DISSERTATION

CONTAINER TYPE AFFECTS NURSERY PRODUCTION, LANDSCAPE ESTABLISHMENT AND IRRIGATION REQUIREMENTS OF WOODY PLANTS

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ABSTRACT

CONTAINER TYPE AFFECTS NURSERY PRODUCTION, LANDSCAPE ESTABLISHMENT AND IRRIGATION REQUIREMENTS OF WOODY PLANTS

The black plastic (BP) pot is the container most used for nursery tree and shrub production. While there are many advantages to producing woody plants in BP containers, a major disadvantage to their use is that circling, girdling and matted roots often form during production and high substrate temperatures can injure or kill roots. The compromised root systems of BP-grown plants can lead to short- and long-term problems following planting in the landscape. We compared the growth of *Pyrus calleryana* Decene. 'Glen's Form' (Chanticleer®) in three container types: black plastic, Root Pouch® (RP) and Smart Pot® (SP), in the nursery over two growing seasons and under two overwintering treatments (consolidated or lined out), and planted into the landscape for three growing seasons. After the first growing season in the nursery, there were no differences in height or dry leaf, shoot and root weight among the three containers. Following the second growing season, caliper, height, leaf area and root ball quality differed among container type were significantly greater for plants grown in the two fabric containers. After the 2010-2011 winter, consolidated trees produced larger root and shoot systems (35.3% and 36.4%, respectively) than trees that were lined out. Substrate temperature maxima and fluctuations during winter and summer were greatest for BP containers compared to RP and SP. After nursery-grown trees were transplanted into the landscape, we found no container effects on above-ground growth one, two and three years following transplant into the landscape. All trees, regardless of container type, doubled their root dry weight annually over the three-year study. We found no significant container effects for any measured root parameters one year after planting. However, two and three years following planting we found a greater percentage of total root growth beyond the original root ball for trees grown in RP and SP containers. Three years after planting, trees grown in BP containers had significantly more fine roots growing within the original root ball compared to RP- and SP-grown trees. There were no significant differences among container type for leaf water potential one and two years following planting. In a four week greenhouse study, BP containers lost half as much water as the fabric containers. Water loss from the two fabric containers was significantly more rapid than that of the BP containers during the first 11 days, with more gradual water loss occurring thereafter. Total potential evapotranspiration (PET) for fabric containers containing established *Viburnum trilobum* was greater than that of BP-grown plants. When irrigated at 75% of black plastic PET (BP-PET), the cumulative ET for RP-grown plants over a two weeks period was significantly lower than that of BP or SP; at 50% of BP-PET, there were no container effects on ET. These results suggest that newly planted fabric containers (where water loss is mostly evaporative and not transpirational) may require greater irrigation needs than plants growing in BP containers. However, as plants in containers become more established and container water loss becomes more a combination of evaporation and transpiration, plants growing in fabric containers may have irrigation needs similar to or less than that of plants growing in BP containers.

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INTRODUCTION AND LITERATURE REVIEW

1.1. The Colorado Green Industry and Nursery Crops

The most recent survey from the United States Department of Agriculture stated that sales of nursery crops in 2007 topped $6.5 billion (USDA, 2007). The largest sectors of production included broadleaf evergreens (18%), deciduous shrubs (14%), deciduous shade trees (13%) and coniferous evergreens (12%) (USDA, 2007). The top states for nursery production, as measured by total gross sales, are California, Oregon and Florida; Colorado ranked 19th.

While Colorado may not be a leading nursery producer, the green industry, as a whole, accounted for $1.78 billion in direct sales in 2007 (Thilmany et al., 2008), compared to $147.8 billion nationally (Hall et al. 2002). This includes nursery and garden centers (retail and wholesale), golf courses, landscape architecture and landscape maintenance. Nursery and tree care sectors amount to $503.3 million annually in Colorado (Thilmany et al., 2008) ($36.4 billion nationally; Hall et al., 2002). Colorado is second (to Arizona) in total jobs created from green industry professions in the Mountain Region West, at 37,630 (Hall et al., 2002). While Colorado is not a large producer state, it does generate 30% of its revenue from exports (national and foreign), mostly from floriculture and greenhouse crops, as well as fruit and turf (Thilmany et al., 2008). While revenue and jobs have likely decreased since these surveys were conducted, due to drought and economic decline, it remains clear that the green industry has an enormous impact on the Colorado economy and those who benefit from these products and services. Relative to traditional agriculture, Colorado's green industry has been one of the most rapidly growing areas of agriculture in the past two decades (Thilmany et al., 2008), and also reflects trends nation-wide (Hall et al., 2002).

1.2. Nursery Production in Containers

Above-ground container nursery production makes up more than 75% of total nursery crop value in 17 of the top nursery producing states in the U.S. (USDA, 2008); it's estimated that 80-90% of woody plants produced in California, Florida and Texas are grown in containers (Davidson et al., 2000). Container tree production has been found to be an efficient and cost-effective way to grow ornamental trees and is used more than field production in many parts of the United States, especially in climates where subzero freezing temperatures are not a concern (Hodges et al., 2008). About 45% of deciduous shade tree commercial production in 2003 was produced in containers (United States Department of Agriculture, 2004). The difference between "container-grown" and "containerized" is that container-grown trees are grown in the container from a seedling, rooted cutting or graft to a saleable size; containerized stock refers to plants being grown in the field (soil) or possibly in grow-bags, and transplanted into a container for sale (Davidson et al., 2000).

Containerized nursery production began in earnest after World War II in southern California, using techniques often used in greenhouse production to produce plants quickly. With soldiers returning home to the United States, and the resulting Baby Boom, housing developments increased. Producing plants in containers proved an advantageous way to grow plants in a faster, more efficient way than traditional field production. Also, because transportation and shipping costs became more efficient, these plants could be produced in climates with more mild temperatures; containerized, actively growing plants were perceived by customers to be more likely to survive than dormant plants (Whitcomb, 2003). However, producing containerized plants in climates dissimilar to where they might be planted did have drawbacks—plants were often shipped during or after budbreak, which led to plant decline or failure from freeze injury and improper handling. Also, early container production used field soil (native site soil), which was not conducive to plant health or growth (Whitcomb, 2003). However, as production techniques improved and nursery growers became more knowledgeable, the initial problems associated with container production became less of an issue. Container production began to be researched and studied more intensively starting in the 1960s.

There are many advantages to woody plant container production, including ease of handling at the nursery, uniformity in plant growth, ease of shipping, consumer appeal, ability to produce more plants on less land, quicker turnover rate, intact root balls during production and a longer seasonal market for plant material (field-grown plants have a narrow window when they can be harvested and shipped) (Davidson et al., 2000; Gilman and Beeson, 1996; Harris and Gilman, 1991; Whitcomb, 2003). Container production can occur on fields that are unproductive, have drainage issues or are too sloped for field-grown nursery crops, though these sites are likely adjusted prior to planting. Container-grown plants do not need to be dug from the field, reducing labor and equipment costs, and plant root systems remain intact throughout the production process (Davidson, et al., 2000; Whitcomb, 1984). Many studies have compared field-grown (planted in the ground) trees to container-grown trees and found that containerized trees generally have better transplant success and less transplant shock issues (Gilman and Beeson, 1996; Harris and Gilman, 1991, 1993; Mathers et al., 2005). While early research solved some container production problems, efficiency in container production can be increased and some problems related to containerized plant production still exist.

Though the benefits may outweigh the drawbacks, there are numerous disadvantages to container production compared to field production. These include: costs of the growing substrate, container costs, increased fertilizer use, greater water requirement and labor (for potting and possibly overwintering materials). Circling and/or malformed roots, a common problem with container-grown plant material, can negatively impact plant health and stability both in the nursery and landscape after transplanting (Nichols and Alm, 1983). Another drawback is increased irrigation requirements, due to greater porosity of the container substrate (Davidson et al., 2000). Further, plastic containers used in container production add to landfill waste, as many containers are not reused or recycled. It was estimated that 408 million pounds of plastic (from containers, cell packs, greenhouse film and trays) are generated by the nursery and floriculture industries; of that, roughly 240 million pounds (58.8%) was plastic containers (Garthe and Kowal, 1993). Another negative is the winter protection needed for container crops in cold climates (Davidson et al., 2000).

While production of plants in containers has many facets, so does marketing of containerized or container-grown plants. For the grower, marketing advantages include less expensive shipping costs (due to lightweight potting medium), the extension of the growing and planting season, ease of care in the nursery (compared to balled-and-burlapped plants, which require heeling in with components like rock, soil or mulch to prevent drying of the root ball) and less potential for damage when handled (Davidson et al., 2000). Challenges include: potential for media to dry out more quickly, requiring additional labor to water more frequently and unattractive container material for customers (though some growers and nurseries have improved the look with colors and designs) (Davidson et al., 2000).

Nursery producers must maximize plant growth so that it minimizes production time, plant stress and remain profitable. One of the biggest challenges of container production is to keep the plant growing quickly in an environment where media, water, fertilizer and container volume may be limiting factors. Also, many states have very strict regulations on water quality, so the reduction or elimination of leaching water with added fertilizer or pesticide inputs must be minimal. Labor is one of the biggest expenses for container-produced plants; many facets to potting, transplant and initial irrigation are done by hand. If automation equipment is used, efficiency may double (Davidson et al., 2000). Moreover, fertilization, pruning and weeding may be done by hand.

Because plants potted in field soil often have poor growth from insufficient nutrients, low oxygen levels from clay soils and/or succumb to disease (such as *Phytophthora* and *Pythium*), the growing substrate used for container production is crucial. Growing media for container production should include the following desirable characteristics: high cation-exchange capacity (CEC), inexpensive, uniform in composition and lightweight (Mathers et al., 2007). Materials most commonly used for container media include pine bark and hardwood mulch, sand, compost and peat moss (Whitcomb, 1984). Desirable physical properties include high porosity and water holding capacity and low bulk density, but these are often less important than availability and cost of materials (Mathers et al., 2007). Container media tends to be light weight (to make handling easier and to reduce shipping costs) and well-drained, compared to native soils. Container plants are generally watered daily during the summer months in most parts of the U.S. As water resources become more limited and expensive, and water quality regulations become stricter and more widely enforced, the nursery industry must learn to use water more efficiently with environmental impacts in mind.

1.3. Container Overwintering

Woody plants grown or overwintered in containers often suffer winter injury and dieback more often when compared to trees and shrubs planted in the landscape. This is, in part, due to in-ground landscape plants having soil as a mass to insulate roots, which prevents fluctuating temperatures unlike those that above-ground container plants experience. In addition, plants covered with vegetation (like turf or groundcovers), mulch or snow will experience less severe temperature fluctuations due to the added insulating cover (Whitcomb, 2003). Above-ground portions of woody plant material can suffer from winter injury caused by desiccation, below-freezing temperatures, rapid freeze/thaw or other physiological and biological agents.

Container plants often experience many periods of freeze-thaw throughout the winter months if proper overwintering methods are not taken. Freeze/thaw periods in spring and fall may be most harmful to plants as they are either breaking dormancy (deacclimating) or acclimating to cold. In northern climates, these early fall or late spring freezes will often injure or kill plants, even though the plants could have endured temperatures far colder when established in the landscape and more acclimated for winter (Davidson et al., 2000). Winter injury on plant tissues may include bark splitting, dieback, reduced flowering and browning of evergreen tissues.

Standard overwintering treatments in USDA Zones 4-6 include consolidating containers pot-to-pot or tipping on their sides and then the containers may or may not be covered with straw and/or plastic. The overwintering technique used will depend upon on local climate and overall plant hardiness of those being overwintered. Overwintering may also include moving plants into a single or double-layer polyethylene (poly) quonset structures. These structures are usually unheated and poly does a poor job of trapping heat, especially in late afternoon (Mathers, 2003c), which would protect plants from cold nighttime temperatures. In these structures, temperature fluctuations are also an issue, since heat is trapped in the poly during the day when the sun is out. The amount of poly (one or two layers) does little to reduce temperature fluctuations (Chong and Desjardines, 1981), though some growers use two layers of poly with air trapped between them. A single layer of milky poly (not clear) can effectively reduce irradiation and minimize temperature fluctuations (Good et al., 1976). As springtime approaches, the poly is either cut to allow for venting (or doors are opened to vent the structure) or removed, depending on day and nighttime temperatures. If the poly is removed too quickly, this can cause freeze injury to expanding buds and plant cells. Gouin (1974) demonstrated how overwintering under poly coverings may compromise later plant health. Though the plants appeared identical following the winter, the plants overwintered in poly suffered from poor top growth the following season, compared to the plants that were overwintered outdoors in a consolidated group. Other issues with covering plant material or moving them into poly structures include chewing and girdling by rodents, as well as the expense of moving plants into overwintering locations.

Physiologically speaking, the hardiness of a plant generally refers to the winter "toughness" of its above-ground growth and the root system to some degree. For example, when a plant is labeled at Zone 4 (according to the USDA Zone Hardiness Map), it is the ability of the top of the plant to withstand freezing temperatures to -37.2 C. The tops of winter hardy plants are able acclimate themselves to tolerate cold winter temperatures when environmental triggers, such as shortened day length, cooling temperatures and lower light levels during the fall stimulate the cold acclimation process. Roots acclimate along with the shoots, but are far more susceptible to freezing temperatures and many cannot tolerate these cold temperatures. As mentioned above, when planted in the ground, soil helps insulate roots. When containers are overwintered above-ground, they have little protection (unless done by the nursery). In containers, both roots and shoots are exposed to temperature fluctuations. This is one of the reasons why many plants are grafted onto hardy rootstocks. The rootstock is selected because of its ability to withstand colder temperatures. One possible solution, as proposed by Neal (2009) is to consider overwintering containers using pot-in-pot production (PIP) systems, where a permanent pot is sunk in the ground, with another pot, containing the plant, is slipped inside. This has been proven to help buffer container root zone temperatures in both the southern United States and in northern United States. One downside is the amount of space required to install PIP systems and the use of land. Another is the cost of plastic containers used in PIP systems

Roots in containers, especially those grown in black plastic, may be located more towards the outside of the container due to restricted root growth. This means the roots are more directly impacted by temperature fluctuations. This is most severe on the south or southwest side of the container; in the summer roots may experience lethal temperatures resulting from the black plastic's absorption of heat (Whitcomb, 2006). In the winter, the same roots are killed due to freezing temperatures due to the fact they were compromised with supraoptimal summer temperatures. Roots of container-grown plants killed by fluctuating winter temperatures may result in stunted plant growth in the spring if many roots need to be regenerated (Whitcomb, 2006). The same goes in the winter—freezing temperatures can rupture root cells and cause death. It has been found that roots of most species (hardy to Zones 4-5) can tolerate temperatures in the range of -12 to -17 C. Havis (1976) found that lethal temperatures for secondary roots range from -5 to -23 C, while Studer et al. (1978) reported that killing temperatures for immature roots ranged from -3 to -11 C.

Roots killed by winter temperatures may not affect plant growth immediately (Whitcomb, 2006). When the top of a plant is killed or injured, the injury is readily apparent with blackened tissues, dry buds and lack of growth. When roots succumb to winter injury, plants may leaf-out and grow the following spring, until root death and the inability to absorb water and nutrients prevents further growth and the plant withers and eventually dies.

Certain woody plant tissues of plants are hardier than others (Bokazkiv, 1961). Plant cells found in stems, the xylem, parenchyma and pith (the living cells) tend to be less cold hardy than cells of the bark tissues (e.g. cambium, phloem, cortex and epidermis) (Potter, 1939). Proper fall acclimation is a critical step for ensuring winter survivial of winter hardy plant species, since actively growing cells exposed to sub-freezing temperatures can be killed immediately. Supercooling of tissues during the fall and winter is an essential contributor to winterhardiness. It prevents the formation of ice crystals in winter hardy plant tissue, maintaining water in a liquid phase between cells at subfreezing temperatures (extracellular freezing) (Wisniewski and Arora, 2000). Supercooling is only effective at temperatures above -40 C; at temperatures below -40 C, ice crystals will begin to form within supercooled plant cells (intracellular freezing), which leads to cell damage and death. Species displaying hardiness at temperatures lower than -40 C survive lower temperatures by excluding water from freezing-susceptible plant cells (dehydration) and simultaneously concentrating solutes (sugars, and other omolytes) in the remaining cell sap. The exported water forms ice crystals between plant cells, where it is less likely to damage or kill sensitive cells.

The environmental conditions that induce hardening in the fall are: decreasing day length, cooler day and nighttime temperatures and adequate moisture, among others. Weiser (1970) states that cold acclimation occurs in three stages. The first stage is triggered by shortened day length (photoperiod); the second by the onset of lower temperatures in the fall; and the third stage is reached after exposure to prolonged low temperatures. Hughes and Dunn (1990) also found that some physiological changes include increased sugar concentrations, desaturated lipids, organic acids, proline and some soluble proteins. Scagel et al. (2010) found that trees which exported nitrogen and imported carbon (as carbohydrates) into stems were more low temperature tolerant than those just importing nitrogen into new stems (due to higher N fertility). They also found that trees without added N fertilizer had no change in carbon and nitrogen values in roots, which led to better cold hardiness, compared to fertilized trees that had higher amounts of nitrogen and carbon in roots.

When plants are fully acclimated, some living bark tissues can withstand temperatures to -196 C, if the freezing rate to -30 C is slow (Sakai, 1960; Krasavtsev, 1967). Fortunately, freezing doesn't occur that rapidly in nature, which is why properly acclimated winter hardy plants survive winter. However, occasional injury from rapidly freezing of cells can occur, of which sunscald and winter browning of evergreens are examples. The rapid freezing (8 to 10 C per minute) can contribute to sunscald which can occur in winter (White and Weiser, 1964).

Weiser (1970) questioned if it was really the lack of tolerance to freezing temperatures that contributes to winterkill of trees, or if it was the inability of plants to properly acclimate in time to withstand the cold temperatures. This is why selecting species (or clones) proven to be winter hardy is so important when planting woody plants in cold climates. For example, it would be more prudent to plant redbuds selected and grown in a northern climate, rather than one selected in and/or grown in a southern climate. Even the most winter hardy species/cultivars require a period of short days, and warm day temperatures and cool night temperatures, followed by prolonged period of low temperatures to induce optimal winter acclimation (Weiser 1970). It has also been proposed that abscisic acid (ABA) can influence freezing tolerance in woody plants, but the possible role of this hormone in the acclimation process is still not fully understood. It was found that ABA levels in woody plants were significantly higher in buds of aspen when measured during long days versus short days (Welling et al., 2002), suggesting that photoperiod and temperatures regulate ABA levels differently.

Nitrogen and irrigation may also affect overwintering potential of plants. If high amounts of nitrogen are applied to plants when actively growing in late summer and fall, the general response of the plant is to push new growth. This leads to the question of the possibility that fall fertilization of lawns (where trees are often planted) and/or fall tree fertilization can negatively affect the acclimation process of trees, an area that warrants additional research. Smiley and Shirazi (2003) found that no fall flushes of growth resulted after fall fertilizer was applied to five species of trees (not planted in turf), and found that hardiness of oak and maple was not affected. Though these researchers did have some treatments that had reduced cold hardiness, temperatures that killed tissues would not occur naturally (hardiness experiments on tissues were conducted in a lab, where temperatures decreased to -40 C). Studies done by Harris et al. (1999) found that fertilizer applied in late summer or early fall allows nutrients to be available to the tree when growth starts in spring; initial shoot growth in spring is dependent on the nutrients stored in the tree from the previous year. It is possible that fall-applied N is does not stimulate late-season growth because of the physiological processes that are occurring in the plant during the hardening process; the plant is storing carbohydrates for winter survival, and fertilization doesn’t appear to affect this process. Most new growth occurs in early spring, while second flushes occur in early summer.

However, the overall level of fertility may influence cold hardiness of woody plants. Research done by Scagel et al. (2010) found that green ash grown in containers with low nitrogen availability in the media became cold tolerant sooner than trees supplied higher amounts of fertilizer. Lower nitrogen levels also kept the trees hardy for longer periods than when trees were supplied with higher nitrogen levels. In addition, the type of slowly available fertilizer applied affected hardiness and dormancy. Trees fertilized with topdressed ureaformaldehyde maintained hardiness in the spring longer than those fertilized with a controlled release fertilizer containing ammonium sulfate (Scagel et al., 2010).

Water availability may also affect the acclimation process and ultimate winter hardiness level. Some studies have found that some level of drought stress in fall actually induced better freezing tolerance due to more favorable osmotic adjustment or adaptation (Levitt, 1980; Xiong et al., 1999). Many nurseries growing forest trees expose the seedlings to moderate water stress in fall at or near the end of their growth period (Kozlowski and Pallardy, 2002). Duryea and McClain (1984) found that subjecting the seedlings to moderate drought stress accelerated budset, induced early dormancy and increased cold hardiness. Irrigation adjustment was timed prior to the natural shortening of days in fall (Kozlowski and Pallardy, 2002). The thought is hardiness results because the water stress prevents the growth of normal late-season (non-hardened) shoot growth, which may be subjected to freeze injury (Kozlowski and Pallardy, 2002).

1.4. Container Effects on Plant Growth

The ideal container for nursery plants should possess the following characteristics: attractive appearance, structural strength, good insulation value, material should not be brittle or decompose rapidly, good durability during handling and shipping, promotes a healthy root system, efficient storage (nesting) potential, light in weight, provide good drainage, be long-lived and affordable, creates no hazard for customers during planting and an ease of disposal (sustainability) of product. It's important to remember that plants don't grow in containers naturally, so this environment is unnatural and different from field-grown or native conditions (Whitcomb, 2003).

The most common container used for nursery production is the black plastic container. While these containers tend to be inexpensive (though cost depends on current petroleum prices), they have benefits and drawbacks. Black plastic containers are lightweight, durable, familiar to growers, well-suited for mechanization and can be reused or recycled. These containers are made from many different plastic types, melted and remolded for the desired shape and size.

There are, however, numerous drawbacks to black plastic containers. First of all, the black color has been found to absorb solar radiation and increase substrate temperatures. Heat stress on containerized plant roots is a continual problem in the nursery industry. Woody plants prefer root temperatures between 15-27 C (Johnson and Ingram, 1984) and root growth is retarded at temperatures greater than 30 C (Mathers, 2003c). Research with container-grown plants concerning substrate temperatures exceeding 30 C have been observed; with root growth ceasing above 39

C (Johnson and Ingram, 1984; Mathers, 2003c). Other studies have observed substrate temperatures greater than 54 C (Ingram et al., 1989; Martin et al., 1989; Mathers, 2000); researchers documented decreased crop quality and/or death at these temperatures. Martin et al. (1989) found that *Ilex crenanta* (Japanese holly) roots died when subjected to temperatures of 51 C for as little as 30 minutes.

Heat stress on root growth affects whole plant function and production. Plants exposed to high root-zone temperatures may display a number of symptoms, including: leaf wilting, discoloration and drop, reduced flowering capacity, abnormal top growth and abnormal or disrupted photosynthesis, respiration, and nutrient uptake (Ingram et al., 1989). High root zone temperatures may promote disease and insect activity, resulting in plant injury and mortality (Ranney and Peet, 1994; Webber and Ross, 1995).

Wong et al. (1971) studied the effect of high substrate temperatures on five woody plant species. There was variability in responses among the species, with black locust root growth reduced by up to 75% when substrate temperature exceeded 35 C; rose and peach roots, except for the very thick upper trunk roots, were killed after a four-hour exposure to 45 C, while only the root tips of the other species (*Fouquieria splendens*, *Parkinsonia aculeate* and *Robinia pseudoacacia*) were killed. These researchers concluded that a single long-term duration (6 hours) of high temperatures was more damaging than several exposures (4 hours) at 45 C. Roots of all species were killed at 50 C.

Studies have examined alternative container colors (light-colored or white) and their potential to reflect solar radiation and eliminate heat stress in the nursery (Fretz, 1971; Harris, 1967; Ham et al., 1993; Ingram, 1981; Markham III et al., 2011; Whitcomb, 1980). Fretz (1971) found that light-colored containers were as much as 5.6 C cooler than dark-colored containers. Whitcomb (1980) found root zone temperatures to be 4-7 C cooler when plants were grown in white poly bags versus black plastic containers. In addition, plant height and stem diameter was greater for trees grown in white poly bags compared to black plastic containers (Whitcomb, 1980). Markham III et al. (2011) concluded that heat-sensitive plants will benefit being grown in white containers or painting the outside of the container white for improved root growth; their study found up to 2.5 times greater root density in white-colored containers. Ingram (1981) compared several woody plant species grown in polyethylene bags and conventional black plastic; the polyethylene bags had an white outer surface (black inner surface). Average maximum temperatures in the black plastic containers were found to be 6 C higher than in the bags. Root growth in the bags was three to four times greater than in black plastic containers, depending on species. Whitcomb (2003, 2006) found that trees grown with a reflective covering on the outside of the container or grown in cinder blocks not only reduced the root zone temperature, but may had reduced water use rates, since root zone temperatures were 11-14 C cooler.

It should be pointed out that specific plant species may respond differently to high root-zone substrate temperatures. Genetics and tolerance to heat and drought may affect relative sensitivity to supra-optimal substrate temperatures. Wilkins et al. (1995) evaluated several red maple genotypes for tolerance to high root-zone temperatures and found that there was great variation in tolerance to high temperatures among genotypes; some were sensitive, while others were unaffected. Another study found that redbud is relatively tolerant of high root-zone temperatures (Griffin et al., 2004).

High root zone temperatures may negatively affect biochemical processes in plants, leading to reduced growth and/or plant decline/death. Martin et al. (1989) found that supraoptimal substrate temperatures can greatly affect photosynthesis, carbon exchange rates, and stomatal conductance. Their study, which exposed plants to root zone temperatures of 42 C each day for six hours over a period of 12 weeks, found that high substrate soil temperatures caused photosynthetic rates to drop below the temperature compensation point, causing respiration to exceed photosynthetic rates. Growth of plants was stunted, plants suffered from early leaf drop, leaves were chlorotic and plants had a decreased root:shoot ratio. In another study Ranney and Peet (1994) similarly found that high root zone temperatures reduced photosynthetic levels, water and nutrient uptake, causing leaf wilt and stomatal closure.

Root growth in containers is also affected by the time of year and where plants are being produced (latitude). A Florida study found that roots in containers on the east and west sides had more damage in the summer because of the duration of exposure and intensity of the solar radiation (Ingram et al., 1989). The same study found that container roots on the south container side experienced higher temperatures; this infers that shading, depending on time of year is a measure nursery producers should consider. Research investigating root zone temperature differences between fiber (pulp) containers and black plastic found that high and low root zone temperatures were similar (Tauer and Cole, 2009). However another study with fiber pots suggested that they allowed for evaporative cooling of the root sides, likely reducing root zone temperatures (Ruter, 1999).

While the container itself and the color of the materials lead to increased root zone temperatures, it has been found that irrigation during the warmest parts of the day will reduce heat buildup in the containers (Martin et al., 1991). The application of just three liters of water can help mitigate lethal temperatures, when applied at mid-day (Martin et al., 1991). When growing in fabric containers, the evaporative cooling effect from the porous material may help dissipate heat more effectively compared to plastic containers (Tauer and Cole, 2009).

Fabric containers have been available to the industry for more than 20 years and there are several brands available (Cole et al., 1998). Fabric containers are available in many sizes and shapes, but growers do not appear to be convinced that the benefits outweigh the negatives, as plastic containers are still the most common type in the nursery industry. One advantage of fabric containers is the ability to continually "air prune" roots (Gilman et al., 2010a; James, 1987; Jones, 1987; Langlinais, 1987; Marshall and Gilman, 1998; Privett and Hummel, 1992; Reese, 1987). Due to the rigidity of the sidewalls, woody plants grown in plastic containers often have more circling roots on the outer periphery of the root ball, while fabric containers may allow for a "more natural" root system because of the effects of air root pruning. However, this effect depends on the length of time the plants are grown in the container. Roots deflected in plastic containers grow in many directions, including up, down or around the root ball; some roots may "kink" 180 degrees and go back the way they grew from, causing constrictions and circling roots (Gilman et al., 2010a). Research has found that fabric containers have fewer circling/girdling roots compared to those grown in other smooth-sided containers (Gilman, 2001; Marshall and Gilman, 1998). Similar findings were published on the shape of the container—plants grown in square plastic (Warren and Blazich, 1991) or wood (Marshall and Gilman, 1998) also resulted in fewer circling roots. Often the length of time the plant is grown in the container—the longer it is container-grown, the greater the chance for kinked or deformed roots (Gilman et al., 2010a). Alternatives to black plastic containers include those containers with air root pruning technology, specialty container shapes, containers without bottoms, woven or non-woven fabrics, containers incorporating chemical compounds, and containers which utilize mechanical deflection (Brass et al., 1996; Marler and Willis, 1996). Containers using chemical compounds, including copper hydroxide coating (Struve et al., 1994), have had varying effects on growth and root:shoot ratios (Arnold and Struve, 1989; Beeson and Newton, 1992; Martin and Bhattacharya, 1995). While producing plants with fewer deformed roots is the ultimate goal, effects on canopy and shoot growth must also be considered. One study found that pine trees grown in air-pruning containers had slower root and canopy growth (Ortega et al., 2006). Other studies found that alternative container types resulted in more or the same amount of roots for trees grown in standard black plastic (Arnold, 1996; Brass et al., 1996). Canopy and root growth were similar among various container types for five months (Marshall and Gilman, 1998) and five years after landscape planting (Fare, 2005). Long-term survival of trees planted into the landscape may be influenced by the container in which they are grown. Researchers Marler and Davies (1987) found that circling and/or kinked roots of citrus trees grown in containers resulted in uneven root development. Malformed roots that begin with container production can lead to later tree instability and possible failure (Lindstrom and Rune, 1999).

Research done by Gilman et al. (2010) grew ‘Florida Flame’ red maple in eight container types (all #3 in size), including various plastic, woven and non-woven types. Caliper and height was not different among the container types. Only trees grown in smooth-sided plastic containers had roots 100% circling around the outer periphery of the container, resulting in a lower root ball quality. The root balls which held together best were trees planted in the woven/fabric containers, though the fabric was difficult to remove from the root ball in some cases. All trees produced in the smooth-sided black plastic containers were graded as “culls” (non-saleable) according to the Florida Grades and Standards for Nursery Plants, because of the frequency and severity of the kinked and circling roots.

Many studies have found that there are few differences in above-ground growth among various container types (Marshall and Gilman, 1998; Owen and Stoven, 2008; Neal, 2009). However, O’Connor et al. (2013) found that height and caliper differences among fabric and black plastic container types occurred during the second growing season for callery pear, with trees grown in fabric containers being taller and possessing greater caliper.

The ratio of total root dry weight to total shoot dry weight is commonly referred to as root:shoot ratio and takes into account total plant biomass. Trees, grown under normal conditions, generally have a root:shoot ratio of 1:5 or 1:6 (Kramer, 1969; Perry, 1982). It is thought that any cultural practice that reduces the root:shoot ratio is negative, but a change in the relative weight of the roots and shoots may not be an accurate measure to the cultural changes (Harris, 1992). In fact, except for root injury, a reduction in root:shoot ratio is almost always the result of more favorable growing conditions; an increase in root:shoot ratio would infer that the tree may be under stress (Harris, 1992). Harris (1992) also suggests that a more useful comparison may be to compare root surface area to the transpiration leaf surface. Some factors affecting root:shoot ratio include plant species, growing environment, plant genetics and any cultural or management practices that affect growth. All of these factors, individually or in combination, will influence how a plant allocates resources (whether to shoot or root growth) (Reich, 2002). How these factors affect root:shoot ratio of container-grown nursery plants, compared to the same plant growing in a landscape, is unclear. While it is an easy measurement to make, root:shoot ratio may be less useful for research with container-grown plants.

Mechanical injury (by pruning, or damage by pests or environmental extremes) to either shoots or roots can affect root:shoot ratio. Coder (1998) states, “Trees will attempt to balance shoot mass and Ps (photosynthesis) rates against root mass and nitrogen uptake. A tree will adjust the mass of roots or shoots to correct any deficiency in photosynthesis rates or nitrogen uptake. Carbohydrate shortages will initiate more shoots and nitrogen shortages will initiate more roots.” The flux of root:shoot ratios differ during the tree’s life and are constantly being affected by age, growth and other factors, a “balance” of roots and shoots doesn’t exist—it simply changes based on the current conditions (Coder, 1998). Perhaps more important to consider than root:shoot ratio is root architecture (i.e. size, shape, surface area, and demography of lateral branches) (Pregitzer, 2008)). Root architecture is influenced by production and planting practices and has potential long-term effects on landscape establishment and growth. Tree root architecture differs among tree species and environmental conditions. Root architecture has important ecological applications since architecture reflects adaptability and function of the roots in an environment (Fitter, 1985). With regards to containerized plants, plastic containers often result in circling roots on the outer periphery of the container; these circling roots can continue to enlarge when transplanted into the landscape, which reduces lateral branching and anchorage.

Another root measurement perhaps deserving of greater scientific attention by tree researchers is the distinction between fine and coarse roots. Researchers differ in how they define “coarse” and “fine”, with some defining anything less than 0.5 mm as ”fine”, while others say that any root smaller than 2.0 mm in diameter is a fine root. Smaller diameter roots, depending on depth in the soil profile, exhibit 2.4 to 3.4 times greater root respiration rates than larger diameter roots (Pregitzer et al., 1998). Fine roots are known to be more important for water and nutrient absorption (Persson, 2002). The turnover rate (death and replacement of fine roots) is affected by environmental conditions, with trees in drier sites having a faster turnover rate than trees growing in wet or poorly drained sites (Persson, 2002). The biomass of fine roots is a significant portion of below-ground growth; fine roots are also a significant part of net primary production in native and managed ecosystems (Harris et al., 1977; Buyanovsky et al., 1987). Pregitzer et al. (2002) found that the fine root systems of woody plants are modular in nature, yet had similar demographic patterns across very different forest ecosystems. Fine roots have also been found to have higher rates of root respiration, which in some species, like aspen, can lead to increased suckering (offshoots)

(Desrochers et al., 2002). Practically speaking, separating roots into fine and coarse categories is very time consuming and laborious; few studies have looked at this measurement for container-grown trees.

1.5. Landscape Establishment of Trees

Some studies have examined tree growth in the landscape as affected by nursery production method (Marshall and Gilman, 1998; Richardson-Calfee et al., 2010; Richardson-Calfee et al., 2007; Richardson-Calfee et al., 2008; Gilman et al., 2003; Schuch et al., 2000; Arnold, 1996; Brass et al., 1996; Gilman, 2001; Gilman and Kane, 1990; Gilman et al., 1996a; Gilman et al., 1996b; Green and Watson, 1989; Warren and Blazich, 1991; Gilman and Beeson, 1996a; Gilman and Beeson, 1996b; Watson, 1986; Watson, 1987; Watson and Himelick, 1982; Watson and Himelick, 1983; Struve and McKeand, 1994; Maupin and Struve, 1997). Their relatively (compared to traditional nursery studies) small number is reflective of their time and labor-intensive nature.

Container type can significantly affect root morphology of container-grown plants (Arnold, 1996; Gilman, 2001). The goal of the nursery grower is to produce plants that do not have circling or girdling roots, which lead to compromised root systems in the landscape (Nichols and Alm, 1983). A long-term study by Gilman et al. (2003) and Marshall and Gilman (1998), which examined production container effects on red maple root and canopy growth five months and five years after establishment, found significant container effects on deflected roots five months after planting. Five years after planting there were significant container effects on trunk caliper, but root weight and number of deflected roots before planting had no effect on root number, root depth and radial root distribution around the trunk in the landscape. However, irrigation frequency significantly affected establishment and radial root distribution, with more frequent irrigation resulting in more uniform root distribution. Though the authors do admit to not evaluating root deformations (circling or kinked roots) in a standard method, they concluded that container type did not have an effect on the quality of the root systems. Interestingly, frequent irrigation affected the number of roots <40 mm diameter—with a greater number of roots occurring in the top 30 cm of the soil profile. This finding emphasizes the value of fine roots (those <2 mm) for water and nutrient absorption and their importance for promoting the growth of newly planted trees. Trees irrigated frequently had approximately 50% more root cross-sectional area than those receiving infrequent irrigation (Gilman et al., 2003).

Until recently, circling roots that developed due to the container shape or size were handled prior to transplant in the landscape by slicing or "butterflying" the outside root ball. Recent research (Gilman et al., 2010b; Gillman, 2011) has found that shaving the outer portion of the root ball (removing 2.5 cm) can remove many circling roots that lead to girdling roots. Gillman (2011) found that comparing shaving (or boxing) was a far superior method of removing circling roots compared to slicing; in fact, that research found that slicing was as problematic as doing nothing in the five-year study. Gilman et al.'s (2010b) work found that shaving did not have adverse effects on tree height or caliper among the seven species studied. Another study found that slicing roots top-to-bottom simply re-distributed roots but did not increase root growth (Gilman, et al., 1996). Other methods of correcting circling roots have included compounds container copper hydroxide (Struve, 1993) and container type. While Gilman et al. (2010b) recommends shaving the root ball prior to transplant, this has been slowly adopted by the industry.

Another potential problem following transplant into the landscape is the proper planting depth —both in the nursery and in the landscape. Transplanting practices strongly influence plant survival, establishment and plant landscape value (Bryan et al., 2009). One factor affecting survival is the location of the root collar relative to soil grade during transplant; optimal planting depth may vary among species and can also depend on cultural and environmental conditions (Bryan et al., 2009). One problem is that commonly used planting practices will vary among businesses and green industry professionals (Watson and Himelick, 1997; TCIA, 2005). Following removal from the nursery container, the depth at which root systems are planted can directly influence tree survival and health. This is a growing concern among horticulture and arboriculture professionals. Trees planted too deeply can lead to poor establishment (limited root spread) or lead to tree decline and failure (Wells et al., 2006; Arnold et al., 2007; Day and Harris, 2008).

A study conducted by Bryan et al. (2009) planted tree species at various depths—at grade, above grade (7.6 cm) and below grade (7.6 cm). The researchers found that for live oak, trees did best planted at grade. This study led to a subsequent study, which looked at planting depth and incorporation of soil amendments. The second study found that bald cypress trees planted at grade had greater shoot dry mass, reduced mortality and less negative stem water potentials compared to trees planted 7.6 cm below grade. The research also found that planting trees below grade, regardless of soil type (and amendments added), had adverse effects on tree health and growth (Bryan et al., 2009).

There is a correlation between the depth of tree in the container (at planting in the nursery) and corresponding transplant into the landscape that can lead to long-term adverse effects in tree health. Additional research compared planting depth during container production and landscape establishment on elm (Bryan et al., 2009). These researchers found that during container production, elm seedlings planted at grade had better growth than those planted 5 cm below grade. The researchers concluded that correcting plant depth problems prior to planting in the landscape may improve tree survival (Bryan et al., 2009).

Gilman and Paz (2009) planted Cathedral oak seedlings at various depths (1.3, 3.8, 6.4, 8.9 and 11.4 cm below grade) in containers to determine if nursery planting depth had an effect on root system quality and above-ground growth. Trees were started in #3 containers and upshifted to #15 containers one year later, and again to a #45 the following year. The deeper the tree was planted in the container, the greater the amount of roots growing in the bottom of the container and fewer roots in the top portion of the container. Trunk flare and surface roots decreased with increasing planting depth. At the conclusion of the study, 40 months later, 80% of the trees were graded as culls, according to the Florida Grades and Standards for Nursery Stock (Florida Department of Agriculture and Consumer Services, 1998), due to deflected roots from the #3 and #15 containers. Though the oaks were planted too deeply, the trees regenerated new roots above the lateral roots only when first planted into #3 containers, not in #15 or #45. The total number of structural roots, located in the top 7.6

cm of the root ball varied, and it was determined that 75% of deflected roots were a result of small container size and occurred in the early stages of the tree's production cycle. In agreement with other researchers (Lindström and Rune, 1999; Sparks, 2005), it was concluded the primary main roots are generated when the tree is in a container, then permanent root defects may remain with the tree, which can lead to compromised tree stability in the landscape. Caliper and height were unaffected by planting depth for this species, similar to findings of Browne and Tilt (1992) and Fare (2005).

After transplanting, producing and maintaining many roots is of primary importance to the tree and if hindered, may contribute to plant stress. Root turnover, which has been defined as the portion of the root system that dies and is replaced (Burton et al., 2000) is also a measure of annual production and/or mortality to the crop (Jones et al., 2003). Richardson-Calfee et al. (2010) found that transplant timing of trees in Virginia significantly influenced root production and root mortality. Regardless of when trees were transplanted (November, December, March, April or July), root growth did not begin until early May, with root production at its peak during the warmest months of the year; rooting ceased after leaf drop in mid-October. This coincided with soil temperatures reaching above 10 C for root growth to begin; with root growth stopping as soil temperatures dropped to 12-14 C in fall. The researchers suggested that the lack of early spring root production was the result of transplant stress or the limited supply of carbohydrates to push both root and shoot growth. Compared to root production, root mortality was more consistent throughout the year, but was greatest in late winter to early spring prior to maximum root production. Again, the researchers concluded that this could be due to demand for assimilates and the resulting competition among roots and shoots. What was even more interesting from this study is that, though the researchers speculated that trees transplanted in fall or early spring would have a greater advantage for root production, trees planted in July produced similar root lengths by the end of the first summer with adequate irrigation available.

Research done by Hummel et al. (2009) looked at various methods of root disruption prior to planting to determine effects on long-term survival and growth of Scotch and shore pine. Of their seven treatments, which varied in disruption severity, they found for Scotch and shore pine, survival and growth was greatest with the least disruptive root treatments. The most disruptive or severe treatments resulted in greater plant death for shore pine. Any treatment that involved cutting or pruning of roots resulted in a higher mortality rate over the three year study. On the Scotch pine trees, the greatest mortality was found in the washing or washing/pruning treatments. Scotch pine had higher transplant success when compared to shore pine; this difference in transplant success likely affected the relative mortality rate of the trees. After the first year, there were no differences in growth (height, width and caliper) among the seven treatments for both species. The researchers concluded that, based on their study, generalized statements regarding tree transplanting may be inaccurate, depending on species, and that these two closely related species (pines) exhibited significant differences in their relative tolerance to root disruption. They also concluded that to correct root deflections caused by the container at planting, the short-term reductions in plant growth are tolerable if the treatment will prevent girdling roots and enhance long-term plant growth.

Researchers in Illinois (Koeser and Stewart, 2009) did a study using B&B trees to evaluate three stages of transplanting (harvest, handling and transport) on the occurrence of transplant shock at three nursery locations in the Midwest. Not surprisingly, they found the greatest amount of transplant shock (as determined by twig growth after one growing season) in trees that were handled and transported. Handling and transport appears to significantly affect post-transplant tree growth and efforts should be made to minimize disruption of the root ball and the length of time between digging and planting.

1.6. Water Use in Containers

There are numerous ways above-ground container plants can be irrigated. These applications include overhead sprinkler irrigation, microirrigation and schedule irrigation (applying irrigation based on the plant's need). The most common method of nursery irrigation is using an overhead sprinkler system (Beeson and Knox, 1991). This system is often used because it can irrigate large numbers and sizes of plants in a given area (Mathers et al., 2005). However, because of the limited root system spread of plants, overhead irrigation must be applied more frequently, sometimes multiple times per day, which can affect efficiency (Mathers et al., 2005). Weatherspoon and Harrell (1980) found that up to 87% of applied water via overhead irrigation falls between containers, resulting in very low irrigation use efficiency rates. The size of the container, plant spacing, plant height and substrate components have impacts on the efficiency of overhead irrigation systems (Mathers et al., 2005). Often, to compensate for poor irrigation coverage, nurseries may over-apply water in an attempt to increase efficiency or to ensure plants receive adequate water. This results in excess water in some plants and misuse of water resources.

Microirrigation is using drip irrigation or spray stakes; these methods are generally used in larger containers (Garber et al., 2002), greater than 20 liters (5.3 gal) by volume (Beeson and Knox, 1991). Larger containers tend to mean larger plant volume, where overhead irrigation may be intercepted by the leafy canopy growth instead of reaching the container surface. Microirrigation techniques tend to be more efficient than overhead irrigation (Mathers, 2003a). Mircroirrigation can also lead to less runoff from applied nutrients and/or pesticides (Green and Rost, 1985). One detriment is that these systems are often more labor intensive to maintain (Regan, 1997). But, Green and Rost (1985) found that if properly maintained, microirrigation, compared to overhead sprinklers, can be more economical for the producer, and leads to less foliar disease and better fertilizer use efficiency. Growers may use a combination of both microirrigation and overhead irrigation at their nurseries, depending on plant size and species.

The final irrigation method that is used for container production is schedule irrigation, which is only applying water when the plant needs it, at the amount needed (Mathers et al., 2005). Done properly, schedule irrigation can save up to 25% in water use (Regan, 1999). Plants are monitored for evapotranspiration (ET) to determine crop coefficients (Burger et al., 1987). For the grower, “like” plants need to be grouped together with similar water needs or growth characteristics (Regan, 1997).

Herbicide use is common in above-ground container nursery production, primarily because weeds compete with containerized plants for water and nutrients

(Berchielli-Robertson et al., 1990; Case et al., 2005; Roul and Lemay, 2000). In some parts of the United States, herbicides are applied as often as three times during a growing season (Riley, 2003). Manual weed control is a major expense to nursery producers, and it's been estimated that they spend $500 to $4,000 per acre (Mathers, 2003b). But economic losses in nursery production due to weed infestations have been estimated to cause up to $17,000/ha in damage (Chong, 2003). Since containers are often watered daily, there is concern for herbicide runoff and leaching. Gilliam et al. (1992) found that up to 80% of applied herbicides do not end up on the container surface and this has been called “non-target loss” (Mathers, 2003b). Factors affecting herbicide application include plant type, size, container size and spacing (Gilliam et al., 1992), as well as method of application and herbicide formulation.

A study conducted by Riley (2003) looked at herbicide runoff with overhead irrigation at two nurseries in the southeastern United States. Immediately after application of the herbicide, herbicidal runoff collected ranged from 0.4 to 4.7%, depending on the water solubility of the herbicide. The greatest potential for runoff and contamination of water sources is immediately after application. Riley concluded that if nursery growers reduce irrigation following herbicide application, they will maintain good plant health and weed control, but with reduced runoff possibilities. These conclusions depend on herbicide type, media texture and porosity, irrigation amount and frequency and container size (Riley, 2003).

Nursery producers fertilize plants to maintain maximum growth, but woody plants grown in containers may have low nutrient use efficiency rates due to inefficient application rates, nutrient addition rates or slow-release fertilizers that do not release when plants are in demand for nutrients (Stoven et al., 2006). In addition, like herbicide runoff, nutrient runoff is another major concern to nursery producers. Due to different container and media properties, and frequent irrigation, nutrient use efficiency and potential for runoff and/or leaching are factors that affect water quality and plant growth.

Nursery producers must carefully consider irrigation volume to avoid nutrient leaching from containers, but apply enough so that plants can obtain sufficient nutrients for maximum growth (Scheiber et al., 2008). The end product must be saleable to consumers; plant qualities depend on water and nutrient availability during production (Cameron et al., 2008; Sharp et al., 2008). As mentioned earlier, container irrigation efficiency is less-than-optimal in many cases, and this directly affects nutrient availability for plant growth (Scagel et al., 2012). It appears that container-grown plants can maintain optimal growth with varying levels of media moisture capacity (40% to 100%) (Beeson, 2006), but nutrient availability may be significantly reduced with drier media moisture levels (Buljovcic and Engels, 2001; Scheiber et al., 2008; Silber et al., 2003; Xu et al., 2004). Studies by Rose et al. (1999) and Tan and Hogan (1997) found that growth can be enhanced by minimizing water stress instead of increasing fertility in some perennial woody plants.

Nitrogen is the most important nutrient for plant production and growth (Marschner, 1995). However, nitrogen deficiency and excess nitrogen can increase plant water stress (Scagel et al., 2011). Decreased growth of woody plants in containers due to excess nitrogen can result from increased salinity, nutrient imbalances or water stress (Bi et al., 2007; Cabrera, 2004). Scagel et al. (2011) found that shrubs fertilized with high rates of nitrogen had decreased water stress when frequently irrigated; but, plants that were nitrogen deficient did not have changes in growth due to greater water availability. This means that nursery producers must maintain media moisture levels that will either enhance nitrogen availability in the media or the ability of roots to absorb nitrogen. As irrigation frequency increased, root:shoot ratio decreased, but total plant biomass was not affected by irrigation frequency (Scagel et al., 2011).

The question arises if salt build-up in the container becomes an issue when irrigation amounts are reduced. Nursery producers continually monitor EC levels to maintain fertilizer salts at non-damaging levels. Growers in high precipitation areas should rarely have high EC levels; but in the arid west, growing plants with zero-leaching fraction is nearly impossible without reaching potentially damaging EC levels.

A study conducted by Davis et al. (2011) compared two irrigation treatments (subirrigation compared to overhead) on the growth and nitrogen content of aspen. The researchers found that subirrigation (watering plants from the bottom using capillary action) reduced water requirements by 45% compared to overhead irrigation, but there was no effect on biomass, leaf nitrogen content, height, caliper and root volume. The main effects Davis et al. (2011) found were reduced nutrient runoff and irrigation volume. Further, Tyler et al. (1996) found that if irrigation volume is reduced to prevent nitrate-nitrogen runoff, shoot and total plant dry weight is reduced by 8% to 10%, when compared to higher irrigation rates. However, root weight was not affected by leaching fraction/irrigation rate. The low leaching fraction reduced nitrate-nitrogen and phosphorus runoff by 66% and 57%, respectively, compared to high leaching fraction; nitrogen use efficiency was not affected by leaching fraction (Tyler et al., 1996).

Production of high-quality plant material requires proper irrigation requirements. Current nursery practices encourage irrigation to be applied during the early-morning hours to prevent water drift from winds and evaporative losses (Warren and Bilderback, 2002). However, irrigation during the afternoon may reduce container media temperature and enhance top and root growth (Keever and Cobb, 1985; Beeson, 1992). This could be due to cooler media temperatures to enhance root growth, along with water and nutrient update and reduced water stress on the plants. Timing of irrigation is something nursery producers should consider and its effect on plant growth and stress during production. Warren and Bilderback (2002) examined early morning, mid-day, afternoon and evening irrigation schedules for woody plants. The irrigation timing that produced maximum growth was at 1200, 1500 and 1800 hours; plants had 57% to 69% greater plant dry weight than plants irrigated during the early morning hours. Afternoon irrigation resulted in highest water use efficiency, highest net carbon dioxide assimilation, greatest stomatal conductance and lowest substrate temperatures. The practical explanation for this is that during the hottest part of the day, plant stress is at its highest, and water is in the greatest demand. The plant's response, if water is not available, is to close stomata, which in turn reduces plant growth. Plants irrigated in the afternoon had 47% higher carbon dioxide assimilation rate compared to morning irrigation (Warren and Bilderback, 2002). In short, increased stomatal conductance as seen with afternoon irrigation, allows for greater carbon dioxide assimilation, thus enhanced plant growth.

Warsaw et al. (2009) attempted to improve water conservation by irrigating less than the industry standard in the southern United States (3/4 inch compared to one inch), and they found that irrigation based on daily water use could be reduced by 6% to 75% without significantly affecting plant growth, depending on plant species. Beeson and Haydu (1995) and Ruter (1998) found that multiple daily irrigations (AKA "cyclic irrigation"), which is splitting out the total amount of irrigation to be applied in equal parts, then applying at various times of the day, opposed to once daily, increased plant growth.

Irrigating multiple times throughout the day may increase growth by reducing media heat load, minimizing water stress and/or increasing nutrient uptake. A study comparing these factors has not reported to date, so it is not possible to claim which effect is greatest. On a practical side, growers need to realize that there are many factors to consider when maximizing plant growth, but cyclic irrigation is something growers should seriously consider adopting.

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CHAPTER 2

CONTAINER TYPE AND OVERWINTERING TREATMENTS AFFECT SUBSTRATE TEMPERATURE AND GROWTH OF CHANTICLEER® PEAR (*PYRUS CALLERYANA* 'GLEN'S FORM') IN THE NURSERY

2.0.1. Summary

The container most used for nursery tree production is black plastic (BP). High substrate temperatures occurring in BP can injure or kill roots; BP-grown trees often develop circling and malformed roots. Root injury sustained during production may negatively affect tree health after planting in the landscape. Many containers are available for nursery production, but few studies have examined the merits of alternative container types for production. We compared the growth of *Pyrus calleryana* Decene. 'Glen's Form' (Chanticleer®) in three container types: black plastic, Root Pouch® (RP) and Smart Pot® (SP), over two growing seasons and under two overwintering treatments (consolidated or lined out). After the first growing season, there were no differences in height or dry leaf, shoot and root weight among the three containers. Following the second growing season, caliper, height, leaf area, percent leaf moisture, and root ball quality differed among container type.

After the 2010-2011 winter, consolidated trees produced larger root and shoot systems (35.3% and 36.4%, respectively) than trees that were lined out. Substrate temperature maxima and fluctuations during winter and summer were greatest for BP containers compared to RP and SP. The potential advantages of producing trees in fabric containers merit consideration from nursery producers.

2.0.2. Significance to the Nursery Industry

Nursery producers are under increasing pressure to maintain production efficiency and grow high-quality plants in a cost effective manner. One cost saving measure may be to switch from solid plastic containers to fabric containers. Due to increasing costs of materials and petroleum, growing consumer interest in sustainable or recyclable products, and awareness that black plastic containers may negatively affect root system structure, nursery growers are looking for alternatives to black plastic containers. We evaluated Chanticleer pear trees in two fabric container types relative to standard black plastic containers over two growing seasons. Pears grown in the fabric containers had greater height and caliper growth and fewer circling roots. Trees not consolidated into a block for overwintering suffered more damaged compared to trees that were placed in a consolidated block. Fabric containers should be considered as a production alternative to solid plastic containers.

2.1. Introduction

Above-ground container tree production is a popular way to grow ornamental trees and is used more commonly than field production in many parts of the United States (Hodges et al., 2008). Some advantages of container production include ease of mobility and handling, less space needed than field-grown trees, greater consumer acceptance, increased productivity attributed to increased production density and shortened rotation times, year-round harvest, and production of difficult-to-transplant taxa. Container production has also expanded the types of taxa that can be economically produced. A major reason for the adoption of container production is reduced transplant shock expressed as increased transplant survival and reduced establishment time (Johnson and Ingram, 1984). Transplant shock associated with field-grown material results from the loss of root mass associated with harvesting; up to 95% of the original root volume is lost when field grown trees are harvested according to national standards (Watson and Sydnor, 1987).

Disadvantages of container production include: additional costs for substrates, fertilizer, water, labor and efforts to overwinter materials. Circling and/or malformed roots are often seen with container-grown trees, which can negatively impact the tree health and stability many years following transplanting into the landscape (Gilman, 1990; Nichols and Alm, 1983). Finally, it is estimated than 350 million pounds of black plastic (BP) containers are thrown away each year (Missouri Botanic Gardens, 2012).

Traditionally, the majority of container nursery stock has been grown in BP containers. There are numerous production challenges associated with container nursery stock, the most important being the prevention of root malformation caused by circling and matting roots (Whitcomb, 1986) and root injury resulting from extreme winter and summer substrate temperatures. Post-production challenges associated with production in plastic containers include transplant survival and establishment success in the landscape. Poor transplant success (root malformation and poor growth into the native soil) can often be attributed to root-related problems that occur during the production process—especially when trees are grown in plastic containers (Long, 1961).

The optimum temperature range for tree root growth is between 15 to 27C (Sibley et al., 1999). Plants growing in black plastic pots can be subjected to excessively high or lethal root temperatures during the summer (Markham III et al., 2011). At soil temperatures greater than 30C, root damage occurs and growth and plant health declines (Ingram et al., 1989; Martin and Ingram, 1991). In the southern United States, root temperatures have been reported to reach 58C (Martin and Ingram, 1991), but these extreme temperatures may only last for a short time. However, temperatures at 42C have been found to last for several hours (Ruter and Ingram, 1990), causing permanent damage to plant roots. Also, extremely cold temperatures can injure roots. Temperatures fluctuating around freezing can cause severe damage to actively growing root systems. Further, the often extreme temperature fluctuations seen in BP containers are a problem for plant root systems. In northern zones, winter substrate temperatures can be modified by overwintering stock in polyhouses, or consolidating plant material, then covering them with wood mulch, straw or other materials. While effective, the labor required for annual winter consolidation and the spring re-spacing is labor intensive, as are material costs for the purchasing, installing and disposing of poly films (Taylor et al., 1983).

Without careful management, container production can result in moderate to severe root malformation. Root malformation is harmful and can be detrimental to tree growth, and often goes undetected during production (Gilman et al., 2010). Root malformation is pernicious in that it is usually first diagnosed when established trees fail, with potentially catastrophic consequences (Day et al., 2009). The smooth sides of BP containers contribute to the formation of circling and/or misshapen roots (Appleton, 1989; Arnold and McDonald, 1999; Gilman et al., 2010). The negative effects of container production on root growth may be minimized by transplanting into larger containers, if detected and corrected during up-canning, but this is a labor intensive and costly process. Plastic containers that rely on air root-pruning are only partially effective in controlling root malformation (Gilman et al., 2010). The use of alternative container types, including fabric containers, may minimize root malformation during production, as well as eliminate the need to correct container-related root problems prior to planting. They may also increase transplant success and more rapid establishment after planting in the landscape.

This research used *Pyrus calleryana* Decene. 'Glen's Form' (Chanticleer®) to compare the effects of container type during nursery production and overwintering on plant growth and survival using two fabric containers (Root Pouch®, Root Pouch, Inc., Hillsboro, OR; and Smart Pot®, High Caliper Growing-Root Control, Inc., Oklahoma City, OK) and BP containers. We hypothesized that the use of fabric containers would reduce the severity of root zone temperature fluctuations relative to BP, reduce root malformation and/or defects, and enhance tree growth rate. Our research examined the feasibility of two overwintering production schemes—leaving plants lined out or consolidating them together. It was our goal to determine which container type and overwintering technique in the nursery produced larger and more vigorous trees, with root balls exhibiting minimal root circling and malformation.

2.2. Materials and Methods

Two year-old, lightly branched whips of Chanticleer® pear (Bailey Nurseries, Inc., St. Paul, MN) were planted on May 7, 2010 at the Colorado State University Plant Environmental Research Center (PERC), Fort Collins, CO (USDA hardiness zone 5a)

(40.56 N, 105.08 W). Prior to planting, roots were rehydrated by soaking in water for 30 minutes. Trees were root pruned to eliminate broken or compromised roots, and planted into three types of containers: (a) 66 L (#15) standard black plastic container (BP) (Lerio Corp., Mobile, AL), (b) 66 L (#15) fabric container (RP) (Root Pouch®, Averna & Associates, Hillsboro, OR), and (c) 66 L (#15) fabric container (SP) (Smart Pot®, High Caliper Growing, Inc., Oklahoma City, OK). The container substrate (pH of 6.8, EC of 3.7 and 39.6% organic matter) was a locally produced nursery mix (Organix Supply, Inc., Platteville, CO), which consisted of 40% composted wood products, 40% sphagnum peat moss, 10% dehydrated poultry waste, 5% bark fines and 5% volcanic pumice. After planting, trees were fertilized by topdressing each container with 250 g (8.8 oz) of Osmocote Pro® 19N-2.1P-6.6K (The Scotts Company, Marysville, OH).

Five trees were destructively harvested for baseline measurements. At planting trees averaged 17.7 mm (SE ± 2.8 mm) in trunk caliper (diameter) measured at a point 15.2 cm above soil line and 161.4 cm (SE ± 17.1 cm) in height. Containers were placed on the ground on black woven cloth in three rows on 0.9 m within row spacing between containers, and 1.8 m spacing between rows. Trees were attached by a 1.8 m bamboo stake to a wire trellis (3/32 gauge) 1.2 m above ground to prevent them from blowing over. Trees were placed in a randomized complete block design, with five replicates per container type and overwintering treatment. Trees were pruned to correct branching structure and remove damaged branches.

Throughout the study, trees were irrigated using a drip irrigation system with 12 in-line emitters per container. The drip system was constructed using 1.3 cm black plastic tubing (one line for each container type) for main lines, with 0.6 cm black spaghetti tubing connecting to 0.6 cm tubing with in-line emitters (12 per container) on 15.2 cm spacing. Irrigation was scheduled to automatically come on for approximately 15 minutes in the early morning (Model 62040, Orbital® Irrigation Products, Inc., Bountiful, UT). Trees received 5.7 liters of water every other day during the 2010 season; irrigation was increased to 5.7 liters every day during 2011 since trees had increased in size. In November 2010, trees were randomly moved to two overwintering treatments from December 2010 to April 2011. Trees either, (a) remained in the plot during winter as they were during the growing season ("lined out"), but were moved together so that trees were pot-to-pot, or (b) consolidated into a rectangular block in which containers were touching. Trees in neither overwintering configuration were protected with mulch or plastic and experienced fluctuating ambient winter temperatures. Trees were irrigated by hand, as needed, throughout the winter months. In April 2011 containers were moved from the overwintering treatments and re-spaced on 0.9 m centers on the wire trellis.

Substrate temperature was measured during December 2010 to April 2011 (winter) and May 2011 to October 2011 (summer) using thermocouples at two locations in the containers: depth of 5 cm in the center and a depth of 5 cm and 5 cm in from the container edge on the southwest side of the containers. Thermocouples were constructed by soldering the junction of iron-constantan thermocouple wire (Type J, 20 gauge, fiberglass insulated; Tempco Co., Part # TCWR-1010, Wood Dale, IL), which were then coated using a thermally conductive polyester epoxy resin (Evercoat Premium Marine Resin, Evercoat Company, Cincinnati, OH) to prevent corrosion of the junction. Thermocouples were attached to thermocouple multiplexers (Model AMT25T, Campbell Scientific Inc., Logan, UT); temperatures were recorded every minute and averaged per hour with a datalogger (Model CR200X, Campbell Scientific, Logan, UT). Air temperature was recorded hourly at a campus weather station, located approximately 0.8 km from the research site.

Height and caliper (measured at 15 cm above the container growing substrate surface) were measured monthly from June to September in 2010 and 2011. At the end of the first growing season in September 2010, 30 trees were destructively harvested. Tree leaf area (LiCor Model Li-3100, Milwaukee, WI) was estimated from subsample leaf area measured using leaves (the second leaf down from the terminal growing tip of the branch or leader) randomly collected from each side of the tree and from the central leader. At harvest, all remaining leaves were removed, weighed fresh and oven-dried at 70C for one week to calculate percent leaf moisture. Total tree leaf area was extrapolated for individual trees using the subsample leaf area and whole tree dry weights.

Measurements at harvest included: fresh and dry shoot weight, fresh and dry washed root weight, new twig growth (measured on randomly selected branches on the north, south, east and west sides of trees, along with central leader), and total new twig growth, which was calculated by totaling individual shoot measurements (not including the leader measurements). Root ball quality was evaluated for four criteria using a visual rating system (Gilman et al., 2010): substrate integrity (how well the root ball held together once removed from the container; scale of 1 to 5, with 1 = root ball totally disintegrated at removal and 5 = root ball held together well), root ball quality (scale of 1 to 5, with 1 = heavy peripheral rooting on outside of root ball, and 5 = no or few peripheral roots), root ball matting (scale of 1 to 5 with 5 = no or few visible roots on the bottom of the root ball, and 1 = heavy root matting) and visible deflected roots (visual presence of deflected roots on the outer periphery of the root ball; yes or no scale). In addition, oven-dried root balls were dissected to determine the percentage of fine (≤ 2.0 mm diameter) and coarse (>2.1 mm diameter) roots.

All plant and temperature data were subject to analysis of variance (SAS Institute Inc., Cary, NC, version [9.2]) using a fixed effects model of analysis of variance. Least significant means were compared using the Tukey Range test.

2.3. Results and Discussion

2.3.1. Substrate Temperature Results (Winter of 2010-2011).

Overwintering treatment significantly affected substrate temperatures in the winter of 2010-2011 (Fig. 2.1). In early winter (mid-December 2010 to mid-January 2011), neither overwintering treatment was consistently colder or warmer than the other. However, over the 18-week period, lined out containers averaged 0.5C warmer than the consolidated containers. Once average substrate temperature exceeded 0C in late January 2011, lined out containers were consistently warmer than consolidated containers.

Container type also affected substrate temperature during the same time period (Fig. 2.2). On dates when significant differences in temperature were found, substrate temperatures in BP containers were consistently warmer than those in RP or SP containers. During the week of January 16, 2011, average weekly substrate temperatures in all containers averaged -4.7C. Weekly average substrate temperatures increased after the week of January 16, 2011, with substrate temperatures of the BP containers consistently warmer than RP and SP. If you compare warming trends among container types over a ten week period in late winter to early spring (January 16 to March 13, 2011), the substrate temperature in BP containers increased 15.8C, RP containers increased 14.6C and SP containers increased 14.4C. Over the 18-week period, average weekly substrate temperatures in BP containers were 1.1C and 1.3C warmer than RP and SP substrate temperatures, respectively.

There were also significant interaction effects for container type by overwintering treatment during January to March 2011 (data not shown). Weekly average substrate temperatures in BP containers for both overwintering treatments were consistently warmer than the two fabric container types. Lined out BP container substrate was consistently warmer than the consolidated BP substrate; however, significant differences only occurred four times during the 18 week period. On average (for the 18 week winter time period), the substrate temperature for BP containers in the lined out overwintering treatment were 1.4C and 1.7C warmer than RP or SP substrate temperatures, respectively. For consolidated treatments, the substrate temperature in BP containers was 0.7C and 0.9C warmer than RP or SP substrate temperatures, respectively.

2.3.2. Substrate Temperature Results (Summer 2011)

Container type affected weekly average substrate temperature in only six of the 20 weeks during the May 9 to September 26, 2011 period (Fig. 2.3). Substrate temperatures in BP containers tended to be warmer through the spring and summer growing season, but differences were seldom significant. Average substrate temperatures in the three container types remained in the optimal temperature range for root growth, between 15 and 27C, as described by other researchers (Barr and Pellet, 1972; Lyr and Hoffman, 1967). However there were periods where temperatures reached levels that may have caused root injury or death (data not shown).

2.3.3. Container Effects on Tree Growth (2010 and 2011)

Tree caliper increased monthly June to September in 2010 for trees in all container types, with BP-grown trees having significantly greater caliper at all dates in 2010 than trees grown in RP or SP containers (Table 2.1). Trees grown in BP increased in caliper by 83.1% from May 2010 to September 2010; RP-grown trees increased by 74.0% and SP by 76.2%.

Tree height increased monthly with all container types (Table 2.1). Trees grown in BP were significantly greater in height when measured in June compared to RP- and SP-grown trees; however, no differences in height were observed among container types at later sampling dates in 2010 (Table 2.1). Trees grown in BP increased in height by 40.0% from May to September in 2010; RP-grown trees increased in height by 37.7%, and SP-grown trees in by 37.4%. Although caliper growth was significantly greater for trees in BP containers for all dates during the 2010 growing season, the differences at the end of the growing season was only 5.0% and 3.7% greater in BP-grown trees, compared to trees grown in RP and SP, respectively. The significantly greater caliper of the BP trees may be the result of more rapid substrate warming, causing greater establishment growth rates at the beginning of the study. Differences in height were only significant in June 2010; height was otherwise not affected by container type. Other studies have found that height and caliper generally do not differ based on container type (Marshall and Gilman, 1998; Neal, 2009). While there was no significant container effect on root:shoot ratio for trees harvested in September 2010, there was for the root:shoot ratio for trees harvested in September 2011 (Table 2.2). Trees grown in BP during 2010 had a root:shoot ratio of 1.01, while trees grown in RP and SP were 0.81 and 0.90, respectively.

At the conclusion of the 2010 growing season there were no container effects for dry leaf weight, dry shoot and root weight, estimated total leaf area, leader and branch growth measurements, and root ball integrity (Table 2.2).

Container type significantly affected root growth. Differences were observed for bottom root ball matting, with trees in BP having the greatest amount of matted roots, compared to RP- and SP-grown trees (Table 2.2). Trees grown in BP containers also had the greatest incidence of deflected roots, compared to trees grown in RP or SP containers (Table 2.2). The greater incidence of bottom root ball matting on trees planted in BP containers was found in a similar study by Gilman et al. (2010), which compared rooting in BP containers with seven other container types, including SP. We also observed that the root balls of BP-grown trees also had significantly more deflected roots (Table 2.2).

While trees planted in BP containers displayed greater growth in 2010 than those grown in both fabric containers, the opposite was observed for both height and caliper in 2011. In 2011 the BP-grown trees increased in caliper by 12.9%, while RP- and SP-grown trees increased by 27.9% and 26.0%, respectively (Table 2.1). Similarly, BP-grown trees increased in height by only 11.6% in 2011, compared to 25% and 26.3% increases for RP- and SP-grown trees, respectively (Table 2.1). We suspect the decreased growth of BP-grown trees is due to the trees in BP containers breaking dormancy earlier, as seen by earlier flower and leaf emergence compared to the fabric containers. This early growth was subsequently injured by a hard spring frost, while the trees in RP and SP containers remained dormant during the fluctuating spring temperatures and did not suffer frost injury. As previously mentioned, substrate temperatures in BP containers averaged 1.4 to 1.7C warmer than RP or SP containers during the winter and spring period. A study on four varieties of shrubs done by Neal (2006) in New Hampshire found that BP containers compared to fabric containers had similar average winter temperatures and had warmer maximum temperatures than fabric containers.

Percent leaf moisture (leaf fresh weight-dry leaf weight/fresh weight x 100) was significantly different among container types in 2011, with RP (56.1%) and SP (56.7%) tree leaves being significantly higher in leaf moisture than those of BP trees (54.3%) (Table 2.2).

2.3.4. Overwintering Effect on Summer Tree Growth (2011 and 2012)

The overwintering method during the 2010-2011 winter—lining out versus consolidating—significantly affected tree growth in 2011. Consolidated trees had greater average leader growth (67.7 cm) compared to the lined out trees (29.5 cm), as well as greater average twig growth (35.9 cm) for consolidated trees, compared to 22.9 cm for lined out trees (Table 2.3). As with leader and twig growth, there was a significant overwintering effect on total leaf dry weight; consolidated trees had significantly greater leaf weight (407.8 g) compared to lined-out trees (252.9 g). There was also a significant overwintering effect on shoot dry weight, with consolidated trees producing 36.4% greater dry shoot weight (1491.1 g) than lined-out trees (1093.3 g) (Table 2.3). Similar results were found for height and caliper on summer tree growth in 2012 following the 2011-2012 winter (Table 2.1).

As with shoot growth, there was a significant overwintering effect on root production. Consolidated trees produced 35.3% greater dry root ball weight (1333.9 g) compared to lined-out trees (985.7 g) (Table 2.3). Substrate integrity for consolidated trees was also greater than that of lined out trees. The interaction of container type by overwintering treatment was also significant. Root balls from BP containers in the lined out treatment were significantly less stable than BP in the consolidated group. However, the substrate integrity of RP and SP trees were not as negatively affected by overwintering treatment.

The greatest differences in tree growth were likely the result of the overwintering treatments, but container type also had some effects. Trees in the consolidated group had significantly greater leader growth, dry leaf weight, dry root weight and average twig growth. At this time, we are unaware of any research that has examined substrate temperatures in various methods of overwintering nursery stock. During the coldest part of the winter (December 2010 to January 2011), substrate temperatures in BP containers were significantly warmer in both overwintering treatments than the fabric containers likely due to greater absorption of solar radiation. Those differences were most pronounced in the lined out overwintering treatment. The difference between substrate temperatures in BP from fabric containers in lined out treatments was approximately twice as great as the difference in the consolidated treatment. This could result in the lined out trees staying warmer and experiencing greater temperature fluctuations, which could negatively impact winter hardiness, root growth and overall plant vigor.

There were significant container effects on the percent leaf moisture, dry shoot weight, root ball quality and root ball matting. Trees in BP containers had smaller leaf area compared to trees in RP or SP. This is likely due to the early spring growth that occurred with trees growing in BP containers, which we speculate is due to earlier deacclimation. Deacclimated plant tissues are more susceptible to injury or death by a late frost (Ingram and Yeager, 2010); the resulting injured or dead tissue is often called "winter injury". When emerging leaves experience cold injury, the rapidly expanding cells form ice crystals that rupture the leaf structure (Taiz and Zeiger, 2010).

The cause of the lower leaf moisture percentages in trees grown in BP containers could be due to the reduced ability of these trees to absorb moisture due to rooting volume and/or abnormalities. Substrate temperatures of woody plants grown in BP containers have been widely researched by many individuals (Adam et al., 2003; Barr and Pellet, 1972; Graves et al., 1089; Havis, 1976; Ingram and Buchanan, 1981; Lyr and Hoffman, 1967; Martin and Ingram, 1991; Miller, 1986; Neal, 2010; Newman and Davies, 1988; Ruter and Ingram, 1990; Ruter and Ingram, 1992). Research has demonstrated that root zone temperatures lower than -5C can be lethal for mature roots of woody ornamentals (Havis, 1976). Our trees experienced temperatures below this point frequently during the early winter of 2010-2011. While summer substrate temperature averages were below damaging temperatures of 30C (Ingram and Buchanan, 1981; Newman and Davies, 1988), there were many occurrences of individual containers reaching above this point throughout the summer of 2011. One of the highest substrate temperatures recorded was 54C. These periods of lethal temperatures likely resulted in root death and loss of plant vigor, including shoot growth (Ingram and Buchanan, 1981; Newman and Davies, 1988).

Root ball quality and matting were significantly different for trees grown in BP containers. Studies have shown that container type has a direct effect on root morphology (Arnold, 1996; Gilman, 2001). Black plastic containers often encourage roots that are kinked and grow along the sides or bottom of the container (Gilman et. al, 2010). Air pruning of roots is a common response to trees grown in fabric containers (Marler and Willis, 1996). This happens when a root tip reaches a pocket of air; the air causes tip desiccation, which allows the root to branch (Whitcomb, 2006). Fabric containers have been proven to be a good alternative to BP containers for this reason. Our research confirms this—both fabric containers had significantly fewer circling roots and bottom root ball matting compared to trees in BP containers.

Our research concludes that fabric containers likely have a place in the nursery industry, and may produce trees having better developed root systems. Whether fabric containers will replace the majority of black plastic containers depends on nurseries adopting alternative containers. In addition, our research suggests that nursery producers must continue to consolidate plant material in northern climates; trees left lined out were smaller and more likely experienced winter injury, which decreased overall plant growth. One option that growers may consider is that since trees in BP containers were taller with greater caliper during the first growing season, likely due to the container warming more quickly to accelerate root growth, compared to trees in RP or SP containers, growers could start whips in BP containers and then transplant to fabric containers the second season. This would give the tree an initial growing advantage. Drawbacks to fabric containers include ease of mobility (the containers are soft-sided and root ball damage may occur during transit) and degradation of the material. In addition, fabric containers may require more labor during planting and upshift compared to black plastic and irrigation inputs may be greater. However, these may be factors nurseries can account for and have success. Our research suggests that the benefits of using fabric containers may outweigh potential downsides to their use and should be considered by nursery producers as viable alternatives to black plastic containers.

Table 2.1. Effect of container type and overwintering treatment on height (cm) and caliper[z] (mm) of Chanticleer® pear over three growing seasons[y].

		2010				2011				2012			
		June[x]	July	Aug	Sept	June	July	Aug	Sept	June	July	Aug	Sept
Height (cm)													
	Black Plastic	197.0[a]	200.0	223.9	226.0	238.4[b]	240.7[b]	250.9[b]	252.2[b]	257.4[b]	262.1[b]	270.2[c]	271.5[b]
	Root Pouch®	185.9[c]	197.9	224.1	222.3	249.1[a]	256.7[a]	274.7[a]	277.9[a]	292.4[a]	301.9[a]	305.4[b]	306.8[a]
	Smart Pot®	190.9[b]	197.1	222.4	221.8	249.6[a]	258.2[a]	273.6[a]	280.1[a]	297.1[a]	309.6[a]	321.2[a]	322.0[a]
Caliper (mm)													
	Black Plastic	23.1[a]	26.0[a]	28.9[a]	32.4[a]	31.6	33.4	35.5	36.6[b]	38.5[b]	41.1[b]	42.7[c]	44.2[b]
	Root Pouch®	22.8[a]	25.3[b]	28.3[b]	30.8[b]	31.4	33.8	36.7	39.4[a]	43.2[a]	44.8[a]	45.0[b]	47.9[a]
	Smart Pot®	21.9[b]	24.4[c]	27.5[c]	31.2[b]	31.0	33.9	36.7	39.3[a]	43.8[a]	46.5[a]	48.4[a]	49.8[a]
Overwintering Treatment													
	Height (cm)												
	Lined Out	na	na	na	na	242.1	245.9	254.7	255.7	267.6	276.1	281.5	282.1
	Consolidated	na	na	na	na	249.3	257.8	278.1	287.0	297.0	306.3	316.3	315.8
						*	**	***	*	*	**	**	*
	Caliper (mm)												
	Lined Out	na	na	na	na	31.1	32.8	35.0	36.9	40.5	42.6	43.3	45.4
	Consolidated	na	na	na	na	31.6	34.6	37.5	41.0	43.1	45.6	47.4	49.2
						ns	**	***	**	ns	*	*	*

[z]Caliper measured at 15 cm (6 in) above the container growing substrate surface.

[y]Trees planted into containers in May 2010

[x]Means within a column for each measurement followed by different letters are significantly different at *Pr ≥ F 0.05*; ns = not significant; *Pr ≥ F*: * 0.05-0.01; ** 0.01-0.001; *** ≥ 0.001

Table 2.2. ANOVA results for effects of three container types on growth of Chanticleer® pear in a nursery setting (2010 and 2011 harvests).

		Final Height (cm)	Final Caliper (mm)[z]	Dry Shoot Weight (g)	Dry Root Weight (g)	Root:shoot Ratio	Dry Leaf Weight (g)	Percent Leaf Moisture	Estimated Total Leaf Area (cm^2)	Leader Growth (cm)	Average Twig Growth (cm)	Root Ball Integrity[y]	Bottom Root Ball Matting[x]	Circling Roots[w]
2010														
	BP	226.0	32.4[a]	483.8	446.7	0.95	141.2	66.3	11577	31.2	17.0	4.9	1.5[c]	2.2[c]
	RP	222.3	30.8[b]	527.2	477.4	0.90	158.0	66.4	12889	33.9	18.5	4.9	3.0[b]	3.7[b]
	SP	221.8	31.2[b]	492.0	439.1	0.92	148.8	66.6	11951	27.5	17.2	4.3	4.0[a]	4.4[a]
		ns	**	ns	ns	ns	ns	ns	ns	ns	ns	ns	***	**
2011														
	BP	252.2[b]	36.6[b]	1217.4	1246.8	1.01[a]	291.6	54.3[c]	11355	43.9	25.7	4.3	1.8[b]	1.7[b]
	RP	277.9[a]	39.4[a]	1363.3	1082.9	0.81[c]	361.5	56.1[b]	11829	52.6	31.5	4.8	3.2[a]	4.3[a]
	SP	280.1[a]	39.3[a]	1295.9	1149.7	0.90[b]	338.1	56.7[a]	11490	50.5	31.1	4.7	3.5[a]	4.6[a]
		*	*	ns	ns	*	ns	**	ns	ns	ns	ns	*	***

[z]Means within a column for each measurement followed by different letters are significantly different at *Pr* ≥ *F 0.05*; ns = not significant; *Pr* ≥ *F*: * 0.05-0.01; ** 0.01-0.001; *** ≥ 0.001

[y]Root ball integrity (how well the root ball held together when removed from the container; scale of 1-5, with 5 holding together well)

[x]Root ball matting (matting on the bottom of the root ball; scale of 1-5, with 1 being many matted roots)

[w]Circling roots (frequency, based on a scale of 1 to 5; with 1 being many circling roots)

Table 2.3. Effects of overwintering treatment on shoot and root growth of Chanticleer® pear (averaged over container type) grown in containers for two seasons.

	Height (cm)[z]	Caliper (mm)	Dry shoot weight (g)	Dry root weight (g)	Dry leaf weight (g)	Percent leaf moisture	Estimated total leaf area (cm^2)	Leader growth (cm)	Average twig growth (cm)	Root ball Integrity	Root ball matting	Circling roots
Lined Out	255.7	36.9	1093.3	985.7	252.9	55.7	12036	30	23	4.2	2.7	3.6
Consolidated	287.0	41.5	1491.1	1333.9	407.8	55.7	11079	68	36	4.9	2.9	3.5
	*	**	***	***	***	ns	ns	***	***	***	ns	ns

[z]Means within a column for each measurement are significantly different at *Pr ≥ F 0.05*; ns = not significant; *Pr ≥ F*: * 0.05-0.01; ** 0.01-0.001; *** ≥ 0.001

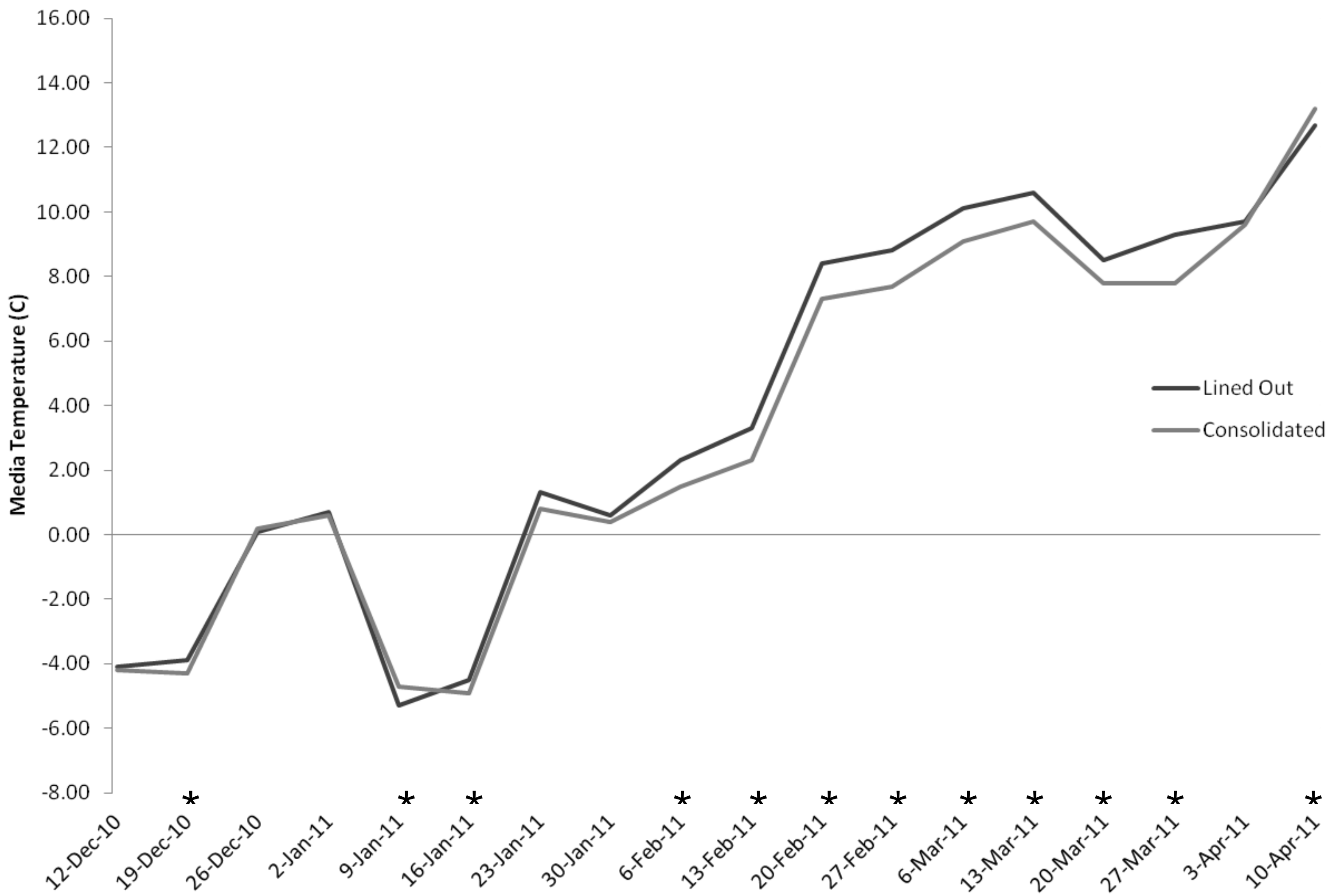

Figure 2.1. Average weekly substrate temperature for overwintering treatments of Chanticleer® pear (2010-2011); *indicates significant difference at that date (*Pr* ≥ *F 0.05*).

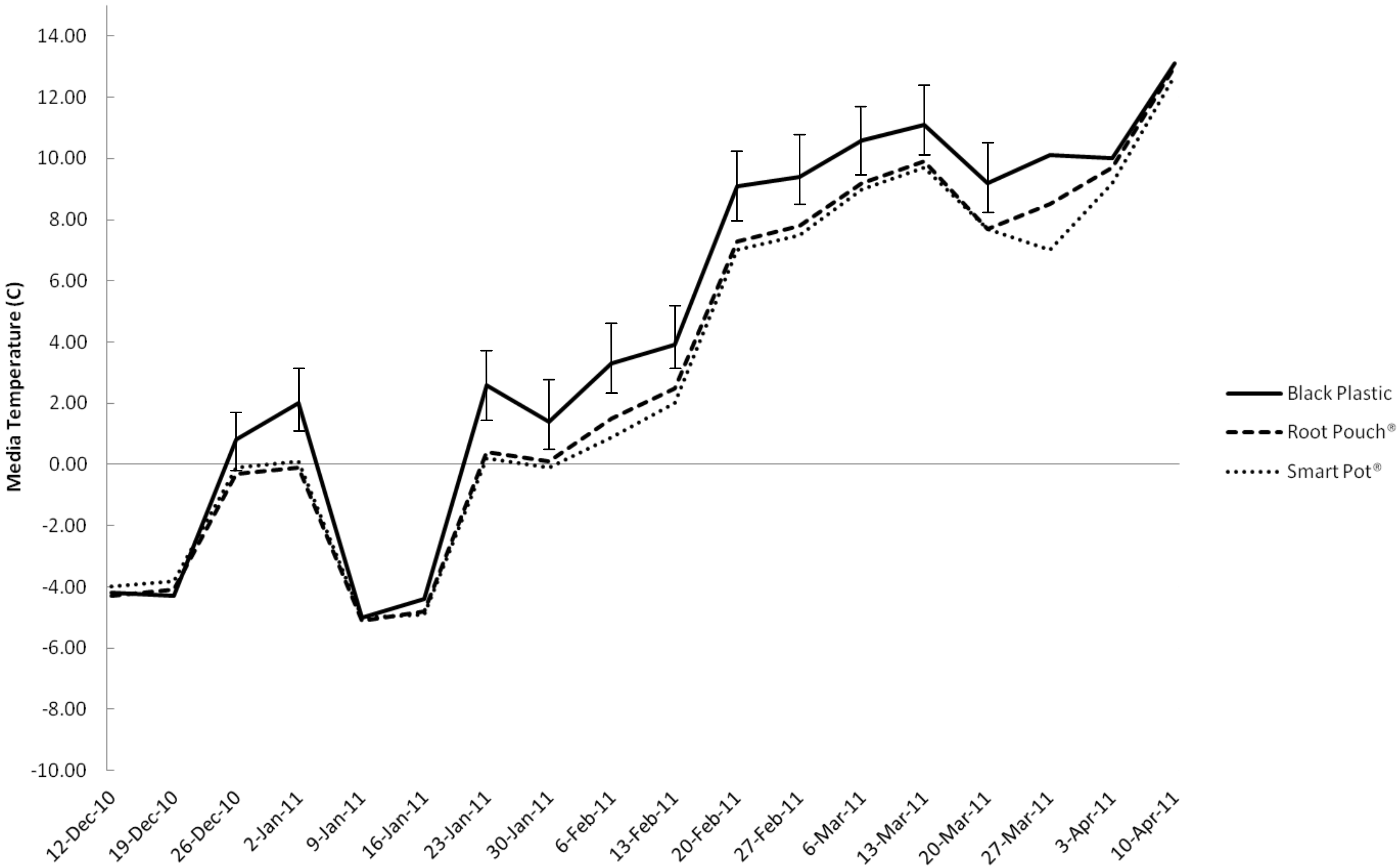

Figure 2.2. Average weekly substrate temperature for Chanticleer® pear grown in three container types (2010-2011); error bars indicate significant differences between black plastic and fabric (Root Pouch® and Smart Pot®) containers at that date (*Pr ≥ F 0.05*).

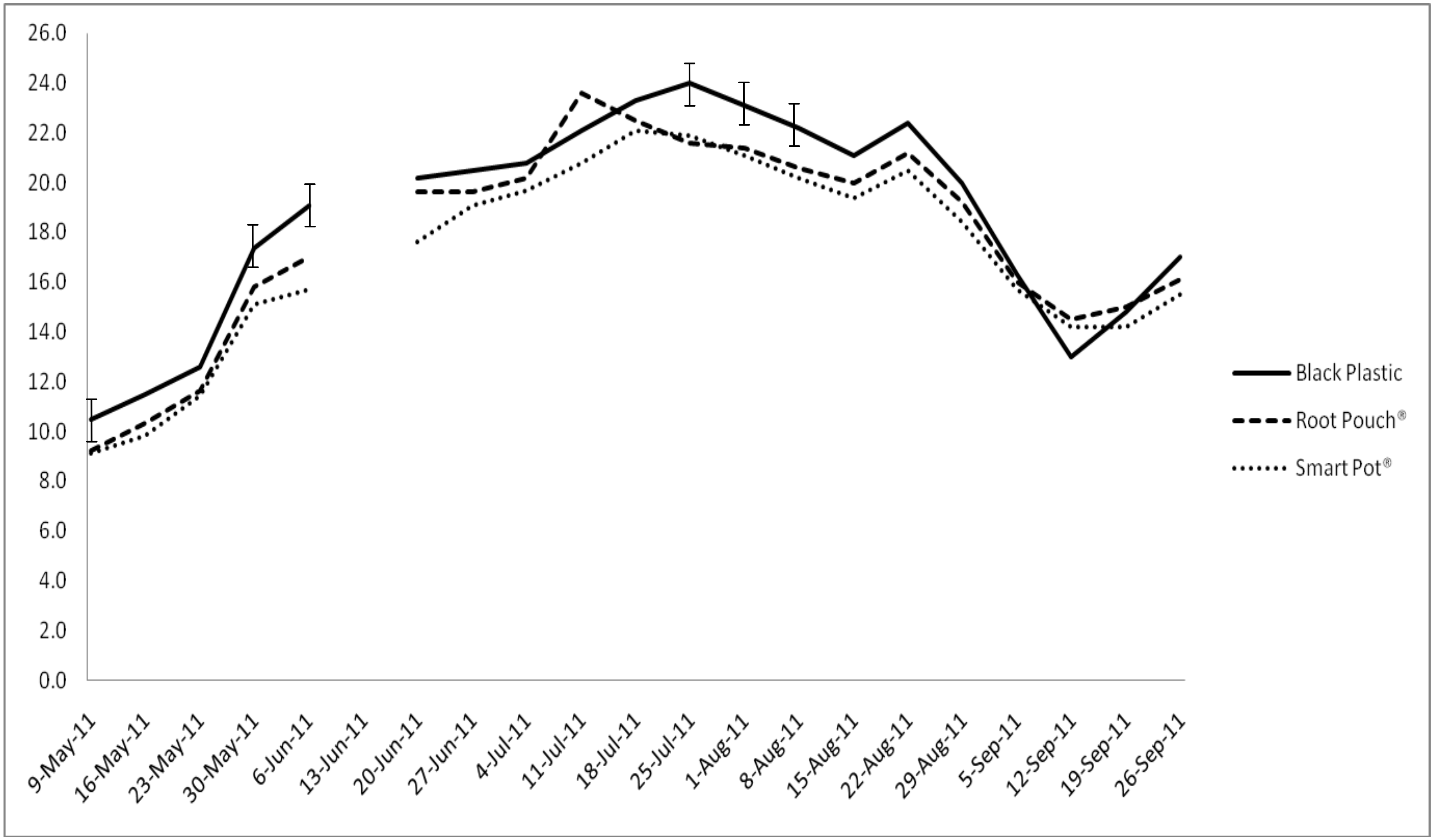

Figure 2.3. Average weekly substrate temperatures in three container types from May to September 2010; error bars indicate significant differences between black plastic and fabric (Root Pouch® and Smart Pot®) containers at that date (*Pr* ≥ *F 0.05*). Note: Dataloggers damaged by water for 6 June to 20 June 2011 period.

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CHAPTER 3

CONTAINER TYPE AFFECTS LANDSCAPE ESTABLISHMENT OF CHANTICLEER® PEAR (*PYRUS CALLERYANA* 'GLEN'S FORM')

3.0. Summary

While there are many advantages to producing woody plants in the industry-standard black plastic (BP) container, a major disadvantage is that root systems are often compromised (i.e. circling and girdling roots), which can lead to problems when transplanted into the landscape. This study evaluated transplant success of *Pyrus calleryana* 'Glen's Form' (Chanticleer®) grown in three container types: black plastic, Root Pouch® (RP) and Smart Pot® (SP). We found no container effects on above-ground growth one, two and three years following transplant into the landscape. All trees, regardless of container type, doubled their root dry weight annually over the three-year study. We found no significant container effects for any measured root parameters one year after planting. However, two and three years following planting we found a greater percentage of total root growth beyond the original root ball for trees grown in RP and SP containers. Three years after planting, trees grown in BP containers had significantly more fine roots growing within the original root ball compared to RP- and SP-grown trees. There were no significant differences among container type for leaf water potential one and two years following planting. It is not possible to know if these establishment rooting differences will continue. However, we believe that fabric containers should be considered as an alternative to BP containers

because there appears to be greater potential for root growth beyond the original root ball and lesser potential for formation of circling and girdling roots within the original root ball.

3.1. Introduction

The most recent survey from the United States Department of Agriculture stated that sales of nursery crops in 2007 topped $6.5 billion (USDA, 2007). The largest sectors of production included broadleaf evergreens (18%), deciduous shrubs (14%), deciduous shade trees (13%) and coniferous evergreens (12%) (USDA, 2007).

Above-ground container nursery production makes up more than 75% of total nursery crop value in 17 of the top nursery producing states in the U.S. (USDA, 2008); it's estimated that 80-90% of woody plants produced in California, Florida and Texas are grown in containers (Davidson et al., 2000). Container tree production is a popular way to grow ornamental trees and is used more commonly than field production in many parts of the United States, especially in climates where subzero freezing temperatures are not a concern (Hodges et al., 2008). About 45% of deciduous shade tree commercial production in 2003 was produced in containers (USDA, 2004).

There are many advantages to woody plant container production, including ease of handling at the nursery, uniformity in plant growth, ease of shipping, consumer appeal, ability to produce more plants on less land, quicker turnover rate, intact root balls during production and a longer seasonal market for plant material (field-grown plants have a narrow window when they can be harvested and shipped) (Davidson et al., 2000; Gilman and Beeson, 1996; Harris and Gilman, 1991; Whitcomb, 2003). Many studies have compared field-grown (planted in the ground) trees to container-grown trees and found that containerized trees generally have better transplant success and less transplant shock issues (Gilman and Beeson, 1996; Harris and Gilman, 1991, 1993; Mathers et al., 2005). While early research solved some container production problems, efficiency in container production can be increased and some problems related to containerized plant production still exist.

Though the benefits may outweigh the drawbacks, there are numerous disadvantages to container production. Circling and/or malformed roots, a common problem with container-grown plant material, can negatively impact plant health and stability both in the nursery and landscape after transplanting (Nichols and Alm, 1983). The most common container used for nursery production is the black plastic container. Container price fluctuates based on current petroleum prices and these containers have both benefits and drawbacks. Black plastic containers are lightweight, durable, familiar to growers, well-suited for mechanization and can be reused or recycled. These containers are made from many different plastic types, melted and remolded for the desired shape and size. Roots deflected in plastic containers grow in many directions, including up, down or around the root ball; some roots may “kink” 180 degrees and go back the way they grew from, causing constrictions and circling roots (Gilman et al., 2010). Research has found that fabric containers have fewer circling/girdling roots compared to those grown in other smooth-sided containers (Gilman, 2001; Marshall and Gilman, 1998). But similar findings were published on the shape of the container—plants grown in square plastic (Warren and Blazich, 1991) or wood (Marshall and Gilman, 1998) also resulted in fewer circling roots. Often it comes down to the length of time the plant is grown in the container—the longer it is container-grown, the greater the chance for kinked or deformed roots (Gilman et al., 2010). Alternatives to black plastic containers include those containers with air root pruning technology, specialty container shapes, containers without bottoms, woven or non-woven fabrics, containers incorporating chemical compounds, and containers which utilize mechanical deflection (Brass et al., 1996; Marler and Willis, 1996). Containers using chemical compounds, including copper hydroxide coating (Struve et al., 1994), have had varying effects on growth and root:shoot ratios (Beeson and Newton, 1992; Arnold and Struve, 1989; Martin and Bhattacharya, 1995).

Fabric containers have been available to the industry for more than 20 years (Cole et al., 1998). Fabric containers are available in many sizes and shapes, but growers are not convinced that the benefits outweigh the negatives, as plastic containers are still the most commonly used type in the nursery industry. One advantage of fabric containers is the ability to continually “air prune” roots (James, 1987; Jones, 1987; Langlinais,1987; Reese, 1987; Marshall and Gilman, 1998; Gilman et al., 2010; Privett and Hummel, 1992). With air root pruning, the root tip is killed, which stimulates secondary root branching.

While producing plants with fewer deformed roots is the goal, effects on canopy and shoot growth must also be considered. One study found that pine trees grown in an air-pruning container had slower root and canopy growth (Ortega et al., 2006). Other studies found that alternative container types resulted in more or the same amount of roots for trees grown in standard black plastic (Arnold, 1996; Brass et al., 1996). Canopy and root growth were similar among various container types five months

(Marshall and Gilman, 1998) and five years after landscape planting (Fare, 2005). Long-term survival of trees planted into the landscape may be influenced by the container in which they are grown. Researchers Marler and Davies (1987) found that circling and/or kinked roots of citrus trees grown in black plastic containers resulted in uneven root development. Malformed roots that begin with container production can lead to later tree instability and possible failure (Lindstrom and Rune, 1999).

Container type can significantly affect root morphology of container-grown plants (Arnold, 1996; Gilman, 2001) once established into the landscape. The goal of the nursery grower is to produce plants that do not have circling or girdling roots, which lead to compromised root systems in the landscape (Nichols and Alm, 1983). A long-term study by Gilman et al. (2003) and Marshall and Gilman (1998), which examined production container effects on red maple root and canopy growth five months and five years after establishment, found significant container effects on deflected roots five months after planting. Five years after planting there were significant container effects on trunk caliper, with low profile air root pruning containers having the greatest caliper, but root weight and number of deflected roots before planting had no effect on root number, root depth and radial root distribution around the trunk in the landscape. However, irrigation frequency significantly affected establishment and radial root distribution, with more frequent irrigation resulting in more uniform root distribution. The authors did not evaluate root deformations (circling or kinked roots) in a standard method, but they concluded that container type did not have an effect on the quality of the root systems. Interestingly, frequent irrigation affected the number of roots <40 mm diameter—with a greater number of roots occurring in the top 30 cm of the soil profile.

Trees irrigated frequently had approximately 50% more root cross-sectional area than those receiving infrequent irrigation (Gilman et al., 2003).

The relative ratio of total root dry weight to total shoot dry weight is referred to as root:shoot ratio and takes into account total plant biomass. The basis for its use is derived from a water balance relationship—a certain amount of transpiring foliage needs a certain amount of roots to absorb soil water and offset transpirational losses (Bernier et al., 1995). It is thought that any cultural practice that reduces the root:shoot ratio is negative (i.e. overfertilizing to increase canopy growth), but a change in the relative weight of the roots and shoots may not be an accurate measure of the cultural effects on the tree's growth (Harris, 1992). In fact, except for root injury, a reduction in root:shoot ratio (greater shoots than roots) is almost always the result of more favorable growing conditions; an increase in root:shoot ratio (fewer shoots than roots) would infer that the tree may be under stress (Harris, 1992). The change in root:shoot ratio may also reflect the relative health and vigor of the plant and this may be the most useful reason for looking at root:shoot ratio. Harris (1992) also suggests that a more useful comparison may be to compare root surface area to the transpiration leaf surface.

Some factors affecting root:shoot ratio include plant species, growing environment, plant genetics and any cultural or management practices that affect growth; all of these factors, individually and in combination, will influence how a plant allocates resources (whether to shoot or root growth) (Reich, 2002). How these factors affect root:shoot ratio of container-grown nursery plants, compared to the same plant growing in a landscape, is unclear. One study concluded that root:shoot ratios have limited use with containerized nursery stock (Bernier et al., 1995), yet it's a common measurement used for forestry settings. While it is a common and easy measurement to make, root:shoot ratio may be less useful for research with container-grown plants. Further, various studies done with conifer seedlings in sandbeds found few differences in growth and survival using root:shoot ratios, especially in low-drought environments (Hocking and Endean 1974; Maass et al., 1989; Zasada et al., 1990).

Many studies have found that there are few differences in above-ground growth among various container types (Marshall and Gilman, 1998; Owen and Stoven, 2008; Neal, 2009), but O'Connor et al. (2013) found height and caliper differences among fabric and black plastic container types occurred during the second growing season for callery pear, with trees grown in fabric containers being taller and possessing greater caliper. Multiple studies have examined tree growth in the landscape as affected by nursery production method (Marshall and Gilman, 1998; Richardson-Calfee et al., 2010; Richardson-Calfee et al., 2007; Richardson-Calfee et al., 2008; Gilman et al., 2003; Schuch et al., 2000; Arnold, 1996; Brass et al., 1996; Gilman, 2001; Gilman and Kane, 1990; Gilman et al., 1996a; Gilman et al., 1996b; Green and Watson, 1989; Warren and Blazich, 1991; Gilman and Beeson, 1996a; Gilman and Beeson, 1996b; Watson, 1986; Watson, 1987; Watson and Himelick, 1982; Watson and Himelick, 1983). These studies are not commonly done due the time and labor-intensive nature of the research.

This research examined three-year landscape establishment effects on Chanticleer® pear after trees were grown in three container types (black plastic, Root Pouch® and Smart Pot®) in a nursery production setting for one season. The objective was to study root and canopy growth as affected by container type and to assess tree survival and establishment following transplant in the landscape.

3.2. Materials and Methods

3.2.1. Nursery Planting

Two year-old, lightly branched bare root whips of *Pryus calleryana* 'Glen's Form' (Chanticleer®) were planted into three container types on 7 May 2010 at the Colorado State University Plant Environmental Research Center (PERC), Fort Collins, CO (USDA hardiness zone 5a) (40.56 N, 105.08 W). Prior to planting, roots were rehydrated by soaking in water for 30 minutes. Trees were root pruned to eliminate broken or crossing roots. The three container types were: (a) 66 L (#15) standard black plastic container (BP) (Lerio Corp., Mobile, AL), (b) 66 L (#15) fabric container (RP) (Root Pouch®, Averna & Associates, Hillsboro, OR), and (c) 66 L (#15) fabric container (SP) (Smart Pot®, High Caliper Growing, Inc., Oklahoma City, OK). The container substrate (pH of 6.8, EC of 3.7 mmhos/cm and 39.6% organic matter) was a locally produced nursery mix (Organix Supply, Inc., Platteville, CO), which consisted of 40% composted wood products, 40% sphagnum peat moss, 10% dehydrated poultry waste, 5% bark fines and 5% volcanic pumice by volume. After planting, trees were fertilized by topdressing each container with 250 g of Osmocote Pro® 19N-2.1P-6.6K (The Scotts Company, Marysville, OH).

Five trees were destructively harvested for baseline measurements. At planting, trees averaged 17.7 mm (SE ± 2.8 mm) in trunk caliper (diameter) measured at a point 15.2 cm above soil line and 161.4 cm (SE ± 17.1 cm) in height. Containers were placed on the ground on black woven cloth in three rows on 0.9 m within row spacing between containers, and 1.8 m spacing between rows. Trees were attached by a 1.8 m bamboo stake to a wire trellis (3/32 gauge) 1.2 m above ground to prevent them from blowing over. Trees were placed in a randomized complete block design, with five replicates per container type and overwintering treatment. Trees were pruned to correct branching structure and remove damaged branches.

During the nursery establishment phase (approximately 6 months), trees were irrigated using a drip irrigation system with 12 in-line emitters per container. The drip system was constructed using 1.3 cm black plastic tubing (one line for each container type) for main lines, with 0.6 cm black spaghetti tubing connecting to 0.6 cm tubing with in-line emitters (12 per container) on 15.2 cm spacing. Irrigation was scheduled to run for approximately 15 minutes in the morning (Model 62040, Orbital® Irrigation Products, Inc., Bountiful, UT). Trees received 5.7 liters of water every other day during 2010. Height and caliper (measured at 15 cm above the container growing substrate surface) were measured monthly from June to September 2010.

3.2.2. Landscape Planting

In October 2010, 27 trees (three replications of three container types to be harvested over three years) were planted into *Poa pratensis* (Kentucky bluegrass), maintained as a home lawn. The turf area was mowed twice weekly (5 cm mowing height), irrigated to prevent drought stress (2.5 to 5 cm/week) and fertilized twice yearly with 48.8 kg N/HA. Soil type was a sandy clay loam, with a pH of 7.7, EC of 0.4 mmhos/cm and 6.4% organic matter. The native soil contained the recommended amounts of nutrients, so supplemental fertilizer was not added to trees, other than what was applied to the turf.

Trees were planted on 1.8 m^2 spacing, in three replicates, each containing 9 trees. Trees which were grown in each of the three container types and harvest date were randomly assigned to the replicates. Each replicate measured 40 m^2. Trees were planted to BMP standards with a saucer-shaped hole approximately three times as wide as the root ball (Watson and Heimlick, 2013). Trees were planted at 2.5 cm above soil grade. Following planting, trees were watered well and mulched with 5 to 10 cm of organic mulch covering the planting hole, but not the top of the root ball. Trees were not staked. Following planting, trees were irrigated with an in-ground irrigation system that watered both the turf and trees. Throughout the year, trees were only pruned to remove broken branches. Tree height and caliper was measured monthly during the 2011 to 2013 growing seasons. Trees harvested in 2011, 2012 and 2013 had height and caliper evaluated for one, two or three seasons; data in Figs. 3.1 and 3.2 are the height and caliper data for the trees harvested in 2013, but height and caliper were collected on those harvested trees in both 2011 and 2012.

Bi-weekly, during the 2011 and 2012 growing seasons (mid-May to September), leaf water potential (Ψ_L) was measured on two leaves per tree for each replicate per container type (3 trees total/container) to measure potential stress. Leaf water potential data was not collected in 2013 because trees were fully established. Selected leaves were located on the south side of the tree located in mid-canopy. Leaf water potential was measured using a pressure chamber (Model 600, PMS Instrument Company, Albany, OR) pressurized with compressed nitrogen. Measurements were taken between 2300 and 2400 hours. Leaf water potential data was compared to leaves taken from an established Chanticleer® pear tree, 25 years old, located approximately 150 m west of the planting area.

3.2.3. Harvesting Methods

In the fall of 2011, 2012 and 2013, nine trees (three from each container type) were destructively harvested. Tree leaf area (LiCor Model Li-3100, Milwaukee, WI) was estimated from subsample leaf area measured using leaves (the second leaf down from the terminal growing tip of the branch or leader) randomly collected from each side of the tree and from the central leader. At harvest, all remaining leaves were removed, weighed fresh, and oven-dried at 70C for one week to measure total leaf weight and to determine percent leaf moisture. Total tree leaf area was extrapolated for individual trees using the subsample leaf area and whole tree dry weights. New twig growth (measured on randomly selected branches on the north, south, east and west sides of trees, along with central leader), and total new twig growth, which was calculated by totaling individual shoot measurements (not including the leader measurements). Total leader growth was measured from the previous point of growth to the tip of the current season.

Trees were air spaded from the ground to attempt to keep the root system as intact as possible. Following air spading, trees were gently pulled from the ground, with the assistance of water to loosen roots that had grown beyond the air spade hole. After excavation, tree root balls were washed to remove as much soil as possible. Branches and trunk were separated from the root ball, weighed fresh and oven-dried at 70 C for one week to obtain shoot growth measurements. Root systems were placed on a template of the original container size and shape. Roots were pruned to obtain measurements of root regrowth for each of the three harvests. Root balls were oven-dried and weighed separately from roots that were cut and removed from the original root ball. Following drying, roots and the root ball were separated into fine (<2 mm) and coarse (>2.1 mm) root groups, and weighed to obtain fine and coarse root totals. Soil, rocks and other debris were discarded during the root separation process.

Root volume was determined using two displacement methods, depending on the size of roots to be measured. Large roots were submerged in a plastic 32-gallon outdoor-grade trash can with a small round opening cut into the side of the trash can, located approximately 10 cm below the can's rim, where a stainless, vented bottle pourer (measuring 7.5 cm long and 0.95 cm wide) was affixed horizontally with silicone caulk. To measure root volume, the trash can was placed on a level surface and filled with clean water, just until water started to flow through the bottle pourer. Water was allowed to stop dripping before roots were submerged. A clean and dry 18.9 L bucket was placed below the bottle pourer spout on a tared balance. The roots were gently lowered into the filled trash can and water was collected in the bucket below the spout; volume (in grams; 1 g = 1 mL) was calculated for the roots once the water ceased dripping from the spout. For smaller roots, a similar process was used, except a plastic graduated cylinder (250 mL capacity) was filled with clean water to 200 mL. Smaller roots were gathered into smaller, compressed bundles for easy insertion in the cylinder. Roots were completely submerged under the water, air bubbles removed by gently tapping, and readings were taken from the bottom of the meniscus. Displaced volume was recorded in mL and recorded as cm^3. The cylinder was rinsed with clean water between root samples; if samples were large, several measurements were taken.

All data were subject to analysis of variance (SAS Institute Inc., Cary, NC, version [9.4]) using a fixed effects model of analysis of variance. Least significant means were compared using the Tukey Range test.

3.3. Results

3.3.1. Above-ground Growth Data

2011 Results

There were no significant container effects for final height, caliper, shoot, leaf and total plant dry weight, root:shoot ratio, leader growth, average branch growth and average canopy growth for trees harvested in October 2011, after one growing season in the landscape (Table 3.1). Height and caliper were very similar among all container types, though trees grown in BP containers had greater caliper when planted (O'Connor et al., 2013). Shoot dry weight of the trees grown in the fabric containers (RP and SP) was larger compared to trees from BP containers, though not statistically significant (Table 3.1). Tree leader growth and average branch length was similar for all container types (Table 3.1). Container type was not found to affect above-ground growth in 2011.

2012 Results

There were no significant container effects for final height, caliper, shoot, leaf and total plant dry weight, root:shoot ratio, leader growth, average branch growth and average canopy growth for trees harvested in October 2012, two years following planting in the landscape (Table 3.1). As was found in 2011, above-ground growth for the trees was not significantly affected by container type in 2012.

2013 Results

There were no significant container effects for final height, caliper, shoot, leaf and total plant dry weight, root:shoot ratio, leader growth, average branch growth and average canopy growth for trees harvested in October 2013, three years after planting into the landscape (Table 3.1). This follows the trend found in 2011 and 2012, where there were no container effects on above-ground tree growth. Although shoot dry weight of trees grown in BP containers was over 1000 g greater than RP or SP shoot dry weight, this difference was not significant.

Monthly Height and Caliper 2011-2013

Height and caliper for trees grown in the three container types was not significant one, two and three years after planting into the landscape (Figs. 3.1 and 3.2). While both height and caliper increased each month, difference among container type was not significant, though trees from BP containers were both taller and had greater caliper each month throughout the experiment. Over the three years, total height increased by 185 cm (BP), 202 cm (RP) and 178 cm (SP). For caliper, the growth over three years increased by 43.5 mm (BP), 43.2 mm (RP) and 41.5 mm (SP).

3.3.2. Root Data (weight, percent and volume)

2011 Results

There were no significant differences among container type for total dry weight for: the root ball, root growth inside and outside the root ball, and total fine and coarse roots (Table 3.2). Fine and coarse root weight was not significantly different for measurements taken inside and outside the root ball. The container that resulted in the greatest total root ball dry weight was BP (1248.2 g), though it was not significantly greater than total root weight for RP- and SP-grown trees (1083.7 g and 1235.5 g, respectively) (Table 3.2).

There were no significant container effects for trees grown in the three container types for measurements based on root percent data (Table 3.3). This is likely due to the fact that the trees were establishing in 2011. Trees grown in fabric containers (RP and SP) had greater percent root re-growth beyond the original root ball compared to trees grown in BP, but it was a small difference and not significant (Table 3.3).

There were no significant container effects for trees grown in the three container types for root volume measurements (Table 3.4).Trees grown in BP containers had a greater number of total roots located inside the root ball, but it was not significant from RP or SP containers. Trees grown in BP containers also had the greatest root ball volume compared to RP- or SP-grown trees; again this difference was not significant. There were no significant container effects for trees grown in the tree container types for percent total root distribution inside or outside of the root ball, as well as percent distribution of fine versus coarse roots (Table 3.5). In 2011, 90-91% of the entire root ball by volume for all container types was coarse roots (Table 3.5).

2012 Results

There were no significant container effects for root dry weight data collected in 2012 (Table 3.2). As was the trend in 2011, total root ball dry weight was greatest for trees grown in BP containers, but this difference was not found to be statistically significant from trees grown in RP or SP containers.

There were no significant differences among the three containers for percent of root re-growth beyond the original root ball, percent of total coarse roots inside and outside the root ball and total roots growing within the root ball (Table 3.3). However, we found significant differences for percent root re-growth outside the original root ball for trees grown in BP containers (21.4%), compared to 30.0% and 27.3% for RP and SP, respectively. Trees from BP containers had more total coarse roots located within the root ball (77.0%) compared to RP (68.7%) and SP (71.5%) containers. In addition, a lower percentage of total coarse roots growing outside the root ball were found for BP containers (19.8%) compared to RP (27.9%) and SP (25.4%) containers.

There were no significant differences among the tree containers for any root volume measurements (Table 3.4). Similar to 2011, the total root ball volume was greatest for trees grown in BP containers, compared to RP and SP, but this difference was not significant. There were significant differences for percent of total coarse roots by volume inside the root ball, percent of total coarse roots by volume outside the root ball, percent of total roots by volume growing inside the root ball and percent of total roots by volume growing beyond the original root ball (Table 3.5). Trees grown in BP containers had the greatest percent of total coarse root growth by volume inside the root ball (73.0) compared to RP (64.3) and SP (67.4) containers. Conversely, there was a greater percent of coarse roots found by volume outside the root ball for RP (31.9) and SP (29.4) containers, compared to BP containers (23.3). This parallels to the total roots by volume found inside and outside the root ball—with trees grown in BP containers having the greatest percent of roots by volume inside the root ball and the least amount of roots by volume outside the root ball, compared to RP- and SP-grown trees that had fewer roots inside the root ball and greater roots outside the root ball.

2013 Results

Container type significantly affected total root ball dry weight, total dry weight of roots inside the root ball, total coarse root weight inside the root ball, total fine root weight outside the root ball and total fine and coarse root dry weight (Table 3.2). Trees grown in BP containers produced root systems that were significantly larger compared to RP and SP, as measured by total root ball dry weight (5875.3 g for BP vs. 4719.4 g for RP and 4395.1 g for SP), total dry weight inside the root ball (4220.0 for BP vs. 3059.4 for RP and 2757.0 for SP) and total coarse roots inside the root ball (4187.5 for BP vs. 3032.6 for RP and 2721.1 for SP). Total fine root weight was greatest for trees grown in SP containers (228.2 g) compared to BP (125.5 g) and RP (119.7 g) containers, while total coarse root dry weight was significantly lower for the two fabric containers (RP; 4599.8 g and SP; 4166.9 g) compared to BP containers (5749.9 g)

There were significant differences found for percent root re-growth outside the original root ball, percent of total coarse roots found inside and outside the root ball, percent of total fine roots outside the root ball and percent of total roots growing inside the root ball of the trees (Table 3.3). While BP-grown trees produced larger root balls (by weight) compared to RP and SP, a greater percent of roots remained within the original root ball (72.0% for BP vs. 65% for RP and 62.7% for SP). Trees grown in BP and RP containers had a greater percent total coarse root weight inside the root ball compared to SP (71.4% for BP and 64.4% for RP vs. 61.9% for SP). Trees grown in SP containers had the greatest total percent fine root development outside the root ball (4.4%) compared to BP and RP (1.6% and 2.0%, respectively).

There were significant container effects on the volume of the total coarse and fine roots inside the root ball, total volume of roots inside the root ball and the total volume of fine roots outside the root ball (Table 3.4). The container that resulted in the greatest root volume inside the root ball was BP (4243 cm^3), which was significantly different from SP (3248 cm^3); but not different from RP (3793 cm^3). Black plastic-grown trees had the greatest volume of fine root development (110 cm^3) compared to RP (69 cm^3) and SP (54 cm^3). Trees grown in BP and RP containers had the greatest volume of coarse roots inside the root ball (4134 and 3724 cm^3, respectively) compared to trees grown in SP containers (3194 cm^3). Total fine root volume was greatest for SP-grown trees (236 cm^3) compared to RP-grown trees (120 cm^3); trees grown in BP were intermediate (151 cm^3). There were significant container effects among the tree containers for total percent of root volume for percent of total coarse and fine roots inside the root ball, percent by volume of total coarse roots outside the root ball, percent by volume of total roots growing inside the root ball and total root growth percent by volume outside the original root ball (Table 3.5). There were greater coarse root volume (by percent) for trees grown in BP containers compared to SP containers; trees grown in RP were intermediate, but not significantly different from BP or SP. The percent of fine roots by volume was greatest for trees grown in SP containers (4.4%) compared to BP (2.5%) and RP (2.2%). The percent of total roots by volume growing inside the root ball was significantly different for BP-grown trees (69.6%) compared to SP-grown trees (60.5%); trees grown in RP were intermediate (64.8%). Root growth, as measured by percent volume, growing beyond the original root ball was greatest for SP-grown trees (39.5%) compared to BP-grown trees (30.4%); RP-grown trees was intermediate (35.2%). In 2013, the percent of total coarse roots by volume in the root ball was approximately 95% for all container types (Table 3.5).

Combined root mass data, volume and percent 2011-2013

Total root ball dry weight increased by 80% averaged across all containers from 2012 to 2013, and 320% for the duration of the experiment (2011 to 2013). There were significant container effects when results were combined and averaged over the three years for total root ball dry weight, total dry weight of roots inside the root ball, total coarse roots inside the root ball, total fine roots outside the root ball, and also total fine and coarse root weight (Table 3.2). Total root ball dry weight was greatest for trees grown in BP containers (3369.3 g) compared to RP (2808.1 g) and SP (2779.2 g), however the majority of these roots were located within the original root ball for trees grown in BP containers (2568.0 g) compared to RP (1955.5 g) and SP (1941.4 g). Fine root growth collected outside of the original root ball was greatest for trees grown in SP containers, having 60% more fine root mass compared to BP and RP (91.6 g for SP vs. 56.5 g for BP and 57.4 g for RP), with non-significant coarse root weight outside the root ball for all three containers. Fine root development within the original root ball, though not significant, was greatest for trees grown in BP containers; this correlates with the greater dry weight of total roots located within the original root ball.

For root percent averages based on the three years of data, there were significant differences among container type for percent of root re-growth beyond the original root ball, percent coarse roots inside the root ball, percent of fine and coarse roots outside the root ball and percent of total root growth inside the root ball (Table 3.3). One of the most important comparisons between BP and the fabric containers was the percent of root re-growth beyond the original root ball. Trees grown in BP only had 19.4% re-growth compared to RP (25.3%) and SP (24.9%). Percent fine root growth for roots outside the root ball was greatest for trees grown in SP (2.9%) compared to BP (1.8%) and RP (2.1%), though percent of coarse roots found outside the root ball was smallest for BP (17.6%) compared to RP (23.2%) and SP (21.9%).

There were significant differences among all years (2011 to 2013) by container for total fine roots by volume inside the root ball and total roots by volume inside the root ball (Table 3.4). The greatest amount of fine roots by volume inside the root ball occurred in trees grown in BP containers (79 cm^3), compared to RP (60 cm^3) and SP (53 cm^3). Trees grown in BP also had a greater volume of roots located inside the root ball (2597 cm^3) compared to SP (2155 cm^3); RP-grown trees were intermediate (2260 cm^3). There were also significant differences for total root volume percent for coarse roots located outside the root ball, percent of root volume growing inside the root ball and percent of total roots by volume outside the original root ball (Table 3.5). It was found that trees growing from BP containers had the greatest percent of coarse roots by volume inside the root ball (74.4%) compared to RP (69.2%) and SP (69.1%). Trees grown in BP containers had the greatest percent of roots by volume inside the root ball (77.4%) compared to RP and SP (72.0 and 71.6%, respectively). Conversely, trees grown in fabric containers had greatest coarse root volume outside the root ball (25.3% for RP and 24.9% for SP) compared to BP-grown trees (20.1%). Trees grown in fabric containers also had the greatest percent of root volume growing beyond the original root ball (28.4% for SP and 28.0% for SP) compared to trees grown in BP containers (22.6%).

3.3.3. Leaf Water Potential 2011-2012

Leaf water potentials did not differ significantly among container type in 2011 and 2012 when measurements were taken with the pressure bomb, nor were they statistically significant from measurements taken from an established Chanticleer® pear located within 500 m of the experiment (Table 3.6). Thought not significant, trees exhibited the greatest drought stress in early August 2011 and early September 2012, however these numbers varied only slightly from other readings taken during the two growing seasons.

3.4. Discussion

Similar to what other researchers have found, we found no container effects on height and caliper of trees harvested in 2011, 2012 and 2013 (Marshall and Gilman, 1998; Ortega et al., 2006; Owen and Stoven, 2008; Neal, 2009). Gilman et al. (2010) found few effects of container type on height and caliper occurred when transplanted trees were given adequate irrigation and fertility. Marshall and Gilman (1998) and

Gilman et al. (2003) found no effects of container type on height and caliper of red maple (*Acer rubrum* L.) five months and five years after planting in the landscape, respectively. Gilman et al. (2003) concluded that irrigation frequency for the first 24 weeks following transplant was a more important factor than container type in influencing establishment and above-ground plant growth. Water was never a limiting factor in our study, since we irrigated to replace Kentucky bluegrass ET, and we were not likely to see container effects on height and caliper of trees following transplanting into the landscape. Ortega et al. (2006) found that though there were container type effects on seedlings prior to transplant in the landscape, there were no differences in physiological effects and growth after transplanting. In that study, air pruning containers produced seedlings that were slower growing, which had lower biomass. Ortega et al. (2006) also found that closed-wall containers produced seedlings with more frequent root deformations. Following planting, the slower-growing air-pruned tree seedlings were more stable and had a more balanced stem and root development.

As with height and caliper, we saw no container effects on other above-ground growth measurements (total dry leaf and shoot weight and twig and leader growth) in 2011, 2012 and 2013. Based on individual above- and below-ground growth measurements, we conclude that our trees were establishing during the 2011 growing season, and were fully established in 2012 and 2013. This agrees with conclusions of other researchers, that carbohydrates are used to regenerate new roots of a transplanted tree – and, as a result, top growth may be significantly reduced until the new root system is sufficiently regenerated (Gilman et al., 1998; Lauderdale et al., 1995; Watson, 1985). Watson (1987) found that for each 2.5 cm of trunk caliper, it takes approximately one year to regenerate enough roots to be at a pre-transplant growth rate in USDA zone 5 (Chicago). It remains difficult to measure transplant success (Gilman, 1990; Struve et al., 2000; Watson, 1985). A study by Gilman (1997) found that in USDA zone 9 (Florida), a 5.1 cm tree established in six months, while the same species in USDA zone 5 takes 24 months to establish. Some arborists and horticulturists base transplant success on incremental new growth on branches

The slowed growth is most pronounced soon after planting, but as the roots reestablish, growth rates increase (Gilman and Beeson, 1996; Watson, 1987). While we observed growth reductions in 2011 compared to 2012 and 2013, the trees did not suffer from transplant shock, which is common following planting. According to Rietveld (1989), transplant shock can occur from tree injuries, depletion of nutrients/water and impaired functions; it's most often a process of recovery and a period of adaptation to a new environment. The trees in this study were planted to BMP standards with appropriate depth, planting hole size and regular irrigation following transplanting, re-establishment occurred primarily from 2012 on. We saw incremental growth increases throughout the experiment on all above-ground growth measurements.

Mature trees, grown under normal conditions, generally have a root:shoot ratio of 1:5 or 1:6 (Kramer, 1969; Perry, 1982). In our study, we saw root:shoot ratios of 1:1.4 to 1:2.1, depending on container type and year following transplant (no significant differences among container types; Table 3.1). Our numbers are lower, simply because our trees had yet not reached maturity. We found that root:shoot ratios decreased as the trees became established and the canopy size increased; this increased maturation could result in the final ratios found by Kramer (1969) and Perry (1982) for established trees.

Unlike Gilman et al. (2003), who found no container effects on rooting five years after red maples were planted in the landscape, we found significant quantitative container effects the second and third year following planting. While we did not develop a scale for measuring root system architecture quality, differences may exist between trees grown in fabric containers versus BP containers (Figs. 3.3, 3.4 and 3.5).

Trees were transplanted in fall 2010, and though the onset of cool weather can reduce root growth, Colorado soils in the Fort Collins area tend to stay warm and rarely freeze before late November (A. Koski, personal communication, 15 February 2014). It was found that it takes anywhere from 6 to 49 d for adventitious roots to form following transplanting (Arnold and Struve, 1989; Shoemake et al., 2004; Struve and Rhodus, 1998). Since our trees were planted in mid-October 2010, they were able to produce some roots before the ground froze (late November 2010). Roots grow quickly after planting if weather and soil conditions are conducive to growth (high soil moisture, warm soil temperatures, regular irrigation) (Gilman, 2014).

While the importance of fine root development on establishment success of landscape trees is unproven, it’s commonly stated that fine root development will aid in tree establishment (Ham and Nelson, 1998). In 2011 we saw greater fine root development within the root ball compared to 2012 and 2013. Frequent watering (as occurred in our study) is said to increase fine root development, and it may slow root maturation rate and slow root senescence (Zeleznik, 2006). Fine roots also aid in the absorption of water and nutrients in the soil (Persson, 1983).

The length of time it takes for trees to become fully established varies with the rate of root elongation and the original root spread (Watson, 1992). The expected rate of root elongation following establishment is 45.7 cm/year, though this is soil and species dependent. We found significantly greater root re-growth (re-establishment) with trees grown in fabric containers, compared to trees grown in BP containers. We attribute the greater root growth and lateral development with fabric containers to the fact that trees grown in fabric containers did not have circling roots prior to planting in the landscape.

Many studies have found that stem girdling roots (SGRs), which can result from circling roots from the container type at planting, can increase tree failure (Meilleur, 2009) due to compromised root systems. Johnson and Hauer (2000) found that 73% of lindens that failed in storms in Minnesota broke at the point where SGRs had constricted the stems. At a private institution in North Carolina, 400 trees of varying species were air spaded to expose the roots and over 75% of these trees were found to have SGRs (Meilleur, 2007). We found that trees grown in BP containers had signs of circling roots three years after transplanting (Fig. 3.3). We can only speculate that those roots would continue to circle and possibly form SGRs in the future. Trees grown in fabric containers had few noticeable circling roots and root systems had greater lateral branching (Figs. 3.4 and 3.5). While circling roots may not continue to grow in a circling pattern following transplant, the fact that they did form and continue to enlarge within the original root ball area, increases the potential for SGRs to form on those trees. Trees with compromised root systems at planting will continue to have compromised root systems long term. The presence of SGRs is a predictor of tree failure (Johnson and Johnson, 1999). While SGRs can be corrected following planting, it can be argued that correcting or preventing SGRs from potentially forming in the nursery or prior to landscape transplant, could be more beneficial and cost effective for tree care experts.

When our trees were planted into the landscape, the only corrective procedure (using 2011 tree planting BMPs) to eliminate circling roots was vertically slicing the root ball on the outside several times using a box cutter. Gilman et al. (2010) and Gillman (2011) found that shaving the roots from the outer periphery (2.5 cm) of the root ball leads to reduced circling and girdling roots. Had we practiced root shaving when transplanting trees in our study, we may have observed improved root systems with trees grown in BP containers – since root shaving has been found to increase straight, radial root production from the trunk (Gilman et al., 2010). This suggests an area of additional research—to compare shaving the root balls of BP containers with non-shaved fabric containers to determine if shaving corrects root deflects from container shape following transplanting and results in a better structured root system.

We have not found any research where entire landscape tree root systems have been excavated and separated by root size, nor any work where root volume has been measured for fine and coarse roots for excavated landscape trees. While a number of container studies have examined root growth during production, few studies have looked at root growth following landscape transplanting. One study (Gilman and Beeson, 1996) did examine post-transplant root establishment from three production methods (fabric-grown, plastic-grown or field-grown) for East Patalka holly and laurel oak, but their study excavated just one-quarter of the root system, after the trees had been in the ground for nine, 28 and 50 weeks. They found that field-grown and fabric container laurel oak generated more roots into the backfill soil at 9 and 28 weeks following transplant compared to plastic-grown oak; but at 50 weeks, only field-grown oak had greater root regeneration. For holly, it was found that field-grown trees had greater root regeneration at 28 and 50 weeks following transplant, compared to fabric-container holly, which was greater than plastic container-grown holly. The same study found that fabric grown holly and oak were also taller than plastic container-grown holly and oak. These finding contradict what we found: no above-ground growth differences among the three container types. However, these studies were done in Florida with soil and climate differences from Colorado.

We found significant container effects on root systems. First, trees grown in BP containers a greater percentage of roots (both weight and volume) that remained within the original root ball compared to trees grown in RP and SP containers. We also found there was a greater percent of root re-growth for the two fabric containers compared to trees grown in BP. We found greater fine root development for SP containers compared to BP. All trees were treated identically both in the nursery and following transplant (water, fertilizer, pruning), and we are convinced that container type can have long-term effects on the growth of trees transplanted into the landscape.

While environmental conditions which could incite plant stress (high temperatures, high solar intensity, high wind, and low relative humidity levels) often existed during this 3-year period, the trees never displayed stress that could be detected via leaf water potentials as measured by the pressure bomb. The summer of 2011 was one of the hottest in Colorado history (>90 days of 32.2C), yet trees did not show significant signs of stress during their establishing year, likely because they received regular irrigation (2.5-6.35 cm/week). Trees displayed the greatest amount of stress (as measured by the pressure bomb) in early August 2011 and early September 2013. However, these readings were considered to be normal for well-irrigated conditions, as described by the University of California-Davis Fruit and Nut Research, where in midsummer conditions in California water potentials were found to be between -6.0 and -10.0 bars (Shackel, 2014). Our trees were watered to replace Kentucky bluegrass ET, and this may explain why the trees exhibited little to no stress during hot and dry periods during the duration of the study. Our observed lack of stress agrees with the findings of Marshall and Gilman (1998) and Gilman et al. (2003), who examined the effects of irrigation frequency on establishment of red maples. They found that trees receiving regular irrigation during the first five months after planting had root systems twice as large as trees receiving less irrigation. Five years later, trees that received regular irrigation during the initial five months following planting had 50% greater root cross-sectional area compared to trees that received infrequent irrigation. Regular irrigation following transplanting can have a beneficial effect on tree root growth for up to six years, after which there were no effects (Fabio et al., 1995).

We found container effects on root volume during 2013 (but not in 2011 or 2012). Total root volume tended to double each year for the duration of the research. The greatest volume of roots was located within the original root ball. Trees grown in BP containers had significantly greater root volume weight compared to trees from RP or SP containers. The ratio of root volume outside:inside decreased throughout the duration of the experiment. Trees grown in BP had an outside:inside root volume ratio of 0.14, 0.31 and 0.44 for 2011, 2012 and 2013, respectively. Trees from RP containers had an outside:inside root volume ratio of 0.18, 0.51 and 0.55 for 2011, 2012 and 2013, respectively. Trees from SP containers had an outside:inside root volume ratio of 0.17, 0.47 and 0.66 for 2011, 2012 and 2013, respectively. As the experiment progressed, the outside:inside root volume increased each year. The ratio was much closer to 1:1 for trees grown in RP and SP containers by 2013 (1:1.8 and 1:1.5; compared to 1:2.3 for BP), meaning that the root development outside the root ball was nearly as great as what grew inside the root ball.

These root production ratios suggest that trees not only have become established by the third year, but also that there is a container effect on tree establishment. We believe that because the fabric containers did not have the significant amount of circling roots that BP-grown trees did at planting, the roots of trees grown in fabric containers had greater potential to extend laterally following planting in the landscape. While circling roots may continue to circle, they eventually do grow lateral roots off the circling roots following transplanting. We speculate that the resources necessary to form new lateral roots from circling roots delays root re-growth, compared to fabric containers, where roots continued on their lateral growth from within the original root ball. In this sense, establishment of trees grown in fabric containers may have an advantage, because establishment root growth is not delayed following transplanting.

Our research found that trees grown in fabric containers had fewer roots located within the original root ball three years after planting with greater lateral branching beyond the original root ball (Tables 3.2 and 3.3). Our results suggest that, in addition to producing healthier trees in the nursery (O'Connor et al., 2013), fabric containers result in healthier trees once planted in the landscape. It should be noted that our work was conducted with one tree species, and we are not suggesting that similar container effects will occur with all other tree species. Additional research is necessary with more coarsely rooted planted (oaks, ginkgoes) or those that have difficultly establishing. Also, this study only examined root growth over three growing seasons; long-term studies (5-10 years) are necessary to determine if the container effects we observed continue beyond 2-3 years following planting. We recommended that landscape contractors consider planting trees that have been produced in the fabric alternatives to black plastic, and that nursery producers more carefully consider growing trees in these containers.

Table 3.1. Shoot, root and leaf growth of *Pyrus calleryana* 'Glen's Form' grown in three container types (black plastic, Root Pouch® and Smart Pot®) and harvested after one, two and three years following planting in the landscape.

Container Type	Year	Height (cm)	Caliper[z] (mm)	Root dry weight (g)	Shoot dry weight (g)	Leaf dry weight (g)	Total plant dry weight (g)	Root:Shoot	Leader growth (cm)	Average branch growth (cm)	Average Canopy width (cm)
Black Plastic	2011	270	42.2	1248.2	1474.2	369.1	3091.5	0.70 (1:1.4)	47	29.7	94
	2012	351	57.3	2984.4	3579.3	972.5	7536.2	0.65 (1:1.5)	77	27.5	108
	2013	438	75.8	5875.3[a]	8662.1	1877.7	16415.1	0.56 (1:1.8)	97	31.1	160
Root Pouch®	2011	267	42.1	1083.7	1567.7	384.1	3035.5	0.55 (1:1.8)	49	26.8	88
	2012	329	57.2	2621.1	3576.1	978.7	7175.9	0.58 (1:1.7)	112	20.6	114
	2013	437	72.9	4719.4[b]	7878.4	1757.3	14355.1	0.49 (1:2.0)	93	38.5	142
Smart Pot®	2011	277	43.4	1235.5	1558.8	349.2	3143.5	0.65 (1:1.5)	42	30.1	88
	2012	345	59.3	2704.3	3676.6	1026.7	7407.6	0.59 (1:1.7)	94	28.2	108
	2013	410	72.1	4395.1[b]	7608.4	1635.1	13638.6	0.48 (1:2.1)	73	33.9	148

[z]Caliper measured at 15 cm above the soil surface

Trees planted into the landscape in October 2010

Means within years for each measurement followed by different letters are significantly different at *Pr ≥ F 0.05*.

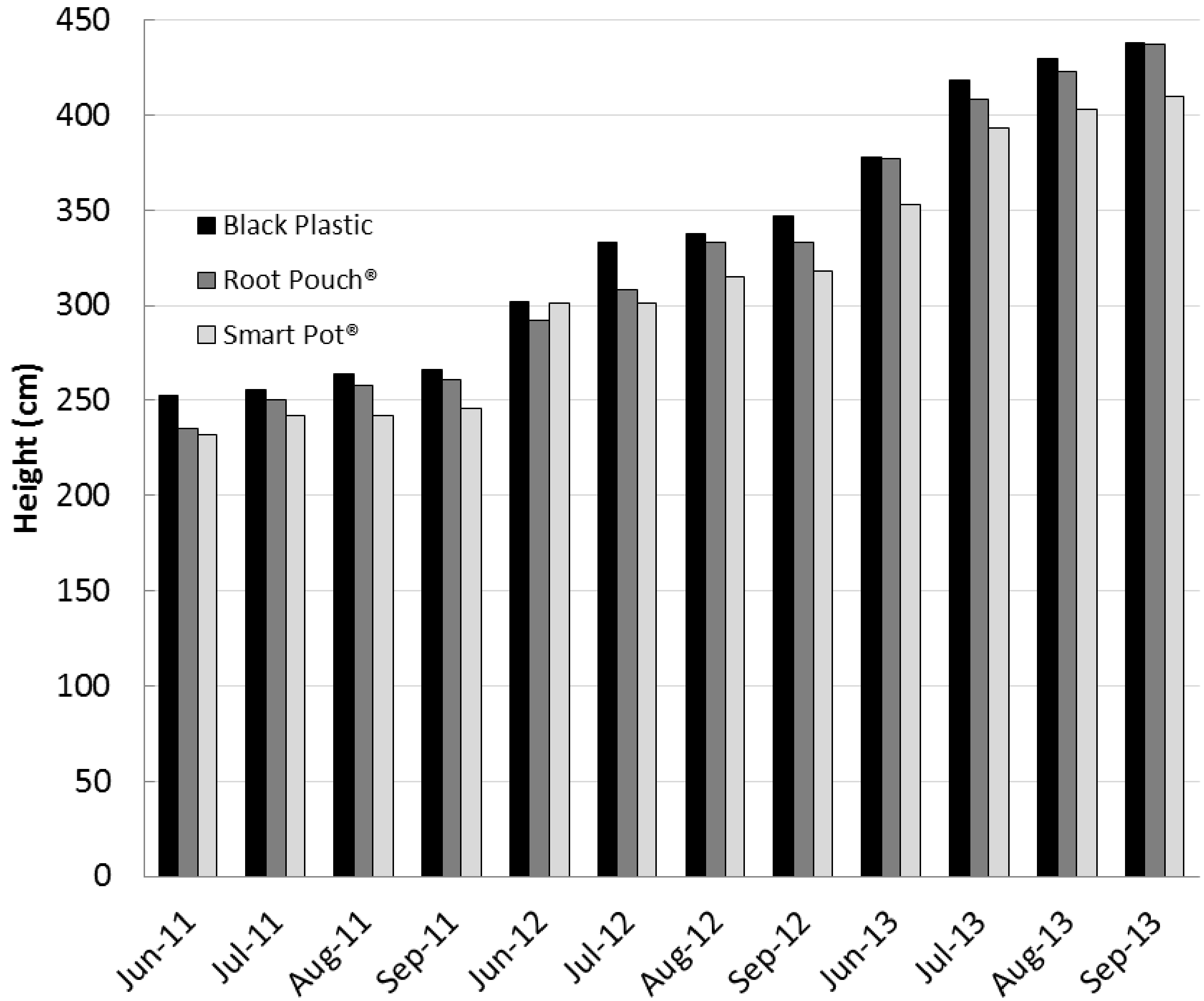

Figure 3.1. Monthly height of *Pyrus calleryana* 'Glen's Form' grown in three container types (black plastic, Root Pouch® and Smart Pot®) one, two and three years following planting in the landscape. There were no significant differences for container type at any date.

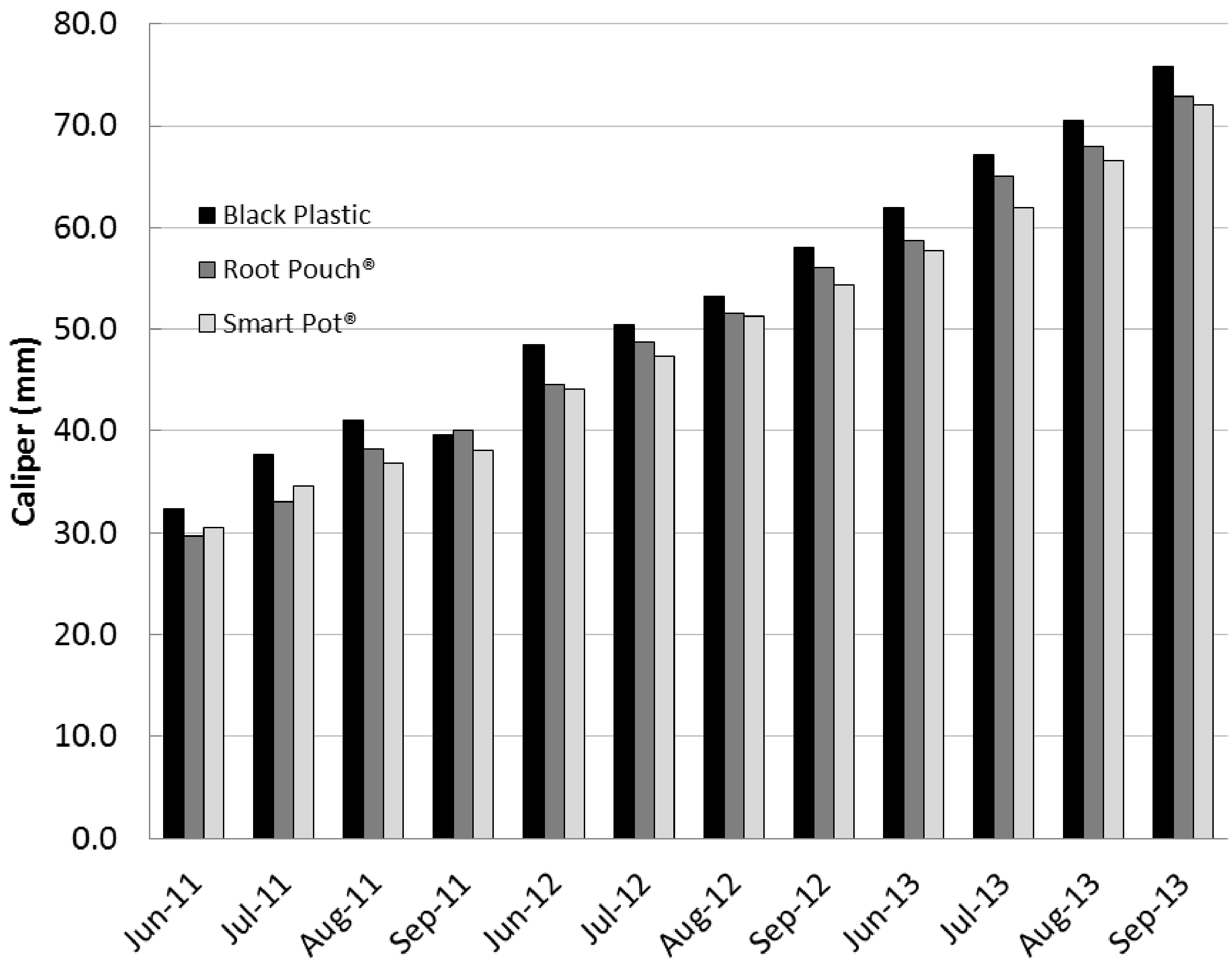

Figure 3.2. Monthly caliper of *Pyrus calleryana* 'Glen's Form' grown in three container types (black plastic, Root Pouch® and Smart Pot®) one, two and three years following planting in the landscape. There were no significant differences for container type at any date.

Figure 3.3. Root systems from trees grown in black plastic containers one, two and three years after transplanting. Notice roots in center of root ball in 2012 and 2013 that mimic the original container.

Figure 3.4. Root systems from trees grown in Root Pouch® containers one, two and three years after transplanting. The root systems from these containers are more laterally branched without root deflects from the original container.

Figure 3.5. Root systems from trees grown in Smart Pot® containers one, two and three years after transplanting. Roots are laterally branched and show no deflects from the shape of the original container.

Table 3.2. Root weight and distribution of *Pyrus calleryana* 'Glen's Form' grown in three container types (black plastic, Root Pouch® and Smart Pot®) and harvested after one, two and three years following planting in the landscape.

Container Type	Year	Total root ball dry weight (g)	Total dry weight root growth outside root ball (g)	Total dry weight roots inside root ball (g)	Total fine roots (≤2.0 mm) inside root ball (g)	Total coarse roots (>2.1 mm) inside root ball (g)	Total fine roots (≤2.0 mm) outside root ball (g)	Total coarse roots (>2.1 mm) outside root ball (g)	Total fine roots (g)	Total coarse roots (g)
Black Plastic	2011	1248.2	105.9	1142.3	161.6	980.7	25.8	80.1	187.4	1060.8
	2012	2984.4	642.7	2341.7	45.5	2296.3	50.8	591.8	96.3	2888.1
	2013	5875.3[a]	1655.4	4220.0[a]	32.5	4187.5[a]	93.0[a]	1562.4	125.5[a]	5749.9[a]
Root Pouch®	2011	1083.7	117.9	965.7	112.7	853.0	24.4	93.5	137.1	946.5
	2012	2621.1	779.8	1841.3	34.3	1807.0	55.1	724.7	89.3	2531.8
	2013	4719.4[b]	1660.0	3059.4[b]	26.8	3032.6[b]	92.8[a]	1567.2	119.7[a]	4599.8[b]
Smart Pot®	2011	1235.5	125.5	1113.0	147.0	966.1	33.4	92.1	180.4	1058.1
	2012	2704.3	749.7	1954.3	33.7	1920.6	49.1	700.6	82.8	2621.2
	2013	4395.1[b]	1638.1	2757.0[b]	35.9	2721.1[b]	192.3[b]	1445.8	228.2[b]	4166.9[b]
Black Plastic	All years	3369.3[a]	801.3	2568.0[a]	79.8	2488.2[a]	56.5[a]	744.8	136.4[a]	3232.9[a]
Root Pouch®	All years	2808.1[b]	852.6	1955.5[b]	57.9	1897.5[b]	57.4[a]	795.2	115.4[b]	2692.7[b]
Smart Pot®	All years	2779.2[b]	837.8	1941.4[b]	72.2	1869.2[b]	91.6[b]	746.2	163.8[a]	2615.4[b]

Means within years for each measurement followed by different letters are significantly different at *Pr ≥ F 0.05*.

Table 3.3. Percent root distribution of *Pyrus calleryana* ‘Glen’s Form’ grown in three container types (black plastic, Root Pouch® and Smart Pot®) and harvested after one, two and three years following planting in the landscape.

Container Type	Year	Percent root growth beyond the original root ball	Percent of total fine roots (<2.0 mm) inside the root ball	Percent of total coarse roots (≥2.1 mm) inside the root ball	Percent of total fine roots (<2.0 mm) outside the root ball	Percent of total coarse roots (≥2.1 mm) outside the root ball	Percent total fine (≤2.0 mm) roots for entire root ball	Percent total coarse (>2.1 mm) roots for entire root ball	Percent of total roots growing inside the root ball
Black Plastic	2011	8.6	13.0	78.5	2.1	6.5	15.0	85.0	91.5
	2012	21.4[b]	1.5	77.0[a]	1.7	19.8[b]	3.2	96.8	78.6[a]
	2013	28.1[b]	0.6	71.4[a]	1.6[b]	26.4[b]	2.2	97.8	72.0[a]
Root Pouch®	2011	10.8	9.7	79.5	2.2	8.6	12.0	88.1	89.2
	2012	30.0[a]	1.3	68.7[b]	2.1	27.9[a]	3.4	96.6	70.0[b]
	2013	35.0[a]	0.6	64.4[a]	2.0[b]	33.0[a]	2.6	97.4	65.0[b]
Smart Pot®	2011	10.1	12.0	77.9	2.7	7.4	14.7	85.3	89.9
	2012	27.3[a]	1.3	71.5[b]	1.8	25.4[a]	3.1	96.9	72.7[b]
	2013	37.3[a]	0.8	61.9[b]	4.4[a]	32.9[a]	5.2	94.8	62.7[b]
Black Plastic	All years	19.4[b]	5.0	75.6[a]	1.8[b]	17.6[b]	6.8	93.2	80.7[a]
Root Pouch®	All years	25.3[a]	3.9	70.8[b]	2.1[b]	23.2[a]	6.0	94.0	74.7[b]
Smart Pot®	All years	24.9[a]	4.7	70.4[b]	2.9[a]	21.9[a]	7.7	92.3	75.1[b]

Means within years for each measurement followed by different letters are significantly different at *Pr ≥ F 0.05*.

Table 3.4. Root volume of *Pyrus calleryana* 'Glen's Form' grown in three container types (black plastic, Root Pouch® and Smart Pot®) and harvested after one, two and three years following planting in the landscape.

Container Type	Year	Total roots >2mm inside root ball (cm^3)	Total roots < 2mm inside root ball (cm^3)	Total roots inside root ball (cm^3)	Total roots < 2mm outside root ball (cm^3)	Total roots > 2mm outside root ball (cm^3)	Total roots outside root ball (cm^3)	Total root ball volume (cm^3)
Black Plastic	2011	1058	75	1133	39	117	155	1288
	2012	2362	53	2415	68	757	825	3240
	2013	4134[a]	110[a]	4243[a]	151[ab]	1700	1851	6094
Root Pouch®	2011	862	62	924	38	124	162	1086
	2012	2016	48	2064	69	984	1053	3116
	2013	3724[ab]	69[b]	3793[ab]	120[b]	1950	2070	5862
Smart Pot®	2011	983	63	1047	50	127	177	1223
	2012	2129	41	2170	61	955	1017	3187
	2013	3194[b]	54[b]	3248[b]	236[a]	1899	2135	5382
Black Plastic	All years	2518	79[a]	2597[a]	86	858	944	3540
Root Pouch®	All years	2200	60[b]	2260[ab]	76	1019	1095	3355
Smart Pot®	All years	2102	53[b]	2155[b]	116	994	1109	3264

Means within years for each measurement followed by different letters are significantly different at $Pr \geq F\ 0.05$.

Table 3.5. Percent root volume of *Pyrus calleryana* 'Glen's Form' grown in three container types (black plastic, Root Pouch® and Smart Pot®) and harvested after one, two and three years following planting in the landscape.

Container Type	Year	Percent of fine roots (<2.0 mm by volume) inside the root ball	Percent of coarse roots (≥2.1 mm) by volume inside the root ball	Percent of fine roots (<2.0 mm) by volume outside the root ball	Percent of coarse roots (≥2.1 mm) by volume outside the root ball	Percent fine roots (≤2.0 mm) by volume for entire root ball	Percent coarse roots (>2.1 mm) by volume for entire root ball	Percent of total roots by volume growing inside the root ball	Percent of total roots by volume beyond the original root ball
Black Plastic	2011	5.8	82.2	3.0	9.0	8.8	91.2	88.0	12.1
	2012	1.6	73.0[a]	2.1	23.3[a]	3.7	96.3	74.7[a]	25.3[a]
	2013	1.8	67.8[a]	2.5[b]	27.9[b]	4.3	95.7	69.6[a]	30.4[b]
Root Pouch®	2011	5.6	79.9	3.4	11.1	9.0	91.0	85.5	14.5
	2012	1.5	64.3[b]	2.3	31.9[b]	3.8	96.2	65.8[b]	34.2[b]
	2013	1.2	63.6[ab]	2.2[b]	33.0[ab]	3.4	96.6	64.8[ab]	35.2[ab]
Smart Pot®	2011	5.2	80.4	4.1	10.4	9.2	90.8	85.5	14.5
	2012	1.3	67.4[ab]	2.0	29.4[b]	3.3	96.7	68.7[b]	31.3[b]
	2013	1.0	59.6[b]	4.4[a]	35.1[a]	5.4	94.6	60.5[b]	39.5[a]
Black Plastic	All years	3.1	74.4[a]	2.5	20.1[b]	5.6	94.4	77.4[a]	22.6[b]
Root Pouch®	All years	2.8	69.2[b]	2.6	25.3[a]	5.4	94.6	72.0[b]	28.0[a]
Smart Pot®	All years	2.5	69.1[b]	3.5	24.9[a]	6.0	94.0	71.6[b]	28.4[a]

Means within years for each measurement followed by different letters are significantly different at *Pr ≥ F 0.05*.

Table 3.6. Leaf water potential for *Pyrus calleryana* 'Glen's Form' grown in three container types (black plastic, Root Pouch® and Smart Pot®) during 2011 and 2012.

Container Type	Year	June #1[y] (bars)	June #2 (bars)	July #1 (bars)	July #2 (bars)	August #1 (bars)	August #2 (bars)	September (bars)
Established Tree[z]	2011	5.0	5.0	3.3	4.5	7.0	5.8	5.3
	2012	5.5	5.5	5.0	3.0	5.3	5.5	5.0
Black Plastic	2011	5.6	5.6	5.0	5.3	4.5	4.9	5.3
	2012	6.1	5.2	5.1	4.6	7.1	5.6	6.6
Root Pouch®	2011	6.5	5.4	4.8	4.3	4.0	4.8	5.0
	2012	6.1	5.1	4.7	3.8	5.9	5.7	6.9
Smart Pot®	2011	6.6	5.9	5.4	5.0	4.5	5.3	5.2
	2012	6.9	6.2	5.6	4.8	5.6	5.3	6.0

[z]Established tree was a single specimen and statistics were not administered; two leaves were tested per date; average of both leaves shown in above table for reference only.

[y]Leaf water potential was collected twice per month during the growing season, except in September for both 2011 and 2012.

There were no significant container effects on leaf water potential at any date.

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CHAPTER 4

EVAPORATIVE AND TRANSPIRATIONAL WATER LOSS FROM THREE CONTAINER TYPES: BLACK PLASTIC, ROOT POUCH® AND SMART POT® IN A GREENHOUSE AND OUTDOORS

4.0 Summary

One obstacle to the adoption of fabric containers by the nursery industry is the concern that production using fabric containers will require greater and/or more frequent irrigation than plants produced in black plastic (BP) containers. This study examined evaporative water loss from three container types in the greenhouse: BP, Root Pouch® (RP) and Smart Pot® (SP). An outdoor study, using *Viburnum trilobum* 'Compactum', was conducted to examine evapotranspirative loss from the three container types. In the greenhouse study, BP containers lost half as much water as the fabric containers over four weeks. Water loss from the two fabric containers was significantly more rapid than that of the BP containers during the first 11 days, with more gradual water loss occurring thereafter. When the fabric containers were wrapped with plastic wrap to prevent sidewall water loss, they still lost twice as much water then BP containers. Total potential evapotranspiration (PET) for fabric containers was greater than that of BP-grown plants. When irrigated at 75% of black plastic PET (BP-PET), the cumulative ET for RP-grown plants over a two weeks period was significantly lower than that of BP or SP; at 50% of BP-PET, there were no container effects on ET. Similar to ET (and likely related to) rates, BP and SP had significantly higher ET rates than did RP-grown

shrubs. In a second experiment, BP containers irrigated at 50% of BP-PET had significantly greater ET loss than both fabric container types. These results suggest that newly planted fabric containers (where water loss is mostly evaporative and not transpirational) may require greater irrigation needs than plants growing in BP containers. However, as plants in containers become more established and container water loss becomes more a combination of evaporation and transpiration, plants growing in fabric containers may have irrigation needs similar to or less than that of plants growing in black plastic.

4.1 Introduction

Above-ground container nursery production makes up more than 75% of total nursery crop value in 17 of the top nursery producing states in the U.S. (USDA, 2008); it is estimated that 80-90% of woody plants produced in California, Florida and Texas are grown in containers (Davidson et al., 2000). Container production is a popular way to grow ornamental woody plants and is used more commonly than field production in many parts of the United States, especially in climates where subzero freezing temperatures are not a concern (Hodges et al., 2008). About 50% of deciduous shade tree commercial production in 2006 was in containers (USDA, 2007).

Some advantages of woody plant container production include: ease of handling at the nursery, during shipping and for the consumer; uniformity of plant growth; greater consumer appeal (compared to bare root and ball and burlap plants); ability to produce more plants on less land; shorter production cycle; consumer receives a plant having an intact root ball; and a longer seasonal market for plant material (field-grown plants have a narrow window when they can be harvested and shipped) (Davidson et al., 2000; Gilman and Beeson, 1996; Harris and Gilman, 1991; Whitcomb, 2004).

Though the benefits may outweigh the drawbacks, there are numerous disadvantages to container production of nursery stock compared to field production. These include: cost of planting substrate, container cost, increased fertilizer requirement, higher potential for nutrient and chemical leaching and runoff, and increased labor requirement (for potting and overwintering operations, where necessary).

The most commonly used container for nursery production is the black plastic (BP) container. While they tend to be inexpensive (though cost depends on current petroleum prices), BP containers present both benefits and drawbacks to the grower and consumer. Black plastic containers are lightweight, durable, familiar to growers, well-suited for mechanization and can be reused or recycled (though this does not commonly occur). Circling and/or malformed roots, a common problem with container-grown plant material, can negatively impact plant health and stability both in the nursery and landscape after transplanting (Nichols and Alm, 1983). Another drawback is increased irrigation requirements, due to substrate with greater pore space and less volume compared to field soil (Davidson et al., 2000). Further, plastic containers used in container production add to landfill waste, as many containers are not reused or recycled. It was estimated that 408 million pounds of plastic (from containers, cell packs, greenhouse film and trays) are generated by the nursery and floriculture industries; of that, roughly 240 million pounds (58.8%) was plastic containers (Garthe and Kowal, 1993). Another negative is the winter protection needed for container crops in cold climates (Davidson et al., 2000).

Fabric containers have been available to the industry for several decades (Cole et al., 1998), and are available in many sizes and shapes. Their use has not been widely adopted by growers, who apparently remain unconvinced that the benefits of using fabric alternatives outweigh the negatives; BP containers are still the most commonly used type in the nursery industry. One proposed advantage of using fabric containers is their ability to continually "air prune" roots (James, 1987; Jones, 1987; Langlinais, 1987; Reese, 1987; Marshall and Gilman, 1998; Gilman et al., 2010; Privett and Hummel, 1992). Due to the rigidity and smoothness of the sidewalls, woody plants grown in plastic containers often have a greater occurrence of circling roots on the outer periphery of the root ball. Fabric containers may produce "more natural" root system because of the air root pruning effects on growing roots; however, this effect depends on the length of time the plants are grown in the container. Roots deflected in plastic containers grow in many directions, including upwards, downwards, and in a circular fashion around the developing root ball; some roots may "kink" 180 degrees and grow backwards in the container, causing constrictions and circling roots (Gilman et al., 2010). Research has found that fabric containers may produce plants having root systems with fewer circling/girdling roots compared to those grown in smooth-sided containers (Gilman, 2001; Marshall and Gilman, 1998). Perhaps the greatest barrier to the adoption of fabric containers for nursery production is the assumption that irrigation amount and/or frequency will be greater than that of BP-produced plants, due to the very porous nature of the container sidewalls and bottom.

Few studies have compared the irrigation requirements of woody plants grown in fabric and plastic containers. One study suggested no differences in container water loss for fabric and plastic containers once plants were established, but that differences may occur as plants are establishing (J. Owen, personal communication, 2013). Due to the semi-porous materials that are used to manufacture fabric containers, there would appear to be greater potential for water to be lost from the sidewalls of the container - unlike with plastic pots. Wang et al. (2012) found that the average water use of euonymus plants grown in paper and wood pulp containers were up to 3-5 times greater compared to plastic containers. Containers comprised of organic materials (peat, wood fiber and manure) had the highest sidewall evaporation rates; bioplastics, solid rice hull and plastic had the lowest evaporation rates (Nambuthiri et al., 2012). While not a woody plant, a study by Taylor et al. (2010) found that geraniums produced in 10 cm plastic containers required 2.1 liters of water, compared to wood fiber containers, which required 4.2 liters.

Our research examined evaporative and evapotranspirative water loss of two fabric containers (Root Pouch® and Smart Pot®), compared to black plastic. In a greenhouse study we examined evaporative water loss from containers that had no plants in them. In a field study, daily gravimetric and volumetric soil moisture measurements were made to determine if container type affected evapotranspirative loss of established viburnums grown in containers. We hypothesized that plants grown in fabric containers would lose water more quickly than plants grown in BP containers.

4.2 Materials and Methods

4.2.1 Greenhouse Study

This study took place in a greenhouse on the Colorado State University campus (Fort Collins, CO). The three container types used in this study were: black plastic (BP) (Lerio Corporation, Kissimee, FL.), Root Pouch® (RP) (Hillsboro, OR.) and Smart Pot® (SP) (High Caliper Growing-Root Control Inc., Oklahoma City, OK.). In January 2013, the #5-size (13.8 L) containers were filled with potting substrate (Nature's Yield Outdoor Planter's Mix; Organix Supply, Inc., Platteville, CO) to equivalent bulk densities (0.35 g/cm^3). The substrate consisted of 40% composted wood products, 40% sphagnum peat moss, 10% dehydrated poultry waste, 5% bark fines and 5% volcanic pumice. Containers were hand-watered daily, from above, for several days to ensure that the substrate in all containers was thoroughly moistened. No plant material was used in the greenhouse study. Experiments were repeated; 21 January to 15 February 2013 (26 days) (Experiments 1a and 1b) and 20 February to 18 March 2013 (27 days) (Experiments 2a and 2b).

Two studies occurred simultaneously during each time period. The first study examined container water loss over time, using five replications of each container type (Experiments 1a and 1b). The second study compared water loss from RP and SP containers wrapped with two layers of plastic food wrap on the outer surface (measuring 5580 and 6200 cm^2, respectively) to BP and non-wrapped RP and SP containers (Experiments 2a and 2b). Containers were placed in a randomized complete block design for all experiments.

At the beginning of each study period, all containers were watered to field capacity and allowed to drain for 24 hours prior to the commencement of weighing. The greenhouse temperature was set at 29.4C day and night, with venting occurring at 32.4C. An atmometer was placed in the greenhouse to record daily evapotranspiration (ET). Each morning, between 0800 and 1000 hours, containers were weighed and volumetric water content (VMC) was measured (ThetaProbe Soil Moisture Sensor, model ML3; Dynamax Inc., Houston, TX). Data collection ceased when VMC was zero for the majority of containers (26 and 27 days respectively, for each experiment).

4.2.2 Outdoor Study

This study took place at the Plant Environment Research Center, located at Colorado State University (Fort Collins, CO). In May 2013, 20.5 cm bare root *Viburnum trilobum* 'Compactum' (American cranberrybush viburnum) were potted (Nature's Yield Outdoor Planter's Mix; Organix Supply, Inc., Platteville, CO) into #5 (13.8 L) containers identical to those used in the greenhouse study. The substrate was the same as was used in the greenhouse study. Shrubs were hand-watered to moisten substrate to field capacity and then irrigated using an in-line drip irrigation system for 10 minutes/day (total irrigation applied was 5.7 L/day) to aid in establishment. Following planting, shrubs were fertilized by topdressing with 130 g/container of Osmocote Pro® 19N-2.1P-6.6K (The Scotts Company, Marysville, OH). Shrubs were allowed to establish for three months prior to beginning the experiment.

Two deficit irrigation experiments were conducted on the established plants, the first from 10 August to 23 August 2013 (14 days; Experiment 75/50) and the second from 24 August to 7 September 2013 (15 days; Experiment 50/25). Experiment 75/50 imposed deficit irrigation levels of 75% and 50% of potential evapotranspiration (PET; well-watered BP containers); Experiment 50/25 examined deficit irrigation levels of 50% and 25% of PET. Potential ET was determined for each container type (3 replications; two experiments PET1 and PET2), but all containers were deficit irrigated using a percentage of black plastic PET. Plants were covered with a 4 mil clear plastic sheet when rainfall was imminent; the sheet was removed immediately following the rain event. Within each study there were five replications for each container type and treatment placed in a randomized complete block design.

Daily PET, for the purpose of irrigation replacement for all container types, was determined by weighing control BP containers and calculating water lost from the previous day's weighing; the weight difference from the previous day was assumed to be evapotranspirative water loss – and thus PET. Water lost from the BP containers (used for the determination of PET) was immediately replaced. All non-control containers were weighed (ET from the previous day was calculated) and then were deficit-irrigated using the appropriate percentage of PET determined for that day (25%, 50% or 75% of BP PET). In addition to measuring daily ET, VMC of each container was measured daily, prior to container irrigation. After two weeks, the shrubs from the 25% of PET irrigation treatments were experiencing visible dieback and leaf scorching, ET loss rates were minimal and VMC readings were unstable.

Following the completion of all experiments, top growth was cut off at substrate level, bagged and dried at 70 C for 72 hours; roots were washed, bagged and dried in a similar manner to shoots. Dry weights for roots and shoots were recorded and root:shoot ratio was calculated.

All data from both the greenhouse and outdoor nursery study were subject to analysis of variance (SAS Institute Inc., Cary, NC, version [9.4]) using a fixed effects model of analysis of variance. Least significant means were compared using the Tukey Range test.

4.3. Results

4.3.1. Greenhouse study—containers and substrate only

Black plastic (BP) containers lost the least amount of water (as measured gravimetrically), and had significantly higher volumetric water content (VMC) than the two fabric containers at the conclusion of both greenhouse experiments. Black plastic containers lost a total of 2383 and 2905 g of water in Experiments 1a and 1b, respectively (Table 4.1). The two fabric containers behaved in a similar manner to each other, losing significantly more water than BP and having much lower final average VMC levels at the conclusion of both experiments. Root Pouch® (RP) lost 4542 and 5268 g of water, respectively, in Experiments 1a and 1b, while Smart Pot® (SP) lost 5339 and 6269 g (Table 4.1). The differential volumetric water content (VMC) loss (between beginning and end of the experiment) for BP containers was 18.5 and 21.3% for the two experiments, compared to 24.1 and 24.7 for RP, and 24.0 and 29.8 for SP containers (Table 4.1).

The two fabric containers lost water more quickly at the beginning (first 7 days) of both experiments and more slowly thereafter; conversely BP containers lost water in a steady, linear fashion in both experiments (Fig. 4.1). At the conclusion of both experiments, the fabric containers had near-zero VMC (0.5 and 0.4% for RP; 3.8 and 1.9% for SP) levels, while the VMC for BP containers was significantly higher, 12.5 and 10.7% (Figs. 4.1 and 4.2).

Similar to what was observed with VMC, gravimetric water loss for both fabric containers was rapid during the initial 7 days of the experiment, compared to BP, which displayed a steady, linear loss of water (Figs. 4.3 and 4.4). At the end of both experiments, BP containers had not only lost the least amount of gravimetric water, but also had higher final VMC levels compared to RP and SP. Of all containers, SP lost the most gravimetric water and had the greatest decline in VMC from the beginning to the end of both experiments (Figs. 4.1, 4.2, 4.3 and 4.4).

4.3.2. Greenhouse study—Wrapped and unwrapped containers

Black plastic containers lost significantly less water than both plastic-wrapped and unwrapped fabric containers in Experiments 1b and 2b (Table 4.2). Though fabric containers were wrapped to prevent evaporative loss from sidewalls, they still lost a greater amount of water than BP containers, but not as much as unwrapped fabric containers (Table 4.2). For RP containers, the plastic prevented about 600 g of water loss, while non-wrapped SP containers lost 800 g more than plastic-wrapped SP containers (Table 4.2). Wrapping fabric containers in plastic did not decrease VMC as significantly as gravimetric moisture loss was affected by wrapping in plastic (Table 4.2). Whether containers were wrapped or not, fabric containers still lost more water and lost water more quickly than BP containers.

Gravimetrically, all fabric containers, whether wrapped or unwrapped, lost water in a curvilinear fashion compared to BP containers, which was linear (Figs. 4.5 and 4.6). Unwrapped fabric containers lost the greatest amount of water during the two experiments and weighed the least at the conclusion of the experiments (Figs. 4.5 and 4.6). As was found in the 3-container experiment described above, fabric containers, whether wrapped or unwrapped, lost a great deal of water during the first 7 days of the experiment, compared to BP containers. They also lost water very slowly beginning at day 15 through the end of the experiment. Black plastic containers lost water in a more consistent manner throughout the entire experiment, with a gradual decrease each day. At the end of the experiment, however, BP containers and the wrapped fabric containers had very similar weight, compared to unwrapped fabric containers (Figs. 4.5 and 4.6). Clearly, there is significantly greater loss of water from fabric sidewalls than from BP containers under identical environmental conditions.

The substrate in the containers had a linear VMC regression, with unwrapped fabric containers having the greatest percent VMC loss at the end of the experiment, compared to BP and wrapped fabric containers (Figs. 4.7 and 4.8). Black plastic containers had the greatest VMC at the beginning and conclusion of the experiments; plastic-wrapped fabric containers had greater VMC than non-wrapped fabric containers (Figs. 4.7 and 4.8). Both wrapped and unwrapped containers behaved in similar ways, though the plastic did seem to prevent some moisture loss from sidewalls. We suspect that water was lost more rapidly from sidewalls of the fabric container (due to greater surface area) than from the substrate surface in the center of the containers - where we took VMC measurements. This might explain why we observed differences among the container types in moisture loss, as measured gravimetrically, but differences among container types in VMC were not apparent.

In Experiment 2b, we found unusual VMC readings from day 8 to 10. We suspect this was caused by measurement error (by a substitute data collector) and was not caused by any container effects (Fig. 4.8). These data points affected the slope of the regression lines and make it appear that water loss from the containers differed between the two experiments. When the points are removed, the regression lines for both experiments appear quite similar – suggesting that the containers behaved similarly in both experiments 2a and 2b (Fig. 4.8).

As was found in the 3-container experiment mentioned above, unwrapped RP containers had the lowest VMC at the conclusion of both experiments (2.1 and 0.2%), while BP containers had the greatest VMC at 12.5 and 10.7% (Figs. 4.7 and 4.8). Volumetric moisture content for unwrapped SP was 3.7 and 0.9% for the two experiments, while wrapped SP had final average VMCs of 6.7 and 5.7%; wrapped RP behaved similarly to wrapped SP with final average VMCs of 7.3 and 4.7% (Figs. 4.7 and 4.8).

4.3.3. Outdoor nursery study—Potential Evapotranspiration (PET)

For both PET1 and PET2, total PET for SP containers was significantly greater than that of BP containers and greater than RP containers in PET2 (Figs. 4.9 and 4.10). In PET2, SP containers had significantly greater PET compared to BP on 13 of 15 days. The difference in container water loss rates between the two experiments could be attributed to the fact that the average daily maximum temperature during PET2 was nearly 3 C warmer than when PET1 was conducted (33.0 C versus 30.2 C) (Figs. 4.11 and 4.12). In PET1 there was only one day when SP PET was significantly greater than that of BP; however the cumulative SP PET over the 14 d period was 20% greater than that of BP (Fig. 4.11). In PET1, RP and BP containers did not differ significantly in total average PET (Fig. 4.9). In PET2, cumulative PET of SP containers was 53% greater than BP containers and 10% greater than that of RP containers (Fig. 4.10). In PET2, RP containers had 38% greater PET than BP containers. In both experiments, average daily PET for all containers closely reflected changes in daily maximum air temperature (Figs. 4.11 and 4.12). Under well-watered conditions (100% of ET), SP containers lose water at a more rapid rate (675 g/day) compared to BP (564 g/day); in PET2, RP and SP containers also lost more water (760 g/day and 840 g/day, respectively) than BP containers (548 g/day).

4.3.4. Outdoor nursery study—75% and 50% (Experiment 75/50)

Containers irrigated at 75% of black plastic PET (BP-PET) lost significantly more water (116% more) than those irrigated at 50% of BP-PET (Fig. 4.13). When averaged over 75% and 50% of BP-PET replacement rates, SP containers lost significantly more water than RP containers (9%) (Fig. 4.14). When containers were irrigated at 75% of BP-PET, SP containers lost significantly more water than RP containers but were not significantly different from BP containers. There were no significant container effects when containers were irrigated at 50% of BP-PET (Fig. 4.15).

Similar to what was observed for ET rates, SP plant shoot and root dry weights were significantly greater than RP shoot and root weights in the 75% of BP-PET irrigation treatment (Fig. 4.16). Shoot dry weight for BP containers were also greater than those of RP at the 75% irrigation treatment level; root dry weight was significantly different among RP and SP containers when irrigated at 75% of PET (Fig. 4.16). Black plastic and SP root and shoot dry weight was not different at the 75% of BP-PET irrigation treatment (Fig. 4.16).

When irrigated at 50% of BP-PET, there were no significant differences in shoot dry weight among the three containers. However, root dry weight was significantly greater for BP containers compared to the two fabric types (Fig. 4.17). When irrigated at 50% of BP-PET, root dry weight for BP containers was 84% greater than RP and 42% greater than SP (Fig. 4.17).

There were no significant container effects for root:shoot ratio when irrigated at the 75% of BP-PET (Fig. 4.18). However, at 50% BP-PET irrigation level, plants grown in BP containers had significantly greater root:shoot ratio than the two fabric containers (Fig. 4.18). This is likely due to the greater root dry weight at the 50% BP-PET irrigation level mentioned above.

4.3.5. Outdoor nursery study—50% and 25% (Experiment 50/25)

Containers irrigated at 50% of black plastic PET (BP-PET) lost significantly more water (32%) than those irrigated at 25% of BP-PET (Fig. 4.19). When averaged over 50% and 25% of BP-PET replacement rates, BP containers used significantly more water than RP containers (20%) and SP containers (11%) (Fig. 4.20). When containers were irrigated at 50% of BP-PET, BP containers lost significantly more water than both

RP and SP containers (23% and 15%, respectively). There were no container effects on water loss when irrigated at 25% of BP-PET (Fig. 4.21).

There were no significant differences in dry shoot and root weight among the container types when irrigated at 50% of BP-PET (Fig. 4.22). Root dry weight for BP containers was greater than that of RP and SP at the 25% irrigation treatment level, however shoot dry weight was not significantly different among containers (Fig. 4.23). There were no significant container effects for root:shoot ratio irrigated at the 50% or 25% of BP-PET irrigation levels (Fig. 4.24).

4.4. Discussion

4.4.1. Greenhouse Studies

Containers were filled to the same bulk density (0.35 g/cm^3), but because containers varied in volume, they had different weights at the beginning of the study. At field capacity, BP containers weighed less than RP and SP containers (Figs. 4.3 and 4.4). However the VMC was greater for BP containers at the initiation of the study (Figs. 4.1 and 4.2). Fabric containers lost water at a faster rate the first 11 days for both Experiment 1a and 1b in the greenhouse: RP containers lost 77% and 74% of their weight, SP lost 74% and 73% compared to BP containers 50% and 45%, respectively. Over the course of both experiments, BP containers lost half as much water per day (95 and 108 g/day), compared to RP (182 and 185 g/day) and SP (214 and 232 g/day) containers. For volumetric water loss, during both experiments, BP containers lost approximately 0.7% of their total moisture per day, compared to approximately 1%/day for the two fabric types.

While no previous studies have compared water loss rates of these two fabric containers to BP containers, Namburthiri et al. (2012) and Taylor et al. (2010) found that porous containers lost water more rapidly than did plastic containers. Clearly the two fabric containers lose water more quickly than BP containers. This is something growers should recognize as a possible limitation to the use of fabric containers and should plan for if adopting in production, especially in regions where water rationing exists or can be implemented.

When fabric containers were wrapped with plastic wrap in an attempt to reduce/eliminate sidewall water loss, they behaved more similarly to BP containers, but wrapping did not reduce water loss to levels seen with BP containers. The water loss of wrapped fabric was somewhere between that of unwrapped fabric containers and BP containers. The water was likely lost from the unwrapped bottoms of the wrapped fabric containers.

Fabric containers, whether wrapped or unwrapped, lost water at a faster rate the first 11 days for both Experiment 2a and 2b in the greenhouse: unwrapped RP containers lost 60% and 54% of their weight, compared to 72% and 54% for wrapped RP containers; unwrapped SP containers lost 60% and 62%, compared to wrapped SP containers (74% and 55%, respectively); BP containers lost 50% and 46% by weight for the two experiments, respectively. With the exception of wrapped RP containers, all fabric types lost twice the water per day compared to BP containers (in both experiments). Wrapped RP containers were closer to BP containers than other treatments, but still lost 1.5 times the water per day compared to BP containers.

4.4.2. Outdoor Experiments

In both experiments PET1 and PET2 outdoors, SP containers had the greatest average PET compared to BP containers; in PET2, RP had greater PET than BP, but less than SP. The differences between SP and BP containers over the duration of each experiment (14 and 15 days) amounted to approximately 1.6 L (0.4 gal) and 4.4 L (1.2 gal). Over an approximate 200 day growing season, this would amount to BP containers using 21.3 L (5.6 gal) to 58.5 L (15.5 gal) less water compared to SP containers. The difference between RP and BP containers over the duration of the second experiment (15 days) amount to 3.2 L (0.83 gal); if you extrapolate this to a 200 day growing season, RP containers would use 42.4 L (11.2 gal) more water than BP containers.

Containers irrigated at 75% of BP-PET had significantly greater ET rates than those irrigated at 50% of BP-PET. This is expected, since plants experiencing greater drought stress will have lower water use rates. We saw the same trend for plants irrigated at 50% and 25% of BP-PET. We could find no research comparing ET rates of our fabric containers with BP containers, but Wang et al. (2012) found that the average water use of *Euonymus fortunei* was 3-5 times higher for porous containers (wood pulp and paper) compared to BP containers.

When irrigated at 50% of BP-PET, there were no differences in ET rates among all container types. However, when irrigated at 75% of BP-PET, BP and SP containers had significantly higher ET rates than RP containers over the duration of the study. When averaged over 75% and 50% irrigation levels, RP and SP containers differed significantly. This is contrary to the findings of the above-mentioned greenhouse study, where the two fabric containers had significantly higher water use rates than BP containers. Unpublished research by J. Owen (personal communication, 2013) suggested that container water loss from fabric containers may not differ from BP containers once plants are established in the containers, but there may be differences as plants are establishing. The plants used in our study had a two-month establishment period, so they were not likely fully established in containers, which may explain the differences in ET that we observed. The higher shoot weight of SP and BP containers compared to RP containers could also explain why we observed higher ET rates for SP and BP containers.

For the second outdoor experiment, when irrigated at 25% of BP-PET there were no significant container effects on ET. However, when irrigated at 50% of BP-PET, BP containers had significantly greater ET rates than either of the fabric container types. A possible reason for this higher BP ET rate is that these plants had significantly greater root mass than plants growing in either of the fabric containers. The greater root mass enabled plants in BP containers to absorb and translocate more water to the top of the plants than either fabric container. The greater root mass in the BP containers likely occurred during the establishment period due to solar heating of the BP container, as was found by O'Connor et al. (2013).

4.4.3. Conclusions

We conducted this research to test the hypothesis that plants grown in fabric containers would lose water more quickly than plants grown in BP containers. Based on our experiments both in the greenhouse and outdoors, regardless if containers contained plant material, the three containers lost water differently (as measured gravimetrically and volumetrically). In the outdoor production study, BP containers had the lowest cumulative water loss at 100% of ET replacement (PET). From our data, even if growers continued to irrigate all container types at 100% ET, the difference between BP containers and fabric container water use over a 15 d period is approximately 4.0 L.

However, we found that BP containers lost significantly more water than fabric containers when irrigated at 50% of BP-PET. If growers deficit irrigate at a percent of ET, BP containers may actually use more water compared to fabric types. One limitation of our study was that we only used one plant species (*Viburnum*). Yet we did see observational differences in physical plant appearance. All containers irrigated at 75% of BP-PET did not exhibit any leaf scorching or stunting; plants irrigated at 50% and 25% of BP-PET did exhibit damage which could make the plant material unsalable.

Our research supported our hypothesis that fabric containers do lose water more quickly than BP containers, but it depends on how they are irrigated. In a greenhouse dry down study, without plants in the containers, the fabric types lost water at a significantly higher daily rate compared to BP containers. In an outdoor field study, with containerized plants, fabric containers generally lost water at a more rapid rate than BP containers, except when the containers were irrigated at 50% of ET replacement. This low ET replacement rate is not normally used for plant production in a “real life” nursery production scenario. When containers were irrigated at 100% or 75% of ET, the total amount of water required for the three container types, though statistically greater for the fabric types, was still relatively small in terms of total water required to produce plants over a growing season.

Air temperature was an important driving factor for water loss in all container types, but higher daytime temperatures had a greater effect on water loss from fabric containers than BP containers. While the irrigation requirement of fabric containers appears to be greater than that of BP containers, the other benefits of using fabric containers should be considered. These benefits include: fewer/or no circling roots compared to BP containers; better transplant success; better root development and architecture following planting in the landscape; more stable/less extreme substrate temperatures during nursery production; and the option of producing these containers using recycled materials. Growers and producers need to weigh the pros and cons of any container before adopting their use and should consider these alternatives to BP containers. Growers can be successful using fabric containers as long as they recognize that production practices must be adjusted to allow for their use.

Table 4.1. Total water loss and substrate volumetric moisture content loss from three container types during two dry-down experiments in the greenhouse (Experiments 1a and 1b).

Container Type		Total water lost (g)	Volumetric water loss*
Black Plastic	Experiment 1a	2383a	18.5a
	Experiment 1b	2905a	21.3a
Root Pouch®	Experiment 1a	4542b	24.1b
	Experiment 1b	5268b	24.7a
Smart Pot®	Experiment 1a	5339c	24.0b
	Experiment 1b	6269c	29.8b

Experiment 1a: 25 days; Experiment 1b: 27 days
*Beginning average moisture content minus the ending moisture content

Means within columns for each measurement and experiment followed by different letters are significantly different at $Pr \geq F$ *0.05*.

Table 4.2. Gravimetric water loss and change in substrate volumetric moisture content from black plastic (BP) and wrapped and unwrapped Root Pouch® (RP) and Smart Pot® (SP) containers for two dry-down experiments in the greenhouse (experiment 2a: 25 days; experiment 2b: 25 days) and planned comparisons of least-square means (*Pr ≥ F 0.05 = *; Pr ≥ F 0.01 =* **).

Container Type		**Gravimetric water loss (g)**	**Volumetric water loss**[#]
Black Plastic	Experiment 2a	2300	15.8
	Experiment 2b	2448	19.9
Root Pouch® wrapped	Experiment 2a	4003	19.0
	Experiment 2b	4542	25.3
Root Pouch®	Experiment 2a	4646	22.2
	Experiment 2b	4943	28.9
Smart Pot® wrapped	Experiment 2a	4602	21.6
	Experiment 2b	5237	25.4
Smart Pot®	Experiment 2a	5437	23.7
	Experiment 2b	5628	29.8

Gravimetric Water Loss	**Experiment 2a**			**Experiment 2b**		
	BP	RP unwrapped	SP unwrapped	BP	RP unwrapped	SP unwrapped
RP wrapped	**	**		**	**	
SP wrapped	**		**	**		**

Volumetric Water Loss	**Experiment 2a**			**Experiment 2b**		
	BP	RP unwrapped	SP unwrapped	BP	RP unwrapped	SP unwrapped
RP wrapped	**	*		**	NS	
SP wrapped	**		NS	**		NS

[#]Beginning average moisture content minus the ending moisture content.

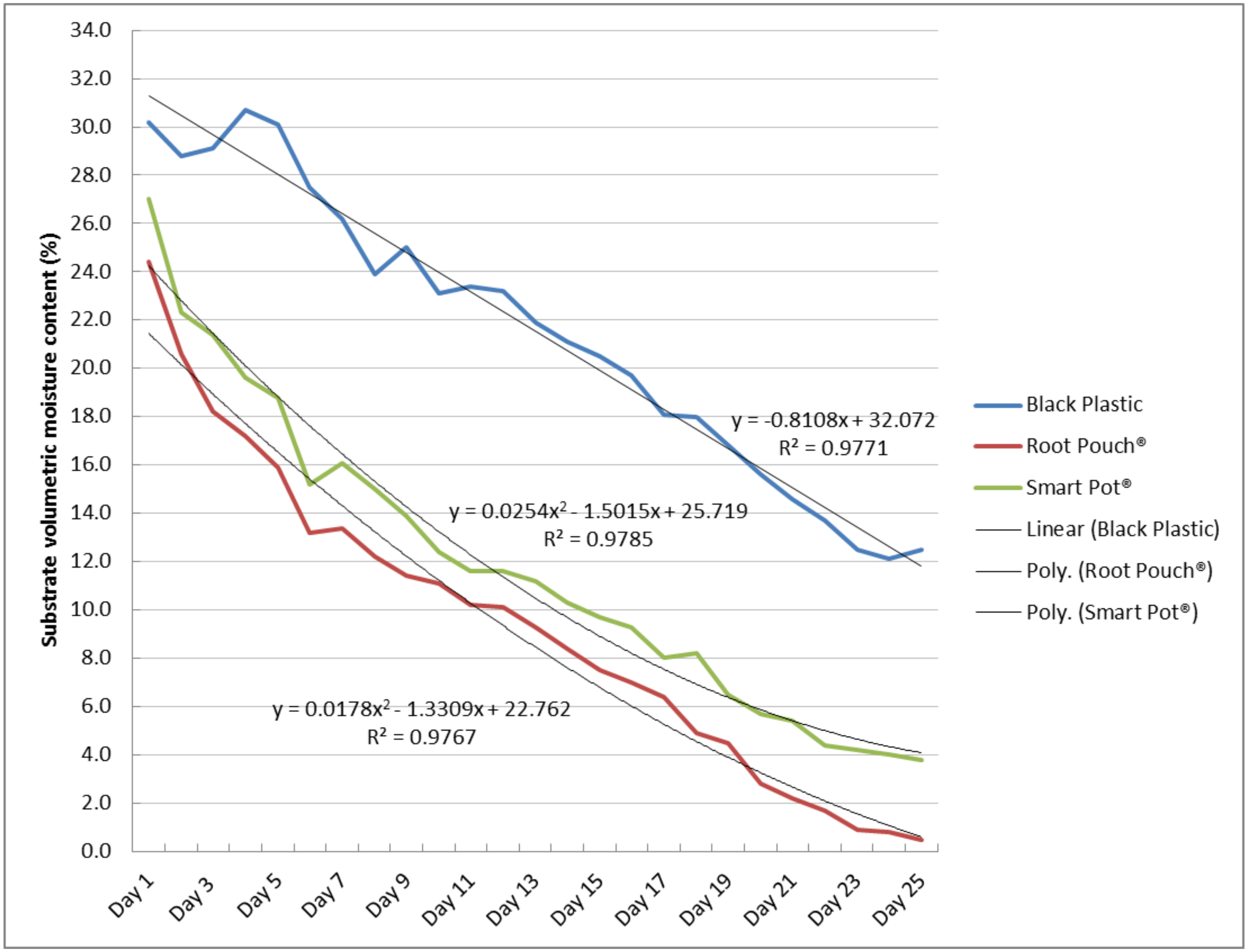


Figure 4.1. Substrate volumetric moisture content for black plastic (BP), Root Pouch® (RP) and Smart Pot® (SP) containers in the greenhouse (Experiment 1a).

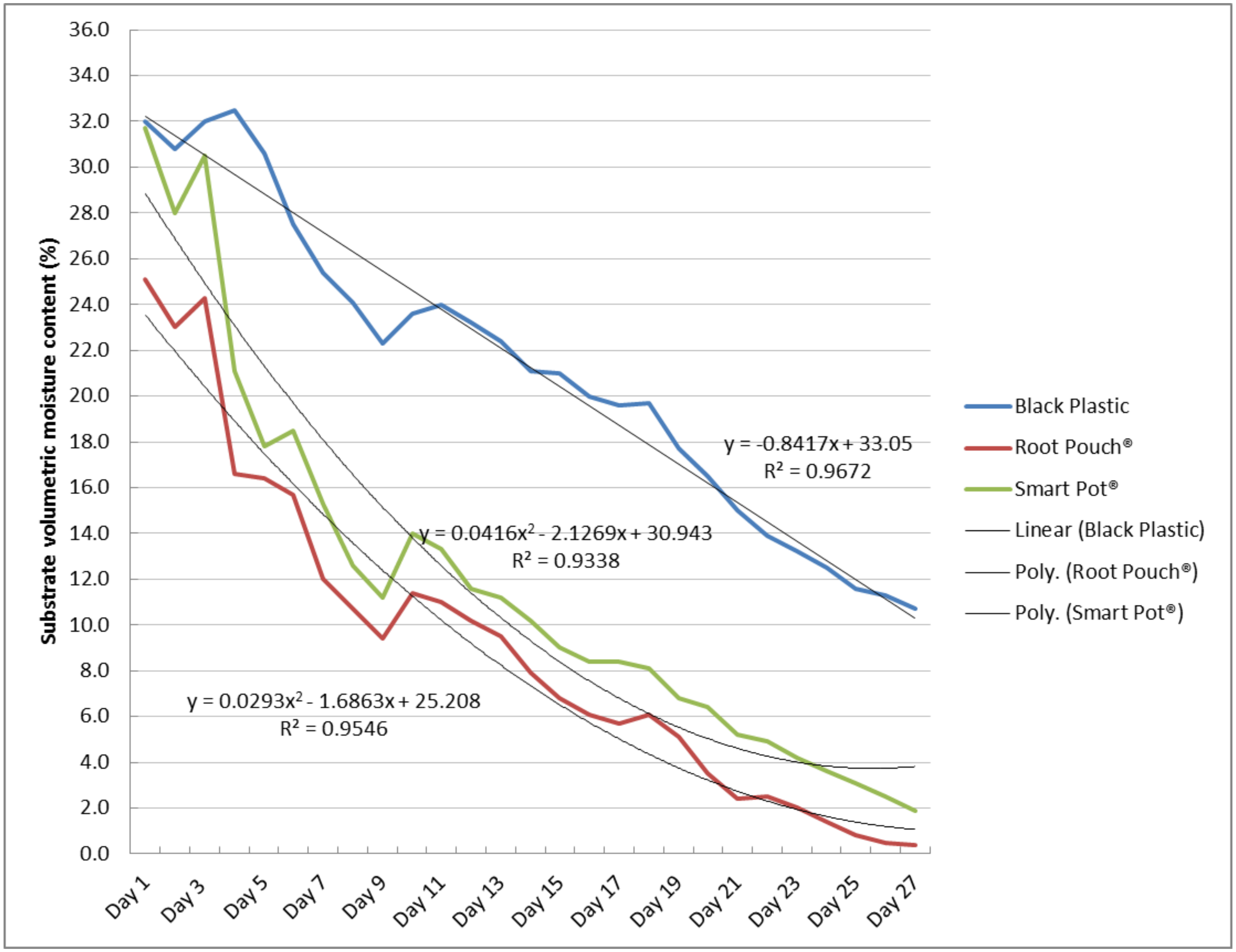


Figure 4.2. Substrate volumetric moisture content for black plastic (BP), Root Pouch® (RP) and Smart Pot® (SP) containers in the greenhouse (Experiment 1b).

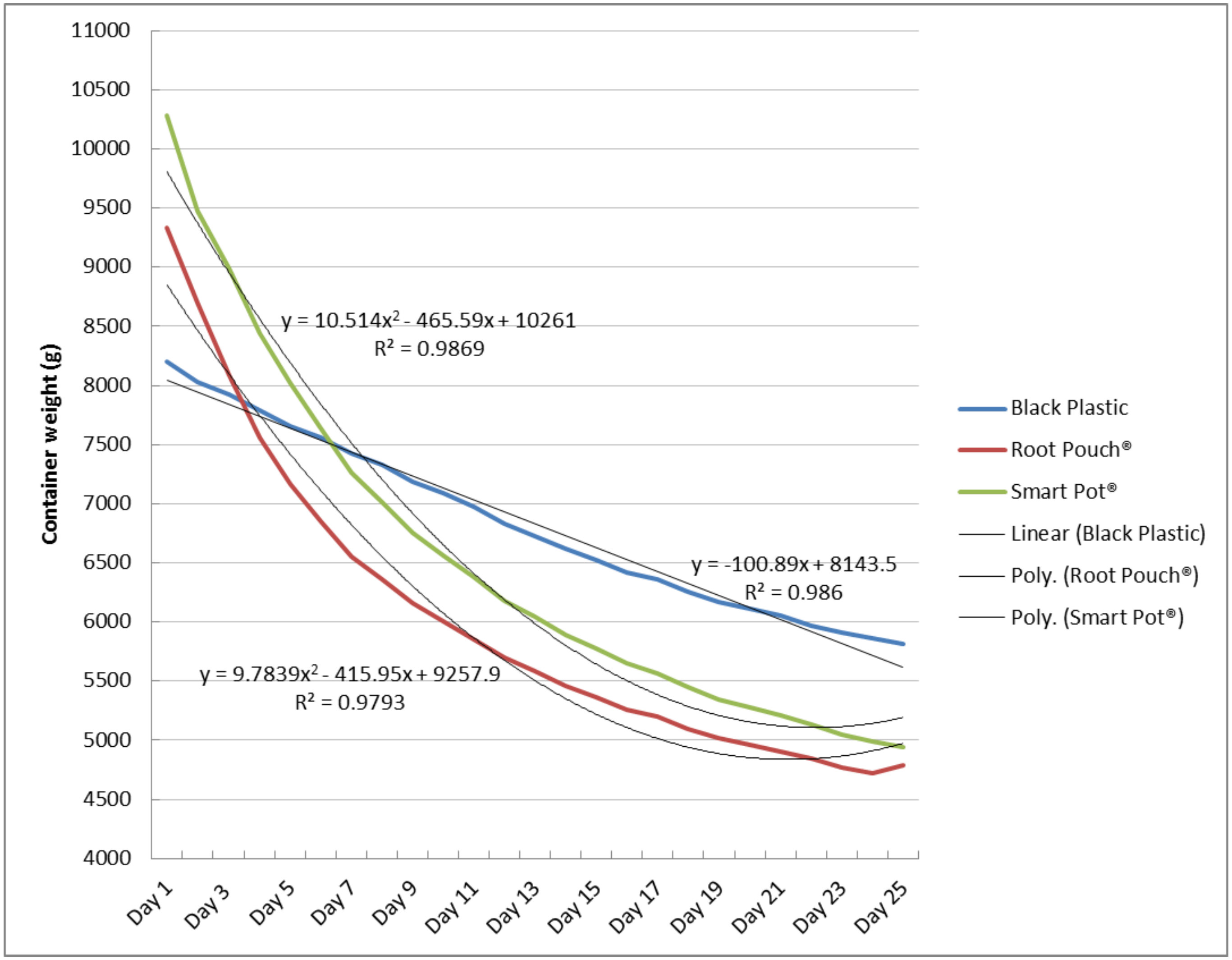


Figure 4.3. Water loss from black plastic (BP), Root Pouch® (RP) and Smart Pot® (SP) containers in the greenhouse (Experiment 1a).

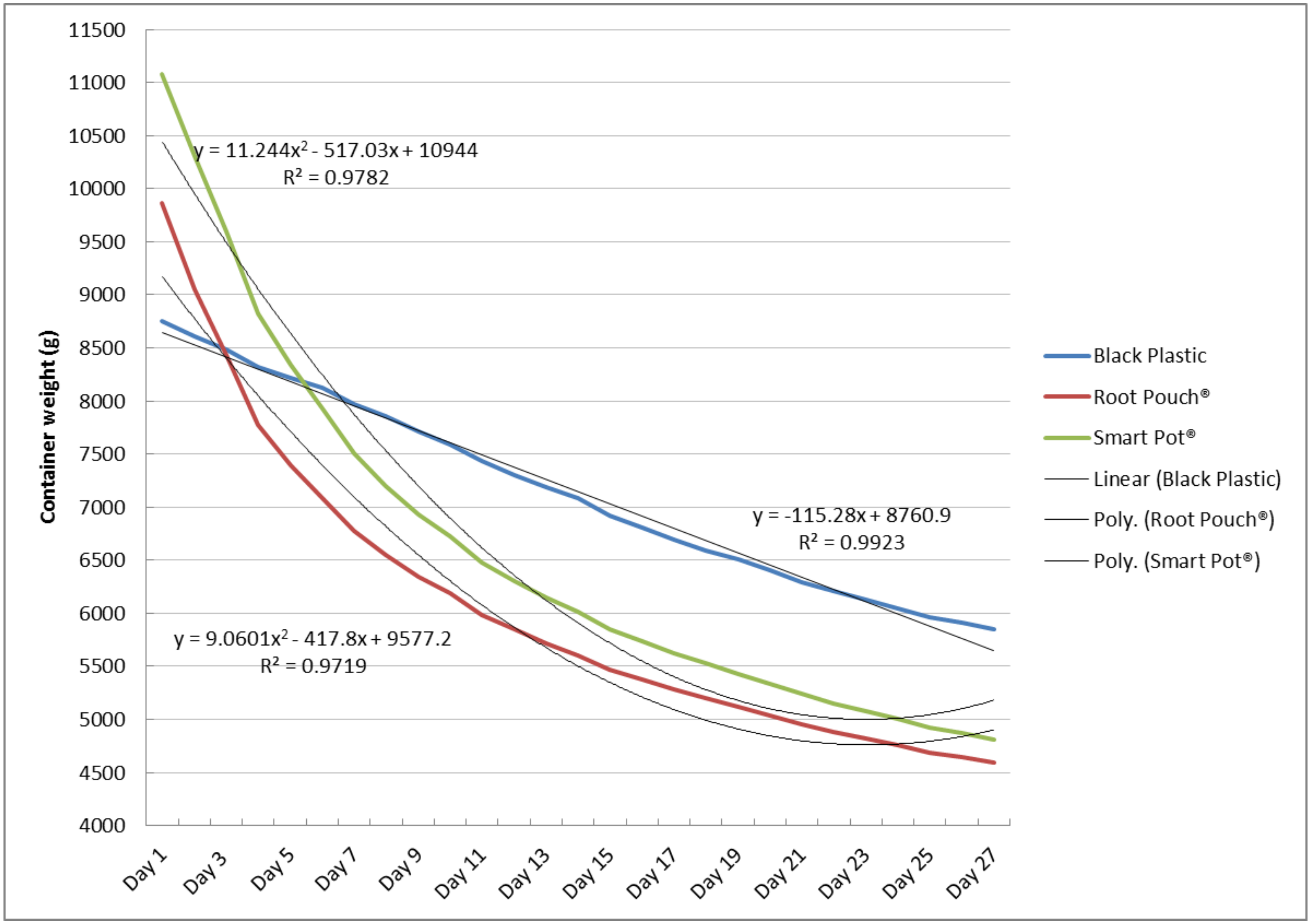
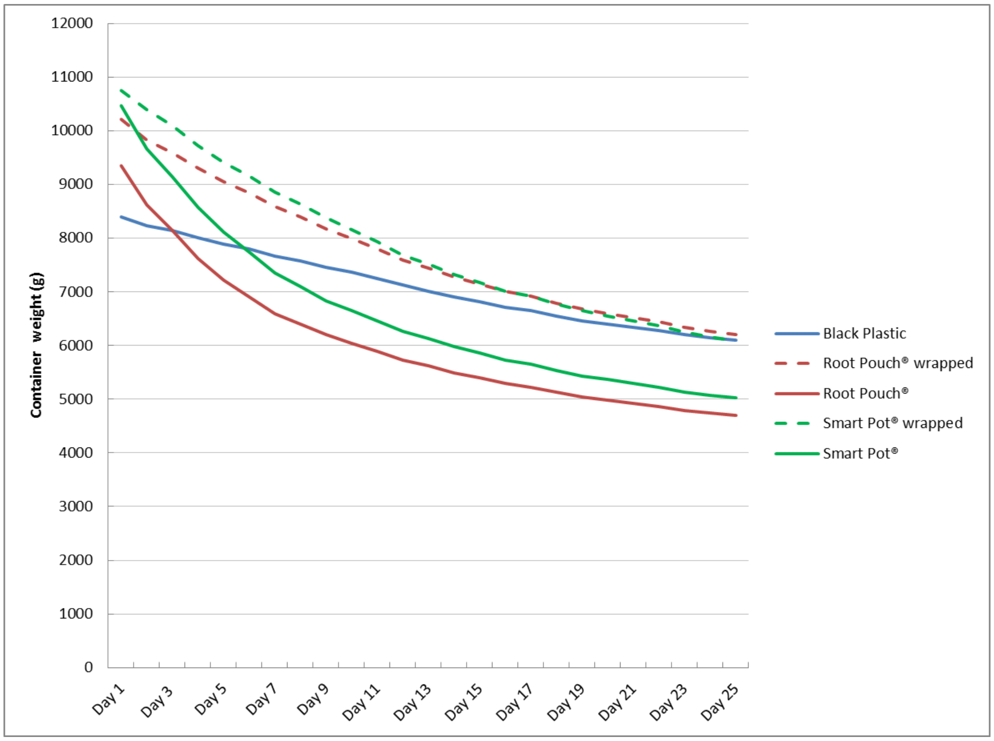


Figure 4.4. Water loss from black plastic (BP), Root Pouch® (RP) and Smart Pot® (SP) containers in the greenhouse (Experiment 1b).



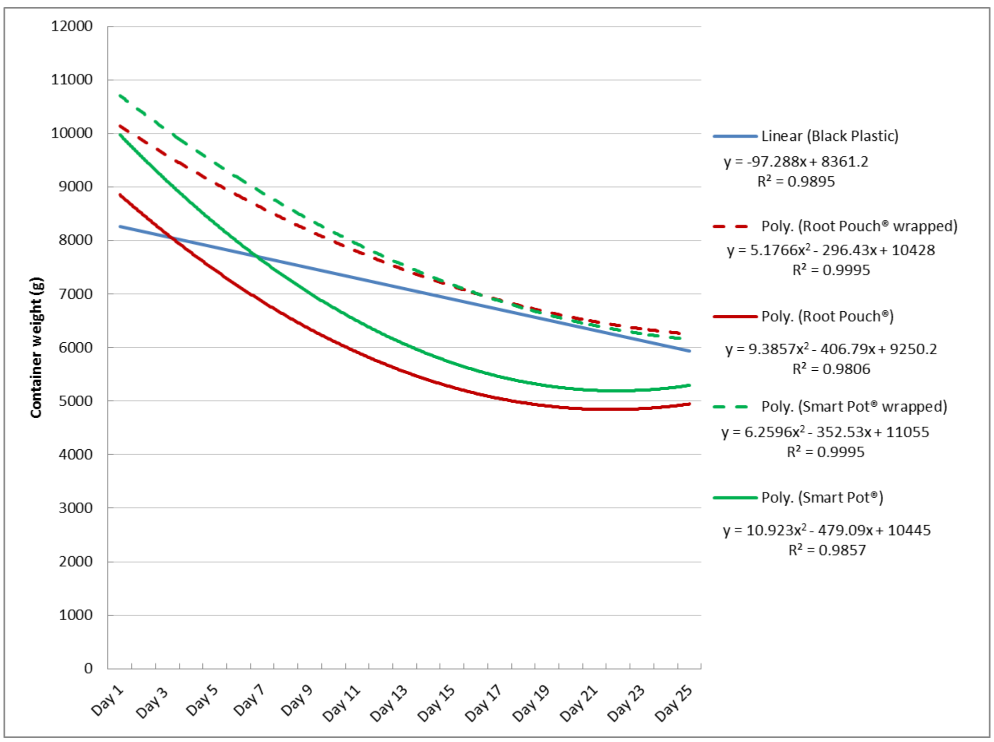
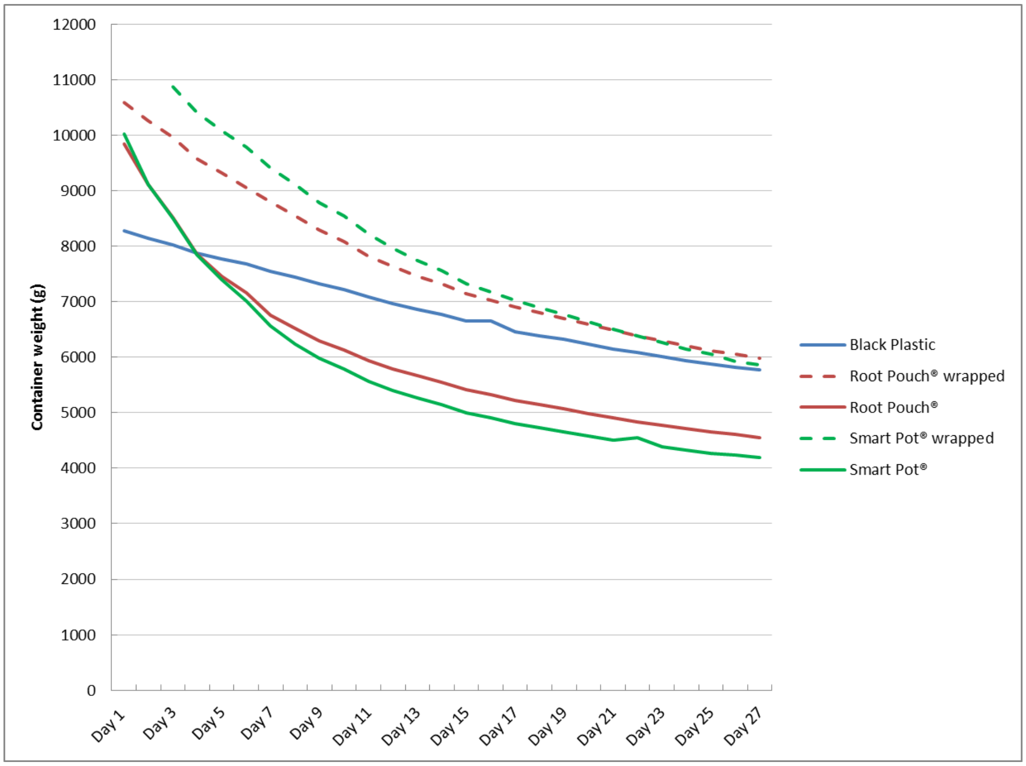


Figure 4.5. Water loss from black plastic (BP) and wrapped and unwrapped Root Pouch® and Smart Pot® containers during dry-down in the greenhouse (Experiment 2a). Regression lines shown in second figure.



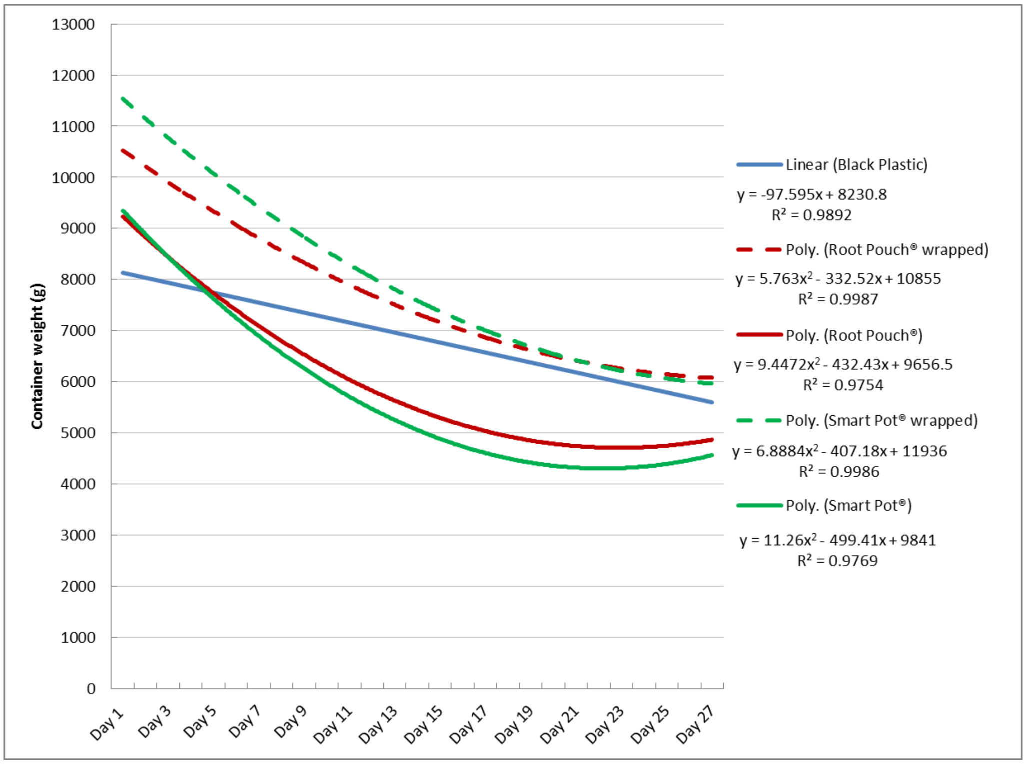


Figure 4.6. Water loss from black plastic (BP) and wrapped and unwrapped Root Pouch® and Smart Pot® containers during dry-down in the greenhouse (Experiment 2b). Regression lines shown in second figure.

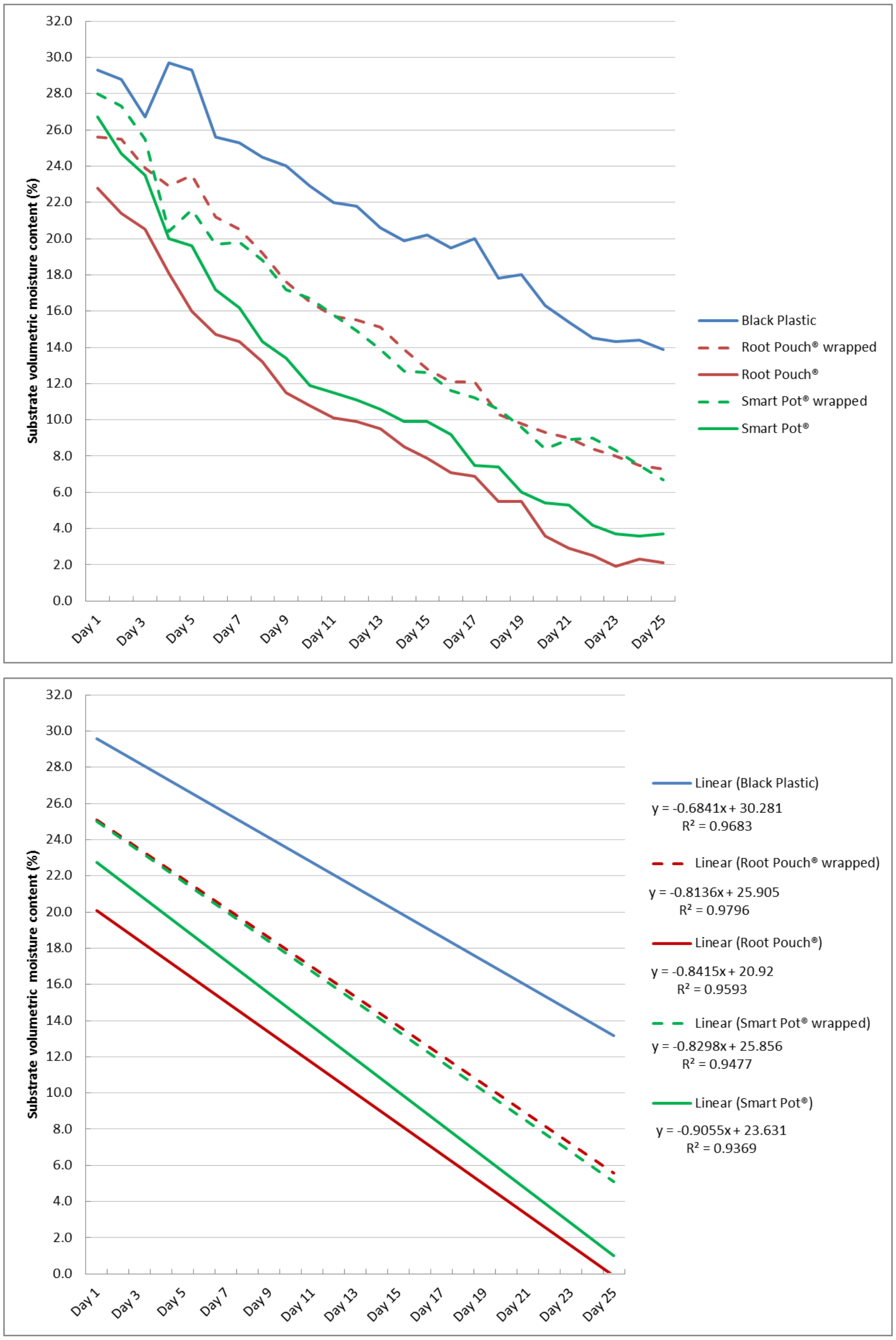


Figure 4.7. Substrate volumetric moisture content from black plastic (BP) and wrapped and unwrapped Root Pouch® and Smart Pot® containers during dry-down in the greenhouse (Experiment 2a). Regression lines shown in second figure.

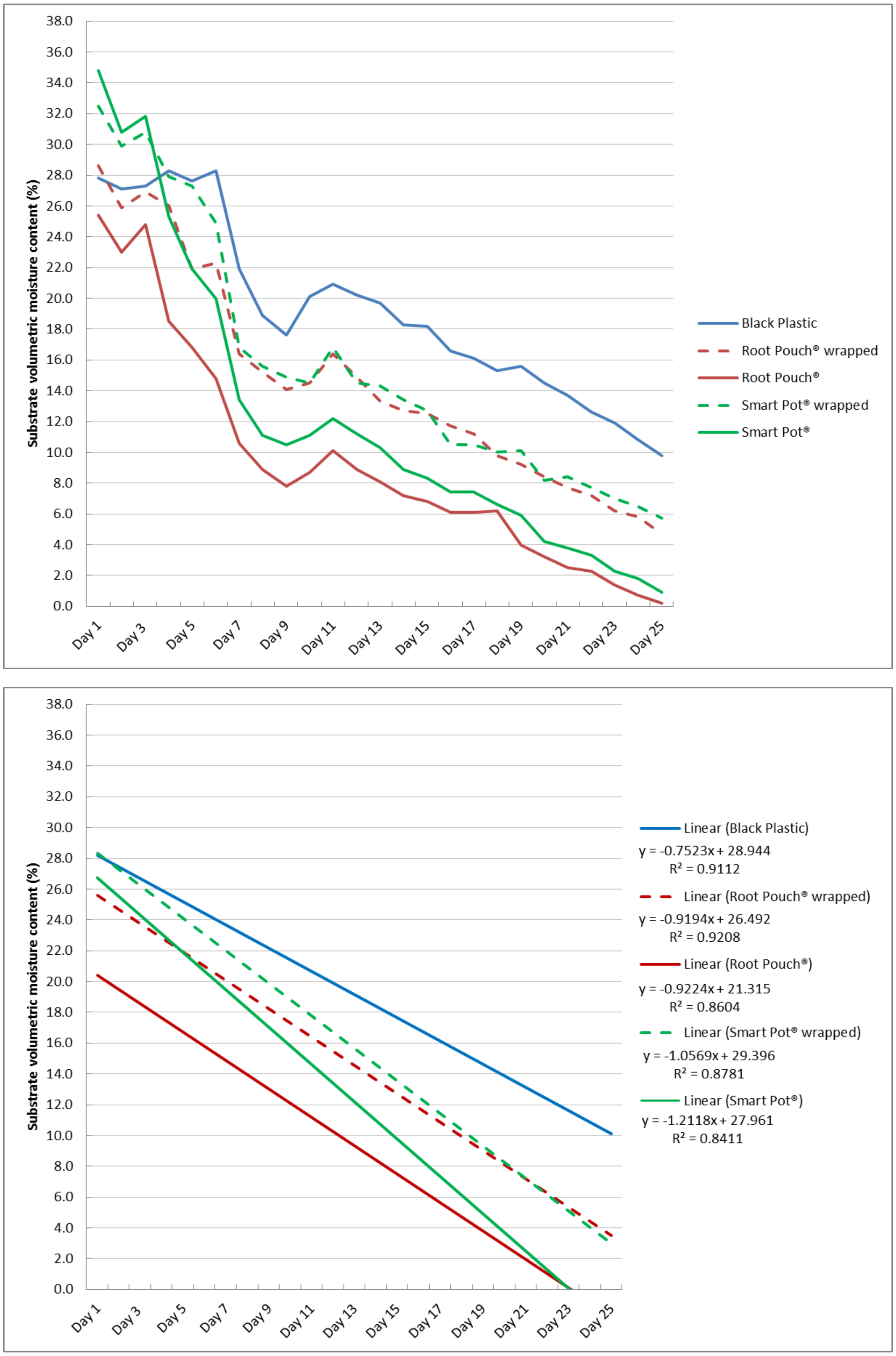


Figure 4.8. Substrate volumetric moisture content from black plastic (BP) and wrapped and unwrapped Root Pouch® and Smart Pot® containers during dry-down in the greenhouse (Experiment 2b). Regression lines shown in second figure.

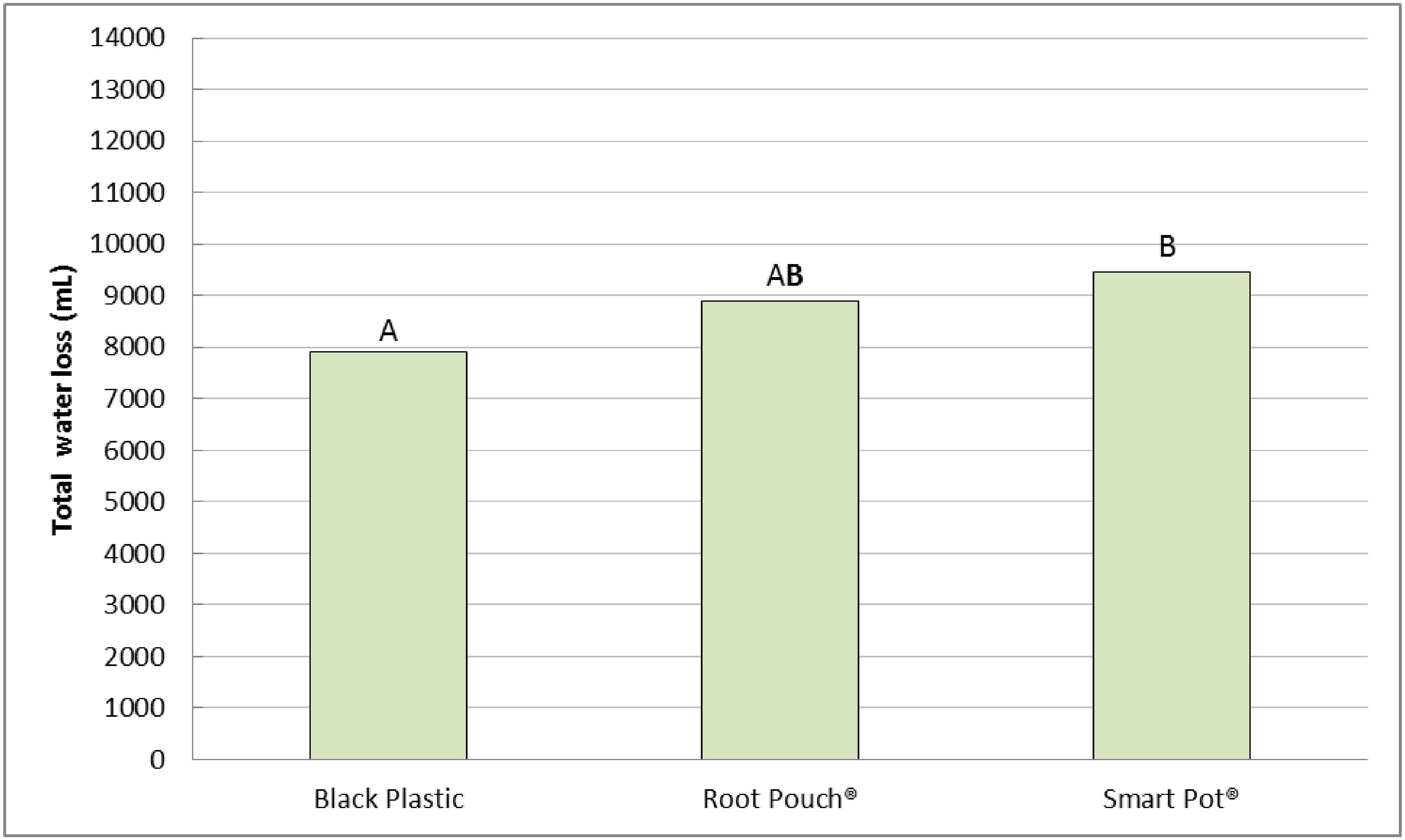


Figure 4.9. Total potential evapotranspiration (PET) for *Viburnum trilobum* 'Compactum' growing outdoors in black plastic (BP), Root Pouch® (RP) and Smart Pot® (SP) containers (PET1).

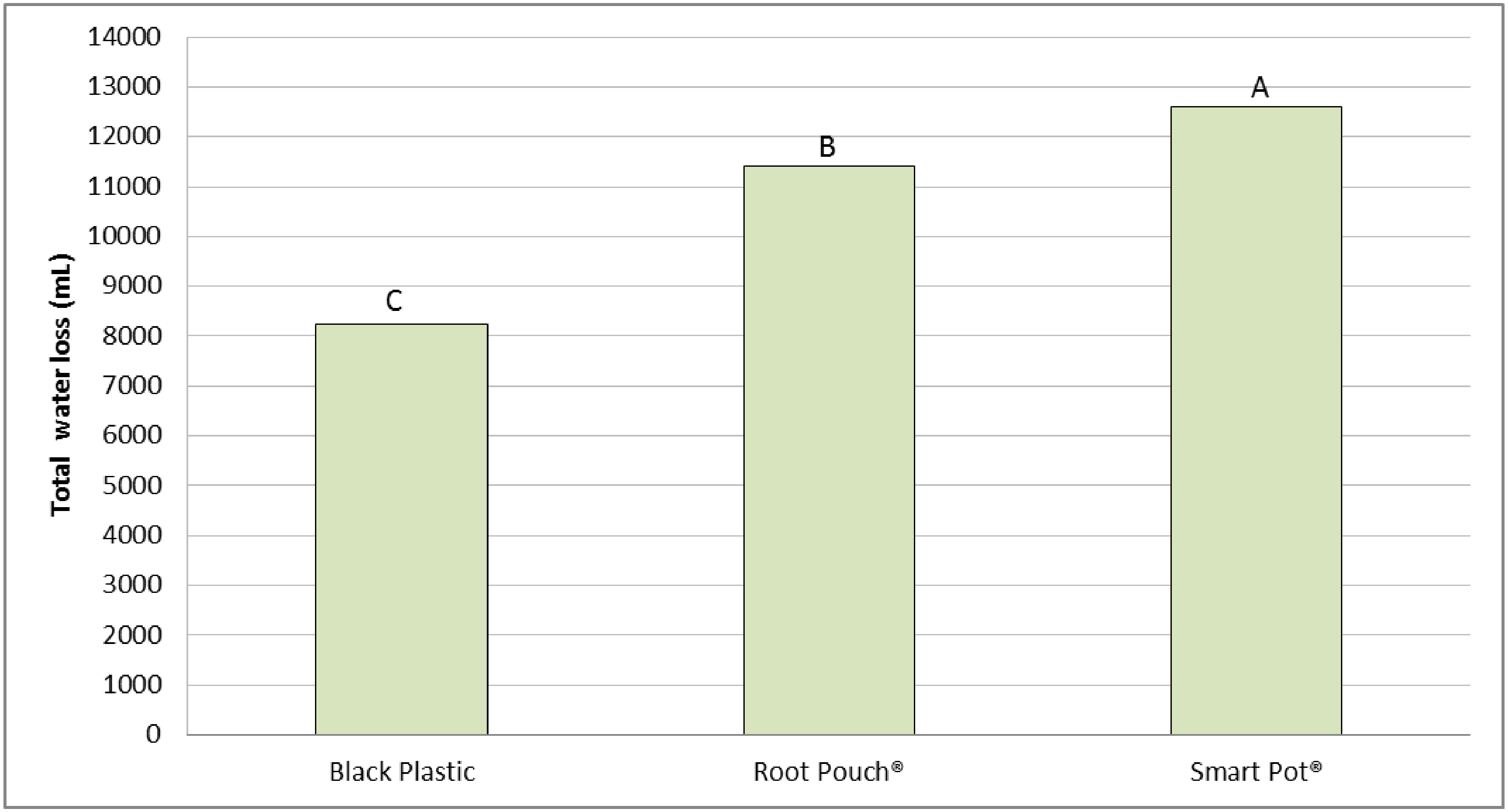


Figure 4.10. Total potential evapotranspiration (PET) for *Viburnum trilobum* ‘Compactum’ growing outdoors in black plastic (BP), Root Pouch® (RP) and Smart Pot® (SP) containers (PET2).

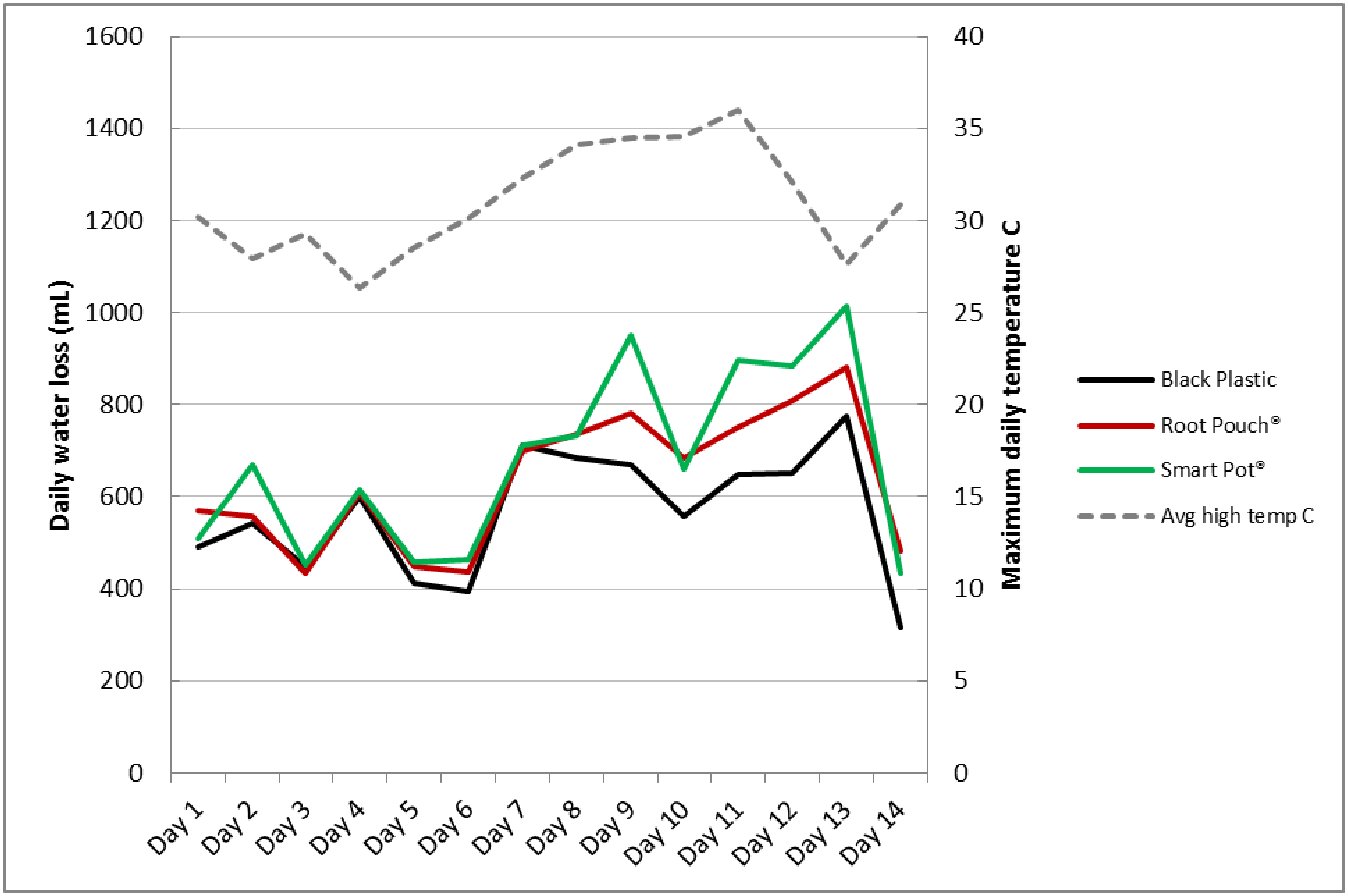


Figure 4.11. Daily potential evapotranspiration (PET) for *Viburnum trilobum* 'Compactum' growing outdoors in black plastic (BP), Root Pouch® (RP) and Smart Pot® (SP) containers (PET1).

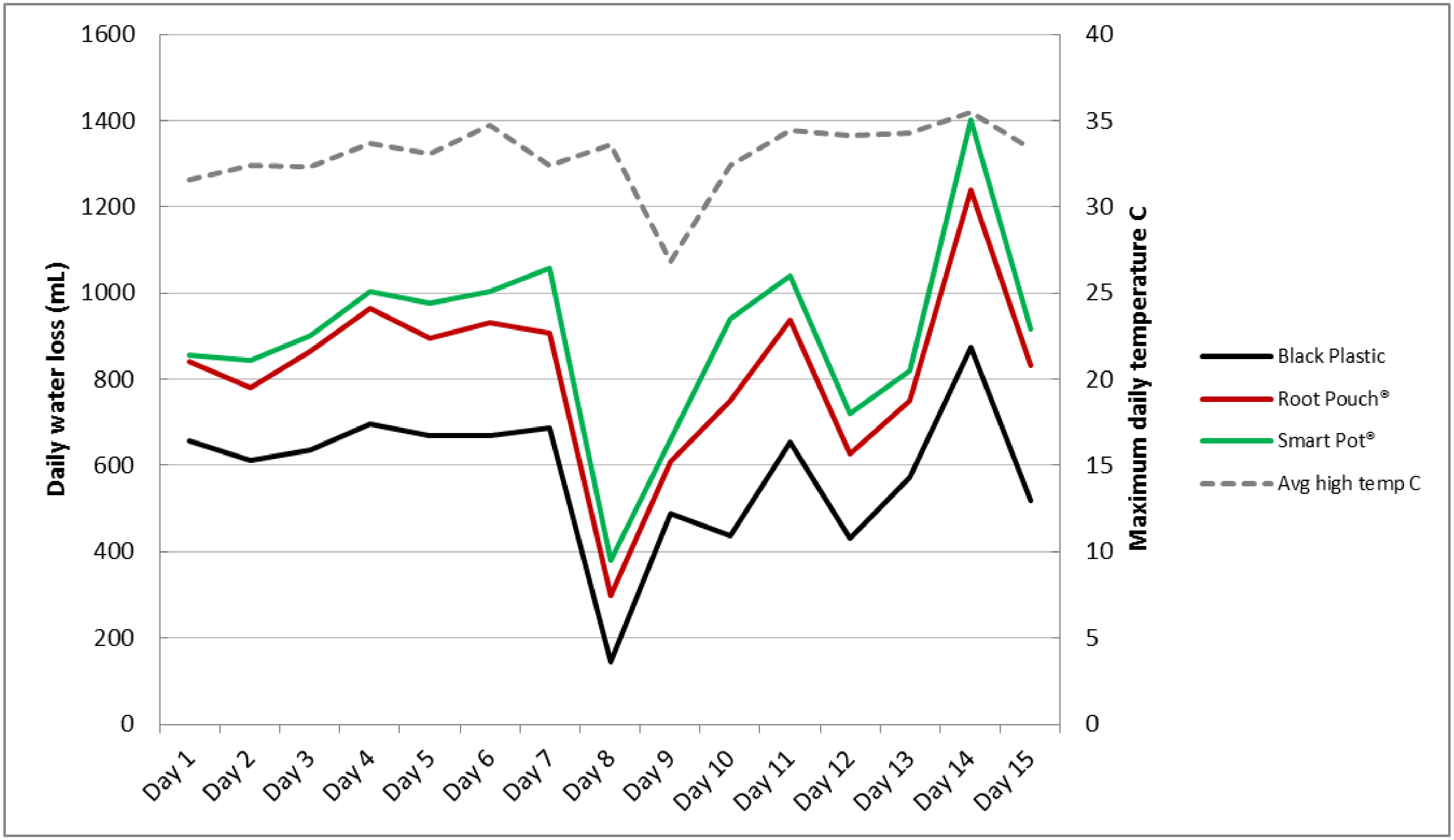


Figure 4.12. Daily potential evapotranspiration (PET) for *Viburnum trilobum* 'Compactum' growing outdoors in black plastic (BP), Root Pouch® (RP) and Smart Pot® (SP) containers (PET2).

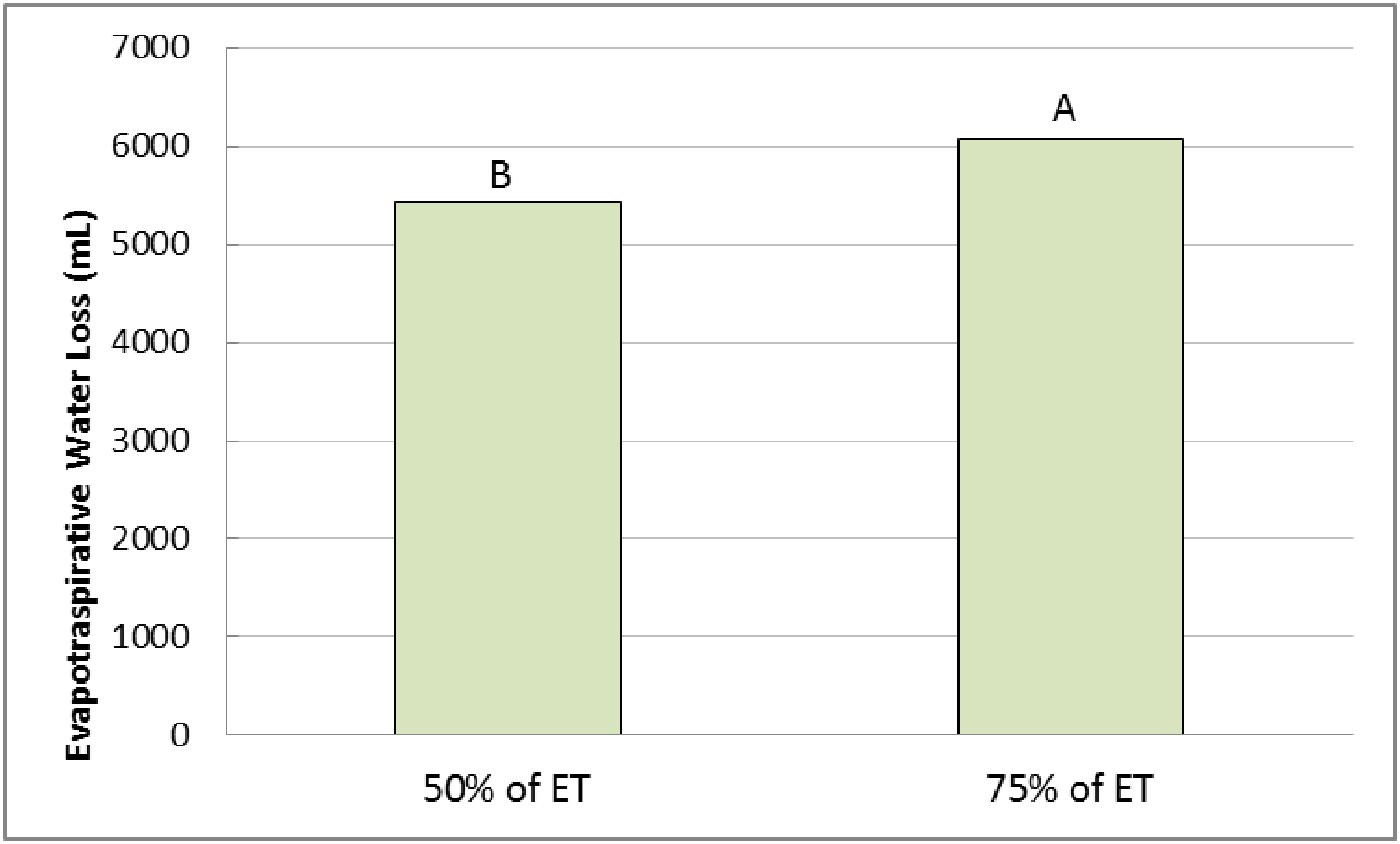


Figure 4.13. Average cumulative evapotranspiration (ET) for *Viburnum trilobum* 'Compactum' growing in three container types (averaged over container types) when irrigated at 75% and 50% of black plastic (BP) potential evapotranspiration (PET) (Experiment 75/50).

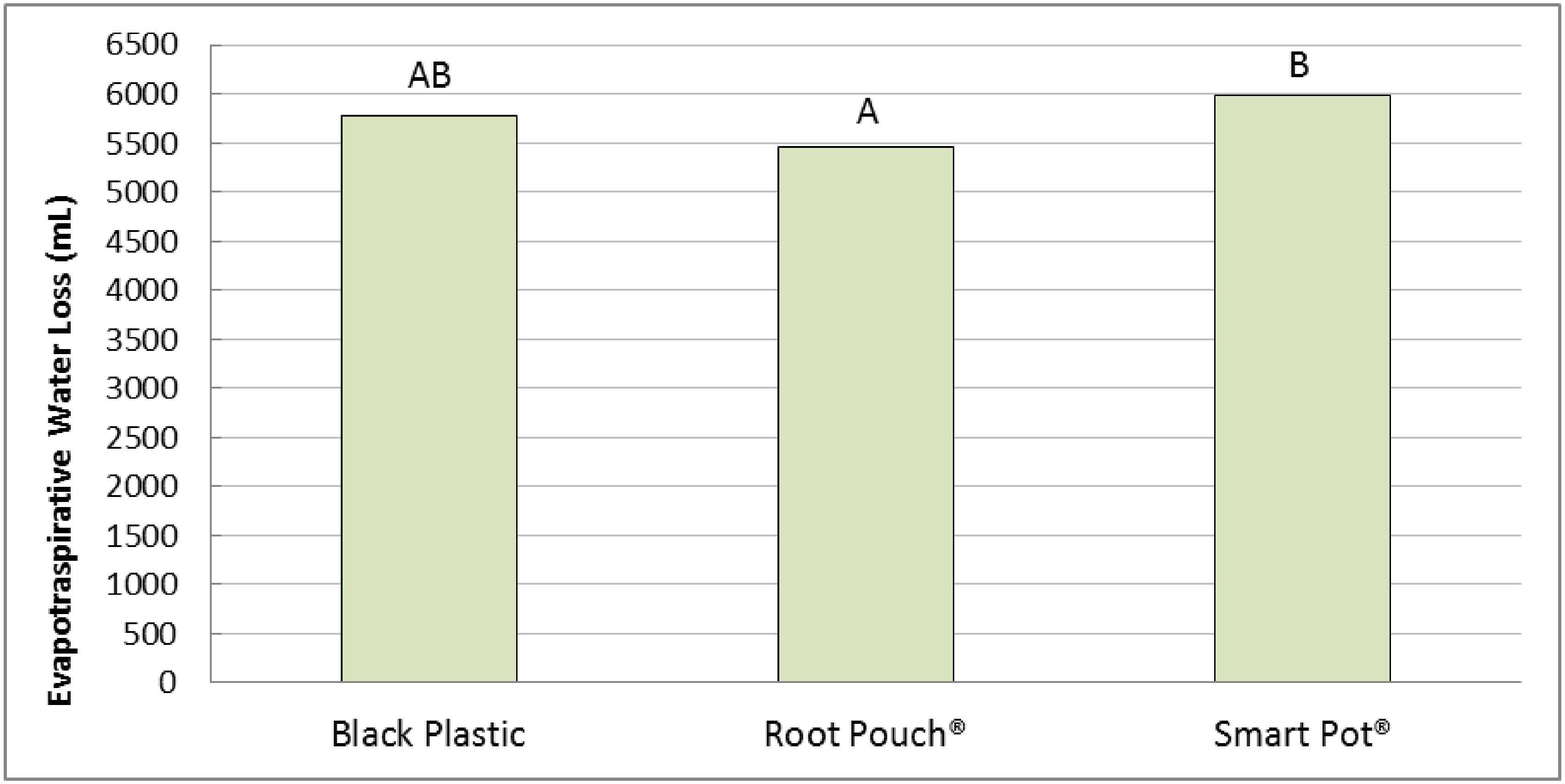


Figure 4.14. Cumulative evapotranspiration (ET) for *Viburnum trilobum* 'Compactum' growing in three container types (black plastic, Root Pouch® and Smart Pot®) averaged over 75% and 50% of black plastic potential evapotranspiration (BP-PET) (Experiment 75/50).

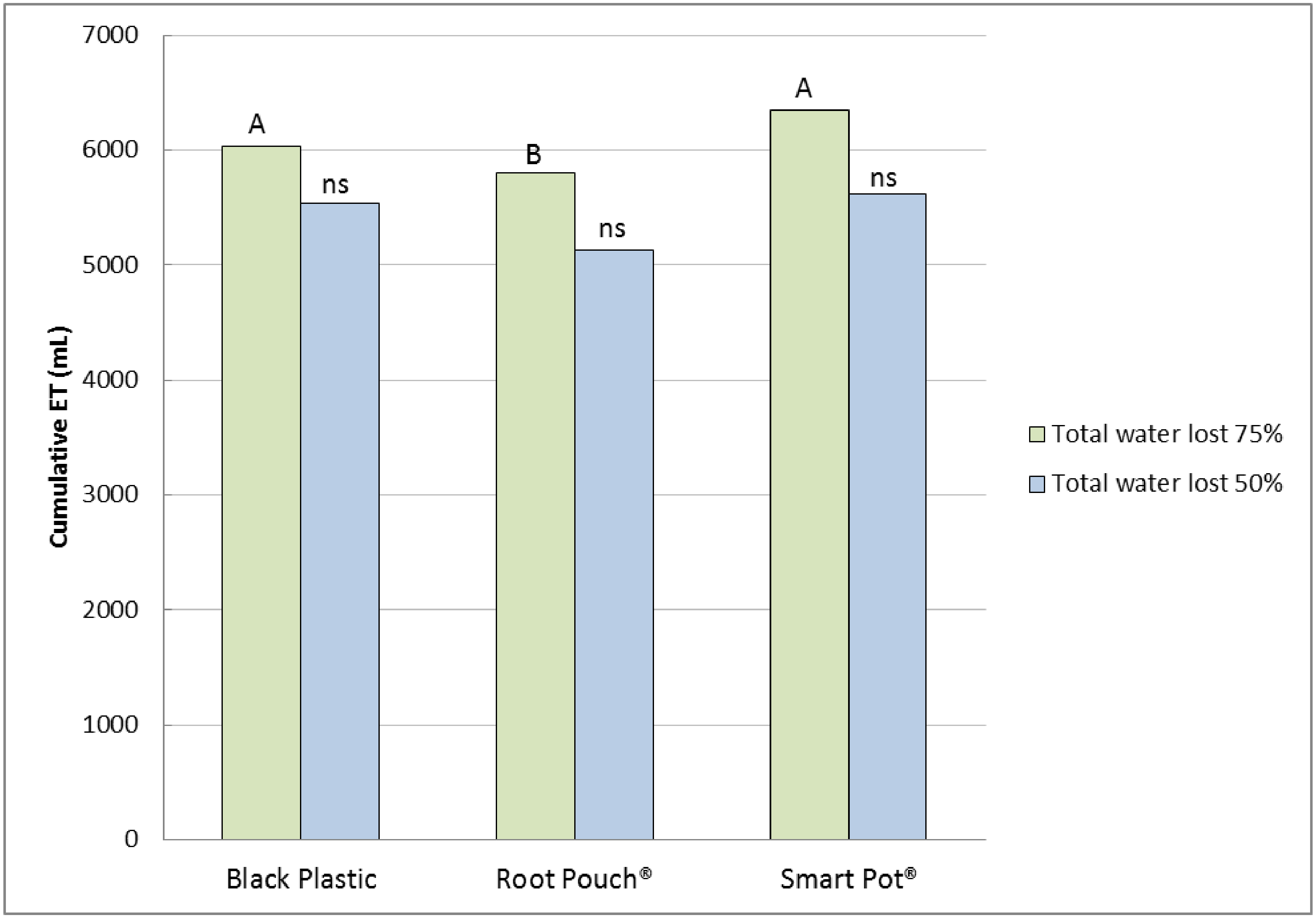


Figure 4.15**.** Cumulative evapotranspiration (ET) for *Viburnum trilobum* 'Compactum' growing in three container types (black plastic, Root Pouch® and Smart Pot®) irrigated at 75% and 50% of black plastic potential evapotranspiration (BP-PET) (Experiment 75/50).

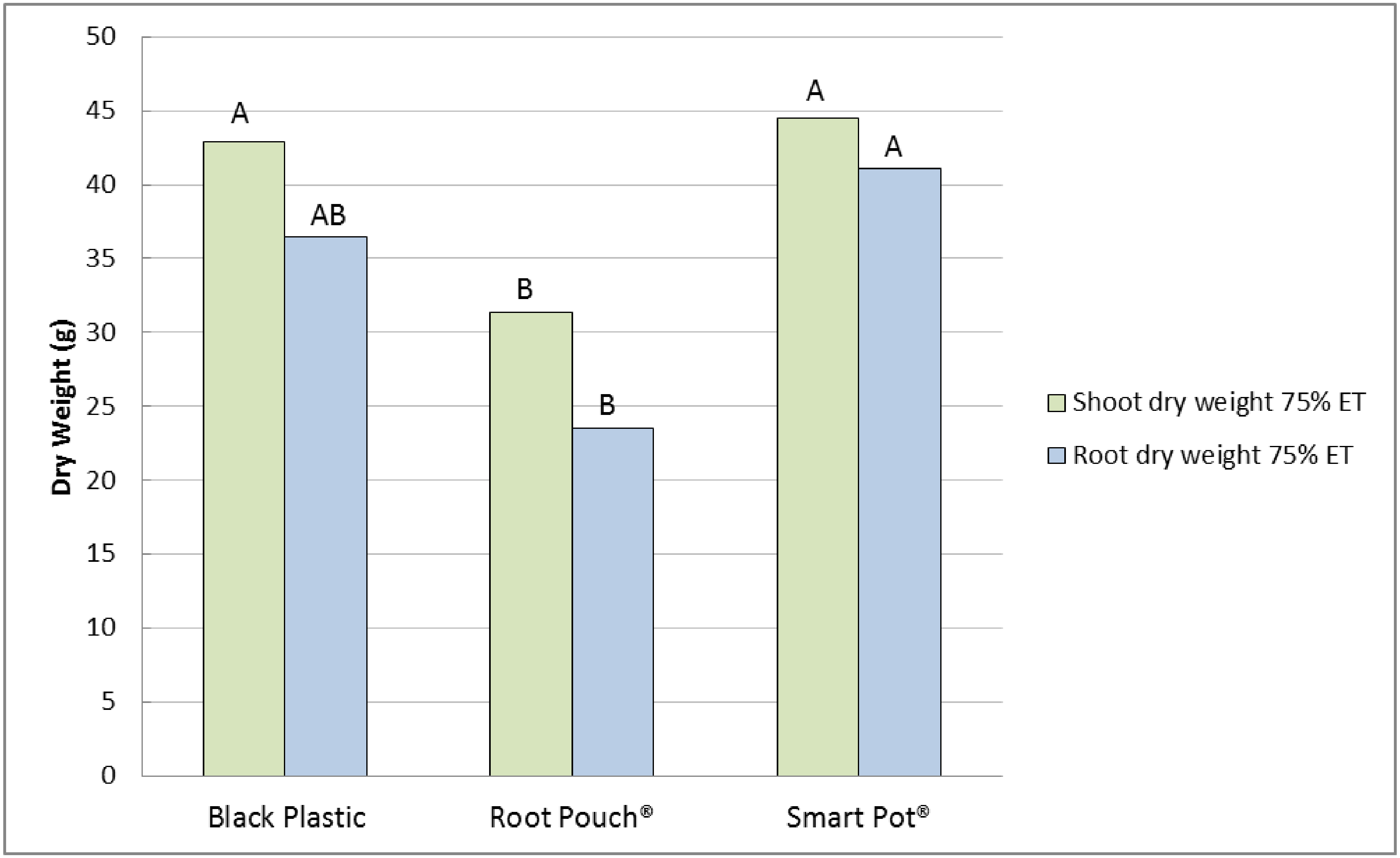


Figure 4.16. Shoot and root dry weight for *Viburnum trilobum* ‘Compactum’ growing outdoors in black plastic (BP), Root Pouch® (RP) and Smart Pot® (SP) containers irrigated at 75% of BP potential evapotranspiration (BP-PET) (Experiment 75/50).

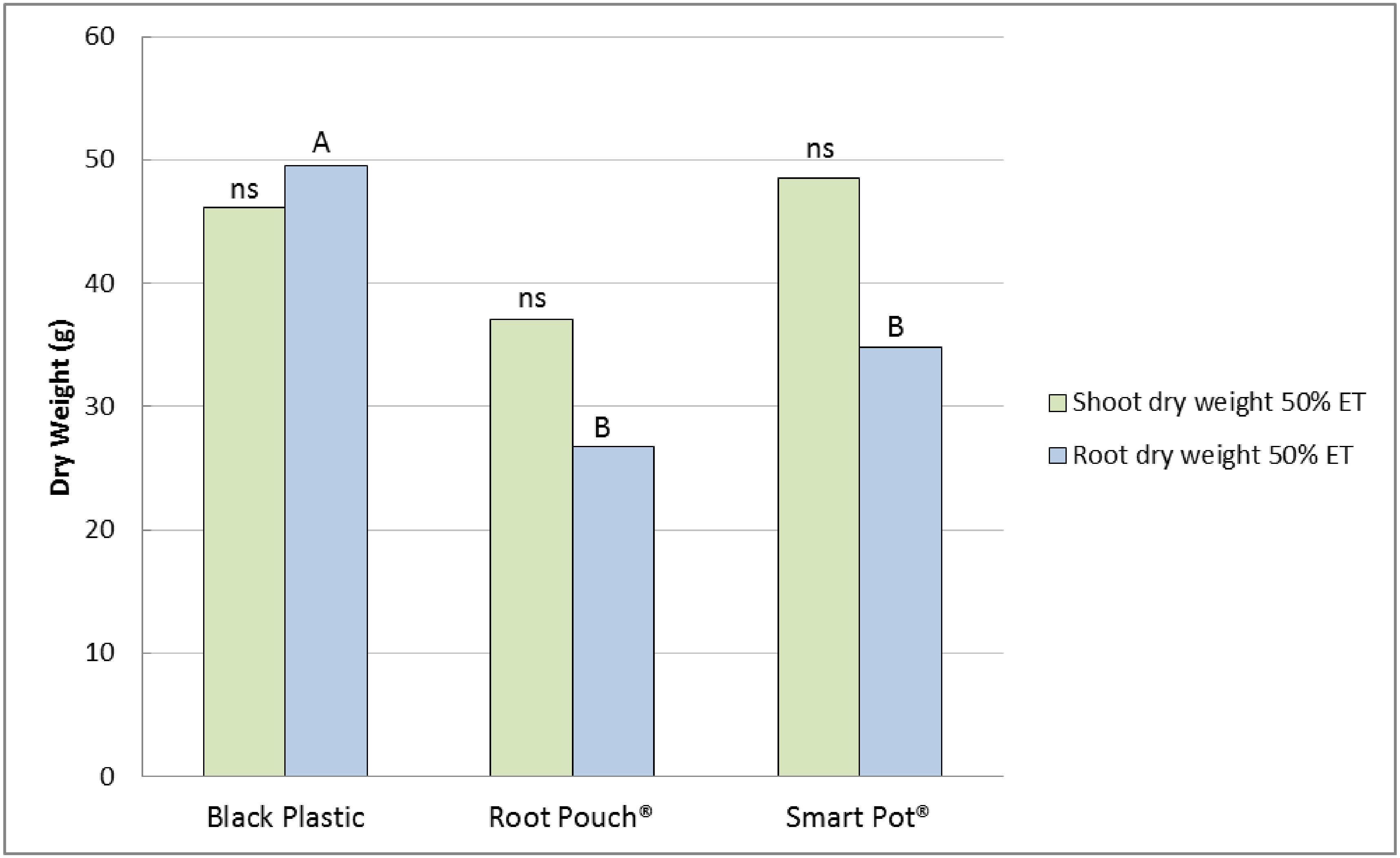


Figure 4.17. Shoot and root dry weight for *Viburnum trilobum* 'Compactum' growing outdoors in black plastic (BP), Root Pouch® (RP) and Smart Pot® (SP) containers irrigated at 50% of BP potential evapotranspiration (BP-PET) (Experiment 75/50).

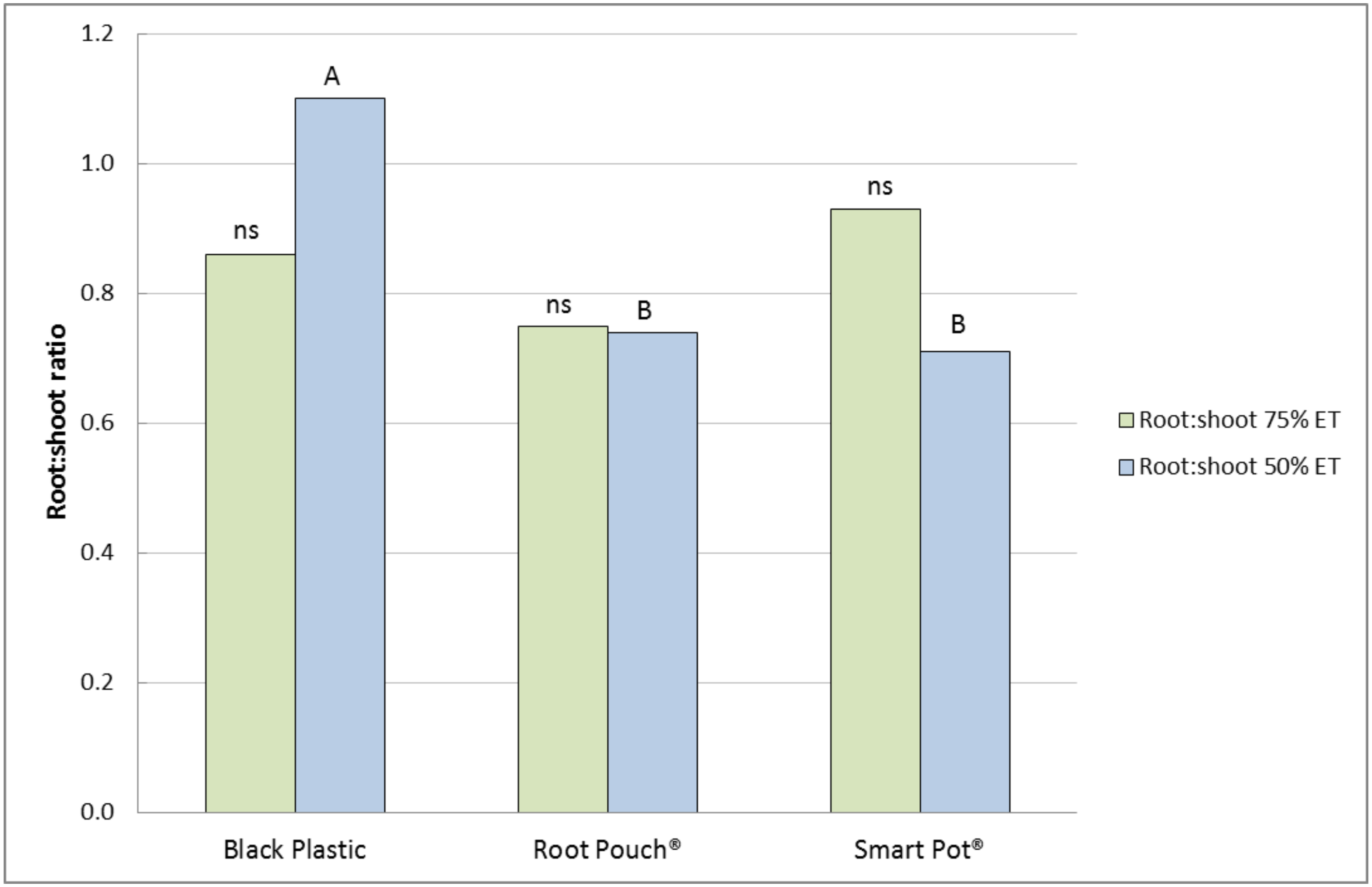


Figure 4.18. Root:shoot ratio for *Viburnum trilobum* 'Compactum' growing outdoors in black plastic (BP), Root Pouch® (RP) and Smart Pot® (SP) containers irrigated at 75% and 50% of BP potential evapotranspiration (BP-PET) (Experiment 75/50).

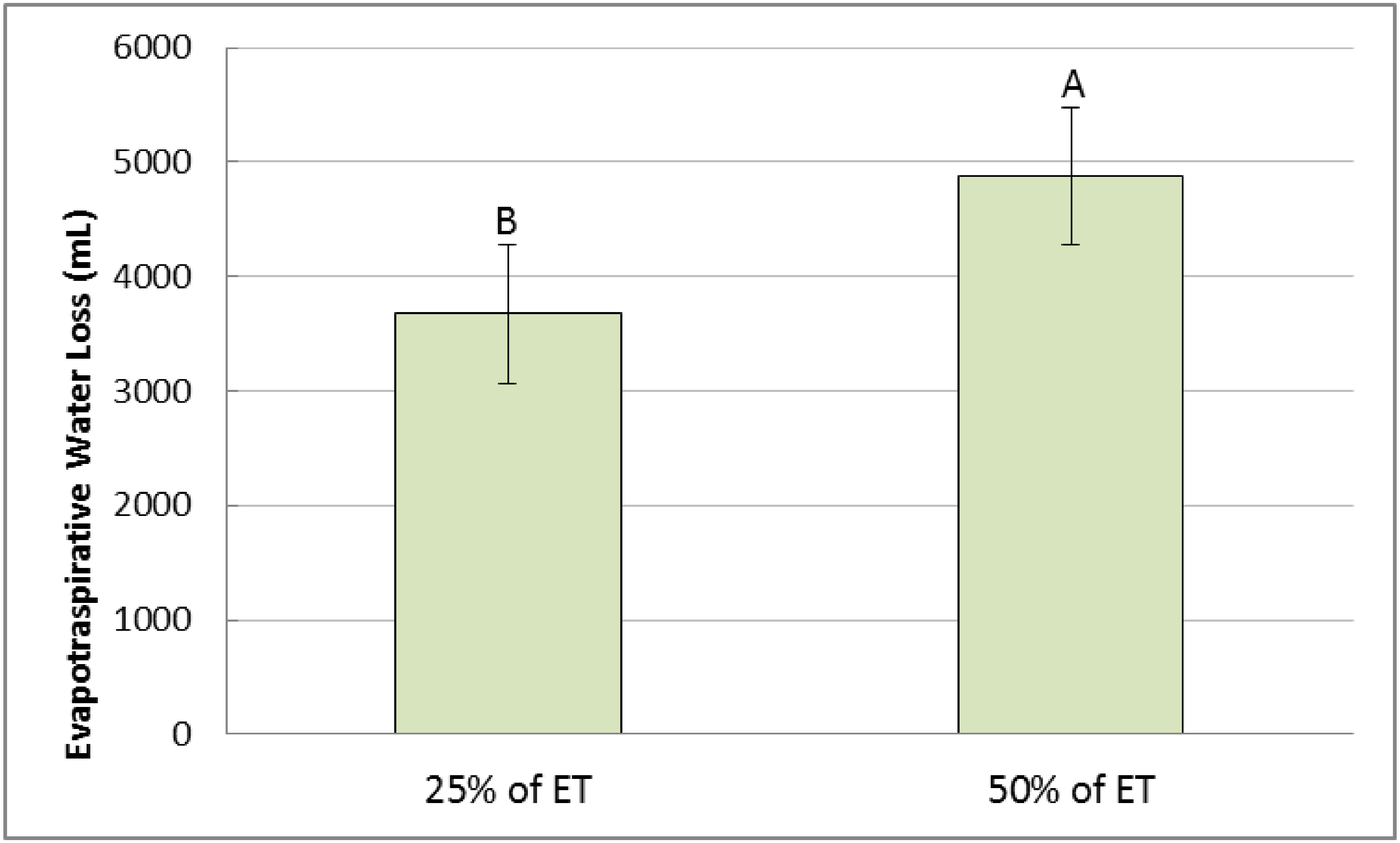


Figure 4.19. Average cumulative evapotranspiration (ET) for *Viburnum trilobum* ‘Compactum’ growing in three container types (averaged over container types) when irrigated at 50% and 25% of black plastic (BP) potential evapotranspiration (PET) (Experiment 50/25).

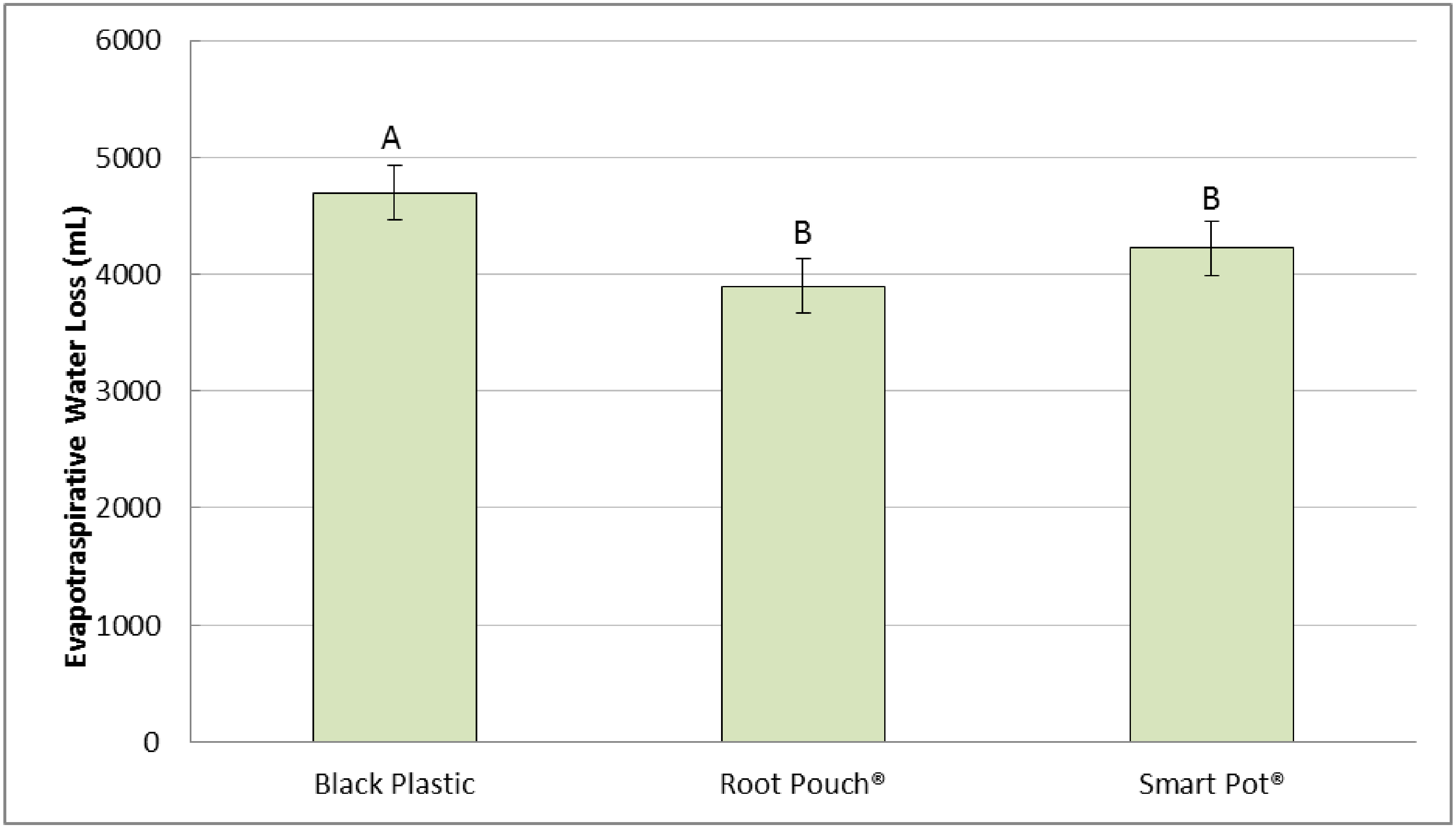


Figure 4.20. Cumulative evapotranspiration (ET) for *Viburnum trilobum* 'Compactum' growing in three container types (black plastic, Root Pouch® and Smart Pot®) averaged over 50% and 25% of black plastic potential evapotranspiration (BP-PET) (Experiment 50/25).

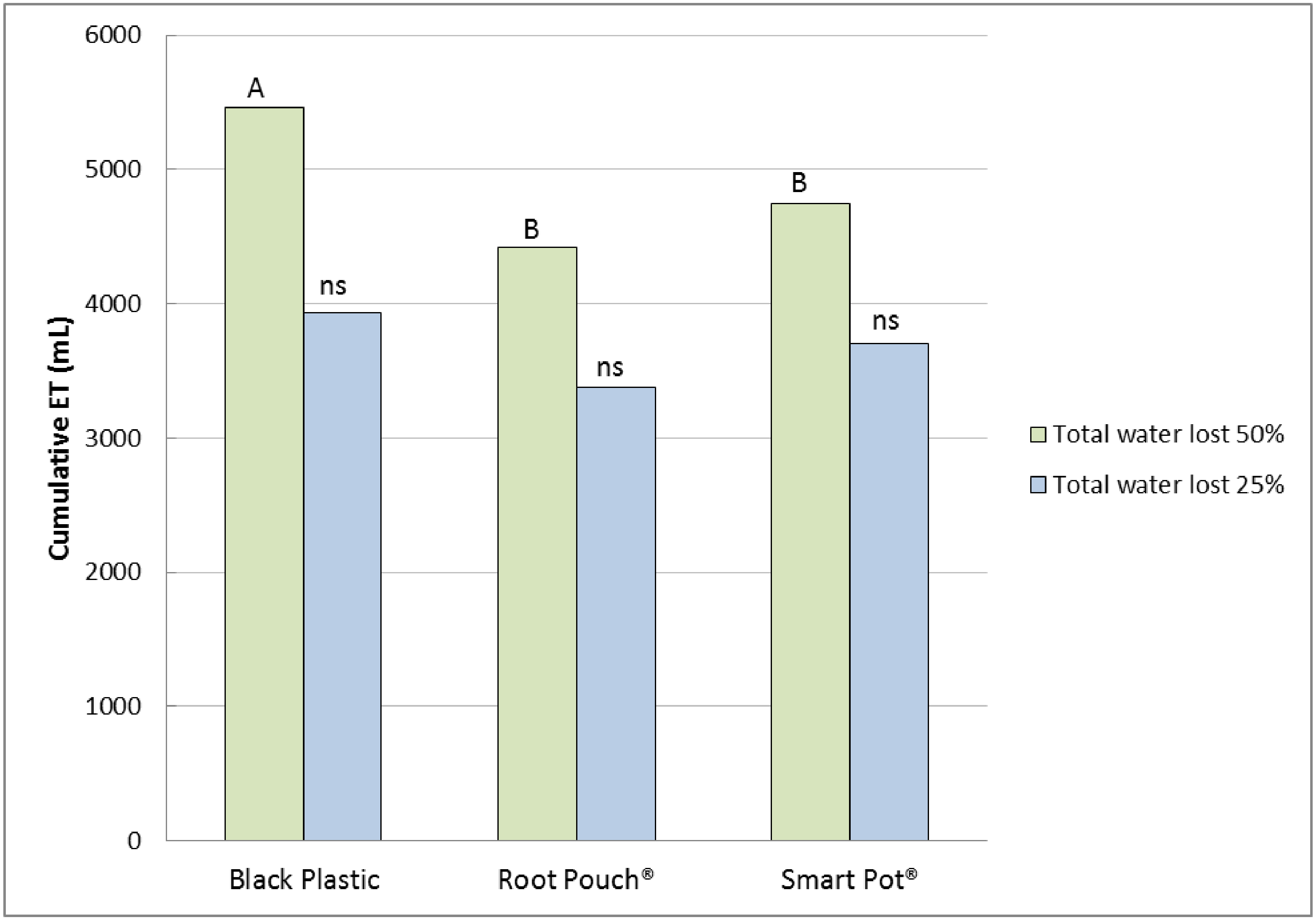


Figure 4.21. Cumulative evapotranspiration (ET) for *Viburnum trilobum* 'Compactum' growing in three container types (black plastic, Root Pouch® and Smart Pot®) irrigated at 50% and 25% of black plastic potential evapotranspiration (BP-PET) (Experiment 50/25).

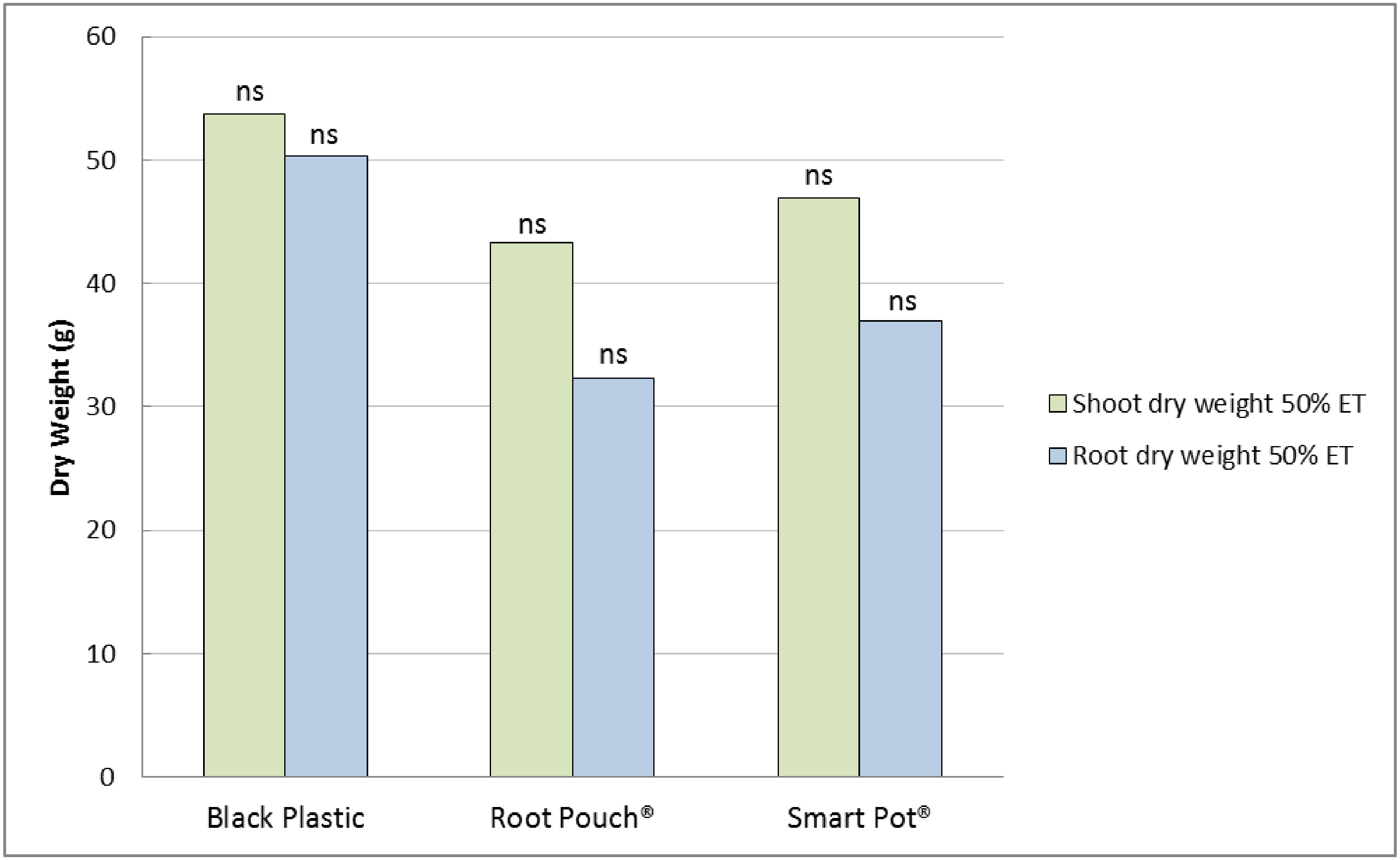


Figure 4.22. Shoot and root dry weight for *Viburnum trilobum* 'Compactum' growing outdoors in black plastic (BP), Root Pouch® (RP) and Smart Pot® (SP) containers irrigated at 50% of BP potential evapotranspiration (BP-PET) (Experiment 50/25).

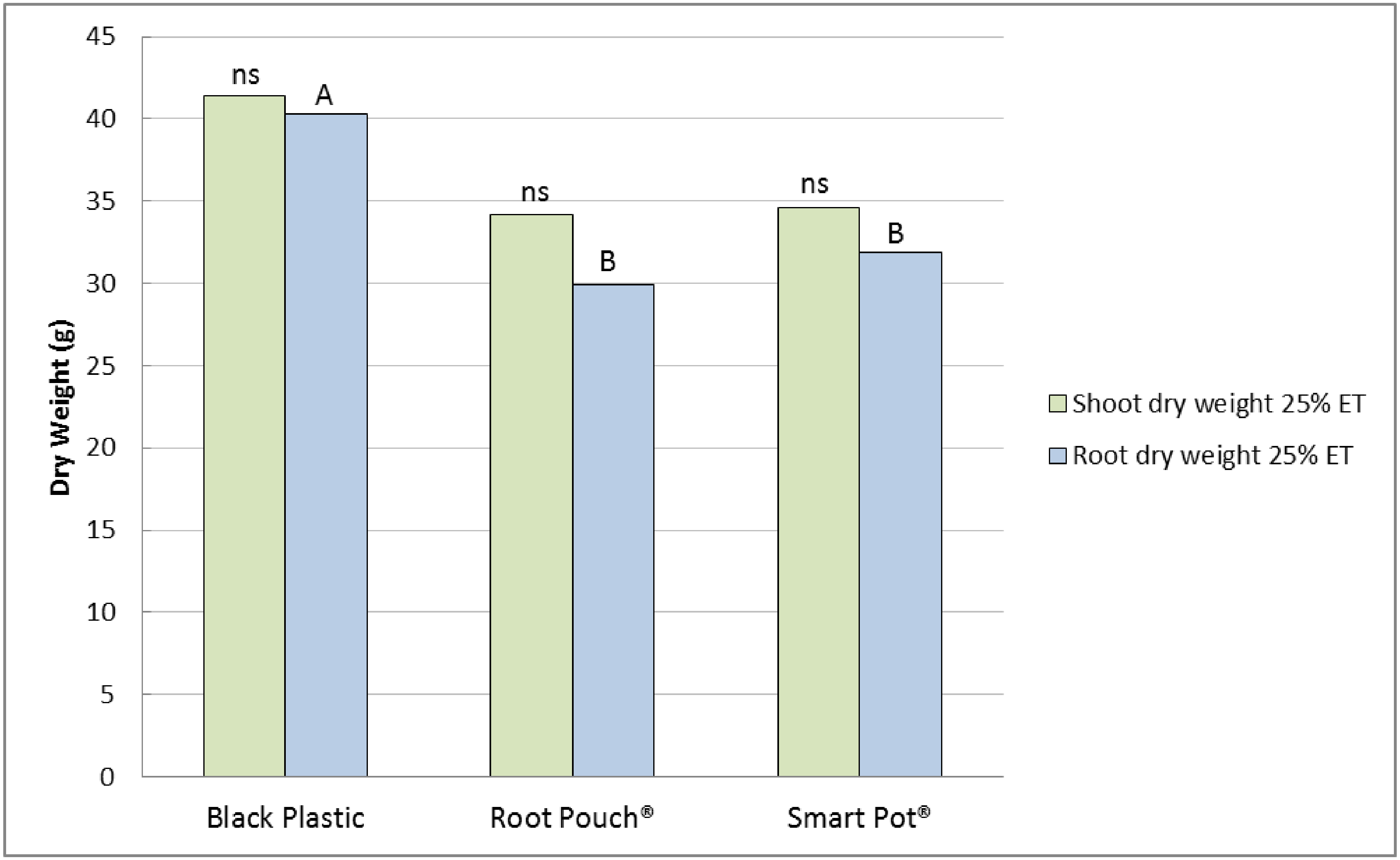


Figure 4.23. Shoot and root dry weight for *Viburnum trilobum* 'Compactum' growing outdoors in black plastic (BP), Root Pouch® (RP) and Smart Pot® (SP) containers irrigated at 25% of BP potential evapotranspiration (BP-PET) (Experiment 50/25).

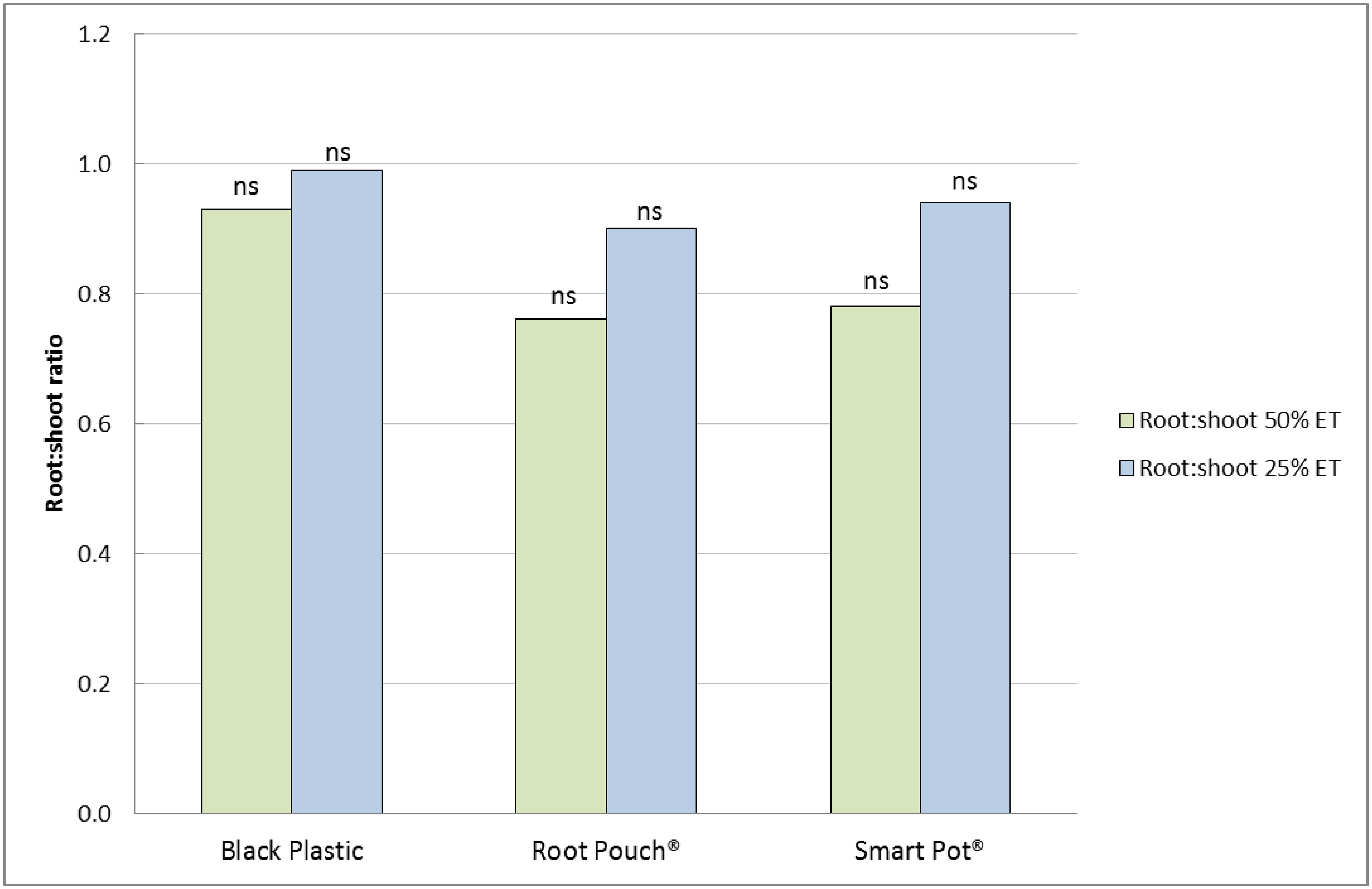


Figure 4.24. Root:shoot ratio for *Viburnum trilobum* 'Compactum' growing outdoors in black plastic (BP), Root Pouch® (RP) and Smart Pot® (SP) containers irrigated at 50% and 25% of BP potential evapotranspiration (BP-PET) (Experiment 50/25).

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CHAPTER 5

SYNOPSIS

The black plastic (BP) container has been the industry standard for the commercial production of container-grown woody ornamental plants for decades. In spite of the many advantages of using BP containers, growers and consumers have recognized that plants grown in BP often develop circling, matted and malformed roots. Left uncorrected at the time of transplanting, a poorly developed root system may compromise the short and long-term health of the plant. Trees grown in BP containers may perform poorly or die a few years after planting when circling roots caused by the container become girdling roots after planting in the landscape. Longer-lived trees can become hazardous if the malformed root system is unable to provide sufficient stability under windy conditions. Measures to correct container-compromised root systems at planting (by teasing, washing, root shaving, box cutting) are time-consuming and laborious. Further, the effectiveness of these corrective techniques has been questioned and there has been limited research to examine the response of plants to root ball correction prior to planting.

For as long as the BP container has been used for container production, alternatives to BP have been developed and offered to the nursery industry. While these alternative containers may avoid the rooting problems associated with BP container production, they have experienced only limited acceptance by growers. Concerns over cost, ease of use, transportability, sturdiness and longevity, mechanization issues, and questions about effectiveness (relative to BP) at reducing negative effects on root structure have been described as impediments to wide-scale adoption by growers. Growers may be reluctant to adopt the use of alternative containers because little research has been conducted to address these questions and concerns – including whether or not their use will produce a better plant in the nursery and in the landscape following planting.

My research sought to address some of the most important questions that the green industry has asked about the feasibility of using alternatives to the black plastic container. I examined the effects of three container types – black plastic and two fabric containers (Root Pouch® and Smart Pot®) – on the growth of Chanticleer® pear (*Pyrus calleryana* 'Glen's Form') in a simulated nursery production system and following transplanting the nursery-grown trees into the landscape. Greenhouse and field studies (using *Viburnum trilobum*) were conducted to compare evaporative water loss characteristics of the three containers – with and without plants growing in them.

In the nursery production study, trees growing in the two fabric containers were significantly taller and had greater caliper than trees growing in BP containers one and two years following planting. For trees grown in BP containers, there were significantly more circling roots and there was greater root ball matting compared to those in the two fabric containers. After one and two years of growth, there were no container effects on total shoot or root dry weight, leader growth, twig growth, or leaf area. After two year's growth in containers, trees growing in the fabric containers were taller with greater trunk caliper, but the growth of the trees was otherwise not significantly affected by the type of container in which they were grown. For the tree species used in this study, I can confidently say that trees grown in the fabric containers grew as well as or better than those grown in black plastic and that the root systems of trees grown in fabric containers will have fewer circling and matted roots after one and two seasons.

As part of the nursery production study, I studied the effects of winter consolidation of containers versus leaving trees lined out. While there were no significant individual container effects or container x overwintering treatment effects on tree growth, trees that were consolidated were significantly larger (height, caliper, dry shoot, root and leaf weight) and exhibited greater leader and twig growth at the end of the two-year nursery study than trees that were lined out during the winter. Container substrate temperature data showed that trees growing in BP containers were subjected to greater temperature extremes and wider diurnal temperature fluctuations than those growing in fabric containers. These results suggest that, regardless of container type used, nursery stock will benefit from consolidation in those regions of the country where winters are cold.

Trees grown in the nursery production experiment were planted into the landscape (Kentucky bluegrass turf), where growth (height and caliper) was measured monthly. Trees were harvested one, two and three years following planting. Over the three-year period there were no container effects on above ground growth – height, caliper, shoot and leaf dry weight, total plant dry weight, and leader and twig growth. At the end of the third year, BP-grown trees had significantly greater root mass (dry weight) than did trees grown in the fabric containers. However, a significantly greater amount of the root dry weight and root volume of the BP-grown trees was concentrated within the original root ball. Trees grown in the two fabric containers formed root systems that grew to a significantly greater extent (greater dry weight and root volume percentage) beyond the original root ball, into the surrounding soil. Root growth and regeneration beyond the original root ball and outside of the original planting hole plays a vital role in stabilizing a tree against wind as the tree becomes larger. Fewer roots growing within the original root ball and the planting hole reduces the potential for girdling roots that can kill or weaken a tree as it matures in the landscape. I feel confident suggesting that, for the tree species used in this study, the use of fabric containers for production will result in a transplanted tree with a root system that will grow farther into surrounding soil (beyond the original root ball) than will the same tree grown in a black plastic container. The more expansive-growing root system of fabric container-grown trees may result in a mature tree that is more stable (against wind) and potentially healthier and longer-lived than the same tree produced in black plastic.

In a greenhouse study, fabric containers (containing only substrate) lost water at a significantly greater rate than did black plastic containers; the fabric containers also lost more total water than did black plastic containers during the replicated studies. When wrapped with plastic film to eliminate sidewall evaporation, the fabric containers still lost more water than did the black plastic containers. The results of the greenhouse studies suggest that fabric containers may require more frequent irrigation – and perhaps more total water – than would black plastic containers under identical climatic conditions.

In a field study using *Viburnum trilobum* in the three container types irrigated at 25 and 50 percent of measured BP evapotranspiration, the black plastic containers had a higher cumulative ET amount over the two-week studies; however, when irrigated at

75% of BP evapotranspiration, differences among container types was small. When potential evapotranspiration was measured, the fabric containers lost significantly more water over a two-week period than did the black plastic containers. I found differences among container types to be small and often not significant under deficit irrigation. My results indicate that differences in irrigation requirement among containers may be small as plants mature in the containers and deficit irrigation is used. However, before plants are established in the containers, irrigation requirement of fabric containers may be greater than that of black plastic containers.

The results of my work with two alternatives to the black plastic nursery container, Root Pouch® and Smart Pot®, would suggest that nursery growers should consider the use of these alternative containers because plants grown in them are less likely have compromised (circling and girdling roots) root systems after transplanting into the landscape. While more water might be required to produce plants in fabric containers in the nursery, the nursery production industry should consider the advantages their use might offer, including the potential for fabric containers to produce higher quality plants that offer greater transplant success and longer-lived trees for the consumer.