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Root Zone Temperatures of *Viburnum odoratissimum* Grown in the Multipot Box System and Conventional Systems: Measurement and Analyses of Temperature Profiles and Predicting Root Zone Temperatures

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Abstract. This research study evaluates the effectiveness of a recently introduced irrigation-plant production system, multipot box system (MPBS), for moderating root zone temperature (RZT) compared with the conventional nursery containers. The study also deals with the development, calibration, and validation of a series of models that can be used to predict maximum (max) and minimum (min) RZT values using commonly available input variables. The *Viburnum odoratissimum* (Ker.-gawl.) was used as the test plant. Models were calibrated in the full growing season and validated during the summer. The RZT was used as the dependent variable while the max and min air temperatures (Tmax and Tmin) and/or incoming solar radiation (R) were used as independent variables. The color of the MPBS had an effect on plant growth. Plants grown in the white MPBS had higher growth indices, shoot and root dry weights, and number of stems as compared with the plants in the black MPBS or the conventional (control) system (CS). White MPBS maintained cooler RZTs than the max air temperature during both seasons. Also, white MPBS maintained cooler RZTs than the black MPBS and CS during the two seasons. In both seasons, summer temperature in the black MPBS was higher than the temperature in the white MPBS contributing to the high RZTs in the black MPBS. The RZT of the black MPBS and CS exceeded the critical value (40°C), which is cited in the literature as negatively impacting root growth, water and nutrient uptake, leaf area, plant survival, root and shoot dry weights, water status, and photosynthesis. The RZT in the CS was above 45°C for most of the summer season and plants were exposed to this extreme temperature for a few hours a day during most of the summer. The white MPBS provided a better environment and enhanced plant growth. For regions where ambient air temperature ranged from 2 to 41°C, the white MPBS can provide adequate and effective RZT protection for plants grown in No. 1, 3.8-L standard black conventional containers. Predicted RZT values were well correlated with measured values in all systems. R did not have an effect on predicting RZT in the MPBS treatments. Wind speed did not contribute to predicting RZT in any production systems. The root mean square error between measured and predicted RZT was relatively low ranging from 0.9 to 2.8°C. Models were able to explain at least 74% of the variability in RZTs using only Tmax, Tmin, and/or R. Models developed in this study should be applicable for estimating RZTs when similar management and cultural practices are present. Models of this study are practical, simple, and applicable to predict RZTs where ambient air temperature ranges from 1.9 to 40°C. Model results should not be extrapolated beyond these limits.

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Predicting Root Zone Temperatures

Although RZT is an important variable in container-grown ornamental plant production, direct measurement of the temperature may not always be possible. With the exception of a few studies, little attention has been given to developing and using models to predict RZT of container-grown plants. Simulation models allow researchers to study the response of RZT to ambient air temperatures and other variables such as solubility of nutrients and their interactions with the plant root and substrate without conducting time consuming, difficult, and expensive field studies. Models also allow researchers to develop and evaluate best management practices to enhance nursery operation.

Martin and Ingram (1992) developed a three-dimensional model using an energy balance approach to numerically simulate the thermal environment of a polyethylene container-root system in 10-L containers in Gainesville, Fla. They studied the effect of net radiation, convection, evaporation, and conduction on thermal energy exchanges at the top surfaces of the substrate. The effect of volumetric water content on substrate temperature patterns for different substrates was also studied. In their study, thermal energy exchanges at the system’s boundaries were a function of solar radiation, convection, evaporation, and conduction energy fluxes. Conduction and evaporation had little effect on thermal energy flows across the substrate surface. Their model required thermal conductivity, bulk density and specific heat capacity of the substrate, solar radiation, wind speed, relative humidity, and maximum and minimum air temperature as input variables. Model validation results were in good agreement with temperatures measured at the exterior walls of the container (0.02 m inside the container wall at north, south, east, and west sides) and the root medium (0.02 m above the container bottom, in the center of the container, and 0.10 m below the substrate surface). They reported that the thermal diffusivity of the substrate increased as volumetric water content increased. They suggested that irrigation applied in the afternoon would help moderate high temperatures in pine bark substrate.

Martin and Ingram (1993) used the model developed by Martin and Ingram (1992) to simulate the effect of container volume and shape on summer temperature patterns for black polyethylene nursery containers filled with a pine bark in Phoenix, Ariz., and Lexington, Ky. They found that, for both locations, predicted temperature patterns in rooting medium adjacent to the container wall decreased as the wall tilt angle increased. Predicted temperature patterns at the center of the container profile were lower with increased container height and wall tilt angle. As the container volume decreased, the temperature at the center of the substrate increased. Based on the simulation results, they suggested that large containers with walls tilted outward may be practical for container nursery production in hot climates.

Using sophisticated empirical equations for RZT estimations can be difficult for growers, consultants, extension personnel, and technicians who may not be familiar with working with complex equations. In addition, variables such as thermal conductivity, bulk density and specific heat capacity of the substrate may not be readily available to solve the energy balance equations for RZT predictions. The simplicity of the use and interpretation of the RZT prediction models can also encourage growers and their advisors to monitor their own RZT data to use them in different applications. Thus, there is a need for developing models that can be used to predict RZT profiles from easily obtainable inputs with a minimum of computations.

Recently, a new irrigation and plant production system—the multipot box system (MPBS)—has been introduced (Haman et al., 1998; Irmak, 2002; Irmak et al., 2001, 2003, 2004) for increased water application efficiency and crop water use efficiency and water conservation for container-grown ornamentals. Irmak et al. (2003, 2004) investigated the growth of V. odoratissimum grown in the black and white MPBS, and conventional (control) system (CS). White and black MPBSs were very effective in increasing irrigation water use efficiencies, rainfall harvesting, and plant biomass production as compared with the CS. The color of the MPBS had an effect on plant growth and no affect on irrigation demand or runoff. The seasonal irrigation water use efficiency was greater for plants grown in the white MPBS than plants in the black MPBS and CS. The white MPBS produced higher plant biomass (stem and root dry matter), growth trend, and growth rates compared with the black MPBS and CS in the summer and fall. They observed that the plants in the white MPBS were exposed to less plant stress, had higher plant water potential values, and lower stomatal resistances to the water vapor transport during both seasons. They attributed the growth differences to temperature stress induced by high RZT. However, quantifying and analyzing RZT profiles in the MPBS and CS treatments have not been studied. Assessment of which system moderates extreme temperatures and provides a better environment for plant growth would help producers select which color of MPBS to use for climatic conditions similar to those in this study.

The main objectives of the study were 1) to quantify and analyze seasonal and diurnal patterns of multiple-depths of RZTs in the containers and water temperatures in the reservoirs of the MPBSs for V. odoratissimum grown in the black and white MPBS and CS, and 2) to develop and validate a series of models for predicting RZTmax and RZTmin for V. odoratissimum grown under north-central Florida conditions using commonly available inputs and a minimum of computations.

Materials and Methods

MPBS description

The MPBS consisted of two sections (lower and upper) made of fiberglass and painted black or white for UV protection (Fig. 1A and B). The surface area of the system is 0.787 m² (0.82 × 0.96 m). These dimensions were selected so that the boxes could be placed end to end in beds to form a continuous surface with walkways interspersed for plant maintenance in a normal nursery operation. The lower section (reservoir) had four longitudinal channels (about 0.106 m high) that formed water reservoirs with three ridges, sized so that the box can be moved by placing forklift tongues under the outer ridges. Each ridge surface was covered with polyester fabric (Knowlton Nonwovens East, Troy, N.Y.) to serve as the wicking material (capillary mat). This material is used to draw water upward by capillary action. Thus, water in the substrate was replaced by capillarity as needed. The upper section of the MPBS supported the containers and minimized evaporation losses from the reservoir. The surface of the upper section was concave around each container opening to capture rain and irrigation water. The lower section (reservoir) stores the captured water until used by plants. Each box holds nine plastic standard containers (C-650; The Lerio Corp., Watertown, N.Y.) equipped with a pressure-compensating drip irrigation emitter (Chapin Watermatics Inc., Watertown, N.Y.). Emitter systems have a 7.6-L·h⁻¹ flow rate were installed directly on the ridge.
mainline and water was delivered to the box using a spaghetti tube and a lead weight placed in each channel. Each box was equipped with a side-mount level switch (model LS-7; State Instruments, Inc., Tampa, Fla.) to trigger irrigations automatically. The level switches were installed at 0.01, 0.02, and 0.03 m from the bottom of the reservoir (depending on the treatment) and triggered irrigations when the water level in the reservoir dropped to predetermined levels.

**Description of the CS (control treatment)**

The CS served as the control treatment and represented the irrigation system commonly used by most nursery growers. Standard containers in the CS were spaced in three rows 0.30 m apart (between rows and within rows) and set directly on separate black polypropylene ground sheeting. The reason of setting the CS containers on separate ground sheeting was that this treatment was irrigated using overhead sprinklers which is a common practice used by many producers in the southeastern U.S.

**Field experiments**

**General experimental procedures.** Field experiments were conducted outdoors on the campus of the University of Florida at Gainesville (latitude 29° 38', longitude 82° 22', elevation 29.3 m) in the summer and fall of 2001. Unless noted otherwise, the experimental procedures were the same for the two growing seasons. *Viburnum odoratissimum,* Ker.-Gawl. (sweet viburnum, Adoxaceae) was grown as a test plant. This plant is being grown extensively as a nursery plant throughout Florida.

Seven treatments were imposed: 1) white MPBS with level switches installed at 0.01, 0.02, and 0.03 m (W1, W2, and W3) from the bottom of the reservoir, 2) black MPBS with level switches installed at 0.01, 0.02, and 0.03 m (B1, B2, and B3), and 3) The CS. There were nine plants in each replication. Treatments (boxes) were replicated using randomized complete block design. Containers were filled with a substrate mix containing pine bark, Canadian peat, and sand (2:1:1, by volume) mix, amended with 4.2 kg·m⁻³ of dolomitic James River Limestone and 0.9 kg·m⁻³ of Micronax (The Scotts Co., Marysville, Ohio) and placed in each MPBS. The same substrate was used for the containers in the CS. Healthy and uniform size plants were transplanted into the substrate-filled containers and grown 3 to 4 weeks in a shadehouse (30% shade) and were hand-watered as needed. Plants were top dressed with 0.014 kg/container of Osmocote 18N–2.6P–9.7K (18–6–12) controlled (slow-release) fertilizer (The Scotts Co.) at the beginning of each experiment. Experiment starting and termination dates for the summer and fall seasons were 17 May to 9 Aug. and 28 Aug. to 21 Dec. 2001, respectively.

The growth index of plants was based on plant height measured from the substrate surface to the tip of the tallest leaf on selected dates. On the same day, plant widths were measured in both east–west and north–south directions. In both seasons, six growth measurements were taken from the plants grown in the white and black MPBSs. Eleven and nine growth measurements were taken from the CS treatment in the summer and fall, respectively. All plants were measured in all replications, thus, 189 plants were measured for each sampling date. Growth indices (GIs) were calculated as

\[
GI = H + [(WEW + WNS)/2]/2
\]

where, \(H\) is the plant height (m), \(WEW\) is the canopy width in east–west direction (m), and \(WNS\) is the canopy width in north–south direction (m). Experiments were terminated when the plants in the MPBS treatments reached approximately a marketable size. A GI value of 40 was assumed to represent marketable size (Florida Dept. of Agriculture and Consumer
Table 1. Statistical analyses of the growth index (GI) at harvest, number of stems, and shoot and root dry weights in summer and fall growing seasons [W3, W2, and W1 = white multipot box systems (MPBS) with level switch installed at 0.01, 0.02, and 0.03 m from the bottom of the reservoir, respectively; B3, B2, and B1 = black MPBS with level switch installed at 0.01, 0.02, and 0.03 m from the bottom of the reservoir; and CS = conventional system].

| Treatment | GI at harvest | No. of stems | Stem dry wt (g) | Root dry wt (g) | GI at harvest | No. of stems | Stem dry wt (g) | Root dry wt (g) |
|-----------|---------------|--------------|----------------|----------------|---------------|--------------|----------------|----------------|
| W3        | 50.4 (4.0)a   | 10.1 (1.7)a  | 46.4 (8.3)a    | 12.9 (2.5)a    | 43.0 (3.1)a   | 8.3 (1.6)a   | 41.0 (7.7)a    | 19.8 (3.0)a    |
| W2        | 49.2 (3.8)a   | 9.6 (1.6)a   | 46.3 (8.0)a    | 12.9 (2.9)a    | 42.5 (5.4)a   | 8.3 (1.4)a   | 38.6 (7.0)a    | 18.8 (2.8)a    |
| W1        | 48.4 (4.6)a   | 9.4 (1.8)a   | 44.4 (8.2)a    | 11.5 (3.0)a    | 42.6 (4.1)a   | 7.9 (1.3)a   | 39.1 (7.1)a    | 19.0 (2.9)a    |
| B3        | 43.1 (4.6)b   | 4.4 (2.0)b   | 32.7 (7.5)b    | 8.9 (1.9)b     | 40.5 (7.2)b   | 7.4 (1.4)a   | 32.4 (6.8)b    | 13.5 (2.6)b    |
| B2        | 40.0 (4.5)b   | 4.3 (1.9)b   | 30.9 (7.5)b    | 8.2 (1.6)b     | 41.1 (4.0)b   | 7.4 (1.4)a   | 34.3 (7.2)b    | 13.4 (2.2)b    |
| B1        | 41.7 (4.7)b   | 4.4 (1.4)b   | 31.9 (6.9)b    | 9.1 (1.9)b     | 40.8 (5.7)b   | 7.5 (1.2)a   | 32.3 (6.8)b    | 12.9 (1.9)b    |
| CSa       | 33.2 (3.7)c   | 2.4 (0.6)c   | 17.7 (5.5)c    | 4.3 (1.6)c     | 30.8 (4.3)c   | 5.0 (1.2)b   | 21.0 (5.1)c    | 10.1 (2.2)c    |

aAverage of 27 plants from three replications (nine plants in each replication).

1Values in parenthesis indicate standard deviations (SD).

2Means followed by different letters among the treatments are different (P < 0.05) as indicated by Duncan’s multiple range test.

3Dry weights, GI, and number of stems of the plants in the CS harvested when the plants grown in the MPBS reached marketable size.

Services, 1997). At termination, shoots of all plants were severed above the uppermost roots, the roots were cleaned from the substrate, and shoot and root dry weights were measured after drying to a constant weight at 70°C. The number of stems on each plant was counted at harvest.

Irrigation applications. The irrigated area of the CS was 6.0 × 6.0 m. The CS plot was irrigated with four rotary drive sprinkler heads (PGM-04-A; Hunter Industries, San Marcos, Calif.) mounted on 1.3-m risers and located at the corners of the plot. Water was applied daily for 1 h with an irrigation application rate of 18 mm-h⁻¹. Irrigations were applied to the MPBSs whenever the reservoir in the bottom of the boxes reached 0.025, 0.035, and 0.045 m, depending on the treatment. Irrigation was applied for 30 min to deliver about 16 L (20 mm) of water. The main purpose of not irrigating the boxes to the full reservoir capacity (0.106 m) was to keep a part of the reservoir empty to provide storage for the rainwater. A rain sensor was installed to both the MPBS and CS plots to shut off irrigations when about 12 mm of rain occurred.

Root zone and water temperature measurements. The RZT measurements were made every 10 min and averaged on hourly basis throughout the two growing seasons. Measurements were taken from 23 May to 9 Aug. in the summer and from 29 Aug. to 20 Dec. in the fall. The center container in three replications in the white and black MPBSs (W2 and B2, respectively), and CS treatments were equipped with thermocouples for RZT measurements (Fig. 2A and B). Copper-constantan (0.0005 m) thermocouples were placed at the depths of 0.03, 0.06, 0.09, 0.12, and 0.15 m from the surface at the center location vertically. The substrate was hand packed to assure an adequate contact with the thermocouples. Additional thermocouples were placed in the reservoirs of the white and black MPBSs to measure water temperature every 10 min. Two thermocouples were placed in each reservoir and temperature readings were averaged. In addition, two thermocouples in the center containers of the two replications of the black and white MPBS treatments were placed at the center to measure the ambient temperature inside the MPBS. Thermocouples were connected to the data acquisition systems and measurements were recorded using a datalogger and a multiplexer (model CR-10X and model 32M; Campbell Scientific Inc., Logan, Utah). An automated weather station was set on the short green grass site about 20 m from the experimental site to record necessary climate variables for temperature profile analyses and model calibration and validation. The data collected at the weather station included air temperature, relative humidity, incoming solar radiation, wind speed at 2 m, and rainfall. Growth and temperature responses to treatments were analyzed by analysis of variance (ANOVA). Duncan’s multiple range test (DMRT) was used to identify which treatments differed at the 5% significance level.

RZT model development

Two models were developed to predict the maximum RZT for the white and black MPBS while only one was developed to predict the minimum RZT. Reasons for developing two models for RZT_max and one model for RZT_min will be discussed later. The average RZT values of all depths for either the white or the black MPBS were used in model development. The models for predicting RZT_max for the black and white MPBSs were calibrated individually. The calibrated models were used to predict RZT_max at 0.12 m from the surface of the container in the CS and results were compared with the measured RZT values for all cases during validation. For the CS, two models were developed to predict RZT_max and RZT_min at 0.12 m from the surface of the containers. During model development the plant root zone was assumed to be approximately at the 1/3 of the distance from the bottom of the container. Most plant root density is assumed to be in this zone. The height of a black no. 1 standard polyethylene container is about 0.17 m and 1/3 of this height corresponds to 0.057 m from the bottom of the container or about 0.12 m from the surface of the container. Thus, RZT measurements made at 0.12 m from the surface of the container represented the critical RZT for the V. odoratissimum.

Unless mentioned otherwise, the same procedures were used to develop models for the white and black MPBS and CS. Multilinear regression was used to develop the coefficients.

Fig. 3. Seasonal pattern of daily maximum root zone temperature in the black (A) and white (B) MPBS, and CS during the summer season.
to determine the equation-specific coefficients. Then, the models were validated using the measured

The general form of the multilinear equation is:

$$ RZT_{\text{m}} = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 $$

where $RZT_{\text{m}}$ is the root zone temperature (°C), $\beta_0$, $\beta_1$, $\beta_2$, and $\beta_3$ represent the slope of the regression line, and $X_1$, $X_2$, and $X_3$ are the independent variables. The root mean square error (RMSE), coefficient of determination ($r^2$) between predicted and measured RZTs, and seasonal average ratio of predicted RZT to measured RZT were computed as indicators of accuracy and consistency of a given model's performance. The RMSE (°C) values were calculated as:

$$ \text{RMSE} = \sqrt{\frac{1}{n} \sum_{i=1}^{n} (y_i - \hat{y}_i)^2} $$

where $n$ is the number of observations, $y_i$ and $\hat{y}_i$ are predicted and measured RZT (°C), respectively.

### Results and Discussion

#### Plant growth analyses

Growth indices (GI), shoot and root dry weights, and the number of stems on the plants grown in the white and black MPBs at different depths are given in Table 1. Plants grown in the white MPBs treatments produced significantly greater shoot and root dry weights (Table 1). White MPBs treatments were also significantly greater in plant roots in the black MPBs compared to the other treatments. In the fall, the white MPBs produced significantly higher shoot and root dry weights as compared to the other treatments.

#### Seasonal pattern of daily maximum and minimum RZT at multiple depths

Maximum RZT profiles during the summer. Figure 4 represents seasonal pattern of daily $RZT_{\text{max}}$ at 0.03, 0.06, 0.09, 0.12, and 0.15 m depths for the containers placed in the white and black MPBs and CS in the summer. Statistical analyses of the differences in RZTs between the black and white MPBs at different depths are given in Table 2.

### Table 3. Maximum, minimum, and seasonal average max root zone temperatures (RZTs) in the conventional system (CS) in the summer and winter growing seasons.

| Growing season | Depth(m) | $RZT_{\text{max}}$ (°C) | $RZT_{\text{min}}$ (°C) | Seasonal avg. (°C) |
|-----------------|----------|--------------------------|--------------------------|-------------------|
| Summer          | 0.03 a   | 48.4                     | 28.3                     | 40.5              |
|                 | 0.06 a   | 48.0                     | 28.9                     | 40.6              |
|                 | 0.09 a   | 46.8                     | 28.7                     | 40.2              |
|                 | 0.12 a   | 44.9                     | 28.5                     | 39.3              |
|                 | 0.15 b   | 42.0                     | 28.1                     | 36.8              |
| Fall            | 0.03 a   | 47.4                     | 20.0                     | 33.8              |
|                 | 0.06 ac  | 47.9                     | 20.4                     | 34.9              |
|                 | 0.09 ad  | 46.8                     | 21.0                     | 34.4              |
|                 | 0.12 b   | 43.6                     | 20.8                     | 32.4              |
|                 | 0.15 ab  | 42.2                     | 20.7                     | 33.0              |

### Table 2. Statistical analyses (ANOVA) of the root zone temperatures (RZTs) between the black and white multipot box system (MPBS) treatments and between the multiple depths in the conventional system (CS) for the summer and fall growing seasons. Analyses were conducted at 5% significance level.

| Growing season | Method | $RZT_{\text{max}}$ (black vs. white) | $RZT_{\text{min}}$ (black vs. white) | $RZT_{\text{max}}$ (black vs. white) | $RZT_{\text{min}}$ (black vs. white) | $RZT_{\text{max}}$ (black vs. white) | $RZT_{\text{min}}$ (black vs. white) | P       |
|-----------------|--------|-------------------------------------|-------------------------------------|-------------------------------------|-------------------------------------|-------------------------------------|-------------------------------------|---------|
| Summer          | ANOVA  | 106.21                              | 14.861                               | 3.901                               | 0.000169                            | 97.41                               | 5.043                               | 3.882   | 0.025738 |
|                 |        | 7.68                                | 2.762                               | 3.034                               | 0.06563                            | 10.16                               | 0.301                               | 3.034   | 0.74020  |

*Significant at 5% significance level as indicated by Duncan’s multiple range test.

**Average values of RZT in all depths in the black and white MPBS treatments.
The RZTs in five depths in the CS treatment were different from those obtained in the summer growing season (Fig. 4C). Statistical analyses of the RZTs in five depths for the CS treatment are presented in Table 2. The max, min, and seasonal average RZT values and DMRT results are given in Table 3. RZTs were lower compared to those measured in the summer for all depths. In contrast to the summer results, the RZT at 0.06 m was the highest in the fall (Fig. 4C), and it was only significantly higher than the RZTs in 0.12 m and 0.15 m depths (Table 2). This might indicate that a heat buildup occurred in this depth. The max, min, and seasonal average of RZT in the 0.06 m depth were 47.4, 20.0, and 33.8 °C, respectively (Table 3). All depths showed significant reduction in temperature starting from 25 Oct. and continued until the end of the growing season due to the lower air temperature and solar radiation in this period.

Overall results of RZT max patterns indicated that the RZTs in the white MPBS were cooler (P < 0.05) than the black MPBS and CS. The RZTs in the black MPBS during periods of extremely high ambient air temperatures in all five depths during the summer providing a better environment and enhancing plant growth. Thus, plants grown in the white MPBSs were 1.3 °C (seasonal average) warmer (P < 0.05) than those in the white MPBS during the fall (Table 2).

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root zone and the heat capacity of the substrate used in the containers. In addition, water has a much higher specific heat than the substrate materials, and heat conductance through the substrate varies directly with substrate moisture content. During a sunny summer day, the temperature of the water may well exceed the RZT. For example, analysis indicated that the water temperature in the black MPBS was as much as 2.2 °C higher than the RZT in the center of the container during the summer. During that season, the average water temperature was higher than the RZT for 44 out of 79 d (total growing season). Thus, since plants in the black MPBS uptake water from the reservoir, the irrigation water which is warmer than the root zone will cause an increase in root zone temperature due to the heat transfer into the root zone.

**Minimum RZT profiles in the summer and fall.** Seasonal patterns of \( \text{RZT}_{\text{min}} \) in the black and white MPBS and CS for the summer are given in Fig. 7A, B, and C, respectively. The \( \text{RZT}_{\text{min}} \) in the same treatment were statistically the same for all depths (\( P > 0.05 \)). Thus, temperature data from all depths in each treatment were averaged and analyzed. The averaged \( \text{RZT}_{\text{min}} \) were not significantly different between treatments for the summer or fall.

**Daily patterns of \( \text{RZT}_{\text{min}} \) in the fall for the black and white MPBS and CS are presented in Fig. 8A, B, and C, respectively.** Fall patterns were similar to those in the summer with lower \( \text{RZT}_{\text{min}} \) in all treatments. In all treatments, daily \( \text{RZT}_{\text{min}} \) fluctuated more in fall than the summer. The \( \text{RZT}_{\text{min}} \) were not significantly different between the treatments (Table 2). The \( \text{RZT}_{\text{min}} \) showed almost identical patterns for all depths and there were no significant differences (\( P > 0.05 \)) between depths for each treatment.

However, on days that the lowest and highest values of \( \text{RZT}_{\text{min}} \) occurred, there were noticeable differences between the treatments. For example, the lowest \( \text{RZT}_{\text{min}} \) in the black MPBS was 2.4 °C on 7 Nov., while the lowest value in the white MPBS of 1.9 °C occurred on the same day but was 0.5 °C lower than the black MPBS. However, in the CS, \( \text{RZT}_{\text{min}} \) on 7 Nov. was very close to freezing temperature (0.2 °C) and was 2.2 °C and 1.7 °C lower than the temperature in the black and white MPBSs, respectively.

**Diurnal patterns of \( \text{RZT} \).** Diurnal patterns of the \( \text{RZT} \)s for different treatments can provide important information on the buffering capability of the black and white MPBSs as compared to the CS containers. For this reason, four extreme days (warmest and coldest), two hottest days in summer and two coldest days in fall, were graphed to evaluate the diurnal \( \text{RZT} \) patterns. Since the patterns were similar for each hot and cold day, the pattern of one of the warmest and coldest days is discussed.

**Warmest day pattern.** On 17 June and 7 July, 2 d when the ambient max air temperature reached 40.0 and 40.1 °C, respectively, were selected for analysis of summer. Diurnal patterns of max temperatures on 17 June and 7 July are presented in Fig. 9A and B for the black and white MPBS, and CS at 12.1 m. The \( \text{RZT} \) in the black and white MPBSs had identical values from 1 AM to 7 AM maintaining

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**Table 4. Statistical analysis of the max ambient temperatures (\( T_{\text{amb}} \)) measured in the black and white multipot box systems (MPBSs) and water temperatures measured in the reservoir of the MPBSs in the summer and fall growing seasons.**

| Growing season and variables | Mean square | F | F critical | P |
|-----------------------------|------------|---|------------|---|
| Summer-\( T_{\text{amb}} \) in the MPBSs (black vs. white) | 107.92 | 14,987 | 3,902 | 0.00016* |
| Fall-\( T_{\text{amb}} \) in the MPBSs (black vs. white) | 163.07 | 9,659 | 3,882 | 0.00213* |
| Summer-\( T_{\text{water}} \) water (black vs. white) | 202.18 | 30,404 | 3,902 | 1.4E-27 |
| Fall-\( T_{\text{water}} \) water (black vs. white) | 183.94 | 10,107 | 3,882 | 0.00168* |

*Significant at 5% significance level as indicated by Duncan’s multiple range test (DMRT).
about 2.3 °C higher temperatures than the air temperature (Fig. 9). The RZT in the CS had identical values to the air temperatures in this period. On 17 June, the air temperature started increasing at 8 AM whereas the temperature in the CS and MPBSs started rising at 10 AM, a 2-h delay. The rate of temperature rise in the white MPBS was the slowest. The RZT in the CS containers reached a max value of 46.8 °C at 5 PM. The RZT in the black MPBS reached a maximum value of 40.8 °C at 6 PM and the white MPBS had the highest temperature as 38.1 °C at the same time. The RZT in the white MPBS was 2.7 °C cooler than the black MPBS and 6.9 °C cooler than the CS at 6 PM. The maximum ambient temperature (40.0 °C) occurred at 2 PM. Both MPBSs responded similarly to the maximum ambient temperature with 4-h phase delays. The ambient temperature started decreasing rapidly at 3 PM. RZT max in the white MPBSs started to decrease slowly at the same time at 7 PM with the RZT in the white MPBS cooling at a slower rate than the black MPBS and CS. The white MPBS maintained temperatures 0.7 to 2.3 °C cooler than the black MPBS and 1.6 to 6.9 °C cooler than the CS treatment until 9 PM. Thus, the white MPBS successfully buffered the high ambient temperature and the system was more effective than the black MPBS and the CS in providing a desirable environment for root development and plant growth.

Coldest day pattern. Although the coldest ambient air temperature (1.9 °C) was recorded on 7 Nov. (Fig. 8C), the hourly temperature data for this day was not available. Therefore, two cold days, 28 Oct. and 19 Dec., when the min ambient air temperature dropped to 5.1 and 6.0 °C, respectively, were selected and graphed in Fig. 10A and B, respectively. Only the diurnal pattern of RZTs on 28 Oct. will be discussed in detail.

On 28 Oct., the lowest ambient temperature occurred at 8 AM as 5.1 °C. The RZTs in the black and white MPBSs were 2.1 to 4.7 °C warmer than the air temperature, respectively, from 1 AM to 8 AM. The RZTs in the CS were 0.4 to 2.1 °C cooler than the air temperature during the same period. The RZT responses were similar for both black and white MPBSs during the day with black MPBS maintaining 0.5 to 2.4 °C warmer temperatures than the white MPBS during the day. Both treatments had the lowest RZTs at 10 AM with 2-h phase delay relative to the lowest ambient air temperature. Note that the RZT in the black MPBS dropped to 3.4 °C at 10 AM whereas the RZTs in the white MPBS were 0.8 °C cooler (2.6 °C) than the black MPBS, but they were both warmer than the CS. RZT min in the CS occurred at 9 AM (2.3 °C) with a 1-h phase delay relative to the lowest ambient air temperature. These results suggest that during the coldest days of the fall, the black MPBS was more effective in moderating the cold ambient temperature in

Fig. 7. Seasonal pattern of daily minimum RZT in the black (A) and white (B) MPBS, and CS (C) during the summer season.

Fig. 8. Seasonal pattern of daily minimum RZT in the black (A) and white (B) MPBS, and CS (C) during the fall season.
the plant root zone as compared to the white MPBS and CS. After 10 AM, the RZTs in the CS increased rapidly to 7.1 °C at 11 AM whereas the temperature in the black and white MPBSs increased at a much slower rate reaching 5.4 and 3.9 °C, respectively. Similar trends of diurnal patterns of the RZTs in all treatments were observed on 19 Dec. (Fig. 10B). Overall results showed that the white MPBS successfully moderated RZTs against extremely high ambient temperatures during the warm periods in the summer and fall. However, the black MPBS was more effective in moderating the cold temperature on the cold days in the fall. On 28 Oct., the lowest temperature in the black MPBS was 0.8 °C higher than the RZT in the white MPBS. Similar results were obtained on the other cold day of the season (19 Dec.). On this day, the RZT in the black MPBS was 1.1 °C warmer than the RZT in the white MPBS (Fig. 10B). These results suggest that in cold climates, the black MPBS might have an advantage over white MPBS in protecting the root zone against cold ambient air temperatures. The RZT moderation with the black and white MPBSs under colder climates needs to be further researched.

Results of RZT predictions

RZT models for the white and black MPBS. Data analyses showed that the maximum temperatures measured in five depths (0.03, 0.06, 0.09, 0.12, and 0.15 m from the surface of the container) in the substrate of the black or white MPBSs were not different between depths. However, when temperatures in five depths were averaged for the season, the black MPBS was warmer ($P < 0.05$) than the white MPBS in two seasons. The min temperatures were not different between the depths or between the black or white MPBSs in both seasons. Therefore, two models were developed to predict the RZT$_{max}$ at the 0.12 m depth for the white and black MPBS. Only one model was developed to predict RZT$_{min}$ at the same depth. Results reported earlier in the paper indicated that there were differences in RZT$_{max}$ between the depths for the CS. However, RZT$_{min}$ between

Table 5. Root mean square error (RMSE), seasonal average ratio of predicted root zone temperatures (RZTs) to measured RZT, $r^2$, and significance of the independent variables for equations developed. RZT was calculated on a daily basis and then averaged to obtain seasonal average.

| Variable | Eq. 4 | Eq. 5 | Eq. 6 | Eq. 7 | Eq. 8 | Eq. 4 | Eq. 5 | Eq. 6 | Eq. 7 | Eq. 8 |
|----------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| RMSE (°C) | 1.4 | 2.2 | 1.3 | 1.3 | 1.2 | 1.0 | 2.1 | 0.7 | 2.8 | 0.9 |
| Average ratio | 0.99 | 1.05 | 1.02 | 1.00 | 1.01 | 1.01 | 1.05 | 1.02 | 1.04 | 1.02 |
| $r^2$ | 0.89 | 0.89 | 0.94 | 0.83 | 0.95 | 0.84 | 0.83 | 0.90 | 0.74 | 0.84 |
| T$_{max}$ | * | * | NS | * | * | 0.84 | 0.83 | 0.90 | 0.74 | 0.84 |
| T$_{min}$ | NS | * | * | NS | * | 0.84 | 0.83 | 0.90 | 0.74 | 0.84 |
| Intercept | * | * | NS | NS | * | 0.84 | 0.83 | 0.90 | 0.74 | 0.84 |
| R$_s$ | NA | NA | NA | * | NA | 0.84 | 0.83 | 0.90 | 0.74 | 0.84 |

*Daily ratios of predicted RZT to measured.
*NA = not applicable.
*NS = Significant at 5% significance level as indicated by Duncan’s multiple range test.

Fig. 9. Diurnal RZTs (warmest days pattern in the summer season) of the black and white MPBSs and CS on 17 June (A) and 7 July (B) when ambient air temperature reached 40.0 and 40.1 °C, respectively.

Fig. 10. Diurnal RZTs (coldest days pattern in the fall season) of the black and white MPBSs and CS on 28 Oct. (A) and 19 Dec. (B) when ambient air temperature dropped to 5.1 and 6.0 °C, respectively.
the depths were the same (\(P > 0.05\)), while the MAX and RZT_{min} were different than the RZTs in the white and black MPBSSs. Thus, for the CS, two models were developed to predict RZT_{max} and RZT_{min} at the 0.12 m depth from the surface.

Fall was selected for model calibration because the temperature range was larger ranging from 1.9 to 40 °C as compared to the summer (17.4 to 40 °C). Calibration equations for predicting RZT_{max} °C for the substrate at the 0.12 m from the surface in the white and black MPBSSs, respectively, were found as:

\[
\text{RZT}_{\text{max-black}} = 1.2728 T_{\text{min}} - 0.0111 T_{\text{max}} - 3.4675
\]

and the equation for predicting RZT_{min} °C in either black or white MPBSS was found as:

\[
\text{RZT}_{\text{min}} = 0.0823 T_{\text{max}} + 0.953 T_{\text{min}} - 1.5011
\]

Key: RZT = canopy air temperature, T_{max} = peak canopy air temperature, T_{min} = minimum canopy air temperature.

Calibration parameters and the RMSE between the predicted and observed RZTs, the seasonal average of predicted RZTs to measured RZTs, and the significance of the independent variables for the calibration season are presented in Table 5.

Data analyses indicated that incoming solar radiation, \(R_s\) did not have a significant effect on RZT_{max} in the MPBSSs, thus, it was excluded from Eqs. 4 and 5. This is related to the fact that the MPBSS containers were protected from direct exposure to the solar radiation with the exception of the container surface in the early growing season due to the reduced canopy cover. In Eq. 4, the \(r^2\) value was 0.89 for the calibration. The intercept and \(T_{\text{max}}\) of the regression line were significant (\(P < 0.05\)), for the calibration (Table 5) with the RMSE average 1.4 °C. In Eq. 5, the \(r^2\) was same as Eq. 4 (0.89). The intercept, \(T_{\text{max}}\), and \(T_{\text{min}}\) were significant with the RMSE averaging with a higher value (2.2 °C) compared to the Eq. 4. In the calibration equation of \(T_{\text{min}}\) (Eq. 6), only the \(T_{\text{min}}\) was significant and the RMSE was 1.3 °C. The seasonal average ratio of predicted RZT_{max} to measured values was 0.99, 1.05, and 1.02 for Eqs. 4, 5, and 6, respectively, with Eq. 5 overestimating \(T_{\text{min}}\) for the black MPBSS. Although \(T_{\text{min}}\) in Eqs. 4 and 5 in Eq. 6 were not significant, they were included in the calibration equations because their inclusion increased the \(r^2\) value from 0.92 to 0.94 and decreased the RMSE of the predictions from 1.6 to 1.3 °C. In the calibration of Eq. 6, the discrepancies between the measured and predicted RZTs were the largest in the measured temperature range between about 10 and 20 °C. This might be due to the larger fluctuations in daily RZT_{min} toward the end of the fall. The largest fluctuations in daily RZT_{min} occurred in the November to December period when the temperature differences between the daytime and nighttime RZT_{max} were the greatest.

The results of the RZT predictions for the validation season (Eqs. 4, 5, and 6 versus measured RZTs in the summer), RMSE, and the seasonal average ratio of predicted RZTs to measured RZTs are presented in Table 5. Predicted RZT_{max} and RZT_{min} using Eq. 4 were well correlated with the measured RZT. Equation 4 resulted in a reasonably low RMSE (1.0 °C) with an \(r^2\) value of 0.84 and the seasonal average ratio of 1.01 (Table 5).

The results of Eq. 5 were slightly poorer than Eq. 4. Note that the calibration results of Eq. 5 in Table 5 showed that the Eq. 6 overpredicted RZT_{max} in the black MPBSS with a seasonal average ratio of 1.05. This overestimation was consistent throughout the season. The overestimation of the Eq. 5 is related to the considerable differences in temperature range between the calibration and validation seasons. For example, in the calibration season (fall), RZT_{max} of the substrate at 0.12 m in the black MPBSS ranged from 19.8 to 40.6 °C whereas it ranged from 27.6 to 40.0 °C in the summer. However, the magnitude of overprediction is within the acceptable range. Predicted RZTs were well correlated with the measured RZTs with an \(r^2\) of 0.83 while the average ratio was 1.05, and the RMSE was 2.1 °C.

Equation 6 predicted RZT_{max} very successfully for the black and white MPBSSs. The RMSE of predictions was the lowest (0.7 °C) and the \(r^2\) was the highest (0.90) among all equations. The average ratio of 1.02 indicates that the equation slightly overpredicted RZT_{max}. The overpredictions were larger at lower RZT_{max} (from 17 to 20 °C). This is because in the model calibration and validation, the average of five depth’s RZT_{max} and RZT_{min} were used and, thus, using average RZTS values from all depths might have introduced some bias to the model performance in the validation season. Also, Eqs. 4, 5, and 6 only use \(T_{\text{max}}\) and \(T_{\text{min}}\) to predict RZTs. They do not account for other environmental variables such as evaporation, conduction, water content and thermal properties of the substrate, and other variables that might influence the RZT. The main objective of this study was to develop simple but practical and accurate models that can be used to predict RZTs using commonly available climate variables. The model performances showed that Eqs. 4, 5, and 6 were effective and can be used to predict RZT_{max} and RZT_{min} with sufficient accuracy for Viburnum odoratissimum grown in the black and white MPBSSs.

RZT models for CS. The calibration equations for predicting RZT_{max} and RZT_{min}, respectively, for the substrate at a depth of 0.12 m in the CS containers were:

\[
\text{RZT}_{\text{max}} = 0.803 T_{\text{max}} + 0.0267 T_{\text{min}} + 0.6979 + 1.217 T_{\text{max}}^2
\]

\[
\text{RZT}_{\text{min}} = 0.1067 T_{\text{max}} + 0.998 T_{\text{min}} - 3.255
\]

where \(R_s\) is the daily average incoming solar radiation (MJ/m²·d). Using only \(T_{\text{max}}\) and \(T_{\text{min}}\) in the model of RZT_{max} for the CS resulted in poor predictions with low \(r^2\) and high RMSE of 0.64 and 4.0 °C, respectively. Therefore, \(R_s\) was included in the calibration. The calibration parameters for Eqs. 7 and 8 are given in Table 5.

In the calibration of Eq. 7, the \(r^2\) value was 0.83 and only \(T_{\text{max}}\) and \(R_s\) were significant (\(P < 0.05\), \(n = 79\)) with the RMSE of 2.3 °C (Table 5). In Eq. 8, the \(r^2\) was the highest (0.93) and the RMSE was the lowest (1.2 °C) among all calibration equations. In Eq. 8, \(R_s\) was not included since it did not have a significant contribution to predicting RZT_{min}. All other variables were significant. The seasonal average ratios of predicted RZT to measured values for Eqs. 7 and 8, respectively, were 1.00 and 1.01 indicating that the model predictions did not deviate from the measured values.

Summary and Conclusions

This study compared RZTs for container-grown V. odoratissimum grown in black and white MPBSSs, and a conventional system (CS) in Summer and Fall 2001 in north-central
Florida. The overhead sprinkler-irrigated CS served as the control treatment and represented the irrigation system used by the majority of the nursery growers. The MPBS treatments were irrigated with drip irrigation. The system reservoir allowed the capture of rain and excess irrigation water for later use by plants via subirrigation. Thus, water in the substrate was replaced by capillary mat as needed. The study also deals with the development, calibration, and validation of a series of models that can be used to predict RTZ and RTZ using commonly available input variables. RTZs were measured at five depths (0.03, 0.06, 0.09, 0.12, and 0.15 m from the container surface). During the model development, the critical plant root zone is assumed to be 1/3 of the distance from the bottom of the container (0.12 m from the container surface). Models were developed using the RTZ as the dependent variable and and as independent variables.

Black MPBSs maintained higher max ambient temperature compared to the white MPBS in both seasons. The RTZs in the black MPBS and CS exceeded the critical value (40°C) for a few hours during the summer. The 40°C value is cited in the literatures as negatively impacting root growth, leaf area, plant survival, root and shoot dry weights, and photosynthesis when plants are exposed to this extreme temperature for the duration of 5 to 6 h d⁻¹. RTZ in the CS was above 45°C for most of the summer. The MPBS successfully insulated plant root zone against extremely high ambient temperatures in all depths during both seasons and provided a more optimal environment which enhanced plant growth. Models based on and were able to explain 84% and 83% of the variability in RTZ of substrate in the white and black MPBSs, respectively. Using and in the model for the CS allowed predicting at least 74% of the variability in RTZ. RTZ predictions for MPBSs and CS were better than for RTZ. White MPBSs can provide adequate and effective RTZ protection for V. odoratissimum grown in no. 1, 3.8-L standard black conventional containers without insulation for regions where ambient air temperature range from 2 to 41°C. Models developed in this study can be used to accurately predict daily RTZ and RTZ of the substrate in the locations where ambient air temperature ranges from 1.9 to 40°C under climatic, management, and cultural practices similar to those found in this study.

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