COLOR AND SHADING OF CONTAINERS AFFECTS ROOT-ZONE TEMPERATURES AND GROWTH OF NURSERY PLANTS

by

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Abstract

Heat stress is an important problem in potted nursery plants, but container color may moderate effects of solar radiation on container soil temperatures. Field studies were conducted near Manhattan, Kansas, USA during summer to evaluate effects of container color on growth of roots and aboveground biomass in: bush beans (*Phaseolus vulgaris*); red maple (*Acer rubrum)*; and eastern redbud (*Cercis canadensis)*. In the tree studies, effects of shaded soil-surfaces on plant growth were also evaluated. Four treatments among studies included containers colored black (control), flat white, gloss white, and silver, with two additional treatments in the tree studies of green and black containers with shaded soil surfaces (black shaded); treatments were arranged in a completely randomized design. Plants were grown in a bark-based soil-less media, and temperatures were measured at 5 cm depths in the sun-facing sides and centers in five containers per treatment. After four months (June-October), plant variables were measured. Roots were separated into three sections: core (10.2 cm diam.), north, and south, rinsed of all media, dried and weighed. In the bean study, media temperatures at the sun-facing side averaged lowest in gloss and flat white (~36 ^{o}C) and greatest in the black control (50.3 ^{o}C). Accordingly, total root biomass at the sun-facing side was reduced by 63 to 71% in black compared to flat and gloss white containers. In heat-sensitive maples, media temperatures at the sun-facing side averaged up to 7.7 ^{o}C greater in black, black shade and green than in other treatments; temperatures in black shade may have been lower if shade cloth had covered the sun-facing sides of containers in addition to only the media surface. Media temperatures in the core averaged 3.5 to 3.8 ^{o}C greater in black than in flat and gloss white, resulting in up to 2.5 times greater belowground biomass and up to 2.3 times greater aboveground biomass in flat and gloss white than in

black pots. In heat-tolerant redbuds, the effects of container color on whole-plant growth were less evident. Data suggests that heat-sensitive plants benefit from using white pots or painting outer surfaces of green and black pots white.

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Dedication

Dedicated to my parents:

John W. Markham Jr.

&

Bernadine B. Markham

And children

John W. Markham IV

&

Heather Marie (Kyungbin) Markham

Introduction

Production and sales of nursery plants is a major segment of the horticultural industry and contributes significantly to the economy of the U.S. In 2002, production of nursery plants in the U. S. was estimated to be \$8.9 billion. Growers in California produced \$2.1 billion, while Texas produced \$ 1.1 billion accounting for 36% of the total production of nursery plants that year (USDA, 2003). In 2006, nursery sales in 17 states surveyed by National Agricultural Statistics Service (NASS) totaled \$4.65 billion, which was a 17 percent increase from 2003 (USDA, 2007). Nursery and greenhouse sales in Kansas grew 181 percent from 2000 to 2006, increasing from \$86.4 million to \$156.7 million (Kansas Department of Agriculture, 2007).

Heat stress in nursery container plants is a very significant and troublesome concern, especially in the southern U.S. where air temperatures are often high. At temperatures over 30 ^{o}C, root growth slows considerably (Johnson and Ingram, 1984). For many woody species root growth will stop completely at temperatures above 39 ^{o}C (Mathers, 2003). The roots of some woody species (e.g., *Ilex crenata* 'Helleri') die when exposed to temperatures of 51 ^{o}C for merely thirty minutes (Martin et al., 1989). Studies have revealed that temperatures inside nursery containers can rise much higher than 51^{o}C, and commonly surpass 54 ^{o}C in the southern states (Ingram et al., 1989; Martin et al., 1989) (Mathers, 2000). Thus heat stress in nursery containers likely has a major impact on the industry.

Some effects of high root-zone temperatures in container-grown nursery plants include reduced growth rate or stunting of growth, wilting, leaf chlorosis or leaf drop, reduced flower numbers and quality, abnormal branching, and interference with normal physiological and biochemical processes (e.g., photosynthesis and respiration, water and nutrient uptake, hormone synthesis and translocation processes) (Ingram et al., 1989). High root zone temperatures may also cause a reduction in the number of seeds or pollen cones, increased incidence of disease, root or plant injury or death, and limited distribution of many plant species (Ranney and Peet, 1994; Webber and Ross, 1995).

Wong et. al (1971) studied the effects of high soil temperatures on five woody plant species planted in polyvinyl tubes 30 cm long with a 37 mm inside diameter. Their study demonstrated that temperatures of 35 ^{o}C reduced the growth of black locust roots by up to 75%. Of the five species tested, octotillo (*Fouquieria splendens)*, Jerusalem thorn (*Parkinsonia aculeata*), black locust (*Robinia pseudoacacia)*, rose (*Rosa spp*.), and peach *(Prunus persica)*), rose and especially peach were the least tolerant to high soil temperature. All roots of the rose and peach, except for the upper trunk roots, were killed by four-hour exposures at 45 ^{o}C. Only the root tips of the other species were killed at 45 ^{o}C. Roots in the latter example were exposed to only one period of high temperatures. A longer duration (6 h) at 45 ^{o}C seemed to be more damaging to roots than multiple exposures at 4 h. When the soil temperature remained at 50 ^{o}C for at least four hours the roots of all five species died and did not regenerate.

Fretz (1971) reported that root growth above 29 ^{o}C may be retarded, while total cessation in many species occurs above 38 ^{o}C. In his study, temperatures above 43.3 ^{o}C were recorded in containers exposed to solar radiation. Fretz (1971) also showed that lighter colored containers resulted in a decrease of soil temperatures by about 5.6 ^{o}C. When pots were placed in a configuration with sides touching, containers with southern exposure were 5.6 to 8.3 ^{o}C warmer than containers more central to the configuration (and therefore shaded), showing that containers with a southern exposure should be protected.

Whitcomb (1980) studied the effects of container color on soil temperatures and root development and plant growth of sugar maple *(Acer saccharum),* amur cork tree *(Phellodendron amurense)*, and bald cyprus *(Taxodium distichum)* in production beds and containers. White containers were fabricated by laminating white colored polyethylene bags to the outsides of black bags; solid white bags by themselves became brittle due to the effects of ultraviolet radiation. He found that temperatures inside the white containers were 3.9 to 8.9 ^{o}C cooler than in black containers. Plant height and growth caliper were greater in plants grown in white containers compared to black containers in all three species.

Ingram (1981) compared the effects of temperature on root growth of *Cornus florida*, *Rhododendron simsii* cv. Formosa, and *Pittosporum tobira* grown in polyethylene bags and conventional, rigid black containers; plants in both containers were grown under full sun and in 47% shaded conditions. The polyethylene bags had a white outer surface with a black inner surface. Maximum daily temperatures in full sunlight on the west side of containers were 6 ^{o}C higher in the black containers than in the white polyethylene bags. Root growth in full sun of plants grown in white polyethylene bags compared to black conventional pots was three times greater in *Rhododendron*, four times greater in *Cornus*, and unaffected in *Pittosporum*. In general, root and shoot growth of all three species was greater in than in full sun, regardless of pot color.

Martin et al. (1989) determined that in *Ulmus parvifolia* 'Drake', elevated soil temperatures of 42 ^{o}C reduced carbon exchange rates and stomatal conductance in the leaves. After 12 weeks of exposure to 42 ^{o}C for six hours per day, the survival rate of elm decreased by 50%. Conversely, Holly *llex x atentuata* 'East Palatka' was more tolerant to similar root-zone temperatures. Results from their study suggested that supraoptimal root-zone temperatures restricted photosynthesis. In their whole-plant study, elevated root zones caused photosynthesis rates to fall below the temperature compensation point, where respiration rates exceeded photosynthesis. Their study also revealed a decreased shoot-to-root ratio, chlorotic or yellow-green foliage, stunted growth, and leaf drop in containers with elevated root temperatures.

Ranney and Peet (1994) reported that net photosynthesis was extremely sensitive to heat stress in the leaves of five species of birch (*Betula* spp.). Reductions in net photosynthesis with heat stress may consequently result in significant reductions of shoot growth of the plant, and potentially necrosis of the shoots based on high leaf temperature. High root zone temperatures also reduce nutrient and water uptake, which results in wilting of the plants and stomatal closure resulting in an inhibition of the exchange of gases necessary for photosynthesis. Plants that are experiencing heat stress in the root zones can also exhibit reduced production of chlorophyll in the shoots. Disruption of the hormonal synthesis can also affect apical dominance and produce more lateral branching (Ingram, et al., 1989). Flower initiation and development can also be negatively affected (Ingram, et al., 1989; Webber et al., 1995).

Respiration is the process by where the plant releases energy which is stored in the fats and carbohydrates (Ingram et al., 1989). This energy is necessary to sustain the plant's integrity of the cells and to support the growth of the plant. During periods of heat stress the requirement for energy to maintain cell integrity increases, which increases respiration. If heat stress is severe, there may be little or no energy remaining for plant growth (Ingram et al., 1989).

The critical temperature of plants that result in injury or death varies among species and cultivars (Martin et al., 1989). When this critical temperature is reached, root-cell membranes suffer irreversible injury and soon die. As the exposure time is increased the required temperature for causing heat stress becomes less. Even if this critical temperature is not reached there may still be tissue damage, which will slow down the plant's development. Regeneration may occur, however, if exposure to high temperature is reduced or halted.

Young plants require higher nutrient levels than established plants. Consequently, young developing plant roots are more susceptible to high root-zone temperatures, which have a deleterious effect on nutrient uptake. For example, calcium is required for cell elongation and division and therefore is important in the formation of new roots. When young roots are injured by heat, however, calcium uptake is reduced and new root growth is disrupted (Mathers, 2002).

MacDonald (1991) found that heat stress in roots predisposed *Dendranthema x grandiflorum 'Paragon'* (Chrysanthemum) roots to *Phytophthora* root rot; infections were greater in containers 40^{o} C or higher than in containers at 25 to $35\,^{o}$C. Two possible explanations were offered for this response. The first is that the natural pathogen-induced plant root responses are disrupted, which allow the pathogen to invade the roots. A second possible scenario is that the pathogen has an altered response to the heat-stressed roots of the plant.

Direct solar radiation on container side walls may cause root zone temperatures to rise well above the air temperature, which may affect root growth in that section of the container. Temperature fluctuations in container media may also be affected by season and latitude. For example, in a study conducted in Florida, U.S., roots located on the east and west sides suffered more in the summer because of exposure to longer and more intense durations of solar radiation. In the fall and winter, however, roots on the south side experienced higher temperatures. Therefore, shading practices for the appropriate season may reduce the effect of solar radiation on soil temperatures (Ingram et al., 1989).

Albedo is the fraction of radiation incident upon a surface that is reflected by the surface. Therefore by increasing the albedo or reflectance of the containers, the root zone temperatures may be reduced. Fiber pots absorb less radiation and allow for evaporated cooling which may reduce the root-zone temperatures (Ruter, 1999). However, average monthly high and low root-zone temperatures are similar between fabric and plastic containers, and differences in growth may be small for some species. (Tauer et al., 2009) Placement of containers in a pot-to-pot arrangement until their canopies touch also may shade the containers and reduce radiation incident on the containers (Mathers, 2000).

The use of 2.6 mm thick white styrene liners inside the containers resulted in a reduction of the temperature of the media (Brass et al., 1996). For example, when styrene liners (2.6mm thick) were added to containers, soil temperatures were reduced significantly by 7^{o} C in 10.3 L containers and by 8 ^{o}C in smaller, 2.7 L containers compared to unlined containers. The authors concluded that the larger containers provided a greater ability to buffer the media due to increased volume of substrate or thickness of the container walls.

Irrigation of containers with at least three liters of water helped to mitigate mean maximum temperatures in the center of containers (Martin et al., 1991). This irrigation practice reduces heat buildup in the containers and is recommended at mid-day, which coincides with the highest temperatures (Martin et al., 1991).

Whitcomb (2003) has also investigated the effects of container color on plant production and has developed specialized products to mitigate container-media temperatures. For example, a laminated fabric material that slips over a conventional pot reduced the media temperature by 10-16^{o}C (RootSkirts®, Rootmaker Products Co., Huntsville, AL). Growing trees in cinder blocks with fabric liners (Typar®, Fiberweb, Inc, Old Hickory, TN) was also helpful in insulating the roots from the summer's heat (Whitcomb, 1999). Whitcomb (2006) investigated the effects of a container made of an insulating black fabric with a bonded white polyethylene coating on the outside on soil temperature. This container used 1.5 times less water than conventional black plastic containers because it kept the media temperatures 11-14 ^{o}C cooler.

The pot-in-pot system involves placing a pot within a pot which has been permanently placed in the ground. These plants also had nearly twice the root biomass and 20% more top growth than conventionally-grown (i.e., containers set on the surface) nursery plants (Mathers, 2000).

The spatial effects of soil temperature on root growth in nursery containers, and the subsequent effects on aboveground plant growth, have not been examined. In particular, how is root growth affected near the edge of the containers compared to in the center? Do these patterns vary among plant species, especially between heat-sensitive and heat-tolerant plants? Because different container colors may affect soil temperature patterns in the root zone, how does container color affect spatial patterns of root growth in nursery plants? Finally, what are the overall effects on aboveground growth among species? In this study, the effects of pot color and shading of individual pots on soil temperatures were examined to determine their impacts on plant growth in an herbaceous species and in a heat-sensitive and heat-tolerant woody species. Spatial effects of media temperature on root growth were examined in different areas of each container. The effects of pot-color and container media temperature on aboveground biomass were also examined.

Materials and Methods

Preliminary Field Study

A preliminary field study was conducted in the fall of 2004 using bush bean plants grown in soil-less potting media (Metro-mix 366p, Sun-Gro, British Columbia, Canada). The bush beans were grown in pots (Classic 1000, Nursery Supplies, Fairless Hills, PA) with 25 cm top diam., 23 cm height, and 21 cm bottom diameter with a volume of 8.694 L. Four treatments included container colors of black as the control, flat white, gloss white, and silver, with four reps of each treatment arranged in a completely randomized design. All pots were initially black, but four each were painted flat and gloss white (ColorPlace Fast Dry Spray Paint, Bentonville, AR) and silver (Rust-oleum Bright Coat Metallic Finish, Vernon Hills, IL). Two soil temperature probes (Fig. 1) were inserted at 5 cm in each container, with one probe at the south or sun-facing side and one in the center (Fig. 2). Soil temperature probes were constructed by longitudinally centering copper-constantan thermocouple junctions (Type T, 24 AWG, TT-T-24, Omega, Stamford, CT) in segments of copper tubing (7.5 cm in length x 6.4 mm diam.) and filling the tubes with thermally conductive epoxy (Omegabond 101, Omega Engineering, Stamfort, CT). Soil temperatures were recorded hourly with a data logger and multiplexer (CR10x, AM16/32, Campbell Scientific, Logan, UT).

After 40 days in the field (August 21to September 30, 2004), fruit and shoot plant material were harvested and leaf area measured with an area meter (LI-3100, LI-COR, Lincoln, NE). All above-ground biomass was separated and dried in a forced-convection oven at 66 ^{o}C for 48 hours and weighed. A 15 cm diameter galvanized stove pipe was used to extract the core of the roots by slicing soil in each container from top to bottom (Fig. 3). To determine differences in root growth between sun-facing and non-sun-facing sides, a sheet metal "slicer" was fabricated to separate the remaining soil-less media along the inside perimeter of the pots into north and south (sun-facing) halves. Roots in all three sections, (i.e., core, north, and south halves) were rinsed carefully, placed in paper bags, dried at 66 ^{o}C for 48 hours in a forced convection oven, and then weighed.

Field Study

Two species of trees were selected for their tolerance and sensitivity, respectively, to heat stress. The eastern redbud (*Cercis canadensis)* is fairly heat tolerant and is a popular landscape tree in the Great Plains region. Conversely, the red maple (*Acer rubrum)* is heat sensitive but is still used widely in the landscape industry. One hundred, bare-root, year-old seedlings (Lawyer Nursery Co., Plains, MT) of each species were transplanted into plastic containers (Classic 600, 7.57 L, 20 cm diam.) using soil-less media (MetroMix 702, Sun-Gro, British Columbia, Canada) and slow-release fertilizer (Osmocote 19-6-12, Scotts-Sierra, Marysville, OH). A cursory visual inspection at planting indicated that the overall development of the maples was more advanced than the redbuds. Containers were then placed in the greenhouse until all trees began to break bud.

Six treatments included the container colors of black, gloss white, flat white, silver, green and black pots with the soil surface shaded (black shaded). As in the preliminary study, all pots were initially black but some were spray painted gloss white, flat white, and silver according to their treatment. Green pots (Classic 600) were used as manufactured. To shade the soil surface in the black shade treatment, individual shading structures were constructed for each pot using sections of tomato cages and woven shade fabric that blocked 63% of irradiance (PAK Unlimited, Cornelia, GA). The fabric was placed horizontally over pots in the black shade treatment at 3.75 cm above surface and extending 3.8 cm beyond the rim of the pot. Initial measurements were taken of initial tree height, number of active buds, and stem caliper at 7.5 cm above the soil surface.

Potted trees were placed at an open, level site in which vegetation had been killed with glyphosate approximately 0.6m in diameter surrounding the tree container bases (Fig. 4). Pots were arranged in completely randomized design with cedar mulch under each pot to hold them above the soil level and thus, confine all root growth inside the pot. The pots remained in the field from June 26 to October 27, 2005 and were watered when symptoms of stress were apparent.

Two soil-temperature probes were placed at 5 cm in five containers of each treatment of maple plants for a total of thirty maple containers. As in the preliminary study, one probe was placed at the sun-facing edge and the other in the center of each pot; the center probe was midway (10 cm) between edges of the pot. Soil temperatures were not measured in redbuds because of a limited number of soil probes and data acquisition capabilities. Soil temperatures were recorded hourly with a data logger and multiplexer (CR10x, AM16/32, Campbell Scientific, Logan, UT). Ambient air temperature was measured with a thermocouple enclosed in a solar radiation shield (RM Young, Traverse City, MI). Six soil encapsulated thermocouples (SET) (Ham and Senock, 1992) were placed on the surface of the soil-less media in three randomly selected pots of two treatments including three in the black and three in black shaded pots. The SETs were used to measure soil-surface temperatures, which were also logged hourly using the same data logger as mentioned above. A 5-watt solar panel (SP5-L, Campbell-Scientific Logan, UT) was used to charge the battery, which powered the data acquisition system. Data were analyzed with the general linear model procedure of SAS (SAS Institute, Cary, NC). Differences between means were separated by the least significant difference (*P*=0.05).

The plants experienced varied weather conditions including strong hot winds, hail, and freezing temperatures. The average early frost for fall in Manhattan, KS, USA (39°11´43´´ N, 96°34´47´´ W) is October, 15. For the last five days that the plants were in the field (Oct. 23-Oct. 27) the frost caused maples to lose their foliage, which prevented measurements of leaf area. The low temperatures for those days were as follows: 0^{o}C, -1.1^{o}C, -3.9^{o}C, -1.7^{o}C, -0.6^{o}C. Redbuds, however, retained their leaves after the frost because they are more cold-tolerant than maples. During the first week of November, leaves were removed from the redbuds, leaf area was measured, and the samples were then dried and weighed.

At the end of the field study, aboveground measurements of total shoot length, total number of branches, and final stem caliper at 7.5 cm above the surface were collected for all trees in both species. In addition, the tallest shoot length was measured in maples. Redbuds had branched out so much that it was impossible to determine a central "leader" and therefore, the tallest shoot length was not measured. Supplemental measurements on the redbuds included the number of branches below the 7.5 cm caliper standard and the caliper below all branches. This measurement was not needed on the red maples because they developed a strong leader and therefore there were no branches below the 7.5 cm caliper standard. Each tree stem was then cut at the soil surface, dried and weighed. A 10 cm diam. core was extracted from each container from top to bottom and the remaining soil-less media divided into north and south (sun-facing) halves, using the same method as described in the preliminary field study. Soil-less media was then carefully removed by rinsing root samples in each section. Root samples were then placed in paper bags, dried at 66 ^{o}C for a minimum of 48 hours and then weighed.

Results and Discussion

Bean Study

Among the four treatments in which bush beans were grown, maximum soil temperatures at the sun-facing side averaged from 35.6 to 50.3 ^{o}C among pots (Table 1). These temperatures are high enough to impede growth of or even kill roots in a number of species (Fretz, 1971; Whitcomb, 1980). In flat white, gloss white, and silver pots, soil temperatures were 14.7 to 8.8 ^{o}C lower than black pots at the sun-facing side. Cooler soils in the lighter-colored pots were likely caused by their greater albedo, which reflected more solar radiation away from their sides than black pots. Soil temperature in silver pots was also higher than in gloss white and flat white pots on the sun-facing side, indicating greater potential for damage of roots in silver than in flat and gloss white pots.

Soil temperatures at the core were 5.9 to 13 ^{o}C cooler than at the sun-facing side among treatments with the exception of gloss white, which was similar at both locations (Table 1). Black pots exhibited the greatest temperature difference between the sun-facing side and the core. Nevertheless, soil temperatures at the core remained greater in black pots among all treatments, while core temperatures were similar among flat white, gloss white, and silver pots. Overall, soil temperatures were greatest in black pots at both the sun-facing side and at the core.

The dry weight of roots in the sun-facing side of black pots was 63 to 71% less than in gloss and flat white pots, respectively, and 50% less than in silver pots (Table 2). Root biomass in flat white, silver, and black pots followed a reverse trend from soil temperatures (Table 1); root biomass clearly decreased with increasing soil temperature among these treatments. The dramatic reduction in root biomass in black pots among treatments illustrates the detrimental effects of higher soil temperatures on root growth and development.

On the north side of pots, the only difference in root biomass among treatments was a 20% reduction in black compared with gloss white pots (Table 2), which reflects the smaller differences in soil temperature among treatments away from the sun-facing side (Table 1). When comparing root biomass between the north and south sides of pots, there was no difference in flat white pots and differences between north and south were 36% smaller in gloss white and 13% smaller in silver than in black pots. In black pots, root biomass was 71% lower in the sun-facing side than in the north, which again revealed the effects of severe heat on root development in the sun-facing side.

The deleterious effects of high temperature on root growth were evident in black pots, in which total root biomass was lower than in flat white and silver pots (Table 3). Root biomass in the core was similar among flat and gloss white and black pots however, soil temperatures at 5 cm were higher in the cores of black pots than in flat and gloss white pots (Table 1). It is possible that soils were cooler below 5 cm, which may have muted the effects of high temperature on root growth in black pots. Nevertheless, the negative effects of high temperature on root growth in the sun-facing side, which strongly reduced total root biomass in black pots, indicates a need to adapt management practices that mitigate high temperatures in nursery containers.

The effects of high temperature on aboveground biomass were less conclusive, with the possible exception of shoot growth. For example, shoot dry weight was less in black pots than in silver pots, and numerically (albeit not statistically) lower than in flat and gloss white pots, which suggests that higher temperatures in black pots may have reduced shoot growth (Table 3). No differences were observed, however, in fruit dry weight among treatments. It is also not evident why leaf area was less in flat white than in silver pots, or why leaf area was similar in black pots among treatments. Grasshoppers had damaged the leaves of the beans prior to harvesting. Although the damage appeared uniform, it may have varied among treatments, which would have confounded the results.

Tree Study

Maples

Soil temperatures at the sun-facing side of pots, recorded over a 90-day period, fell into two distinct groups among treatments. Soils in black, black shade, and green were consistently warmer than flat white, gloss white, and silver (Fig. 5A). Daily maximum temperatures, when averaged over the entire 90 days, ranged from 4.9 to 7.7 ^{o}C higher in black, black shade, and green than in the other treatments (Table 4). Interestingly, soil temperature in black shaded pots was not reduced by the shade cloth at the sun-facing side, probably because the shade cloth did not extend far enough beyond the edge to shade the side of the pot. Therefore, the same amount of solar radiation was probably incident on the sides of black shaded pots as on the sides of all other pots.

The same general trend of two distinct groups of soil temperatures among treatments was observed in the core (center) of the pots, although differences between groups were generally smaller than at the sun-facing side (Fig. 5B). The lowest daily maximum temperatures were in flat and gloss white and silver pots, which averaged 2.8 to 4.3 ^{o}C lower among treatments (Table 4). Soil temperatures in the core also averaged 1.2 ^{o}C lower in black shade than in green pots, indicating a measurable cooling effect of the shade cloth in the black shade treatment. Core soil temperatures were similar, however, between black and black shade pots, indicating the cooling effect of the shade cloth was slight. It is likely that the effects of solar irradiance incident on the sides of the pots, which were not shaded in the black shade treatment, resulted in a significant transfer of heat into the core. This suggests that shading of the sides is important to cool the soil throughout the pots.

Soil-surface temperatures, which were measured in three black and three black shade pots, were similar between treatments. Closer inspection of average soil temperatures among pots, however, revealed relatively uniform temperatures in the three black pots (mean=38.7 ^{o}C) and in one black shade pot (37.9 ^{o}C) (Table 5). Surface temperatures in the remaining two black shade pots averaged about 6 ^{o}C lower than in the other black shade pot. The reason for this discrepancy is uncertain but suggests that one black shade pot may have been exposed to greater solar radiation or another heating source. Nevertheless, soil temperatures were nearly identical at five cm in the core among the six pots, which indicates that any cooling effects of shading the surface were negligible at lower depths. Temperatures in the sun-facing side were uniformly high among the same pots, which also suggest that heat transfer from the sides into the core was significant.

In all pots, soil temperature averaged 11 to 22% higher at the sun-facing side than at the core (Table 4). The greatest differences in soil temperatures between the sun-facing side and core were in black, black shade, and green pots, in which the greatest soil temperatures were also observed among treatments. Clearly these results indicate the greatest potential for damage to root growth and development among treatments are in the black, black shade, and green pots. The critical killing temperatures of root tissues in red maple cultivars has been evaluated to range between 51.2-53.8 ^{o}C (Sibley et al., 1999). In our study, maximum temperatures on the sun-facing side of black, black shade, and green treatments exceeded this critical level on several days during the recorded period (data not shown).

At the sun-facing edge of pots, dry root weight of maples averaged 2.7 to 8.3 times greater in flat and gloss white and silver than in black, black shade, and green pots (Table 6). The same trend was evident in the north section although the effects were muted compared to the hotter sun-facing edge; root biomass in the north section was 2.1 to 3.8 times greater in flat and gloss white and silver than in black, black shade, and green pots. This demonstrates a significant advantage of using lighter-colored pots when growing a heat-sensitive species such as maple. Root biomass was also lower in silver than in flat white pots at the sun-facing edge and lower than in gloss white pots in the north section, indicating a further advantage to root growth in maples in flat and gloss white pots than in silver pots.

Root biomass in the core and in the whole pot (total) was 1.4 to 2.5 times greater in flat and gloss white containers than in all other treatments, including silver (Table 7). In silver pots, however, root biomass was 1.4 times greater than in black pots in the core and 1.7 greater than in green and black shade when integrated over the entire container. Total dry weight however, was not greater in silver than in black. Thus, a general trend was observed of greatest root biomass in flat and gloss white pots, followed by silver and finally by black, black shade and green pots. This suggests that greater heat damage occurred to roots in silver than in the flat and gloss white containers despite similar soil temperatures (Table 4). In the earlier bean study, soil temperatures were greater in silver than in flat and gloss white pots at the sun-facing edge (Table 1); temperatures in maples at the sun-facing edge were also numerically, albeit not significantly, greater at the sun-facing edge of silver than in flat and gloss white pots (Table 4). Therefore, our data indicate that flat and gloss white containers provided the best environment for root growth in maples among treatments, while black, black shade, and green consistently provided the poorest.

Trends in aboveground biomass were similar to patterns of belowground biomass among treatments. For example, all parameters of aboveground biomass were greater in flat and gloss white than in black, black shade, and green with the exception of tallest shoot length, which was similar between gloss white and green (Table 7). In silver pots, all parameters of aboveground biomass were lower than in flat white except for number of branches, which was similar between treatments. Aboveground biomass was generally similar, however, between silver and gloss white pots except for growth caliper, which was lower in silver pots. Interestingly, aboveground biomass was no greater in silver than in black, black shade, and green, with the exception of stem dry weight, which was greater in silver than black and green pots.

Our results indicated that growth of maple, a heat-sensitive tree, was negatively affected by higher soil temperatures. Correlation analyses revealed significant, negative relationships between soil temperature and growth of maples (Table 8). The strongest correlations of -0.62 and -0.64 were between soil temperature at the sun-facing side and root biomass in the north and south sections of containers (see also Table 6). Correlations were also significant, however, between soil temperatures at the sun-facing edge and all aboveground and belowground growth parameters except for number of branches; the latter was significant at $p=0.1$.

Soil temperatures at the core were correlated most strongly with root biomass in the north and south sections ($r=-0.56$), but were also correlated with total root biomass, total stem dry weight, and total shoot length. Correlations between soil temperature at the core and plant growth were fewer because of lower temperatures and smaller differences in temperature and plant growth among containers at the core compared to the sun-facing side.

In summary, heat-sensitive maple trees grew more vigorously in flat and gloss white pots, in which soils were cooler, than in black, black shade, and green pots. Whitcomb (1980) and Ingram (1981) also reported cooler soil temperatures and greater growth in a number of species in white compared to black containers. In our study, soil temperatures were also higher and plant growth reduced in green compared with flat and gloss white pots. Furthermore, growth of maples was generally less in silver pots than in flat and gloss white. Therefore, nursery production of heat-sensitive trees would likely benefit from using white containers.

Redbuds

In the south section of containers, where presumably heat-stress effects were greatest, root biomass was 2.2 to 2.8 times greater in black shade, gloss white, and flat white than in silver and green pots (Table 9). The most consistent trend in root biomass in the south, north, and core sections of the container was greater root biomass in black shade and flat white than in silver containers (Tables 9 and 10). For example, root biomass in black shade and flat white pots was about 1.5 times greater than in silver pots in the north section and 2.2 to 2.7 times greater than in silver pots in the core. When averaged over the entire container, total root biomass was 1.1 to 1.7 times greater in black shade and flat white than in the other treatments. Thus, roots in redbuds apparently benefited most when grown in flat white pots or in black pots covered with shade cloth.

Aboveground biomass was highly variable and no clear patterns emerged among treatments when compared across the six parameters of aboveground biomass (Table 10).

In fact, aboveground biomass exhibited more similarity than differences among treatments, indicating a relatively small effect of container color on plant growth. For example, total shoot length was similar among treatments except for silver. In all other aboveground biomass parameters, four of the six treatments were similar although the patterns among treatments were inconsistent.

Redbud, a heat tolerant tree, apparently demonstrated little vulnerability to the affects of container color on growth. Some parameters such as root biomass and growth caliper were greater in flat white and black shade than in green and black, suggesting an advantage to using flat white containers or shading the containers. Confirmation of the beneficial effects of shading on growth of redbuds will likely require further study, where the entire sides of the containers are shaded. Above and belowground biomass was consistently low among treatments in black pots, which indicates a slight disadvantage to using black containers.

Comparisons of maples and redbuds

In the north side of flat white, gloss white, and silver containers, and in the south side of flat white and silver containers, the average root dry weight was 2.1 to 5.0 times greater in maples than in redbuds (Fig. 6). Generally greater root biomass in maples than in redbuds in lighter-colored pots illustrates the beneficial effects of cooler soils on root growth near the container sides in heat-sensitive maple (Fig. 5; Table 4). Interestingly, root biomass in the sun-facing section of black shade pots was 2.9 times greater in redbuds than in maples, indicating a significant response in redbuds to shading compared with maples.

In black, black shade, and green pots, root dry weight in the core was 39 to 54% less in maples than in redbuds; a similar trend was observed in total root biomass in the containers (i.e., total) (Fig. 7). Lower root biomass in maples than in redbuds in darker-colored pots illustrates the detrimental effects of higher soil temperatures (than in lighter-colored pots) to root growth in heat-sensitive maple but not in redbuds (Fig. 5; Table 4). Lighter-colored pots reduced the impact of solar radiation on soil temperature, which minimized differences in total root biomass between the heat-tolerant redbud and heat-sensitive maple.

The number of branches was similar among treatments with the exception of flat white and gloss white, where the number of branches was greater in maple than in redbud (Fig. 8). This indicates that cooler soils in the lighter-colored pots improved top branching in heat-sensitive maples, and a fuller canopy at a higher level as compared to the redbuds. In all other parameters that were measured in both species, redbuds exhibited either greater or similar growth as maples among treatments. For example, the average growth caliper was higher in redbuds than in maples in all treatments except for gloss white, in which there were no differences between species (Fig. 9). Similarly, total shoot length and stem dry weight were greater in redbud than in maple among treatments except for flat white, in which growth between species was similar (Figs. 10 and 11).

Compared with redbuds, growth of maples was more detrimentally impacted by being grown in green, black, and black shade treatments, and benefited more by being grown in gloss and flat white pots. Presumably, warmer soils in darker- than in lighter-colored pots had significant detrimental impacts on the growth of maples, but relatively negligible effects on redbuds. Silver pots, however, did not seem to improve the growth of maples relative to redbuds with the exception of root growth in the north and south sections.

Conclusions

For the bean study, our study showed that the black container had the highest temperature for the sun-facing side, 50.3 ^{o}C, as well as the highest temperature at the core, which was 37.3 ^{o}C. Gloss white had the lowest sun-facing temperature at 35.6 ^{o}C. Flat white had the lowest core temperature of 31.0 ^{o}C. Flat white had the largest amount of sun-facing side root biomass at 597 mg. Of the two sides, north and south, the highest amount of root biomass was on the north side of the container among treatments, with the black pot having 70.6% more in the north than in the south side. Silver had a 51.3% increase. Flat white showed a 13.6% increase, allowing for the most evenly distributed root biomass. Flat white had the highest total dry weight of 4117 mg.

As stated earlier for the maples, a distinct line of separation of temperatures was observed between the black, black shade and green as opposed to the lower temperatures of the flat white, gloss white and silver for both the south sun-facing and the core measurements. For the maples, the total dry root biomass was 2.5 times more in flat white compared to black containers. Gloss white had 2.34 times more than the black. Green and black shade were only slightly higher than the black. Silver was nearly identical to flat and gloss white.

This study shows that the redbud was not as affected by the higher temperatures as was the red maple, indicating redbud's higher heat tolerance. The coolest temperature in the sun-facing side was the gloss white followed by the flat white. In these examples, root biomass in maples was significantly greater than in redbuds in the south and north sections of the flat white treatment and in the north section of gloss white, and were numerically higher, but similar, for the south gloss white treatment.

It would seem that the more heat sensitive plants do benefit from a gloss white or flat white colored pot and show a better response, than a more heat tolerant species, because of the resulting cooler media. The silver only helped to significantly improve the growth of the maples except for the north and south dry root biomass sections. Shading of the individual pots did help to cool the surface temperatures some, but did not have a significant impact on the sun-facing side temperature reading. This finding would seem to indicate that further research in shading the sun-facing side would be in order. Our findings indicate that using flat white or gloss white colored containers would be of benefit, especially to those more heat sensitive species.

Our findings indicate that the development and use of an economical, durable white colored pot could be beneficial for the nursery industry, replacing the industry standard of black containers. White containers would reduce the loss in profits and plant quality caused by heat stress, especially in heat-sensitive nursery crop species.

Figures and Tables

Table 1. Daily maximum soil temperatures, averaged over the duration of the study, of bush beans grown in flat white, gloss white, silver, and black containers (n=4). Soil temperatures were measured at 5 cm at the south, sun-facing edge and in the core.

	Season Average Temperatures (C)		
Container Color	South Sun-Facing	Core	Difference (Sun-Facing-Core)
	---------------------	C^o	---------------------
Black	50.3A[†]a[‡]	37.3Ab	13
Flat White	36.9Ca	31.0Bb	5.9
Gloss White	35.6Ca	33.1Ba	--
Silver	41.5Ba	32.8Bb	8.7

[†] Means followed by the same upper-case letter within a column were not significantly different (P=0.05).
[‡] Means followed by the same lower-case letter within a row were not significantly different (P=0.05).

Table 2. Average dry weight of bush bean roots in the north and south (sun-facing) sections of black, flat white, gloss white, and silver containers (n=4).

Container Color	South Sun-Facing	North	Difference (North – South)
	------------------------------ mg ----------------------------		
Black	173Cb	589B[§]a[**]	416
Flat White	597Aa	678ABa	--
Gloss White	473ABb	740Aa	267
Silver	345Bb	709ABa	364

[§] Means followed by the same upper-case letter within a column were not significantly different (P=0.05).
[**] Means followed by the same lower-case letter within a row were not significantly different (P=0.05).

Table 3. Average root dry weights in the cores and in the entire containers, total dry weight fruit dry weight, and shoot dry weight for bush beans grown in black, flat white, gloss white, and silver containers (n=4).

Color	Below Ground Biomass		Above Ground Biomass		
	Core Dry Wt	Total Dry Wt	Fruit Dry Wt	Shoot Dry Wt	Leaf Area
	---------- mg	----------	----------	----------	cm2
Black	2871AB[††]	3633B	7.7A	15.6B	1079AB
Flat White	2778AB	4117A	7.4A	16.1AB	955B
Gloss White	2594B	3762AB	9.1A	17.9AB	1124AB
Silver	3071A	4077A	7.2A	18.6A	1163A

[††] Means followed by the same letter within a column were not significantly different (P=0.05).

Table 4. Average soil temperatures at 5 cm at the sun-facing edge and in the core for maple trees grown in black, shaded black, flat white, gloss white, silver, and green containers (n=5).

Treatment	South Sun-facing	Core	Difference (Sun-Facing-Core)
	-----------------------	C^o	--------------------
Black	44.5A[‡‡]a[§§]	37.1ABb	7.4
Black Shade	44.3Aa	36.4Bb	7.9
Flat White	36.8Ba	33.3Cb	3.5
Gloss White	37.4Ba	33.6Cb	3.8
Silver	38.1Ba	33.6Cb	4.5
Green	43.0Aa	37.6Ab	5.4

[‡‡] Means followed by the same upper-case letter within a column were not significantly different (P=0.05).
[§§] Means followed by the same lower-case letter within a row were not significantly different (P=0.05).

Table 5. Soil temperatures on the surface and at 5 cm in the core (center) and in the sun-facing side of three black and three black shade treatments (n=3).

	Black Containers				Black Shade Containers			
	Container Number				Container Number			
Location	1	2	3	Average	1	2	3	Average
Surface	38.8	39.2	38.0	38.7a***	33.4	31.9	37.9	34.4a
Core	37.6	36.9	36.2	36.9a	37.2	36.9	36.9	37.0a
Sun-Facing Side	44.2	43.0	44.6	43.9a	44.8	45.4	44.3	44.8a

*** Means followed by the same letter within a row were not significantly different (P=0.05).

Table 6. Average dry root weight of maples in the north and south (sun-facing) sections of black, shaded black, flat white, gloss white, silver, and green containers (n=15).

Color	South Sun-Facing	North	Difference North-South
	---------------------------- g ----------------------------		
Black	0.54C[†††]a[‡‡‡]	0.72Ca	--
Black Shade	0.29Cb	0.95Ca	0.66
Flat White	2.41Aa	2.45ABa	--
Gloss White	1.74ABb	2.70Aa	0.96
Silver	1.46Ba	1.95Ba	--
Green	0.39Ca	0.85Ca	--

††† Means followed by the same upper-case letter within a column were not significantly different (P=0.05).
‡‡‡ Means followed by the same lower-case letter within a row were not significantly different (P=0.05).

Table 7. Average dry weight of belowground biomass, which includes roots in the core sections and in the entire container (total), and aboveground biomass in maples among treatments.

	Below Ground Biomass		-----------------------------Above Ground Biomass---------------------------				
Treatment	Core Dry Weight	Total Dry Weight	Number of Branches	Growth Caliper	Total Shoot Length	Stem Dry Weight	Tallest Shoot Length
	---g---	---g---		---mm---	---cm---	---g---	---cm---
Black	4.6 C[§§§]	5.8 BC	6.1 B	2.4 B	61.6 C	3.7 D	43.4 C
Black Shade	5.1 BC	6.3 C	5.1 B	2.9 B	57.6 C	4.1 CD	42.7 C
Flat White	9.6 A	14.5 A	10.5 A	4.0 A	110.9 A	8.4 A	52.2 A
Gloss White	9.2 A	13.6 A	10.0 A	4.1 A	93.7 AB	7.0 AB	51.6 AB
Silver	6.6 B	10.0 B	6.9 AB	3.1 B	78.1 BC	5.6 BC	45.9 BC
Green	4.7 BC	5.9 C	5.1 B	2.4 B	55.9 C	3.8 D	46.0 BC

[§§§] Means followed by the same letter within a column were not significantly different (P=0.05).

Table 8. Pearson's correlation coefficients (r) between plant parameters in maples and daily maximum soil temperatures at 5 cm, averaged over the study period, at the sun-facing side and in the center of containers. Data from all container colors were used in this analysis (n=30).

Plant Parameter	Sun-Facing r	P****	Center r	P
Aboveground				
Total Shoot Length	-0.52	0.006	-0.45	0.02
Number of Branches	-0.33	0.09	-0.28	0.16
Caliper	-0.42	0.03	-0.33	0.09
Tallest Shoot	-0.41	0.03	-0.32	0.11
Stem Dry Weight	-0.56	0.002	-0.46	0.02
Root Dry Weight				
Core	-0.45	0.02	-0.34	0.08
North	-0.64	0.0004	-0.56	0.003
South	-0.62	0.0006	-0.56	0.002
Total	-0.56	0.003	-0.46	0.02

**** Probability values.

Table 9. Average dry weight of root biomass in south (sun-facing) and north sides, and differences between the two locations (north-south), of redbuds grown in black, black shade, flat white, gloss white, silver, and green colored pots (n=11).

Color	South Sun-Facing	North Dry Weight	Difference North-South
	--------------------------------	g --------------------------------	
Black	0.43BC[††††]a[‡‡‡‡]	0.76 BCa	--
Black Shade	0.83ABb	1.29Aa	0.46
Flat White	0.82ABa	1.05ABa	--
Gloss White	0.93Aa	0.76BCa	--
Silver	0.33Ca	0.48Ca	--
Green	0.37Ca	0.76BCa	--

[††††] Means followed by the same upper-case letter within a column were not significantly different (P=0.05).
[‡‡‡‡] Means followed by the same lower-case letter within a row were not significantly different (P=0.05).

Table 10. Average core dry weight and total dry weight of roots of redbuds and number of branches, growth caliper, total shoot length, stem dry weight, and leaf dry weight of redbuds of black, shaded black, flat white, glossy white, silver, and green containers (n=11).

	Redbuds Below Ground (Root) Means		--------------------------------Redbuds Above Ground (Shoot) Means------------------------					
Treatment	Core Dry Weight	Total Dry Weight	Number of Branches	Growth Caliper	Total Shoot Length	Stem Dry Weight	Leaf Dry Weight	Leaf Surface Area
	---g---	---g---		---mm---	---cm---	---g---	---g---	---cm^2---
Black	7.5 C[§§§§]	8.7 BC	4.7 ABC	3.6 B	112.0 B	7.5 B	6.8 ABC	628 ABC
Black Shade	11.0 A	13.1 A	4.3 C	4.8 A	124.3 AB	9.3 AB	9.0 A	794 A
Flat White	10.7 AB	12.6 A	4.6 BC	5.3 A	122.1 AB	10.8 A	7.7 AB	640 ABC
Gloss White	9.4 ABC	11.1 BC	6.3 ABC	4.6 A	133.2. AB	10.5 A	7.4 AB	686 AB
Silver	7.0 C	7.8 C	6.5 AB	4.5 AB	143.5 A	9.1 AB	3.7 C	372 C
Green	8.1 BC	9.2 BC	6.6 A	3.6 B	126.9 AB	8.1 B	4.7 BC	446 BC

[§§§§] Means followed by the same letter within a column were not significantly different (P=0.05).

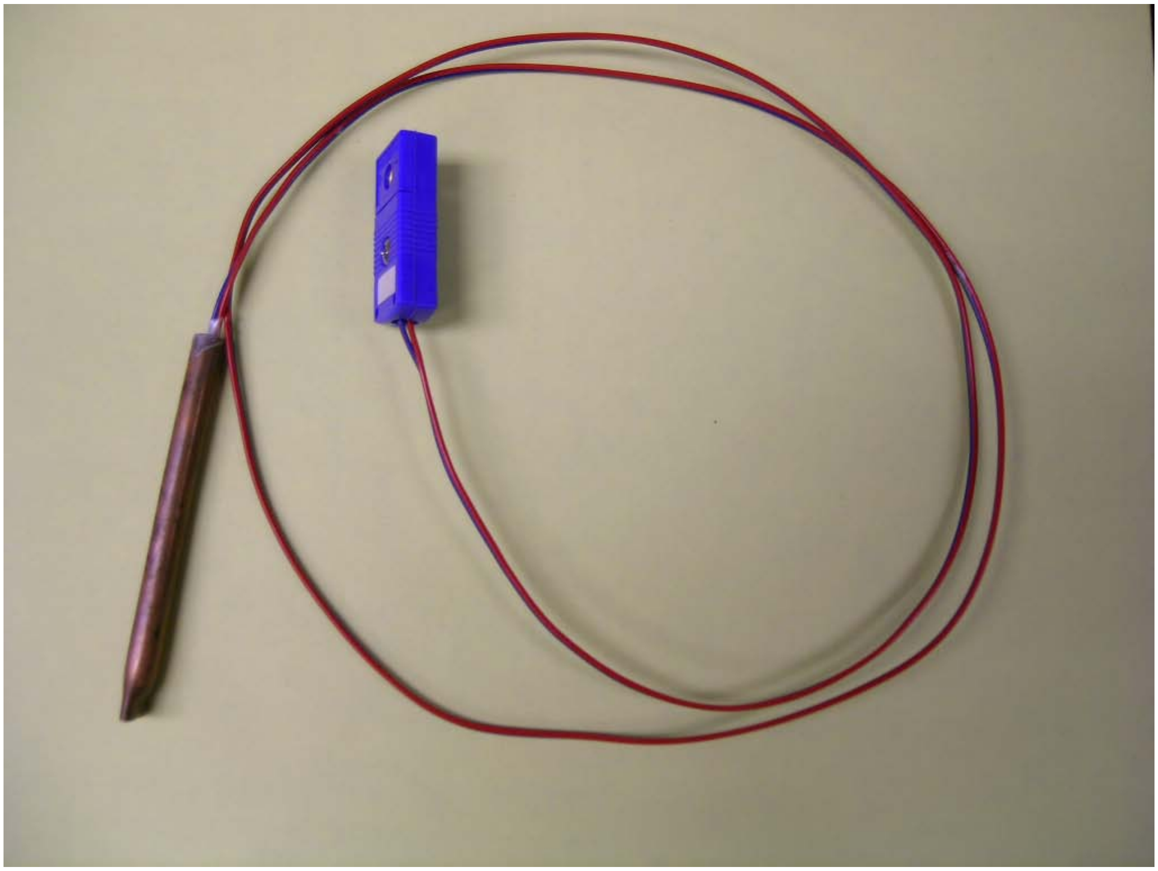


Figure 1. Soil temperature probe.

Figure 2. Preliminary Field Study using bush beans in a 1.2 X 4.9 m grid.

Figure 3. Removal of core section of soil from container.

Figure 4. Photograph of tree (maples and redbuds) layout for field study

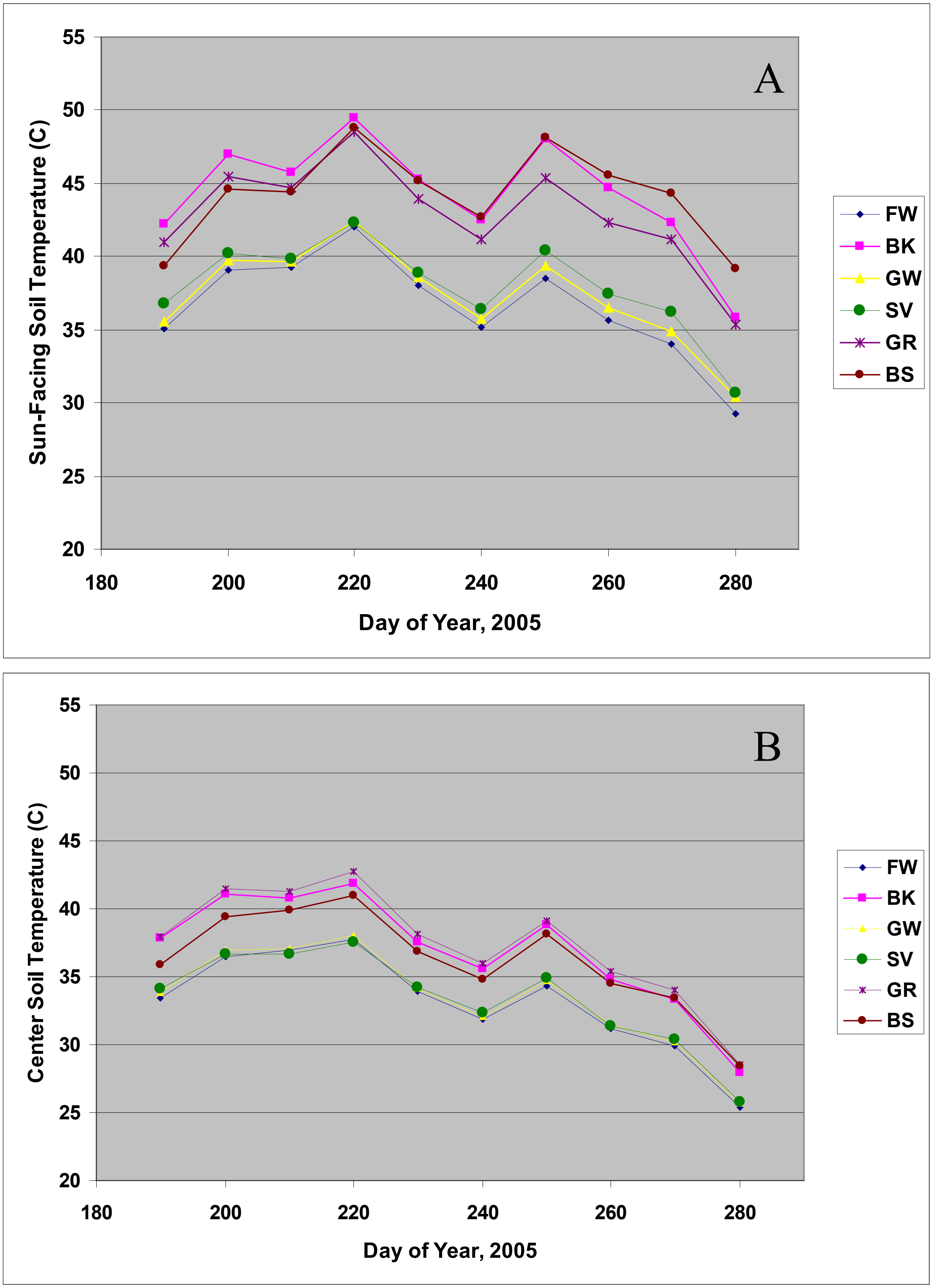
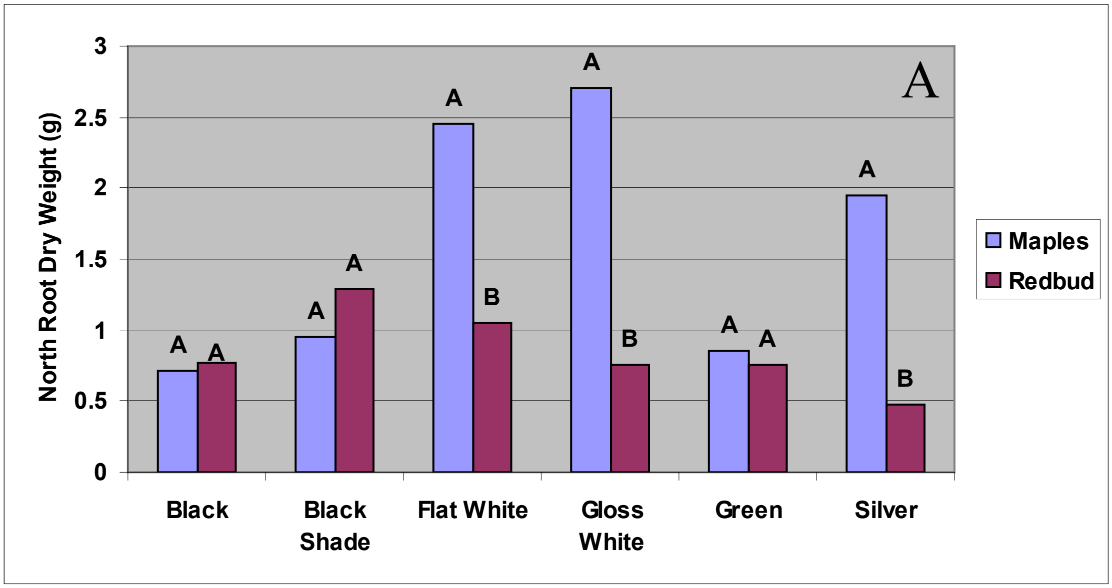


Figure 5. Daily maximum soil temperatures at 5 cm at the sun-facing side (A) and center (B) of flat white (FW), black (BK), gloss white (GW), silver (SV), green (GR), and shaded black (BS) containers in maples. Data are presented as 10-d averages to show seasonal trends.



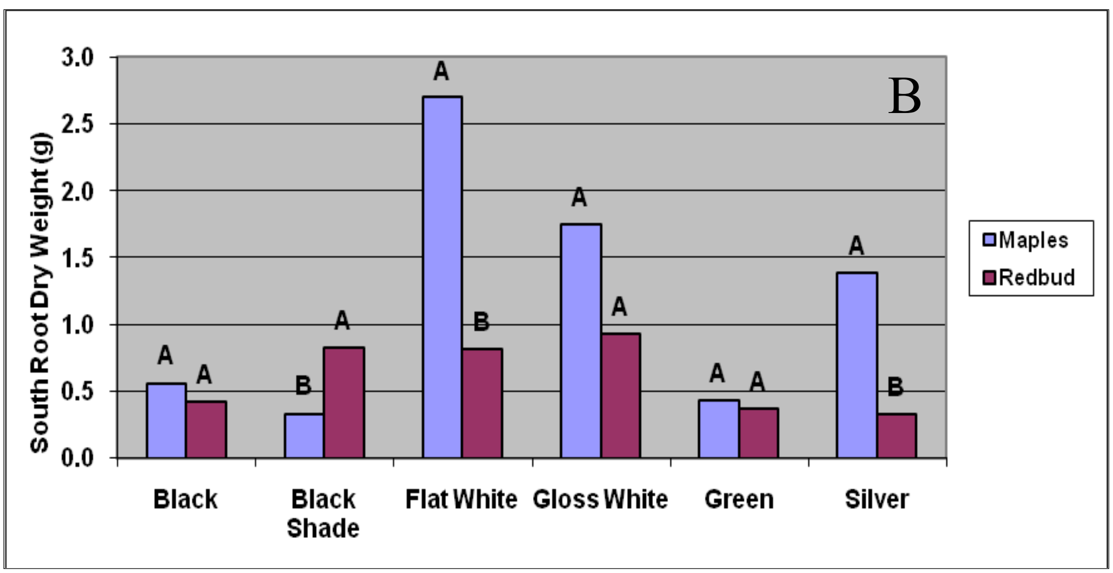


Figure 6. Paired comparison between maple and redbud trees of the average dry weight of root biomass in the north (A) and sun-facing (south) (B) sides of black, shaded black, flat white, glass white, green, and silver containers. Means in each pair (container color) with the same letter are not significantly different.

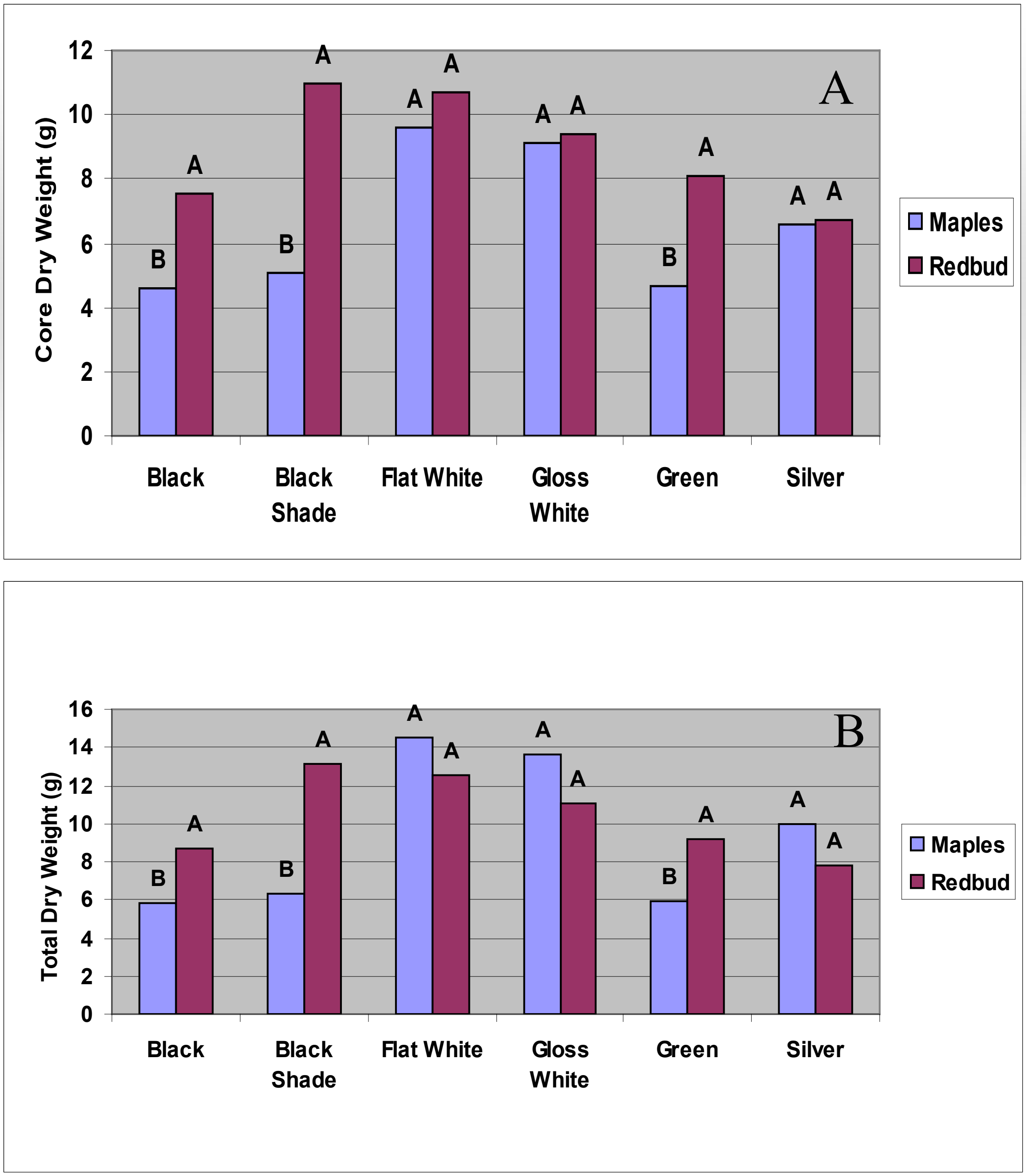


Figure 7. Paired comparisons between maple and redbud of the average dry weights of root biomass in the core (A) and in the entire container (B). Maples and redbuds were each grown in black, black shade, flat white, gloss white, green, and silver containers (n=x). Means in each pair (container color) with the same letter are not significantly different.

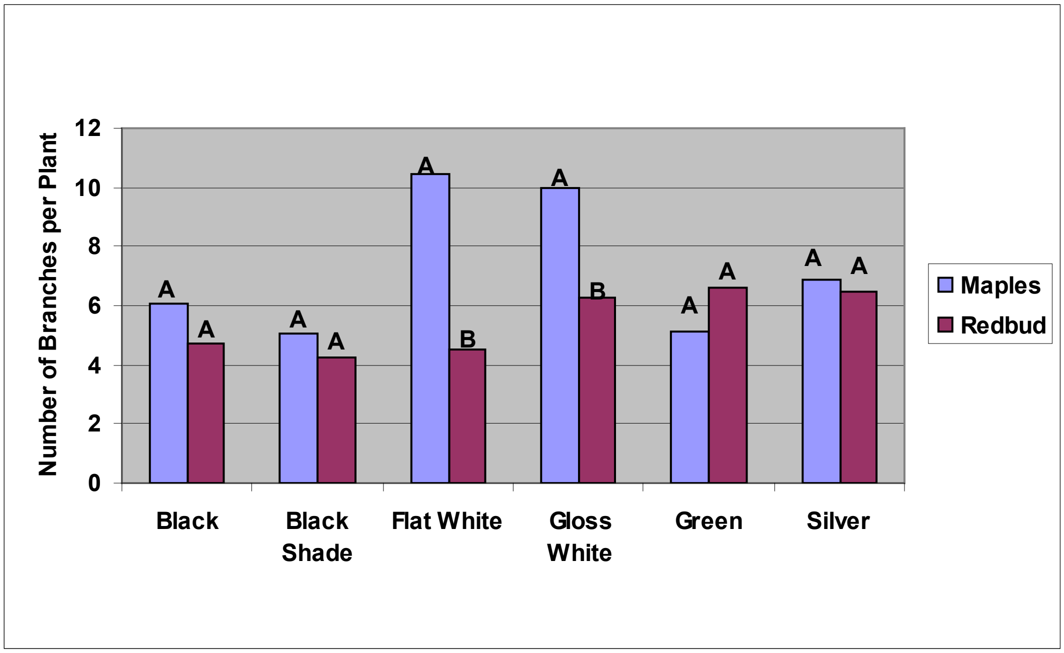


Figure 8. Paired comparisons of average number of branches between maple and redbud trees grown in black, shaded black, flat white, glass white, green, and silver containers. Means in each pair (container color) with the same letter are not significantly different.

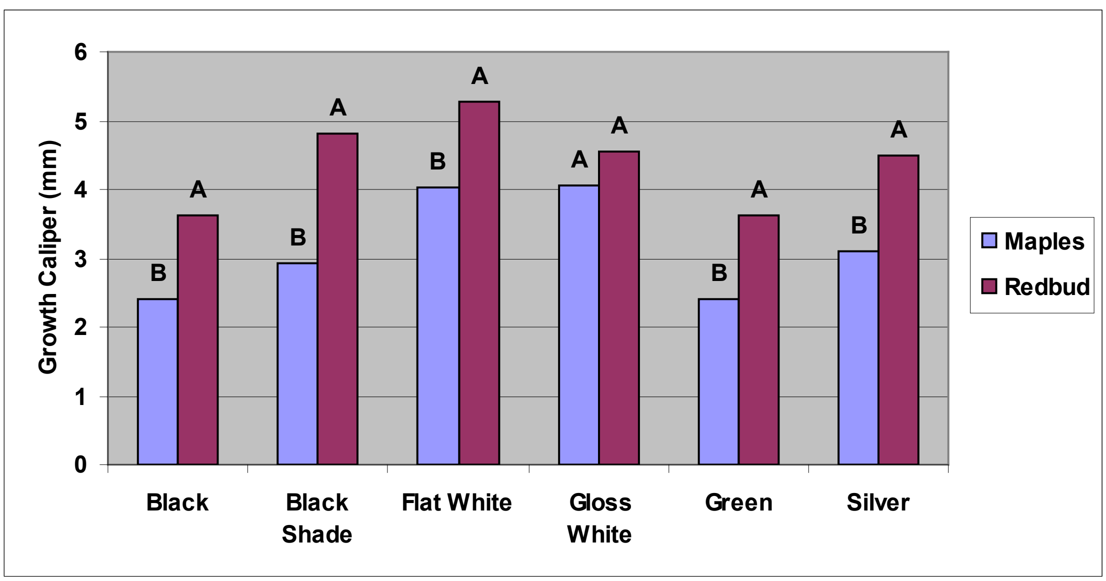


Figure 9. Paired comparisons of average stem-diameter growth (caliper), at 7.5 cm above the surface, between maple and redbud trees grown in black, shaded black, flat white, glass white, green, and silver containers. Means in each pair (container color) with the same letter are not significantly different.

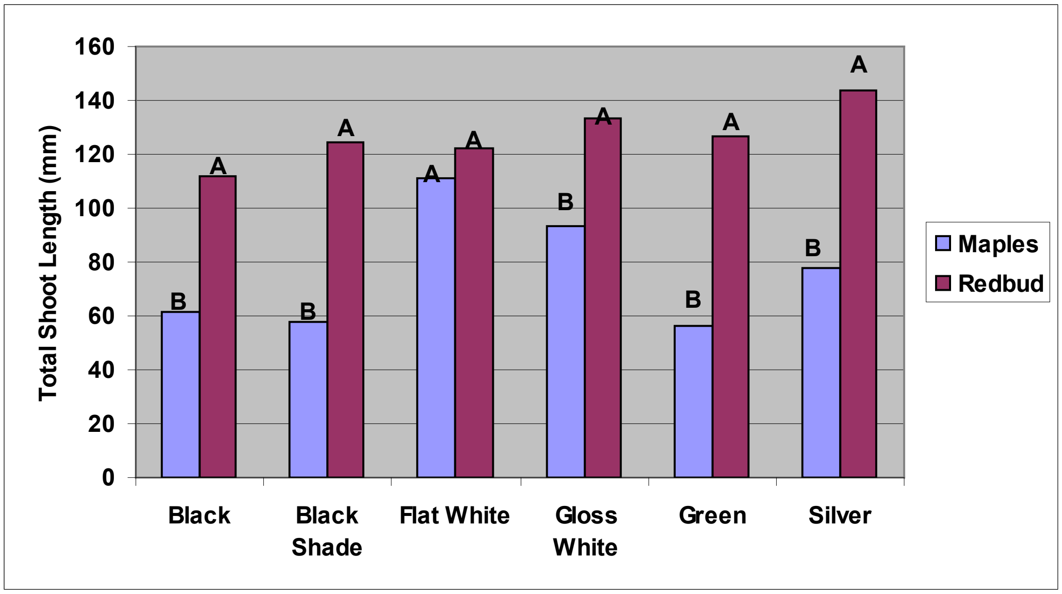


Figure 10. Paired comparisons of average total shoot length between maple and redbud trees grown in black, shaded black, flat white, glass white, green, and silver containers. Means in each pair (container color) with the same letter are not significantly different.

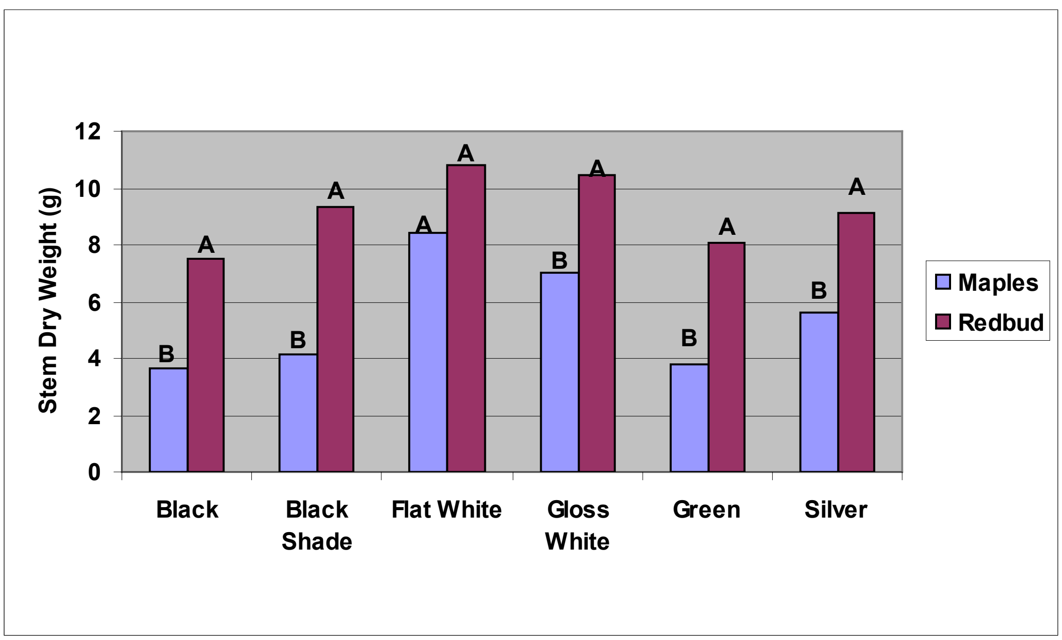


Figure 11. Paired comparisons of the average stem dry weight between maple and redbud trees grown in black, shaded black, flat white, glass white, green, and silver containers. Means in each pair (container color) with the same letter are not significantly different.

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