would implement during a normal year. This included fertilization, pest control, weeding, pruning, and watering. Fertilization, pest control, and weeding remained constant across all container size trees (Fig 3.3). However, the cost of pruning increases exponentially indicating that larger container size trees require greater input to maintain pruning. Finally, watering costs are relatively similar across all container sizes; however, a slight increase can be found in the watering costs of larger container sizes. Despite the larger numbers of liters applied to larger container-grown trees, the current low cost of water mitigates the impact of this difference. If in future years the cost of water increases, more substantial differences in cost of watering different container-grown trees would become apparent.

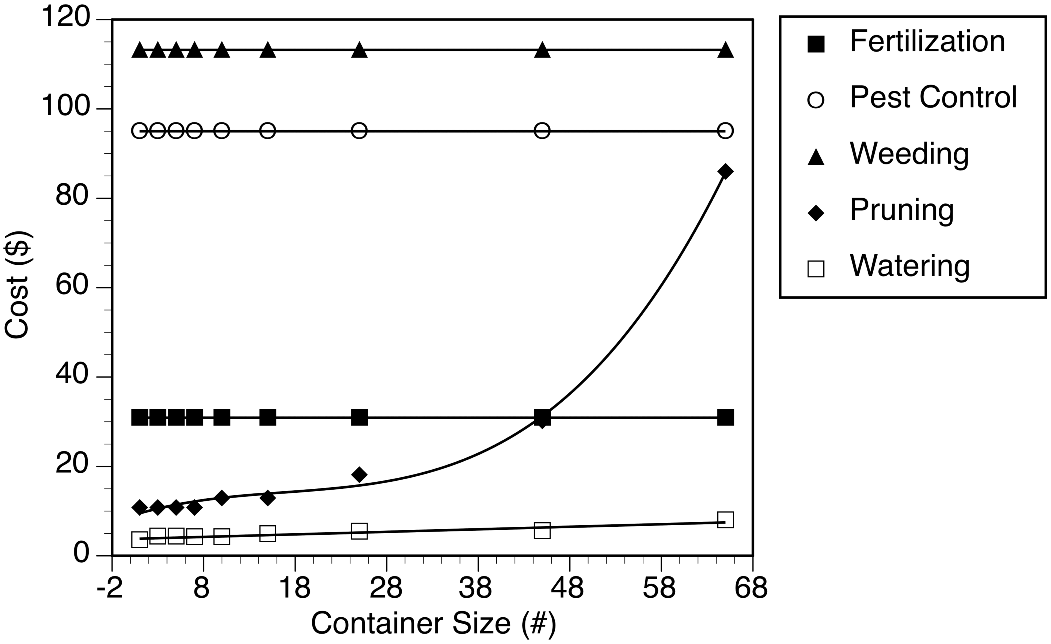

Fig. 3.3. Mean maintenance costs of various container sizes for three tree species (*A. rubrum*, *T. distichum*, and *V. agnus-castus*) over a two year period when looking at fertilization, pest control, weeding, pruning, and watering.

3.2.2 Equivalent Costs

In order to predict the ending value of each tree, height and caliper of each tree at the end of the second growing season were compared to ANSIZ60.1 (American Association of Nurseryman, 2004). Given the different growth rates of the three species of tested trees, the value varies dependent on species.

Greatest container size changes for *A. rubrum* occurred in the #3 and #7 container size trees which ended the second growing season at a mean #15 and #20 container-grown tree, respectively (Fig. 3.4). In the meantime, #25 and #45 container-grown trees ended with very little change from their initial container sizes. Both #25 and #45 container-grown *A. rubrum* ended the second season with only one of the six repetitions increasing their equivalent container size.

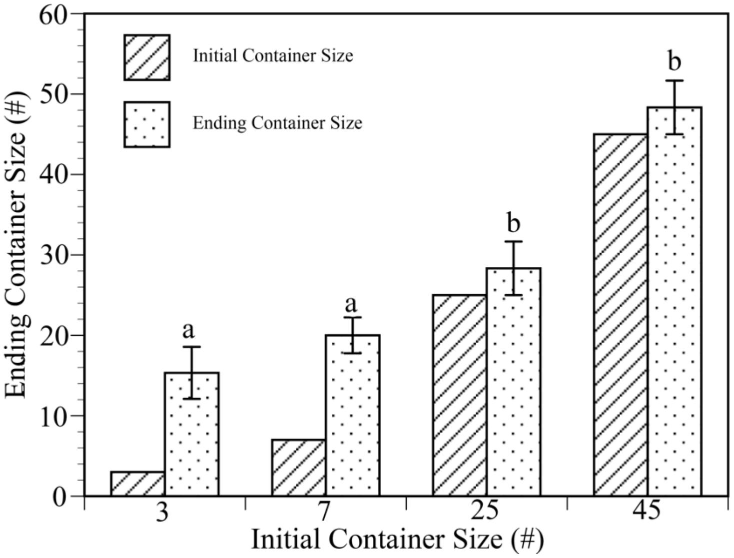

Fig. 3.4. Equivalent mean container size of *Acer rubrum* from transplant to end of second growing season for #3, #7, #25, and #45 container-grown trees; n = 6. Means of ending container sizes topped by the same letter are not significantly different at $P \leq 0.05$.

These equivalent container sizes were then used to predict the gain or loss for the two growing seasons. The price of the tree at planting was compared against the price equivalent of the tree at the end of the second growing season (Fig. 3.5A). The #3 and #7 container-grown trees had the greatest increase in price while the #25 barely increased and #45 had no increase in price equivalent. Analyzing the cost to install the initial container size versus the cost to install the ending container size after two growing seasons also indicated that while the costs are low for the smaller container sizes, it was also more cost efficient to plant the smaller container sizes (Fig. 3.5B). Finally, maintenance costs increased across container sizes for the two growing years; however if the ending equivalent container size had been initially transplanted, a slight increase in savings can be seen in the smaller container sizes while there is minimal change in the larger container size trees (#25 and #45) (Fig. 3.5C). This information allowed analysis of the overall value of the tree. The value of the tree increased the most in the smaller container sizes for *A. rubrum*, yet the ending value was still not equal to the value of the #45 container-grown trees (Fig. 3.5D). Therefore, while overall gains are largest in #3 and #7 container-grown tree (Fig. 3.5E.), initially transplanted #45 trees still maintain the greatest overall value after two growing seasons. Trends over longer time frames are unknown.

The stress and initial growth rates of *A. rubrum* greatly influenced ending gallon sizes at the end of the two growing season study. The increased container sizes ultimately increased the wholesale cost of the equivalent tree, the cost of labor, and the cost of maintenance. Therefore, overall value of the tree was increased, although the final value of the smaller container sizes did not catch up to or surpass that of the larger container sizes for *A. rubrum*. However, the gain or loss trees from each container helps to present the overall picture. Smaller container-grown *A. rubrum* produce a greater gain for homeowners over a two growing season time frame after transplant to the landscape than did trees from larger container sizes.

For *T. distichum*, the greatest container size changes occurred in the #3 and #7 container size trees which ended the second growing season at a mean size of #11 and #22 container-grown trees (Fig. 3.6). In the meantime, #1, #25, and #45 container-grown *T. distichum* ended with very little change from their initial container sizes. The #25 container-grown *T. distichum* ended the second season with only one of the six repetitions increasing their equivalent container size and #45 trees did not have any increase in container size equivalents. One of the six #1 container-grown trees in *Taxodium distichum* died during the two years, which was calculated as a #0 container tree, likely decreasing the mean equivalent of the remaining container sizes. Mortality was greater in the #1 container-grown trees most likely due to their small size, which exposed them to more drift of salinity in the irrigation water from the mini-spray-stakes used during irrigation.

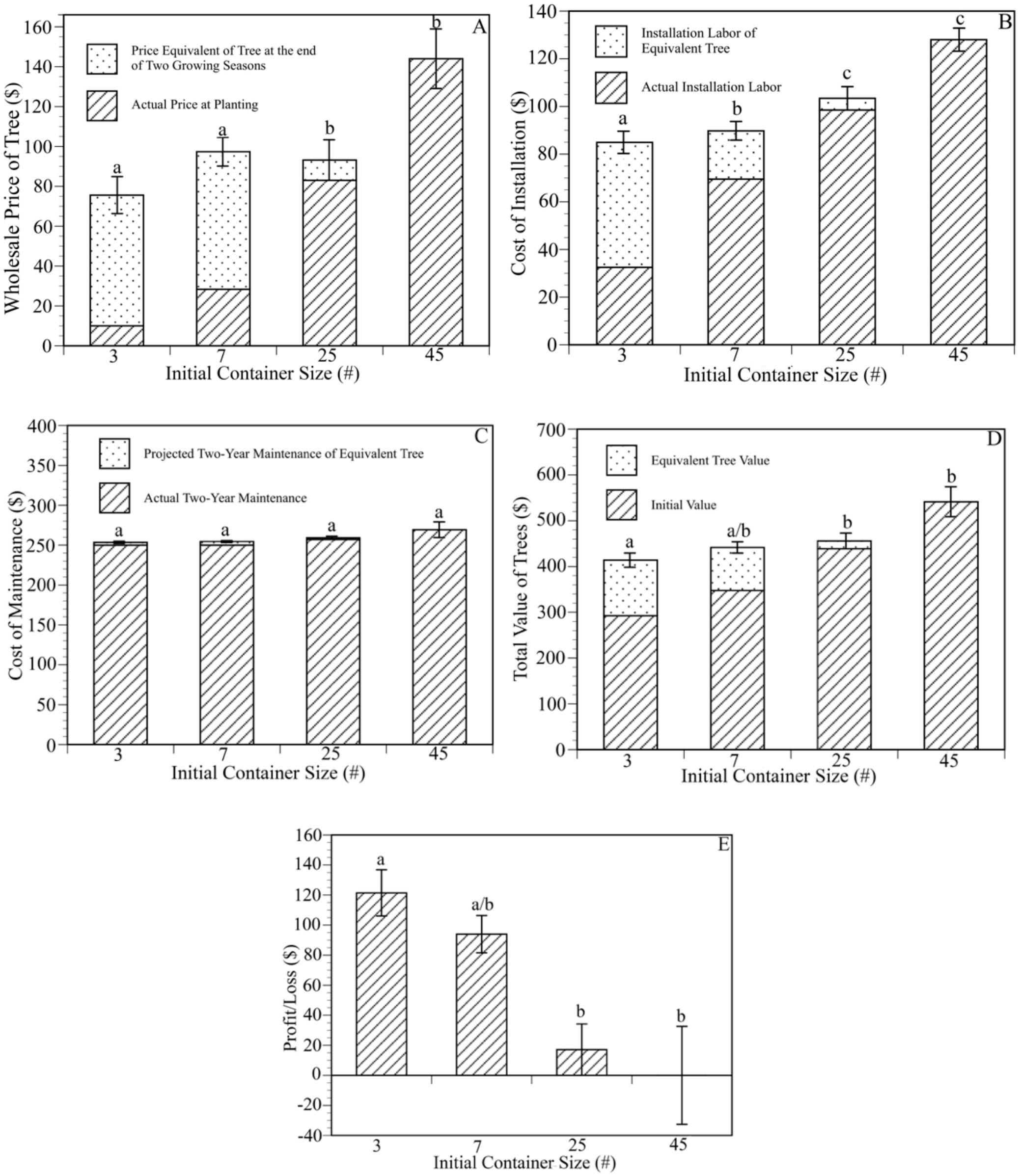

Fig. 3.5A. Mean change in wholesale cost of *Acer rubrum* from transplant to the end of the second growing season for #3, #7, #25, and #45 container-grown trees. B. Mean change in of *Acer rubrum* of installation from transplant till the end of the second growing season for #3, #7, #25, and #45 container-grown trees. C. Mean change in maintenance costs of *Acer rubrum* from transplant till the end of the second growing season for #3, #7, #25, and #45 container-grown trees. D. Mean change in value of *Acer rubrum* from transplant till the end of the second growing season for #3, #7, #25, and #45 container-grown trees. E. Mean gain or loss in dollars of *Acer rubrum* from transplant till the end of the second growing season for #3, #7, #25, and #45 container-grown trees. Means of ending container sizes topped by the same letter are not significantly different at $P \leq 0.05$.

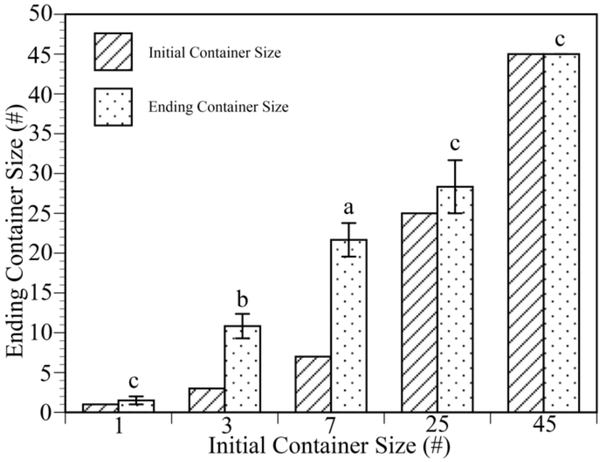

Fig. 3.6. Mean change in container size equivalents of *Taxodium distichum* from transplant to the end of the second growing season for #1, #3, #7, #25, and #45 container-grown trees. Means of ending container sizes topped by the same letter are not significantly different at *P*≤0.05.

These equivalent container sizes were then used to predict the gain or loss for the two growing seasons for *T. distichum*. The price of the tree at planting was compared against the price equivalent of the tree at the end of the second growing season. The #3 and #7 container-grown trees had the greatest increase in value while the #1 and #25 barely increased and #45 had no increase in price equivalent (Fig. 3.7.A). Despite these increases in cost equivalence, only the #3 container-grown trees resulted in price equivalence greater than the actual price at planting. The #45 container-grown trees remained the most costly to initially purchase, but retained the greatest cost equivalent at the end of the two growing seasons despite no increase in size equivalent. Analyzing the cost to install the initial container size versus the cost to install the ending container size after two growing seasons also indicated that while the costs are low for the smaller container sizes, it was also more cost efficient to plant the smaller container sizes as greatest savings on transplant costs occur in the #3 and #7 container-grown trees (Fig. 3.7.B). Finally, maintenance costs of *T. distichum* were relatively equal across container sizes for the two growing years; however, if the ending equivalent container size had been initially transplanted, a slight increase in savings can be seen in the #7 container-grown trees while there is minimal change in the remaining trees (Fig. 3.7.C). The summation of this information allowed analysis of the overall value of the tree. The value of the tree increased the most in the #3 and #7 container sizes for *T. distichum* (Fig. 3.7.D), yet the ending value was still not equal to the value of the larger trees transplanted from #45 containers. Therefore, while overall gains are largest in *T. distichum* from #3 and #7 containers (Fig. 3.7.E), initially transplanted #45 trees still maintain the greatest overall value. However, because the #45 container-grown trees did not increase in size, money put into maintenance over the two years was considered a loss, as it did not generate an output in increased growth. Similar losses are seen in the #1 and #25 container-grown trees.

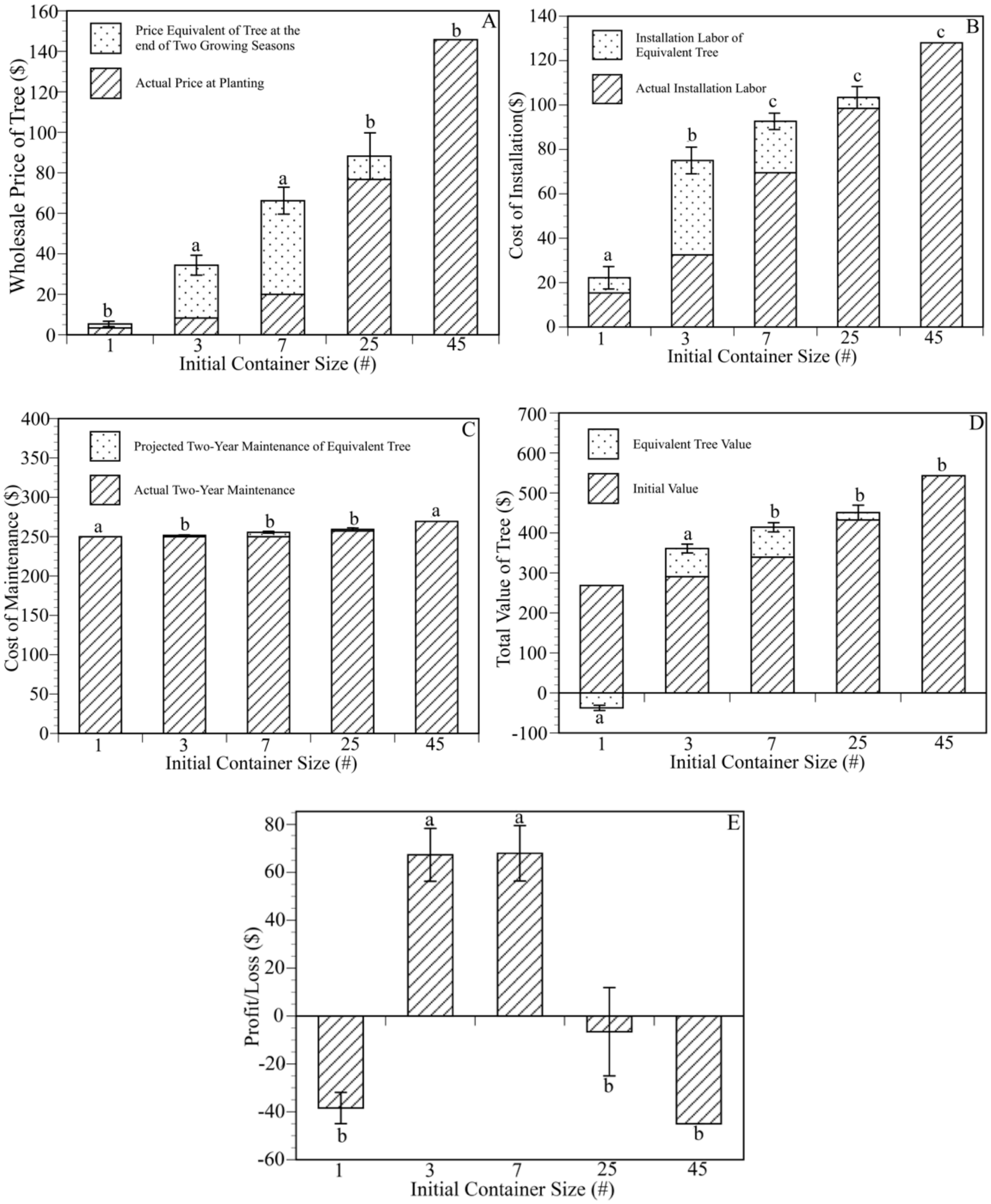

Fig. 3. 7. A. Mean change in wholesale cost of *Taxodium distichum* from transplant to the end of the second growing season for #1, #3, #7, #25, and #45 container-grown trees. B. Mean change in of installation of *Taxodium distichum* from transplant till the end of the second growing season for #1, #3, #7, #25, and #45 container-grown trees. C. Mean change in maintenance costs of *Taxodium distichum* from transplant till the end of the second growing season for #1, #3, #7, #25, and #45 container-grown trees. D. Mean change in value of *Taxodium distichum* from transplant till the end of the second growing season for #1, #3, #7, #25, and #45 container-grown trees. E. Mean gain or loss in dollars of *Taxodium distichum* from transplant till the end of the second growing season for #1, #3, #7, #25, and #45 container-grown trees. Means of ending container sizes topped by the same letter are not significantly different at $P \leq 0.05$.

Slow recovery and growth ultimately impacted the economic cost analysis. Ending gallon size equivalents of *T. distichum* was similar to initial gallon size for all container sizes. While greatest changes occurred in #3 and #7 container-grown trees, neither surpassed the #25 or #45 container-grown trees after two growing seasons. Similar findings were determined from the wholesale costs of trees, the labor necessary to install the trees, and maintenance. In the combined output of these measures, we see that the overall value of the tree increased for #3 and #7 container-grown trees as well as the gain over the two growing seasons. Losses in net value occurred in the remaining container-grown trees.

Greatest container size changes occurred in *V. agnus-castus*, with the #3 and #7 container size trees indicating they had the greatest increase in container size differences over the two growing seasons (Fig. 3.8). The initial #3 and #7 container-grown trees ended at mean #36 and #28 container size trees, respectively. In the interim, #1 and #25 container-grown trees ended with lesser changes from their initial container sizes and #45 increased the least. Ending container sizes were very close among the #3, #7, #25, and #45 container-grown trees.

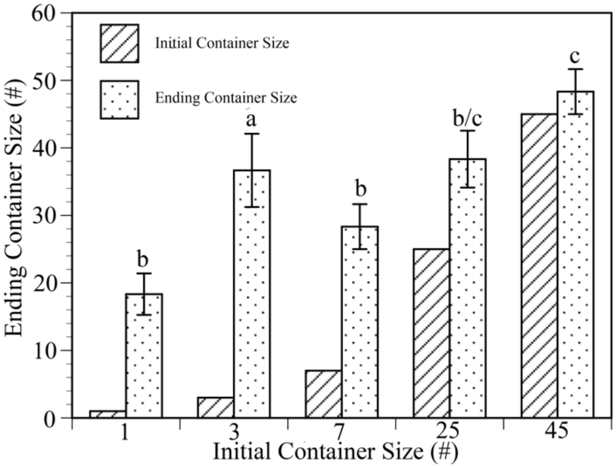

Fig. 3.8. Mean change in container size of *Vitex agnus-castus* from transplant to the end of the second growing season for #1, #3, #7, #25, and #45 container-grown trees. Means of ending container sizes topped by the same letter are not significantly different at $P \leq 0.05$.

Gains or losses for the two growing seasons were then projected from the obtained container sizes. The price of the tree at planting was compared against the price equivalent of the tree at the end of the second growing season. The *V. agnus-castus* from #3 containers had the greatest increase in price while the #1, #7, and #25 container-grown trees had similar increases (Fig. 3.9.A). Overall, #3 and #25 container trees had similar ending values for final container sizes, but #3 container trees would save homeowners the most money from transplant given the higher initial purchasing and planting costs of the #25 container trees. The #45 container-grown trees had no increased value for the price equivalent value of the ending tree. Analyzing the cost to install the initial container size versus the cost to install the ending container size after two growing seasons also indicated that while the initial costs of trees were low for #1, #3, and #7 container-grown trees, it was also more cost efficient to plant the smaller container sizes in terms of installation costs (Fig. 3.9.B). Maintenance costs were substantial across container sizes for the two growing years. However if the ending equivalent container size had been initially transplanted, a slight increase in savings can be seen in the #3, #7, and #25 container-grown *V. agnus-castus* while there is minimal change in the #1 and #45 container size trees (Fig. 3.9.C). This information allowed analysis of the overall value of the tree. The overall value of the tree increased the most in the smaller container sizes for *V. agnus-castus*, with ending values of #3 and #25 very close to that of the #45 (Fig. 3.9.D). The #1 and #7 container-grown trees end above the initial value of the #25 container-grown trees. A slight decrease in value of the #45 container-grown trees occurred after two growing seasons. For *V. agnus-castus*, ending values of #3 container-grown trees actually surpassed that of those from #45 containers, reflective of the high gains that #3 container-grown trees produced (Fig. 3.9.E). Gains were positive in transplanted #3, #7, and #25 container-grown trees, with a slight loss in #45 container-grown trees after two growing seasons in the landscape.

Greatest changes in economic cost analysis also occurred in *V. agnus-castus*. Overall increase in ending gallon size was pronounced for #1, #3, and #7 container-grown trees, with increases occurring in all but some of the trees from the #45 containers. This was reflected in the wholesale cost of the tree, installation costs, and maintenance with #25 showing changes similar to the smaller container sizes in many cases. Value increases occurred in the #1, #3, #7, and #25 with #3 or #7 demonstrating the greatest increases in value and overall gain across the three species and under the tested conditions.

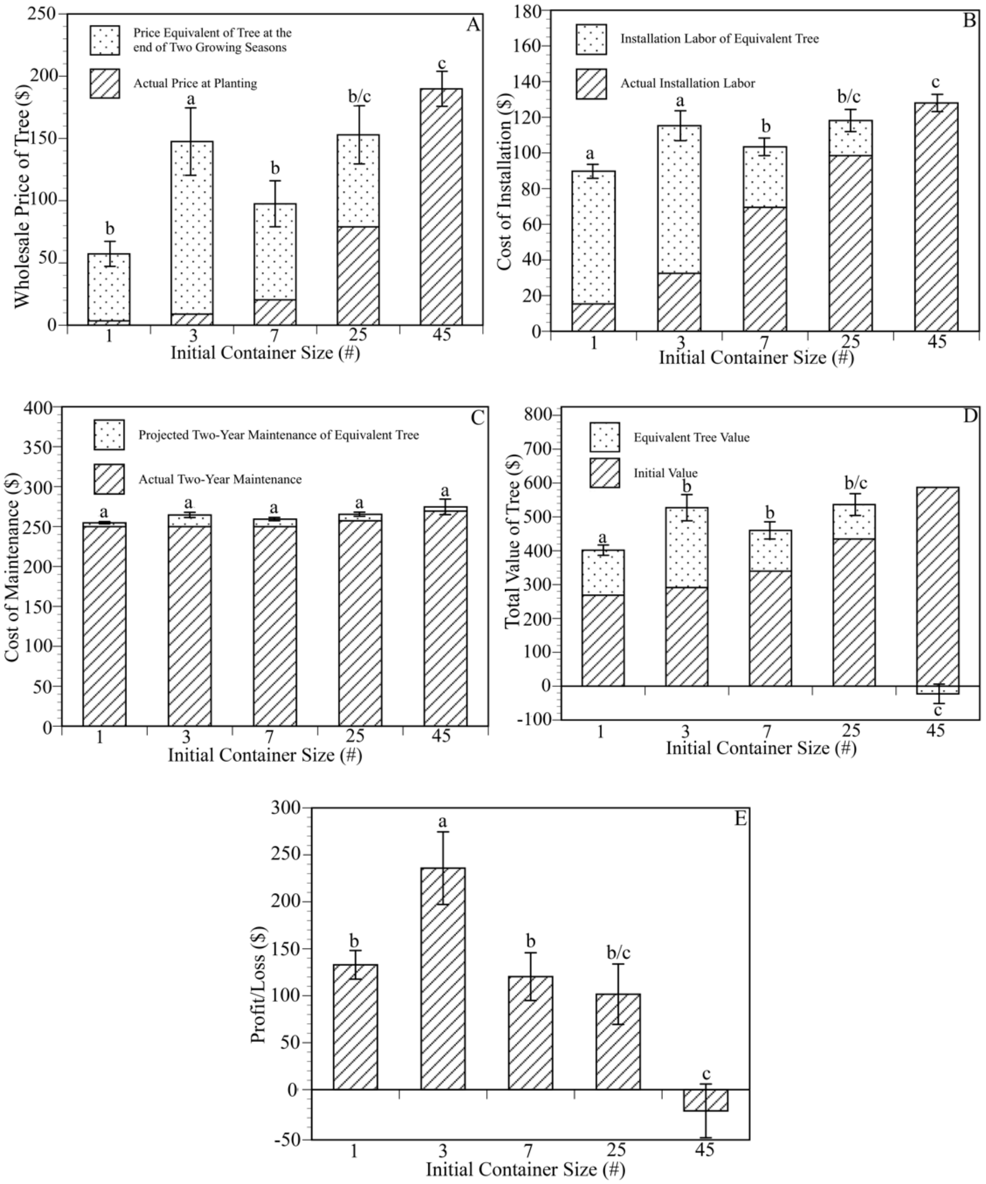

Fig. 3. 9. A. Mean change in wholesale cost of *Vitex agnus-castus* from transplant to the end of the second growing season for #1, #3, #7, #25, and #45 container-grown trees. B. Mean change in of installation of *Vitex agnus-castus* from transplant till the end of the second growing season for #1, #3, #7, #25, and #45 container-grown trees. C. Mean change in maintenance costs of *Vitex agnus-castus* from transplant till the end of the second growing season for #1, #3, #7, #25, and #45 container-grown trees. D. Mean change in value of *Vitex agnus-castus* from transplant till the end of the second growing season for #1, #3, #7, #25, and #45 container-grown trees. E. Mean gain or loss in dollars of *Vitex agnus-castus* from transplant till the end of the second growing season for #1, #3, #7, #25, and #45 container-grown trees. Means of ending container sizes topped by the same letter are not significantly different at $P \leq 0.05$.

CHAPTER IV

CONCLUSION

Nurseries over the years have produced trees in larger and larger container sizes (Arnold, 2004; Watson, 2004), and even large box stores, such as Walmart, Lowe's, and Home Depot, now sell trees in up to 100 gallon containers. While debate continues over the relative merits of different container sizes (Watson, 2004), the benefits and costs of varying container sizes had yet to be fully evaluated to determine which container size affords the most advantageous opportunity for consumers. With trees being offered to the public in an ever-increasing array of sizes, it is important to determine the requirements for successful establishment of differing size stock and the trade-offs associated with initial size and establishment requirements in terms of growth and costs.

The establishment period of a plant is of utmost importance to determining vitality, growth rates, and maintenance needs in the landscape. There are several measures of plant establishment: re-establishment of growth (Watson, 1985; Gilman, 1997), 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). It is often generally accepted that smaller size planting stock establishes more quickly after transplanting than larger stock (Gilman et al., 2010; Lambert et al., 2010; Struve, 2009), but formal studies are limited. The value of a tree, defined as its monetary worth, is based on people's perception of the tree (Cullen, 2000). Arborists use several methods to develop a fair and reasonable estimate of the value of individual trees (Council of Tree & Landscape Appraisers, 2000; Cullen, 2005; Watson, 2002).

The objective of this thesis was to identify initial stresses expressed by three taxa from various container sizes during landscape establishment and the recovery and resumed growth exhibited by each of the taxa in each container size. Furthermore, this thesis looked to determine the initial and replacement cost values of five different container sizes in each of the three tree species at transplant and after two growing seasons in the landscape.

Effects across container sizes between taxa were not analyzed as each species constituted a separate, but concurrent experiment. *Acer rubrum*, across all four container sizes, exhibited transplant stress reactions during the first growing season based on water stresses, stomatal conductance, and photosynthetic rates. However, in the second growing season, #3 and #7 container trees resumed regular activity and growth. The *A. rubrum* trees from #25 containers appeared to be near establishment while the #45 still exhibits signs of lingering transplant stress. *Acer rubrum* transplanted from #3 and #7 containers additionally displayed large increases in trunk diameter, ending at half the trunk diameter of the #45 container-grown trees. Height was increased by a greater percent in the trees from #3 and #7 containers than those from larger containers. Finally, it was found that smaller container size (#3 and #7) trees extended their root systems a further distance, proportionally, than did the larger container sizes. This root extension could explain the greater growth rates and decreased stress rates found in the transplanted smaller container-grown trees. The stress and initial growth of the *A.*

rubrum greatly influenced ending gallon size equivalents by the end of the two growing season study. The increased container size equivalents ultimately increased the wholesale cost of the equivalent tree, the cost of labor, and the cost of maintenance. Therefore, overall value of *A. rubrum* was increased, although the final value of the smaller container sizes did not surpass that of the larger container sizes during the two growing seasons following transplant. However, the gain or loss each container size experienced helps to present the overall picture. Smaller container-grown *A. rubrum* produce a greater return on investment for homeowners over a two growing season time frame.

Taxodium distichum, across all five container sizes, exhibited transplant stress responses during the first growing season based on water stress, stomatal conductance, and photosynthetic rates. However, in the second growing season, while #3 container trees resumed regular activity and growth, none of the *T. distichum* appeared to be fully established. Given their slower rate of growth, this could explain delayed establishment and growth. Trunk diameters still increased by a larger amount in #3 container-grown trees, but were relatively low across all container sizes. Similar observations were found with the height of *T. distichum* from each container size as both #1 and #3 container-grown trees increased height by over 100% of their initial transplant size after the second growing season. As with *A. rubrum*, the growth and stress reactions of the trees can be explained by the root growth. While trees from #3 and #7 containers increased their root growth by large percentages, there remained apparent size differentials still identifiable among trees from the various container sizes. This slow recovery and growth ultimately impacted the economic cost analysis. Ending gallon size of trees was similar to the initial gallon size for all container sizes. While greatest changes occurred in #3 and #7 container-grown *T. distichum*, neither surpassed the trees from #25 or #45 containers grown trees. Similar findings were determined from the wholesale costs of trees, the labor necessary to install the trees, and maintenance costs. In the combined output of these measures, we see that the overall value of *T. distichum* increased for trees transplanted from #3 and #7 containers as well as the gain over the two growing seasons. Net loss occurred in the remaining sizes of container-grown *T. distichum*.

Vitex agnus-castus is a reportedly fast-growing tree (Welch, 2008), which could explain why, across all five container sizes, mild transplant stress responses occurred during the first growing season. In the second growing season, all *V. agnus-castus* from all container sizes resumed regular activity and growth. Given the growth of the trees and their stress measures during the second growing season, it would appear all container sizes of *V. agnus-castus* were established by the second growing season. However, #1 and #3 trees showed faster recovery resulting in a period of time in which they were able to "catch up" to the #7, #25, and #45 container-grown trees. This "catch up" occurred due to the large percent changes in trunk diameter and height. Additionally, the large percent change in root length during the first growing season helps to explain the reduced stress levels, quick establishment, and large percent change in shoot growth that occurred in *V. agnus-castus*. Greatest changes in economic cost analysis also occurred in *V. agnus-castus*. Overall increase in ending gallon size was pronounced for #1, #3, and #7 container-grown trees, with increases occurring however in all container sizes. This was reflected in the wholesale costs of the trees, installation costs, and maintenance, with trees from #25 containers showing changes similar to the smaller container sizes. Value increases occurred in the #1, #3, #7, and #25, with trees from #3 containers demonstrating the greatest increase in value and overall gain.

All three taxa ultimately underwent less stress and recovered according to stress measures quicker in the smaller container sizes. The #1 container-grown trees are an exception as it appeared this size stock was too susceptible to changes in the environment, perhaps due to the much smaller initial biomasses (Tables 2.1, 2.7, and 2.12), as well as susceptibility to salt damage from irrigation and herbivory. In all three taxa, the #3 container-grown trees outperformed the remaining container sizes in most measures of growth and experienced quicker recovery in physiological stress measures. The large percent changes in trunk diameter, height, and root length across all three taxa indicates potential ability of #3 container-grown trees to outperform and overcome initial differences compared to larger container size trees within a relatively short period of time. Paired with the economic cost analysis, #3 container-grown trees consistently increase in value and provide economic gains for the owner. In contrast, the #45 container-grown trees consistently demonstrated higher stress levels, lower relative growth rates, and minimal increases in value over the two years of the experiments. The #45 container-grown trees, in fact, often produced no gain or even losses for the owner and rarely increased in size beyond their initial #45 container equivalents.

It would be the recommendation at the end of this study based on economic returns for smaller container-grown trees larger than #1 container-grown trees but less than #45 container-grown trees to be transplanted. The greatest relative returns occurred at the #3 container size trees, but benefits can be derived from the #7 and #25 container-grown trees as well. The advantages of trees from #25 and #45 were for immediate impacts of size in the landscape, but if clientele are willing to wait a few years for the desired landscape effects the smaller size materials are likely more cost effective.

NOMENCLATURE

ANSI	American National Standards Institute
Arn.	George Arnott Walker
Hook.	William Hooker
IBA	Indole-3-Butyric Acid
L.	Carl Linnaeus
LWP	Leaf Water Potential
NAA	Naphthalene Acetic Acid
Nutt.	Thomas Nuttall
Rich.	Achille Richard
Sarg.	Charles Sprague Sargent
SAS	Statistical Analysis System

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