Evaluating a Physiological-based, On-demand Irrigation System for Container-grown Woody Plants with Different Water Requirements

Susmitha Nambuthiri

Department of Horticulture, University of Kentucky, Lexington, KY 40546

Ethan Hagen and Amy Fulcher¹

Department of Plant Sciences, University of Tennessee, 2431 Joe Johnson Drive, 252 Ellington Plant Science Building, Knoxville, TN 37996

Robert Geneve

Department of Horticulture, University of Kentucky, Lexington, KY 40546

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Abstract. Two sensor-based irrigation scheduling systems were compared for water use and plant growth in container-grown Green Velvet boxwood (*Buxus sempervirens* L. × *B. microphylla* Siebold & Zucc. var. *koreana* ‘Green Velvet’) and slender deutzia (*Deutzia gracilis* Siebold & Zucc). These crops were chosen because they have different water requirements during production. The two sensor-based irrigation systems included a physiological-based on-demand (OD) irrigation system where the set point was derived from the relationship between substrate moisture and photosynthetic rate. The second system was a daily water use (DWU) method where the amount of water used by the crop was replaced each day. The objective of the study was to evaluate and compare water use and growth metrics using the OD and DWU irrigation scheduling regimes for two container-grown woody plants that differed in their water consumption. There were no differences in root and shoot biomass or growth index due to the irrigation schedule employed for either boxwood or deutzia. For boxwood plants, OD irrigation reduced water consumption by 35.5% and enhanced water use efficiency (WUE) by 54.5% compared with DWU. Total water use of deutzia in OD zones was reduced by 26.5% compared with DWU. DWU offers the labor scheduling advantage of irrigation occurring at a set time of day, and OD offers the advantage of watering as required, potentially reducing water stress as the season progresses and as the plant size and atmospheric demand increase.

Nursery crop production is an intensively managed form of agriculture, consuming large amounts of water, nutrients, and pesticides (Beeson, 2010; Bethke and Cloyd, 2009). Nursery growers commonly use static, timer-driven irrigation systems that are not responsive to environmental or plant-based demands and this can lead to over irrigation (Fare, 2014). However, potential restrictions on irrigation and regulations on water quality necessitate that the green industry find alternative ways to manage water without negatively impacting production schedules,

or crop or environmental quality (Majsztrik et al., 2011). Irrigation scheduling refers to the amount of water to be applied to a plant, as well as the timing and duration of application (Warren and Bilderback, 2005). Irrigation scheduling has a significant impact on water use efficiency (WUE). Scheduling can be relatively static and arbitrary (timer driven), use environmental models such as evapotranspiration (ET), or be designed to estimate periodic water loss using sensors or physical methods (Jones, 2004; van Iersel et al., 2013). Advanced irrigation scheduling methods have to be developed to address the concerns of the green industry.

Environmental models have been used to estimate water use in container-grown nursery crops by using a modification of the Penman–Monteith equation (Bacci et al., 2008; Beeson and Brooks, 2008; Niu et al., 2006). The models are based on meteorological data and plant-related characteristics such as growth phase, plant height, growth index (GI), canopy coverage, plant/container spacing, container surface area (Beeson, 2004, 2012; Grant et al., 2012;

Irmak, 2005). Some major limitations of ET-based scheduling models include the need to determine specific crop coefficients for numerous species and cultivars in production (Beeson, 2005) and for each crop at various growth stages (Niu et al., 2006) and time of year (O’Meara et al., 2013). ET estimates also assume that the crop has access to unlimited water resources, which is often not the case in a container-grown crop (Incrocci et al., 2014; Pardossi et al., 2009).

Another method of irrigation scheduling is to apply the volume of water used in ET each day as calculated relative to container capacity, returning the substrate to container capacity (Warsaw et al., 2009). The most direct method for using estimated ET to schedule irrigation is by weighing containers to assess periodic water loss followed by water replacement to bring a container’s substrate water content back to near container capacity (Million et al., 2010). Substrate moisture sensors have also been used for implementing this type of conservative daily water use (DWU)-based irrigation scheduling for production of several evergreen and deciduous shrubs in the Northern United States (Pershey, 2014) and *Hydrangea macrophylla* ‘Fasan’ and *Gardenia jasminoides* ‘Radicans’ in Southern United States locations (O’Meara et al., 2013).

User-defined set points for controlling substrate water content and triggering irrigation via automated irrigation systems have also been used for irrigation scheduling (Nemali and van Iersel, 2006). A sensor-driven automated irrigation study in *Hibiscus acetosella* ‘Panama Red’ tested threshold water contents ranging from 0.10 to 0.45 cm³·cm⁻³ and found 0.35 cm³·cm⁻³ was an optimal set point based on the substantial water savings and acceptable plant growth compared with other volumetric water content (VWC) used in the study (Bayer et al., 2013). By maintaining a constant substrate VWC the irrigation system effectively replaces the water that is lost from the substrate by evaporation, transpiration, or leaching, assuring a constant water supply for the plants. However, the issue of selecting an ideal set point based on both plant and environment demands that controls the timing and volume of irrigation still exists.

A plant-demand-based irrigation system evaluates plant response to environmental changes to predict the amount and timing of irrigation. Photosynthesis is closely linked with stomatal conductance (g_s) and it can be influenced by root-to-shoot signaling and both are influenced by leaf water potential. Therefore, photosynthesis has been proposed as a sensitive indicator of plant water status (Fulcher, 2010). An irrigation set point was established that reflected the substrate water content at which photosynthesis began to drop (photosynthetic rate was lowered to 90% of maximum), which corresponded to a reduction in g_s . By maintaining substrate moisture content just above this set point, a crop could be produced using 27% less water than the control, and without adversely

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¹Corresponding author. E-mail: afulcher@utk.edu.

impacting quality or production time (Fulcher et al., 2012). Development of an irrigation system based on photosynthetic rates would require a smaller data collection to establish irrigation set points and could easily be modified for use with other species. The plant on-demand (OD) irrigation scheduling system has since been employed successfully on a number of crops including *Hibiscus rosa-sinensis* (Fulcher et al., 2012), oakleaf hydrangea (*Hydrangea quercifolia*) (Hagen et al., 2014), and redbud (*Cercis canadensis*) (Nambuthiri et al., 2015a) without incurring a growth or quality “penalty.”

In this OD irrigation system, the amount of water delivered at each irrigation is the same (determined by the set point), but irrigation timing and frequency varies based on plant water use and environmental demand. This is in contrast to the DWU method (Pershey, 2014; Warsaw et al., 2009) where the amount of irrigation will vary based on plant water use but the time irrigation occurs is constant (every 24 h). These two soil moisture sensor (SMS)-based methods of nursery irrigation scheduling were compared in a previous study by producing 1 and 3 gallon oakleaf hydrangea (*Hydrangea quercifolia*) in outdoor and controlled environments. With the OD treatment, there was generally either no or a positive difference in plant growth and water use was considerably lower in treatments using the OD scheduling method (Hagen et al., 2014). However, oakleaf hydrangea is a relatively high-water-use species, so it is important to monitor the impact of these two conservative irrigation scheduling systems in species with relatively moderate and low water use. Therefore, the objective of this study was to evaluate and compare water use and growth metrics using the OD and DWU irrigation scheduling regimes for two container-grown woody plants that differed in their water use demand under different growing environments.

Materials and Methods

Experiment locations and plants. A series of experiments were conducted to test physiologically based and DWU irrigation systems in an outdoor, aboveground nursery and controlled environment settings. Plants used included Green Velvet boxwood (*Buxus sempervirens* L. × *B. microphylla* Siebold & Zucc. var. *koreana* ‘Green Velvet’) and slender deutzia (*Deutzia gracilis* Siebold & Zucc). Two container sizes were used; 3.8-L containers were used in Lexington, KY (38.105°N, –84.486°W) for growing boxwood plants and 11.4-L containers were used in Knoxville, TN (35.946°N, –83.939°W) for growing deutzia plants. Containers were placed on a level surface of gravel with landscape fabric underlay at a 15 cm depth to reduce weed emergence.

Instantaneous water use efficiency assessment. Instantaneous water use efficiency (WUE_i), which is defined as the moles of CO_2 absorbed per mol of H_2O lost through transpiration, i.e., net photosynthe-

sis/transpiration (Ni and Pallardy, 1991) was assessed in greenhouse-grown plants. The WUE_i was calculated by dividing the photosynthetic rate when at 90% of maximum by the simultaneously measured transpiration rate using an infrared (IR) gas analyzer (LI-6400; LI-COR, Lincoln, NE) using the same settings described under the physiological measurements section below (Griffin et al., 2004).

Transpirational water loss. Transpirational water loss of boxwood and deutzia was evaluated in a controlled environment chamber (Parameter Generation and Control, Black Mountain, NC) with temperature and humidity control (Fulcher et al., 2011). Lighting was supplied by eight 24-W fluorescent bulbs (Sun Blaze T5HO-28; Sunlight Supply, Vancouver, WA) suspended above the canopy. Before moving plants to the transpiration chamber, the containers were hand watered, soaked for 20 min in 1 inch of water to thoroughly wet the substrate and reduce channeling of water (Hoskins et al., 2014). Containers were drained to container capacity and then bagged and sealed around the lower trunk with wire ties and parafilm to minimize evaporative water loss. Here, container capacity is defined as substrate moisture content following irrigation, once gravitational water has drained but before evaporation losses occur. Initial steady state transpiration was recorded. Plants were tested under two environments at vapor pressure deficits; 0.5 kPa (20 °C and 78.5% relative humidity) and 1.5 kPa (23 °C and 47% relative humidity). There were six plants of each taxa in each experiment. Container weight was recorded hourly for 9 h until there was no significant weight change (steady state transpiration). Hourly evaporative water loss in grams was converted into moles by using the conversion factor that 1000 mL of pure liquid water with a density of 1.00 g·mL⁻¹ would weigh 1000 g. This mass divided by the molar mass of water (18.0152 g·mol⁻¹) gives 55.5 mol·L⁻¹.

Irrigation systems, plot description. Root proliferation was periodically monitored in a cohort of plants that was not included in the experiment to determine root establishment. Plants were hand watered until roots reached the container sidewall. Once the roots reached the sidewall, irrigation was controlled by an automated system. Substrate moisture levels were measured and controlled using dielectric capacitance sensors (ECHO-5; Decagon Devices Inc., Pullman, WA) connected to a data logger (CR1000; Campbell Scientific Inc., Logan, UT) with a multiplexer (AM16/32; Campbell Scientific) and a 16-channel relay controller (SDM-CD16AC; Campbell Scientific) to operate solenoid valves. VWC values were calculated from mV output and sensor-specific calibration equations in the program (Hagen et al., 2014). One capacitance sensor per container was installed halfway between the center of the container and the container sidewall. Sensors were oriented vertically with the broad side of the sensor facing the

plant stem and inserted into the substrate so that the sensor over mold/wire junction was 2.5 cm below the surface of the substrate. The VWC of each irrigation zone (plot or replicate) was calculated by averaging values from three sensors per zone. The data logger measured VWC every minute and recorded 15-min averages. Water use over the course of the experiment was calculated for each zone based on the amount of time each solenoid remained open and the flow rate, calculated by measuring the volume of water captured in pans during timed trials. A rain gauge was wired to the data logger to collect precipitation data.

The two irrigation systems tested in this experiment were OD, a system with a physiological basis, and DWU. Both programs calculated the difference between the instantaneous VWC and container capacity and applied the exact water volume required to return the substrate to 100% container capacity. The main difference between the two systems was the static timing for initiation of irrigation in DWU vs. dynamic irrigation scheduling for OD. In OD plots, irrigation was triggered when the average VWC fell below 0.28 m³·m⁻³ for boxwood and 0.33 m³·m⁻³ for deutzia. These values were chosen based on a preliminary experiment that recorded repeated measurements of photosynthetic rate in plants along with VWC as the substrate was dried from container capacity to permanent wilting point (Hagen, 2013). A sigmoidal curve best described the relationship between photosynthetic rate and VWC. The selected irrigation set point, 0.28 m³·m⁻³ for boxwood and 0.33 m³·m⁻³ for deutzia, corresponded to the substrate moisture level that supported photosynthesis at 90% of maximum predicted photosynthetic rates and when 92% of plant-available water had been used (Fig. 1A and B). DWU was irrigated on a static 24-h cycle. DWU during the previous 24-h cycle was calculated as the difference between 100% container capacity and the instantaneous VWC measured immediately before irrigation. Container capacity was calculated as the water held in a substrate when completely saturated and after all free water has been allowed to drain (Jones and Tardieu, 1997). The program multiplied the VWC difference by the container volume and divided by the irrigation flow rate to calculate irrigation time. Examples of irrigation scheduling for each plant can be seen in Fig. 2A and B. Container capacity was determined in preliminary experiments to be 0.52 m³·m⁻³ for the 11.4-L containers and 0.50 m³·m⁻³ for the 1-gallon container studies. For DWU, an afternoon irrigation time of 1 PM was chosen to allow photosynthetic measurements during the time of day with high light intensity. Irrigating in the afternoon ensured that photosynthesis could be measured before irrigation, at the DWU treatment plants’ driest point, as it was for OD plants.

For the experiments, irrigation zones consisted of six independently controlled, square irrigation plots of 3.1 m², constructed from

Fig. 1. The relationship between photosynthetic rate and volumetric water content of (A) 'Green Velvet' boxwood and (B) slender deutzia plants characterized by a three-parameter sigmoidal curve. The y in equations indicates photosynthesis. The irrigation threshold chosen at 90% maximum predicted photosynthetic rate is shown by the vertical arrow. $n = 5$.

standard 1.9-cm PVC pipe (schedule 40) with an additional 0.76 m between each zone. There were three replicate irrigation zones and treatment combinations for a total of six zones per species. Irrigation was applied by four overlapping sprinklers (Toro® 570 Shrub Spray; The Toro Co., Riverside, CA) per irrigation plot. Each emitter provided 5.5 $\text{L} \cdot \text{h}^{-1}$. Emitters were mounted on 1.3-cm-diameter risers at a height of 66 cm.

Outdoor experiment: 11.4-L containers. Deutzia liners (10.2 cm Spring Meadow Nursery, Grand Haven, MI) were potted into 11.4-L plastic containers on 13 June 2012 (C1200; Nursery Supplies Inc., Fairless Hill, PA) with a 85 pine bark : 15 peatmoss (by volume) substrate mix (Renewed Earth Inc., Kalamazoo, MI). Substrate physical properties were measured (Fonteno et al., 1995) as follows: 89.9% total porosity, 30.7% available water, 30.6% unavailable water, 28.6% air space, and 0.16 g/cc bulk density. One week after transplanting, plants were top dressed with 19N–1.75P–11.6K, 5–6 month controlled release fertilizer with micronutrients (Polyon®; Harrell's Inc., Lakeland, FL) at 53 g per container (medium label rate). A wetting agent (Aquaagro® L; Aquatrols, Paulsboro, NJ) was applied as a drench

of 600 $\text{mg} \cdot \text{L}^{-1}$ 2 weeks after planting to ensure even wetting of the substrate. Eight plants (subsamples) were placed in the center of each irrigation zone in staggered rows of 3–2–3 with 15.25 cm between container sidewalls. Border plants of the same species were spaced around the perimeter of the containers in the experiment to mitigate edge effects.

Leaf water potential and gas exchange were measured three times for each treatment (chamber conditions: 800 $\mu\text{mol m}^{-2} \cdot \text{s}^{-1}$ light and 400 ppm CO_2) when two criteria were met: the plants were at the lowest substrate water content permitted by their respective treatment and when the time was between 10:00 AM and 3:00 PM. Gas exchange and leaf water potential measurements were taken during the following periods: 21 Aug., 20 Sept., 25 Sept., and 16 Oct. 2012. Experiments were conducted for 112 d from 27 June to 16 Oct. 2012.

Outdoor experiment: 3.8-L containers. On 15 May 2012, boxwood liners (Spring Meadow Nursery) were potted into 3.8-L plastic containers (C400, Nursery Supplies Inc.) using the same substrate described for Tennessee. One of two irrigation regimes was assigned to each zone, and a completely

randomized design was used for all experiments. Fifteen plants were placed in the center of each zone. Border plants of the same species were spaced around the perimeter of the containers in the experiment to mitigate edge effects. One week after transplanting, plants were top dressed with 19.0N–2.2P–7.5K 5–6 month controlled-release fertilizer with micronutrients (HFI Topdress Special; Harrell's Inc.) at 11 g per container (medium label rate). Fifteen plants were placed in the center of each zone. Border plants of the same species were spaced around the perimeter of the containers in the experiment to mitigate edge effects. Electrical conductivity (EC) and pH measurements were recorded every other week. Gas exchange and leaf water potential measurements were taken during the following periods: 27 Aug., 30 Aug., and 7 Sept. 2012 using the same sampling criteria described previously for deutzia. Experiments were conducted for 121 d from 21 June to 20 Oct. 2012.

Data collection. Photosynthesis, g_s , transpiration, vapor pressure deficit, and WUE_i (net photosynthesis/transpiration) were obtained using three plants at the center of each zone during the trials using an IR gas analyzer with the extended reach 1-cm² Arabidopsis chamber (LI-6400-15; LI-COR) at 400 ppm CO_2 and light intensity at 2000 $\mu\text{mol} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$. The Arabidopsis chamber was used because it is designed to measure photosynthesis on small leaves and concomitant low leaf area exposed in the chamber. One fully expanded, most recently matured leaf from each of the three plants (subsamples) that contained sensors was selected per irrigation zone for data collection.

These measurements were taken only when the VWC of the OD treatments was within 5% VWC of the lower irrigation set point and when it was between 10:00 AM and 3:00 PM to ensure light conditions supported maximum photosynthetic rates. Petiole water potential (hereafter referred to as leaf water potential for simplicity) of the second fully expanded, most recently matured leaf was measured immediately following photosynthetic measurements on three plants (subsamples) per plot using a pressurized chamber (Soil Moisture Equipment Corp., Santa Barbara, CA). Because the process required destructive harvesting, plants chosen for water potential measurements were rotated to limit the defoliation to which each individual plant was subjected.

Leachate was captured with 25.4-cm drip pans (Curtis Wagner Plastics Corp., Houston, TX) on two plants per irrigation zone. The leachate pans were shielded from the overhead irrigation by an inverted 11.4-L plastic container with the bottom removed (Hagen et al., 2014). EC and pH measurements were taken every other week according to the pour through method (Wright, 1986) carried out 1 h after irrigation for both DWU and OD treatments with a portable meter (HI 9811-5; Hanna Instruments,

Smithfield, RI). Leaching fraction was calculated by the formula (volume of leachate/total irrigation volume) $\times$ 100.

Plant GI of all plants in each zone was determined using the formula [(plant width A + plant width perpendicular to plant width A + plant height)/3]. Plant width was measured at the greatest plant span and a second measurement was taken perpendicular to that line, without altering the natural branch architecture. Plant height was measured from the base of the plant at the substrate surface to the most distal growth without altering the natural arch of the branches.

For dry weight measurements, the above-ground portion of each experiment plant was harvested at ground level and roots were gently hand washed of substrate. Roots and shoots were dried separately in an oven at 55 °C until there was no change in mass (about 3 d). To estimate WUE per plant, the increase in GI over the course of the experiment was divided by total irrigation water volume applied for experiments in 3.8-L containers. WUE was not calculated for the experiments using 11.4-L containers as the initial GI values were not available. Precipitation days were defined as days when at least 7 mm of precipitation was recorded. Rainfall was recorded by weather stations located on site at each of the research facilities.

Data were analyzed separately for each species except for the transpiration data. All data were subjected to an ANOVA and mean separation (Tukey's HSD $\alpha = 0.05$) using the PROC MIXED procedure in SAS® version 9.3 (SAS Institute Inc., Cary, NC). Individual plants were treated as subsamples and irrigation zones as replicates. Gas exchange, nutrient, and pH data were analyzed as repeated measures.

Results and Discussion

Relative water use between species. To establish the relative water use by deutzia and boxwood, transpirational water loss was measured at 0.5 and 1.5 kPa VPD_{air} (Table 1). Both plants lost water at a faster rate at 1.5 kPa than at 0.5 kPa and deutzia showed a higher whole plant transpiration rate compared with boxwood under both VPD conditions (Table 1). WUE_i estimated from simultaneously measured transpiration and photosynthesis when plants were photosynthesizing at 90% of maximum was 45% greater for boxwood compared with deutzia. Higher WUE_i categorizes boxwood as a low-water-use species as observed in water use studies reported in several conifer and hardwood species (DeLucia and Heckathorn, 1989; Ni and Pallardy, 1991). Boxwood also has a periodic growth pattern and typically has one growth flush per growing season, which would also reduce seasonal water use demand compared with deutzia. Deutzia has a pattern of continual growth during the growing season until flowering in late spring and is a relatively low-water-using species (Warsaw et al., 2009) compared with hydrangea.

Fig. 2. Examples of typical volumetric water content measurements from the experiments (A) 'Green Velvet' boxwood and (B) slender deutzia for the two irrigation schedules: on-demand (OD) and daily water use (DWU). Time elapsed between two DWU peaks is 24 h. Peaks are indicative of irrigation events. Horizontal lines indicate upper and lower irrigation set points.

Table 1. Transpiration and instantaneous water use efficiency for boxwood and deutzia in a controlled environment chamber under 0.5- and 1.5-kPa vapor pressure deficit conditions.

Genus	Transpiration (mol H ₂ O/h) ^a		90% of maximum photosynthesis (μ mol CO ₂ /m ² /s)	Transpiration at 90% of maximum photosynthesis (mmol H ₂ O/m ² /s)	Instantaneous water use efficiency ^b (μ mol CO ₂ /mmol H ₂ O)
	0.5 kPa	1.5 kPa			
Boxwood	33.86 b [*]	36.08 b	7.37	2.62	2.77
Deutzia	59.39 a	73.26 a	9.49	4.98	1.91
P value	0.0290	0.0223			

^a1 L of water = 55.5 mol.

^bInstantaneous water use efficiency was calculated as the ratio of 90% of maximum photosynthesis to transpiration measured at the same time using LI-6400.

^{*}Means within the same column followed by the same letter were not significantly different at $\alpha = 0.05$ by Tukey–Kramer honestly significant difference test.

Plant growth and water use. There were no differences in root and shoot biomass or growth due to the irrigation schedule used for either boxwood or deutzia (Table 2). Shoot and root dry matter production and hence total dry matter accumulation was not different between the two treatments for both boxwood and deutzia. Final GI (Table 2) and estimated plant quality for boxwood and deutzia (data not shown) were not different between the two irrigation treatments. Thus, it seems that although OD plants were exposed to short periods of low VWC, the treatment did not reduce overall growth.

Although irrigation scheduling treatments had no impact in either species for plant growth, total water use in boxwood and deutzia was affected by irrigation treatment

and thus influenced WUE (Tables 2 and 3). For boxwood plants, OD irrigation lowered water consumption by 35.5% and improved WUE by 54.5%. Total water use of OD zones in deutzia plants was lowered by 26.5% compared with DWU (Table 3). Both DWU and OD lowered water use by 41% and 68% compared with a traditional timer-based 0.75 inch per day irrigation application in boxwood (data not shown). Deutzia showed similar trends and lowered water use compared with traditional irrigation by 61% and 70%, respectively, for DWU and OD treatments (data not shown). Similar studies conducted using a high-water-demanding plant, hydrangea, in two container sizes in the same locations also generally showed no difference in final GI between the OD and

Table 2. Biomass and growth index for boxwood and deutzia plants grown in an outdoor nursery and irrigated by two different scheduling systems; daily water use (DWU) and on-demand (OD).

Treatment ^z	Shoot dry wt (g)	Root dry wt (g)	Total dry wt (g)	Final growth index (cm)
Boxwood				
DWU	12.1 a ^y	10.1 a	24.3 a	22.6 a
OD	11.9 a	9.3 a	21.7 a	19.4 a
<i>P</i> value	0.9570	0.3213	0.2324	0.1913
Deutzia				
DWU	98.1 a	61.5 a	160.4 a	49.0 a
OD	103.4 a	69.0 a	172.5 a	51.1 a
<i>P</i> value	0.0961	0.1183	0.3904	

^zBoxwood trial was conducted from 21 June to 20 Oct. 2012; deutzia trial was conducted from 27 June to 16 Oct. 2012.

^yMeans within the same column followed by the same letter were not significantly different at $\alpha = 0.05$ by Tukey–Kramer honestly significant difference test.

Table 3. Water use, water use efficiency, and leachate data for boxwood and deutzia plants grown in an outdoor nursery and irrigated by two different scheduling systems; daily water use (DWU) and on-demand (OD).

Treatment ^z	Total irrigation applied per container (L)	Water use efficiency ^y (increase in cm·L ⁻¹)	Total leachate (L)	Leaching fraction ^x (%)	EC (μS·cm ⁻¹)	pH
Boxwood						
DWU	25.1 a ^w	1.1 b	6.3 a	25.2 a	331 a	6.7 a
OD	16.2 b	1.7 a	2.8 b	17.1 b	405 a	6.5 a
<i>P</i> value	0.0310	0.0312	0.0426	0.0327	0.6420	0.4312
Deutzia						
DWU	70.9 a	— ^v	19.9 a	28.1 a	276 a	7.1 a
OD	52.1 a	—	8.9 b	17.2 b	434 a	7.0 a
<i>P</i> value	0.4441		0.0264	0.0091	0.1143	0.3611

^zBoxwood trial was conducted from 21 June to 20 Oct. 2012; deutzia trial was conducted from 27 June to 16 Oct. 2012.

^yWater use efficiency per plant was estimated as the increase in growth index over the course of the experiment divided by total irrigation water volume applied for experiments.

^xLeaching fraction = (volume of leachate/total irrigation volume) × 100.

^wMeans within the same column followed by the same letter were not significantly different at $\alpha = 0.05$ by Tukey–Kramer honestly significant difference test.

^vData not available.

Table 4. Photosynthesis and gas exchange taken just before an irrigation event for boxwood and deutzia plants grown in an outdoor nursery and irrigated by two different scheduling systems; daily water use (DWU) and on-demand (OD).

Treatment ^z	Photosynthesis (μmol CO ₂ /m ² /s)	Transpiration (mmol H ₂ O/m ² /s)	Stomatal conductance (mol H ₂ O/m ² /s)	Leaf petiole water potential (MPa)	Vapor pressure deficit (kPa)
Boxwood					
DWU	7.3 a ^y	2.14 a	0.90 a	−0.283 a	2.03 a
OD	7.6 a	2.03 a	1.06 a	−0.314 a	1.96 a
<i>P</i> value	0.461	0.272	0.23	0.193	0.152
Deutzia					
DWU	8.1 a	4.41 a	0.179 a	−0.385 a	2.49 a
OD	7.9 a	3.92 a	0.177 a	−0.393 a	2.39 a
<i>P</i> value	0.713	0.248	0.932	0.259	0.304

^zBoxwood trial was conducted from 21 June to 20 Oct. 2012; deutzia trial was conducted from 27 June to 16 Oct. 2012.

^yMeans within the same column followed by the same letter were not significantly different at $\alpha = 0.05$ by Tukey–Kramer honestly significant difference test.

DWU irrigation treatments even though there was considerable water savings with OD treatment (Hagen et al., 2014).

Crop growth and quality can be maintained in irrigation scheduling systems that follow moderate deficit irrigation regimes, where irrigation is withheld until substrate water loss meets a managed allowable deficit (MAD) (Welsh and Zajicek, 1993). Beeson (2006) found that 20% MAD based on ET produced acceptable sweet viburnum (*Viburnum odoratissimum*) growth while higher MAD levels lengthened production times by

reducing plant growth rate. It is possible that there is a similar pattern of water use related to crop performance with the OD resembling a moderate MAD treatment considering the longer interval between irrigation events for OD plants compared with DWU plants reaching container capacity on a daily basis. Another consideration explaining lower water use for OD irrigation is that plants were irrigated on average every 3.4 d in boxwood and 1.6 d in deutzia. This contrasts with the daily irrigation event that occurs with DWU. A set point-based irrigation can allow optimization of both

air-filled porosity and water potential of the substrate, maximizing plant growth (Welsh and Zajicek, 1993). Typical examples of the two treatments showing the irrigation frequency are shown in Fig. 2A and B.

An ET-based model for nursery production was successful in conserving water, and the authors partially attributed the water savings to lower irrigation frequency when plants were young (Beeson and Knox, 1991). As overhead irrigation has been reported to have only a 25% to 37% application efficiency, the less frequent irrigation events associated with OD treatments would lead to lower water loss (Beeson, 2006). Overhead irrigation event is inherently inefficient due to nonuniform distribution, lower interception efficiency, and evaporation during application (Beeson, 2006; Hagen et al., 2014). Beeson (2004) also observed low rates of evaporation from substrate surfaces that were irrigated less frequently. Less frequent irrigation also promoted root growth deeper into a container substrate, where larger water storage was available for roots (Spoomer, 1974). A lowered irrigation frequency could also reduce electricity costs, lower disease pressure, reduce runoff to surface water and infiltration to groundwater, reduce use of irrigation equipment, and lower maintenance costs (Beeson, 2006). Based on the absence of negative effects on growth and positive water use and leachate results, the OD system effectively prevented over and under irrigation as well as transient water deficits that occur with traditional temporal-based irrigation (Warren and Bilderback, 2004).

Leachate EC and pH. Although both irrigation scheduling systems differed in total water applied during the growing season, it was apparent that there was also a larger leaching fraction for DWU compared with OD for both species (Table 3). Leaching fraction was almost 47% higher for the DWU treatments in 3.8-L containers and about 63% higher for DWU treatment in 11.4-L containers compared with OD treatment. OD treatments were closer to the recommended leaching fraction, 15%, whereas DWU treatments were more than double the recommendation (Bilderback et al., 2013). The greater leachate volume of DWU treatments in both container sizes, in spite of receiving a smaller volume of water at each irrigation event (640 mL compared with an average of 870 mL), could be attributed to the increased frequency of DWU-based irrigation (Beeson, 2006). OD irrigation regime involved far fewer irrigation events than the DWU regime thus fewer opportunities to leach. Substrate physical properties change as roots fill air voids and substrate components decompose, decreasing the container capacity (Warren and Bilderback, 2005) and causing higher leaching loss. Although both treatments were designed to hydrate substrates to container capacity thereby eliminating leaching, as the substrate's ability to retain water diminished, the OD treatment may have been at an advantage. The OD treatment generally became much drier

Table 5. Calculated irrigation set points [substrate moisture content (VWC)] to maintain photosynthetic rates at 90% or 98% of maximum for various woody ornamental species grown in peat or pine bark-based substrates.

Species	Set point (cm ³ ·cm ⁻³)	% of maximum photosynthesis	Substrate	Reference
<i>Buxus sinica</i> var. <i>insularis</i> × <i>B. sempervirens</i> 'Green Velvet'	0.28	0.90	85 pine bark : 15 peatmoss	Nambuthiri et al. (2015b)
<i>Cercis canadensis</i> 'Appalachian Red'	0.31	0.90	85 pine bark : 15 peatmoss	Nambuthiri et al. (2015a)
<i>Cercis canadensis texensis</i> 'Oklahoma'	0.27	0.90	85 pine bark : 15 peatmoss	Nambuthiri et al. (2015a)
<i>Cercis chinensis</i> 'Don Egolf'	0.38	0.90	85 pine bark : 15 peatmoss	Hagen et al. (2014)
<i>Cornus florida</i>	0.30	0.98	bark-based ²	Fulcher (2010)
<i>Cornus kousa</i> var. <i>chinesis</i>	0.28	0.98	Metro-Mix	Fulcher (2010)
<i>Cornus kousa</i>	0.27	0.98	bark-based	Fulcher (2010)
<i>Deutzia gracilis</i>	0.33	0.90	85 pine bark : 15 peatmoss	Nambuthiri et al. (2015b)
<i>Hibiscus moscheutos</i> 'Pink Elephant'	0.34	0.90	85 pine bark : 15 peatmoss	Hagen et al. (2014)
<i>Hibiscus rosa-sinensis</i> 'Cashmere Wind'	0.30	0.98	Metro-Mix ³	Fulcher et al. (2012)
<i>Hydrangea quercifolia</i> 'Alice'	0.33	0.90	85 pine bark : 15 peatmoss	Hagen et al. (2014)
<i>Viburnum dentatum</i> 'Ralph Senior'	0.35	0.90	85 pine bark : 15 peatmoss	Hagen (2013)

VWC = volumetric water content.

²Bark-based substrate: (Barky Beaver Professional Grow Mix, Barky Beaver Mulch and Soil Mix, Moss, TN).

³Metro-mix: sphagnum peatmoss and bark-based substrate (Metro Mix 280; Sun Gro Horticulture, Bellevue, WA).

between irrigation events than the DWU treatment and therefore may have had a greater ability to retain water as it was applied as long as the substrate did not dry to the point of being hydrophobic, compromising the sensor-based scheduling (Hagen et al., 2015). Also as plants grow, the capacity of container-grown plants to intercept overhead irrigation water increases (Million and Yeager, 2015), thus, plants may have received more water per container later in the experiment than what was originally measured and calculated for the program run time, which would cause leaching.

EC and pH were not different between treatments in any trials (Table 3) and the levels never raised above the recommended range due to periodic irrigation and/or precipitation flushing excess salts from the substrate. At the location of the 11.4-L containers, precipitation occurred on 20 of 112 d (18%) in 2012 amounting to a total of 520 mm. At the location of the 3.8-L containers, precipitation occurred on 33 of 121 d (27%) for a total of 151 mm. Frequent rainfall provided a significant portion of water to nursery plants and enhanced a conservative irrigation regime's ability to reduce water use.

Gas exchange, leaf water potential. Gas exchange was unaffected by irrigation treatment for boxwood or deutzia (Table 4), although VWC became much lower during each irrigation cycle for OD than DWU (Fig. 2). Similarly, there were no differences for leaf water potential or vapor pressure deficit values. Leaf water potential values were at levels that indicated that plants were not under stress as observed in various woody plants (Ni and Pallardy, 1991) and that even though OD plants received less irrigation they were at similar physiological levels compared with DWU plants.

Species-specific set point. The species-specific information necessary to operate the OD system was developed by conducting model development experiments as described by Fulcher et al. (2012). The OD method used SMS to schedule irrigation based on physiological species-specific thresholds for initiating irrigation (Table 5). Conservative OD

irrigation schedules for a number of woody plant species were possible without causing a growth or quality decline (Fulcher et al., 2012; Hagen et al., 2014). The relative similarity of set points in Table 5 suggests that a common range of set points may exist for diverse taxa and a range of commonly used substrates.

Since each overhead irrigation event is generally inefficient (less than 50% of irrigation volume entering the container substrate), the more frequent irrigation events associated with DWU treatments would lead to greater water losses thus increasing the volume of water applied and decreasing WUE.

Conclusions

In these studies, both DWU and OD automated irrigation scheduling regimes dramatically decreased water use over the traditional industry practice of applying ≈19–25 mm per day (Fare et al., 1992; Warsaw et al., 2009). OD treatment reduced total water use, total leachate, and leaching fraction in boxwood and deutzia trials compared with DWU. The current data indicate that OD can be used over a range of plant species with differing water use across different environments and container sizes. Future studies could explore a way to group plants with similar water use by set point without performing the model development experiments to determine the relationship between photosynthesis and container moisture content for each crop. Based on existing data (Fulcher et al., 2012; Fulcher and Geneve 2011; Hagen 2013; Hagen et al., 2014), there could be two or three VWC set points for irrigating woody plants such as 0.33, 0.30, and 0.28 based on maintaining photosynthetic rates at or near 90% of maximum. This research has shown that automated irrigation systems have the potential to accurately measure crop water use without extending production time and that an OD system predicated on the relationship between photosynthesis and VWC shows great water saving potential for outdoor nurseries. Additionally, the fact that the OD treatment lessened water use without

decreasing growth while becoming drier during each irrigation cycle suggests the 90% threshold is conservative, yet robust enough for use in variable outdoor conditions without jeopardizing plant growth and lengthening the production cycle. Although the DWU system did not result in as significant water conservation as the OD system, it does reduce water use substantially and offers a labor scheduling advantage because of the consistent time of day that irrigation operates.

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