Determining Plant-available Water of Woody Ornamentals in Containers In Situ During Production

Richard C. Beeson¹

University of Florida, MREC, 2725 South Binion Road, Apopka, FL 32703

Additional index words. irrigation management, container production, nursery production, precision irrigation, substrate water relations

Abstract. In nursery production, small root balls are transplanted into larger containers and grown for sale or further transplanting into still larger containers. When a root ball is smaller than a container, the amount of plant-available water (PAW) is initially limited to that of the original root ball. With growth, roots colonize new substrate and thereby increase the volume of water available to a shoot. Because of hydraulic gradients in container substrates, PAW is not linearly proportional to the volume of substrate occupied by roots. To practice precision irrigation in nursery production, it is important to know the extent of PAW and how it changes with growth. A method is detailed that calculates in situ PAW in containers based on changes in actual evapotranspiration while irrigation is withheld. The method is applied under field conditions and requires only daily mass loss measurements and corresponding reference evapotranspiration. An example of how PAW changes during production from rooted cuttings to marketable size plants is provided.

Commercially acceptable growth rates of woody ornamental nursery stock can be achieved using managed allowed deficits, i.e., deficit irrigations, of 20% to 40% plant-available water (PAW) before initiating irrigation (Beeson, 2006; Welsh and Zajicek, 1993). Deficit irrigation can reduce irrigation frequency (Beeson, 2006), thereby reducing nursery water runoff and energy consumption. Using deficit irrigation for container production of nursery stock is especially valuable for water conservation when rain occurs, because rainfall can account for part or all of a plant's daily evapotranspiration. Rainfall is more effective in penetrating plant canopies than overhead sprinkler irrigation (Beeson and Yeager, 2003), being nearly 100% efficient and more uniform than overhead irrigation. Therefore, less rainfall is required to return a container to capacity than overhead irrigation. However, to apply deficit irrigation strategies, or determine how much rainfall is sufficient and when additional supplemental irrigation is required, knowledge of PAW is necessary. This is especially critical during the early stages of plant production, when roots have not completely colonized a container's volume. At this stage, the lower substrate may be at or near 100% container capacity, whereas PAW may be critically low within the actual root ball.

PAW can be found by first recording the mass of a plant/container with a saturated substrate from which excess water has been allowed to drain. The plant is then allowed to

transpire until wilted. PAW is calculated as the difference in mass between saturated and wilted conditions (Beardsell et al., 1979b). For a container with a full root ball, total PAW (PAW_{Total}) can be consistent across species if the container size and substrate are identical (Beeson, 2006).

Although a similar approach can be applied to plants growing in a container in which roots have not yet filled the container volume, there are drawbacks. Stressing a plant to physical wilt can cause leaf drop in some species and may stunt shoot growth after stress is relieved. Because roots are growing into uncolonized substrate, volume of PAW continues to increase, delaying shoot wilt and therefore skewing the estimate of PAW. In situations in which root colonization of a substrate is not complete, PAW can be termed effective PAW (PAW_{Effec}). This skewing is especially prominent when evaporative demand is low during the drying period. For evergreen species that are dormant or that have rigid leaves and stems, determining the point of plant wilt can be difficult. Applying supplemental irrigation that exceeds the PAW_{Effec} is a waste of water and can lead to excessive leaching of nutrients. Overestimating PAW_{Effec} would result in underirrigation and perhaps commercially unacceptable growth rates. Precision irrigation of container plants requires an accurate estimate of PAW_{Effec} .

An alternative for plants that have not colonized a container's volume is to determine root ball volume relative to total container volume. Volume of a developing root system can be easily determined by water displacement. One could then calculate a percentage of container volume and infer PAW_{Effec} if PAW_{Total} is known. However,

water distribution in container substrates varies by substrate composition (Beardsell et al., 1979a; Bilderback et al., 1982; Richards et al., 1986), container size (Bunt, 1976), and container configuration (Bilderback and Fonteno, 1987; Davis et al., 1964; Spooner, 1974; Williams, 1978). In general, hydraulic gradients are established by opposing forces of capillary rise from water interacting with pores within a substrate and gravity pulling water to the bottom of a container (Bilderback and Fonteno, 1987). Although gradients can be determined, they vary with substrate composition and root ball height (Bilderback and Fonteno, 1987). Thus, simple determination of percent root ball volume of a developing root system in a container cannot accurately predict PAW_{Effec} , even if PAW_{Total} is known.

With increasing demands being placed on landscape nurseries to reduce ground or watershed water withdrawals for irrigation, and to reduce nutrients in runoff water, nurseries should begin practicing precision irrigation, applying only as much water as needed, when needed. To do so, knowledge of PAW accessible at a given stage of growth is needed to accurately apply deficit irrigation strategies. Previously, there has been no research in this area for container-grown nursery crops. Objectives of the research presented here were to: 1) verify a nondestructive method for determining PAW in containers in situ, 2) verify the method was valid across plant species, and 3) to examine relationships between PAW and canopy variables among species. To demonstrate the use of this method, a partial data set from an experiment to quantify water use of *Viburnum odoratissimum* was used to calculate PAW_{Effec} and PAW_{Total} during production from rooted cuttings to market-sized plants.

Materials and Methods

In mid-Oct. 1997, four plants of five species of woody ornamentals were selected and placed in an open-sided, single-layer clear polyethylene-covered shelter to exclude rain fall. Species were selected for their range of plant size, representation in nursery production, and commercial reputation for drought tolerance or intolerance in containers. Species selected, as ranked from least to most drought-tolerant, were *Viburnum odoratissimum*, *Ligustrum japonica*, *Photinia × fraseri*, *Elaeagnus pungens*, and *Raphiolepis indica*. Each plant had been grown to marketable size in an 11.4-L black polyethylene container (Lerio Corp., Kissimmee, FL) at the Central Florida Research and Education Center in Sanford, FL during the previous 2 years. Substrate consisted of 64% composted pine bark, 27% Florida sedge peat, and 9% coarse sand by volume amended with 0.88 kg·m⁻³ micronutrients (Peter's Fritted Trace Elements; Scotts Company, Marysville, OH) and 2.9 kg·m⁻³ dolomite limestone blended by a commercial vendor (Sunrise Landscape, Apopka, FL). Each plant was placed in a suspension lysimeter

Received for publication 9 Apr. 2007. Accepted for publication 1 July 2007.

¹To whom reprint requests should be addressed; e-mail rbeeson@ufl.edu.

(Beeson, 2006) and suspended ≈ 5 cm above the ground. Lysimeters were spaced such that there was ≈ 1.5 m between plants. Briefly, a lysimeter consisted of a 22.7-kg load cell (SSM-50; Interface, Scottsdale, AZ) suspended from a tripod 2.2 m in height. A plant was placed in a basket suspended from a load cell by small galvanized chains. Load cells were connected to a system of multiplexers (AM-32 and AM-416; Campbell Scientific, Logan, UT) and a data logger (CR-10; Campbell Scientific) that measured and recorded individual mass changes every half hour. Each plant was irrigated at 0100 HR using a single-spray stake (26.6 L·h⁻¹; Roberts Irrigation Products, San Marcos, CA). Plants were irrigated to supersaturate the substrate each night for three nights before the experiment began.

After irrigation on 21 Oct., nightly irrigation was suspended and an initial maximum container mass was recorded at 0500 HR for each plant. This allowed time for excess water to drain. Each plant was then allowed to transpire to the point of leaf wilt, at which point it was harvested the next morning within 1.5 h of sunrise. Leaf wilt was defined as leaves on three or more branches drooping by 1000 to 1200 HR. Shoots on all plants were mature and all buds were dormant throughout data collection. Just before shoot harvest, lysimeter mass was recorded (LM_{wilt}). The shoot was then removed at the substrate surface and wilted mass of the shoot ($Shoot_{wilt}$) determined immediately using an electronic balance (PB5001; Mettler, Mettler-Toledo, Switzerland). Plant shoots were then dried at 65 °C until a constant dry weight was obtained ($Shoot_{dwt}$). Once a shoot was harvested, a spray stake was returned to a container and nightly irrigation resumed. After the last plants were harvested (4 Nov.), irrigation duration was increased to resaturate all root balls within containers. By 14 Nov., all containers had exhibited a near constant mass for three or more consecutive days at 0630 HR, 2.5 h after the last irrigation. Container mass at this time was recorded as the saturated root ball mass ($RB_{saturated}$).

Daily actual evapotranspiration (ET_A) for each plant was determined by subtracting mass recorded for each plant at midnight by that recorded the next midnight. Daily ET_A for each plant was summed to give a cumulative ET_A for each plant. The difference between maximum mass the day of harvest (at midnight) and mass just before harvest was included in a cumulative ET_A total.

During the drydown period, daily recordings of net solar radiation (LI-190 pyranometer; LI-COR, Lincoln, NE), maximum and minimum temperature (HMP45C; Campbell Scientific), and daily cumulative wind distance (model 014 anemometer; Met-One Instruments, Medford, OR) were recorded using a data logger (CR10; Campbell Scientific). From these, daily potential evapotranspiration (ET_P) was calculated using a regional modification of the Penman-Monteith equation (Jones et al., 1984).

Calculations. Subtraction of LM_{wilt} from maximum hydrated lysimeter mass ($LM_{saturated}$) calculated PAW_{Total} within the saturated container-plant system (Eq. 1).

$$PAW_{Total} = LM_{saturated} - LM_{wilt} \quad (1)$$

Subtraction of resaturated root ball mass ($RB_{saturated}$) from $LM_{saturated}$ calculated the shoot mass at presumably 100% relative water content ($Shoot_{max}$; Eq. 2).

$$Shoot_{max} = LM_{saturated} - RB_{saturated} \quad (2)$$

Shoot relative water content at wilt (RWC_{wilt}) was calculated as follows (Eq. 3):

$$RWC_{wilt} = (Shoot_{wilt} - Shoot_{dwt}) \div (Shoot_{max} - Shoot_{dwt}) \quad (3)$$

where $Shoot_{wilt}$ is shoot mass at wilt, $Shoot_{dwt}$ is the shoot dry weight, and $Shoot_{max}$ was calculated from Eq. 2.

To evaluate the method to determine PAW in situ, daily ET_A was normalized by dividing each day's ET_A by the corresponding ET_P (Eq. 4). This calculated a normalized ET_A (ET_{Amm}^{-1}) with the units of mL·mm⁻¹·ET_P.

$$ET_{Amm}^{-1} = ET_{Ai} \div ET_{Pi} \quad (4)$$

Normalized ET_A on the first day of the dry down was then used as a divisor to calculate the percent reduction in normalized ET_A (%Max ET_A ; Eq. 5) for each day of the drydown until plant wilt. For each day, the corresponding cumulative ET_A (ΣET_A) was also calculated. The ΣET_A at the time of shoot harvest was considered to be the total PAW (ΣET_{ATotal}). For each plant, a plot of %Max ET_A as a function of ΣET_A was developed (Fig. 1). Any additional ET_A between midnight and shoot harvest on a day of harvest was not included.

$$\%Max ET_A = (ET_{Ai+1} mm^{-1} / ET_{Ai} mm^{-1}) \times 100 \quad (5)$$

where i is the days after saturation of the root ball and the first day is 100% of maximum ET_A .

Demonstration. In Mar. 2005, rooted cuttings of *V. odoratissimum* were transplanted into 11-L containers using the same substrate formulation but supplied by a different commercial company (Florida Potting Soil, Apopka, FL). At times throughout the 13-month production period, plants were selected and placed in similar lysimeters under an open-side, single polyethylene-covered rainout shelter at the Mid-Florida Research and Education Center (Apopka, FL). After an initial saturating irrigation at midnight, 0100 HR and 0200 HR, water was withheld and plant mass recorded every half hour for 5 d or until visible midmorning shoot wilt. Thereafter, containers were hand-irrigated and canopy widest width, width perpendicular to widest width, and average shoot height were recorded. These were then multiplied to calculate a canopy volume [growth

Fig. 1. Representative plots of cumulative ET_A versus %Max ET_A for five species of woody ornamental plants. Species were (A) *Rhaphiolepis indica*, (B) *Elaeagnus pungens*, (C) *Ligustrum japonica*, (D), *Photinia × fraseri*, and (E) *Viburnum odoratissimum*. The solid line was calculated from a linear regression based on five points and 18% minimum %Max ET_A .

index (GI)]. Root ball volume was measured by first carefully removing the container substrate to a point of visible root tips. The remaining undisturbed root ball was then enclosed in a polyethylene bag and root ball volume determined by volume displacement in a 19-L bucket. The bucket was set at a slight angle so that water beaded always at the lowest point on the rim. The volume of water required to return the water surface to the original, maximum bead was determined. Effective PAW was determined as described subsequently for each replication and means were calculated.

For the statistical analysis, each plant was an experimental unit. Because of malfunctions, one replication each of *E. pungens* and *L. japonica* was discarded, resulting in all nonregression analyses being conducted

using the general linear model (GLM) in SAS (version 9.0; SAS Institute, Cary, NC). GLM was used to compare PAW_{Total} as a split plot with species as the main plot and two determinations of PAW as a subplot. Similar comparison of LM_{wilt} and sum of RB_{wilt} + Shoot_{wilt} were also analyzed as a split plot design with species as the main plot and methods of determination as subplots. Regression equations were calculated using SAS (PROC REG) and used to analyze relationships between %Max ET_A and daily Σ ET_A. Statistics were calculated for both linear and quadratic curves using daily Σ ET_A as an independent value. Values of total Σ ET_A were inserted into the resulting equations to estimate %Max ET_A that occurred the day of plant wilt (%Max ET_{A,wilt}). Regression was also calculated using %Max ET_A as an independent variable for the first four and five data points for each replication. GLM was then used to test the strength of four and five data point regressions to estimate total Σ ET_A measured at plant wilt using both calculated %Max ET_A at the day of wilt and with %Max ET_A fixed at 18%. The 18% was the mean minimum %MaxET_A across all species in which total Σ ET_A measured at plant wilt was achieved. Analysis was conducted for each species independently and compared paired combinations of measured Σ ET_A against the three estimates of Σ ET_A. Analysis of other variables of Shoot_{max}, Shoot_{wilt}, Shoot_{dwt}, RWC_{wilt}, and %Max ET_A mm⁻¹ wilt were compared among species as a one-way analysis of variance using GLM.

Results and Discussion

Estimates of PAW were similar ($P = 0.19$) when calculated as the difference between LM_{saturated} and LM_{wilt} (PAW_{Total}, Eq. 1) and total Σ ET_A determined by summing daily ET_A (data not shown). The greatest difference between these two methods of calculation across all plants was 200 g or 6.01% of total Σ ET_A. Mean absolute difference among the 18 plants was 50 g or 1.45% of a system's PAW_{Total}. There was a slight tendency for total Σ ET_A to overestimate PAW_{Total} (11 of 19 plants).

Measurement of Shoot_{wilt} with an electronic balance was consistent with its calculation from LM_{wilt} at harvest. There were no differences ($P > 0.9$) between LM_{wilt} mass at harvest and the sum of Shoot_{wilt} and root ball mass at wilt (RB_{wilt}). The mean absolute deviation was 15 g. There were differences ($P < 0.01$) in LM_{wilt} among species. However, because basket and chain mass was not recorded for each lysimeter, comparisons of absolute mass could not be made.

Shoot dry weight was significantly different among species (Table 1). Because plants were market size for 11-L containers, woody stem mass contributed the majority of Shoot_{dwt}, especially for the larger canopy species. The species with the largest Shoot_{dwt}, *L. japonica*, *P. × fraseri*, and *V. odoratissimum*, were all at least 0.75 m in height

Table 1. Mean values for components of plant mass and relative water content during determination of plant-available water.^z

Genus	Shoot dry mass (g)	Shoot mass at wilt (g)	Shoot dry wt: shoot wilt mass	RWC at shoot wilt ^y	Saturated shoot mass (g)
<i>Rhaphiolepis</i>	237.2 b ^x	532.2 c	0.445 a	0.524 d	824.3 b
<i>Elaeagnus</i>	312.2 b	690.0 c	0.452 a	0.783 b	797.0 b
<i>Ligustrum</i>	563.1 a	1275.0 ab	0.442 a	0.814 b	1438.7 a
<i>Photinia</i>	506.4 a	1163.3 b	0.446 a	0.667 c	1521.0 a
<i>Viburnum</i>	499.1 a	1455.2 a	0.340 b	0.938 a	1465.7 a

^zGenus are listed in relative order from most to least drought-tolerant in containers.

^yRelative water content of a shoot the morning after midday visible wilt.

^xMeans with the same letter are not significantly ($P > 0.05$) different based on Fisher protected least significant difference. Means based on five replications except for *Elaeagnus* and *Ligustrum*, which were four replications.

and had comparable shoot dry weight. These three species are considered to be upright spreading shrubs (Gaskalla, 1998). *Rhaphiolepis indicia* was the shortest species at ≈ 0.3 m with *E. pungens* height midway between the extremes.

Shoot_{wilt} mass varied among species, but relative rankings were similar to that for Shoot_{dwt} (Table 1). *V. odoratissimum*, *L. japonica*, and *P. × fraseri* had much greater mass, nearly double that of *E. pungens* and *R. indicia* at canopy wilt. Similarly, these same three had nearly double the estimated shoot saturated mass (Table 1). Relative ranking by mass at wilt was different from for Shoot_{dwt} for the three largest species. Although not significant ($P > 0.05$), *V. odoratissimum* had the least Shoot_{dwt} but ($P < 0.05$) greater mass at wilt than *P. × fraseri* (Table 1). Despite differences ($P < 0.05$) among species in both Shoot_{dwt} and Shoot_{wilt}, ratios of Shoot_{dwt}:Shoot_{wilt} was 0.44 ± 0.01 for all species except *V. odoratissimum* with a ratio of 0.34 (Table 1). This ratio was consistent across most species, although there were substantial differences in plant size and observational responses to water stress. Thus, when water content of a shoot of most plants evaluated declined to ≈ 2.25 times Shoot_{dwt}, a plant was visibly wilted. For *V. odoratissimum*, generally considered least tolerant of water stress in containers, visible wilt occurred with at a higher level of tissue water content. Mean RWC_{wilt} of *V. odoratissimum* of 93.8% was higher than that of other species (Table 1). With the exception of *L. japonica* and *E. pungens*, RWC_{wilt} was unique and different ($P < 0.05$) among all species, although Shoot_{dwt}:Shoot_{wilt} ratios were consistent. Water in the xylem likely contributed substantially to plant mass at wilt and is likely the reason for different RWC_{wilt} among species. This difference in RWC_{wilt} accounts for the higher Shoot_{wilt} for *V. odoratissimum* than *P. × fraseri* relative to their Shoot_{dwt}. Importance and significance of the Shoot_{dwt}:Shoot_{wilt} ratio is unknown and may deserve further investigation.

RWC_{wilt} was not predictable from other shoot measurements such as Shoot_{dwt}, Shoot_{wilt}, or ratios of these two. Of these species, *V. odoratissimum* is considered to have low drought tolerance in containers, whereas *R. indica* is considered to be very tolerant. The relative order of RWC_{wilt} appears

reasonable. Previously, Beeson (1992) suggested water potential thresholds for stomatal closure for *L. japonica* and *E. pungens* were similar with *E. pungens* being somewhat more drought-tolerant. However, the lower RWC_{wilt} for *P. × fraseri* is opposite of what would have been expected based on previous reported stomata thresholds. These differences in RWC_{wilt} suggest a possible quick way to screen landscape shrub species for drought tolerance.

Normalized values of ET_A the first day of the drydown were always highest independent of plant species or replication. As days without irrigation progressed, ET_A normalized by ET_P declined, resulting in continuous declines in %MaxET_A for at least the first 4 to 5 d of the drydown (Fig. 1). After ≈ 5 d, declines in %MaxET_A slowed and became variable for some species (Fig. 1A–B). This variability became more conspicuous as duration of the drydown increased as exemplified by *R. indica* (Fig. 1A). However, for *V. odoratissimum*, canopy wilt was achieved within a 4- to 5-d timeframe (Fig. 1E). For all plants of the other species, 7 to 14 d was required until visible wilt was observed. This long duration resulted from both all plant tissue being mature and relatively low ET_P that occurred during the drydown period. ET_P ranged from 1 to 3.7 mm daily with a median value of 3.3 mm.

Regression analysis was applied to all data sets to calculate %MaxET_A as a function of Σ ET_A to determine the best fit relationship between the two variables. Because there were no differences between Σ ET_ATotal and PAW_{Total}, daily Σ ET_A is representative of cumulative daily water loss from a plant–substrate system over time. Some plots, particularly those of *P. × fraseri*, suggested a quadratic relationship between Σ ET_A and %MaxET_A (Fig. 1D), thus, regression analysis was calculated for both linear and quadratic curves for each replication. Correlation coefficients (r^2) were similar between linear and quadratic equations for most replications (data not shown). Values for r^2 ranged from 0.849 to 0.976. Quadratic equations increased the r^2 value by 5% to 11% for three of the four *P. × fraseri* (average $r^2 = 0.882$ linear to 0.961 quadratic) and by 6% for one *R. indica* replication. Quadratic terms were not significant ($P > 0.5$) for *V. odoratissimum*.

Values of ΣET_{ATotal} were inserted into both linear and quadratic equations derived to compare $\%MaxET_A$ estimated by these lines with $\%MaxET_A$ derived from the last day of the drydown ($\%MaxET_{Awilt}$) for each replication. Comparing $\%MaxET_{Awilt}$ with calculated values found little difference between values generated by linear or quadratic equation (data not shown). Linear equations tended to be more accurate in predicting $\%MaxET_{Awilt}$ than quadratic equations (data not shown). Thus, for simplicity and accuracy, only linear equations were carried forward.

Having established a linear relationship between $\%MaxET_A$ and ΣET_A , the next step in establishing a method to estimate in situ PAW_{Effec} was to define the relationship between PAW_{Effec} and some level of $\%MaxET_A$. For all species except *V. odoratissimum*, a linear decline in $\%MaxET_A$ with increasing ΣET_A was followed by a pronounced slowing of that decline, either linearly or with oscillating variability (Fig. 1). The initial linear decline is proposed to be a direct result of gradual stomata closure resulting from decreases in available water within access of a root system. Gradual stomatal closure would reduce transpiration while drying of the substrate surface would reduce evaporation (Kramer and Boyer, 1995). The abrupt deviation in the linear decline is proposed to be the result of stomata closure. Thereafter, water lost would be mainly through cuticular transpiration and substrate evaporation. Because there is little to no photosynthesis with stomatal closure of most temperate woody plants, it is proposed that PAW at this point is essentially the PAW_{Effec} . Although a plant may or may not exhibit wilt at this point, its net carbon balance would be near zero or less. In production situations in which the objective is growth, complete stomata closure is unacceptable. Thus, the minimum $\%MaxET_A$ was sought where PAW_{Effec} was achieved. Plots of $\%MaxET_A$ versus ΣET_A were visually examined for all plants to determine PAW_{Effec} . These were then inserted into the linear equations derived and $\%MaxET_A$ calculated. Mean minimum $\%MaxET_A$ across all species was 18% (Fig. 1). Individual plant values ranged from 15.0% to 21.8%.

The final step was to determine the minimum number of days of a drydown required for accurate calculation of PAW_{Effec} . Using 18% as $\%MaxET_A$ and linear regression lines calculated from the first 4 and 5 d of a drydown, ΣET_A was calculated for both regression equations for each plant. These values of estimated ΣET_A were compared with actual measured ΣET_A and ΣET_A calculated with each plant's actual $\%MaxET_A$ at PAW_{Effec} . Overall, estimates from regressions based on 5 d of drydown were more accurate than those based on 4 d (data not shown). However, the gain in accuracy was generally small, from near 0% to 5%. On both a species basis and among species, there were no differences ($P > 0.05$) between ΣET_A estimated from the first 5 d of the drydown

using 18% as $\%MaxET_A$ or estimated from the actual $\%MaxET_A$. Similarly, both these estimates of ΣET_A were not different ($P > 0.05$) from measured values. Errors using 18% as $\%MaxET_A$ were between near 0% and 6% with an average error of 2.5% compared with measured values.

Using a 4-d drydown, overall, there were no differences ($P > 0.05$) between estimated ΣET_A using 18 as $\%MaxET_A$ or actual $\%MaxET_A$ and measured values. Estimates of ΣET_A based on 18 as $\%MaxET_A$ and a four-point curve had a mean error from the measured ΣET_A of 3.9% and ranged from near 0% to 8.2%. Thus, for species evaluated, a 5-d drydown was sufficient for an accurate estimate of PAW_{Effec} and mostly avoided pushing plants into a wilted state. However, with reference evapotranspiration (ET_0) greater than 4.5 mm and plants two-thirds grown or better, where declines in PAW occur more quickly than in this experiment, a 4-d drydown would be acceptable and preferred.

To demonstrate changes in PAW_{Effec} during a production cycle, data were extracted from an experiment using *V. odoratissimum* grown from rooted cuttings (30052202 Jiffy Strips; Jiffy Products of America, Norwalk, OH) in an 11-L container. A month after transplanting in the 11-L container, root exploration into the substrate was approximately one-fourth the total container volume. However, mean PAW_{Effec} of 0.51 L was $\approx 17\%$ of PAW_{Total} of a root ball at full container volume (Fig. 2). Roots generally had not reached the side walls at this point, but were growing in a wide cone shape downward. This illustrates the increasing gradient of the PAW of this substrate from top to bottom of the substrate column. Canopy volume was 1526 cm³, 0.4% of that

of harvested plants (Fig. 2). Three months later, PAW_{Effec} had almost doubled to $\approx 32\%$ of PAW_{Total} with the root ball volume extending to approximately half the available container volume. Canopy volume had doubled to 3899 cm³, but still only $\approx 1\%$ of the harvested canopy. Although canopies were visually developing at a good rate, root growth was much more rapid, expanding into virgin PAW . At 109 d after transplanting, root ball volume was roughly 25% larger than shoot volume in this substrate blend. Based on observations since 1990, root ball to canopy volume is more dependent on PAW than physical volume (unpublished data). Irrigation managers should take advantage of this greater increase in PAW than canopy volume, conserving irrigation for later in the production when daily ET_A can reach one-third of PAW_{Total} (data not shown). Seven months after transplanting (day 232), PAW_{Effec} had tripled to 3.1 L, although physical root ball volume had only increased $\approx 20\%$ over the same period. At this point, root systems had not completely engulfed the substrate with the containers, but a few roots were at the bottom of the root ball. Canopy volume, however, increased 5.8-fold to 0.026 m³ over the same period. With the drydown at harvest 13 months after transplanting, PAW_{Total} was the same ($P > 0.05$) as that calculated at 7 months, although root ball volume had increased $\approx 30\%$ to completely encompass the substrate volume. Correspondingly, canopy volume had increased nearly 12-fold to 0.34 m³.

PAW_{Total} for *V. odoratissimum* measured at harvest was not as great as that measured in 1997 nor was it consistent with PAW_{Total} of the other species in similar containers (Table 2). There are several possible reasons for this. In 2006, plants at harvest were

Fig. 2. Measured values of effective plant-available water (PAW_{Effec}), root ball volume, and shoot volume (growth index) of *Viburnum odoratissimum* grown from rooted cuttings to market-sized plants. Plants were of market size and harvested at day 397. Means represent four to seven plant replications, depending on time after transplanting. Error bars represent the sd.

Table 2. Total plant-available water (PAW_{Total}) based on cumulative ET_A ($\sum ET_A$) for the five species from the 1997 experiment and for the *V. odoratissimum* taken from the 2005 to 2006 experiment.^z

Species	Mean PAW _{Total} (L)
<i>Rhaphiolepis indica</i>	3.444 ± 0.165
<i>Elaeagnus pungens</i>	3.357 ± 0.177
<i>Ligustrum japonica</i>	3.799 ± 0.45
<i>Photinia × fraseri</i>	3.551 ± 0.0258
<i>Viburnum odoratissimum</i>	3.434 ± 0.166
<i>Viburnum odoratissimum</i> —2005–2006	2.898 ± 0.212

^zGenus are listed in relative order from most to least drought-tolerant in containers. The ± SD is based on four (*Ligustrum*, *Elaeagnus*), nine (2005–2006 *Viburnum*), or five (remaining species) replications.

overhead-irrigated normally and the root balls were likely not fully saturated as they were with excessive microirrigation in 1997 or as they were in previous measurements in 2005. This is the most probable explanation because PAW at harvest was the same as that at 7 months, although root ball volume at 7 months was not at the maximum as it was at the harvest. Additionally, harvested plants in 2006 were smaller than those used in 1997 as evident by the smaller ($P < 0.05$) dry weight (272.4 g versus 499.1 g). This would have lowered the amount of PAW derived from woody stem tissue.

Through applying this procedure many times since its inception, there are two conditions that are critical to its successful use. One, the first day of a drydown must be one that has the best chance of having an average or higher reference ET₀ for the region and season. Midday rain and prolonged cloudiness the first day, followed by a mostly sunny day resulting in higher ET₀, can shift the day of maximum ET_A to the second day, damaging the correlation of %MAXET_A with $\sum ET_A$. This is more critical the less time a plant has been in a container with uncolonized substrate. Should low ET₀ conditions occur after the first day, consequences are less severe. The other critical item, as was seen in the 2006 harvest results, is to thoroughly saturate a root ball initially to be able to determine an accurate volume of PAW.

Results suggest that determining RWC_{wilt} could be used to rapidly screen plant species for drought tolerance. Lower RWC_{wilt} suggests an indicative tolerance of a species to water stress, which could be verified by pressure-volume curve analysis (Tyree and Hammel, 1972). Evaluation of this hypothesis using established in-ground plants appears warranted. From a practical perspective, quantification of PAW_{Effec} results in more accurate characterization of deficit irrigation on plants growth in containers. It can also be used to quantify root growth in containers nondestructively and repeatedly. In nursery production, PAW_{Effec} could be determined every 4 to 6 weeks over a 5-d period with mass recorded before dawn each day. Measurement the fifth morning would provide the four minimum points to generate the linear regression curve with PAW_{Effec} calculated using 18%MaxET_A. With experience, irrigation managers could determine PAW_{Effec} relative to container water capacity. Applying principles of deficit irrigation, irrigation would be frequent and light after transplanting, progressing rapidly to less frequent and greater volume as roots explore the substrate. This would result in less nutrient leaching and greater capture of rainfall. Irrigation in excess of PAW, especially for young crops, wastes water and energy and promotes excessive leaching of nutrients from a substrate. The main limitation with this method is the need for accurate calculation of daily ET₀. Although some states have this available through the Internet, in states like Florida where cloud cover can be sporadic, a good onsite weather station would be preferred. These results from market-sized plants suggest PAW_{Total} is more an effect of container geometry and substrate composition and physical properties than plant species. Differences in root growth and growth direction would influence the rate at which PAW_{Effec} increases with time.

Literature Cited

- Beardsell, D.V., D.G. Nichols, and D.L. Jones. 1979a. Physical properties of nursery potting-mixtures. *Sci. Hort.* 11:1–8.
 Beardsell, D.V., D.G. Nichols, and D.L. Jones. 1979b. Water relations of nursery potting-media. *Sci. Hort.* 11:9–17.

- Beeson R.C., Jr. 1992. Restricting overhead irrigation to dawn limits growth in container-grown woody ornamentals. *HortScience*. 27: 996–999.
 Beeson R.C., Jr. 2006. Relationship of plant growth and actual evapotranspiration to irrigation frequency based on managed allowable deficits for container nursery stock. *J. Amer. Soc. Hort. Sci.* 131:140–148.
 Beeson R.C., Jr. and T.H. Yeager. 2003. Plant canopy affects sprinkler application efficiency of container-grown ornamentals. *HortScience* 38:1373–1377.
 Bilderback, T.E. and W.C. Fonteno. 1987. Effects of container geometry and media physical properties on air and water volumes in containers. *J. Environ. Hort.* 5:180–182.
 Bilderback, T.E., W.C. Fonteno, and D.R. Johnson. 1982. Physical properties of media composed of peanut hulls, pine bark, and peatmoss and their effects on azalea growth. *J. Amer. Soc. Hort. Sci.* 107:522–525.
 Bunt, A.C. 1976. Modern potting compost. The Pennsylvania State Univ. Press, University Park, PA.
 Davis, W.D., S.T. Besemer, and D.H. Close. 1964. Landscaping in planters without natural drainage. *U.C. Agr. Ext. Serv. AXT* 124:1–13.
 Jones, J.W., L.H. Allen, S.F. Shih, J.S. Rogers, L.C. Hammond, A.G. Smajstrala, and J.D. Martsolf. 1984. Estimated and measured evapotranspiration for Florida climate, crops and soils. *Ag. Exp. Station, Instit. Food and Agric. Sci. Univ. of Florida. Bulletin* 840.
 Gaskalla, R. Director Division of Plant Industry. 1998. Grades and standards for nursery plants, 2nd ed. Florida Dept. of Agr. and Consumer Services. Tallahassee, FL. p. 237.
 Kramer, P.J. and J.S. Boyer. 1995. Water relations of plants and soils. Academic Press, Inc., San Diego, CA.
 Richards, D., M. Lane, and D.V. Beardsell. 1986. The influence of particle-size distribution in pinebark:sand:brown coal potting mixes on water supply, aeration and plant growth. *Sci. Hort.* 29:1–14.
 Spooner, L.A. 1974. Two classroom exercises demonstrating the pattern of container soil water distribution. *HortScience* 9:152–153.
 Tyree, M.T. and H.T. Hammel. 1972. The measurement of turgor pressure and the water relations of plants by the pressure-bomb technique. *J. Expt. Bot.* 23:267–282.
 Welsh, D.F. and J.M. Zajicek. 1993. A model for irrigation scheduling in container-grown nursery crops utilizing management allowed deficit (MAD). *J. Environ. Hort.* 11:115–118.
 Williams, D.J. 1978. Handling plants in containers. *J. Arbor.* 4:184–186.