Comparison of Water Management in Container-Grown Nursery Crops using Leaching Fraction or Weight-Based On Demand Irrigation Control[1]

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Abstract

Water management should be the foundation of container nursery production as it is linked directly to both water use and nutrient uptake efficiency and ultimately, environmental impact. In this study a gravimetric water management technique was used by means of a load cell/computer interface to determine irrigation volume and time of application. *Cotoneaster dammeri* 'Skogholm' was grown in 14 liter (#5) containers with an 8:1 pine bark:sand mixture. The treatments were: an industry control that was irrigated cyclically at 1200, 1500, and 1800 HR to maintain a 0.2 LF (PM 0.2 LF); and a gravimetric treatment that irrigated when container capacity (CC) dropped below 94% and returned the CC to 98% with percentages lowered over the course of the season, always in a 4% spread, to maintain < 0.15 LF (On Demand). The number of irrigation cycles were similar until the end of the study when On Demand cycled up to seven times a day. PM 0.2 LF had a greater WUE_p (gram of dry weight produced per mL of water retained in the substrate). Time averaged application rate for On Demand was always lower than PM 0.2 LF resulting in a LF of 0.06 compared to 0.14 LF for PM 0.2 LF.

Index words: automated irrigation control, gravimetric moisture content, pine bark, micro-irrigation.

Species used in this study: *Cotoneaster dammeri* C.K. Schneid. 'Skogholm'.

Significance to the Nursery Industry

Irrigating *Cotoneaster dammeri* 'Skogholm' using a gravimetric irrigation technique produced an equivalent plant compared to the cotoneaster produced with a 0.2 leaching fraction applied cyclically at 1200, 1500, and 1800 HR. Concurrently, the gravimetric technique maintained an average leaching fraction of 0.06. This is an improvement over typical cyclic irrigation regimes and these results cannot be obtained by grower-monitoring alone without significant labor cost. The gravimetric technique is ideal because it requires no calibration and no special skills to setup or operate. In addition, it directly measures the quantity of water lost since the last irrigation thus requiring no data interpretation.

Introduction

Water restrictions are becoming more prevalent throughout the horticultural world causing growers to rethink current water management strategies. Soon, to be competitive in their industry, growers will be required to make efficient water management one of the highest priorities in container-grown crop production.

Currently, irrigation of container-grown nursery crops is an inefficient practice (11). Most container nurseries in the southeastern United States maintain ≥ 0.5 leaching fraction [LF = irrigation volume leached (mL) ÷ irrigation volume applied (mL)] (authors' personal observations) resulting in less than 50% of the water applied being used by the plant per irrigation event. As water is a finite resource, every effort should be made to maximize a plant's use of all water applied to a container. Many nurseries have implemented the Best Management Practice (13) of recycling water to increase overall water use efficiency; however, this water is typically pumped and treated, which can be costly. To prevent the detrimental effects limited water can have on plant production, it is important that irrigation monitoring and application techniques improve water use efficiency while continuing to maximize crop growth.

Best Management Practices (BMPs) have been created to give growers guidelines and strategies to minimize and more effectively use vital resources. BMPs include use of controlled release fertilizers (CRFs), retention ponds to recycle irrigation water, soilless substrates with a high water-retaining capacity, and implementation of practices such as cyclic irrigation and reduced LF, which minimize run-off (3, 9).

BMPs for the southeastern United States currently recommend an 80 to 90% water application efficiency {WAE = [(volume applied − volume leached) ÷ volume applied] × 100} to ensure proper rewetting of the substrate, with LF not to exceed 0.25. Unfortunately, for many growers how much water to apply (volume) and when to apply it (timing) are based on work hours and/or irrigation system limitations (pump run time). To apply the proper volume requires weekly or most often, daily monitoring during the growing season. Without proper monitoring it is difficult to know precisely the status of substrate moisture in the container during the day.

New methods of irrigation monitoring and control are introduced to the nursery industry on a regular basis, but

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few are adopted due to unreliable accuracy, required training for use, difficulty of use, and complexity of data interpretation. The most recently reported methods use tensiometry and time domain reflectometry (TDR) to monitor substrate water levels. However, there are numerous problems with these systems including calibration required for each substrate, limited operating range, response lag time, continuous maintenance, and the fact that tensiometers or sensors must maintain good contact with the substrate. These methods overlook the 'age-old' method of gravimetric determination. The simplest way to determine water loss is to weigh the container [container, substrate, and plant = container mass (CM)], where 1 g of weight is equivalent to 1 ml of water. The difference in weight from CM determines the milliliters (fl oz) of water needed to return the container to 100% CM.

The gravimetric technique has the potential to be extremely grower friendly. It requires no calibration and no special skills to set up or operate following initial program installation. Once the system can be commercially developed, ease of use will increase over time. In addition, the system directly measures the quantity of water loss since the last irrigation thus requiring no data interpretation. Knowing this information the grower can determine how much and when to irrigate to replace the available water needed to minimize diurnal plant stress. In this experiment load cells were used to weigh containers and add back precise volumes of water. The objective of this research was to compare a traditional schedule of irrigation, in which volume applied was determined using LF, to an automated gravitational method of irrigation control.

Materials and Methods

There were two treatments: an 8:1 pine bark:sand ratio (by vol) substrate irrigated at 1200, 1500, and 1800 HR to maintain a 0.2 LF (served as the industry control and hereafter referred to as PM 0.2 LF), and the same pine bark:sand substrate irrigated to return the substrate to 98% CM (method described below) when the water content reached 94% of CM as determined by weight regardless of time (hereafter referred to as On Demand). As newly planted cuttings require frequent irrigation to ensure survival, the upper and lower CM limits in the On Demand treatment were initially set at these high values. These irrigation parameters could maintain adequate water in the upper portion of the substrate for the small root systems while maintaining a minimum LF. As plants grew and evapotranspiration increased the upper and lower CM limits were decreased, always maintaining a 4% spread. Seventy-nine days after planting (DAP), the 98 to 94% CM was reduced to 96 to 92% CM, and at 99 DAP this was reduced to 94 to 90% CM. These parameters were chosen based on the results of an earlier study (8). Further research would need to be conducted to determine the correct parameters for different taxa with varying water needs.

This experiment was conducted on a gravel pad at the Horticulture Field Lab (lat. 35°47'37"N, long. –78°41'59"W), North Carolina State University, Raleigh, in a randomized complete block design with four blocks and seven containers per replication. Uniform rooted stem cuttings of *Cotoneaster dammeri* C.K. Schneid. 'Skogholm' were potted on April 19, 2007, into black plastic 14 liter (#5) containers (C-2000, Nursery Supplies Inc., Chambersburg, PA). The substrate consisted of a coarse builder's sand and local North Carolina pine bark (Pacific Mulch, Henderson, NC) with a bulk density of 533.42 $kg \cdot m^{-3}$ (33.3 $lbs \cdot ft^{-3}$), 77% total porosity, 48% container capacity, 29% air space, 27% unavailable water, and 21% available water (5).

The substrate was amended with dolomitic limestone and a micronutrient fertilizer (Micromax, Scotts Company, Marysville, OH) at a rate of 1.8 $kg \cdot m^{-3}$ (0.11 $lb \cdot ft^{-3}$). After planting, containers were topdressed with CRF according to the label of 71.2 g (2.5 oz) 16N-2.6P-9.0K (16-6-11 six-month CRF, Harrell's, Lakeland, FL).

Each gravel-covered plot [8 × 1 m (26.3 × 3.3 ft)] was underlain with corrugated plastic at a 2% slope to direct all leachate from each plot to a 19 liter (5.0 gal) collection vessel. Volumes from irrigation water applied via pressure compensated spray stakes [Acu-Spray Stick; Wade Mfg. Co., Fresno, CA, 200 $mL \cdot min^{-1}$ (6.8 fl $oz \cdot min^{-1}$)] were measured as the volume collected in a 4 liter (1.0 gal) vessel from a spray stake in each plot. Volumes of irrigation water applied (influent) and leached (effluent) for each plot were measured daily, and from these measurements LFs were calculated. Influent volumes were adjusted daily to maintain the 0.2 LF for each plot in the PM 0.2 LF treatment. Data were compiled to determine cumulative influent volume per container and cumulative effluent volume per container. Cumulative water volume retained per container was calculated as the sum of the daily difference between influent and effluent volumes per container. Effluent volumes were measured following rain events with < 0.64 cm (0.25 in) measurable precipitation; however, data collected on these days were not used in the cumulative influent and effluent calculations. From influent and effluent data, water use efficiency of productivity (WUE_p = total irrigation volume retained in substrate via applied water ÷ total plant dry weight) and time averaged application rate (TAAR = water applied day ÷ application duration time) were calculated.

Within each treatment and block, one plant was positioned on a load cell (total of 16). Real time monitoring of container weight (plant + substrate + container) was performed using a low profile, two-beam single aluminum (Al) point load cell with a 30 kg (66.1 lb) capacity (± 0.02% error) (Model RL 1042, Tedea-Huntleigh Inc, Covina, CA). The load cell was mounted between two 15 × 15 cm, (5.9 × 5.9 in) 0.6 cm (0.24 in) thick square Al plates. One 0.6 cm (0.24 in) thick Al spacer was attached between the top and bottom plates and the load cell to keep debris out. The top surface area was expanded with a 23 × 23 cm (9.1 × 9.1 in) square, 3 mm (0.12 in) thick Al plate (Fig. 1). The load cells were connected to a CR3000 Micrologger® via an AM32 multiplexer (2). Weight was recorded every 15 minutes, and every 10 seconds when the irrigation was running using a custom program (Greg Kraus, technical consultant) deployed at the initiation of the experiment. Container mass was determined by saturating the containers approximately every 3 weeks. Saturation was achieved by placing the container from the load cell into a 20 liter (5 gal) bucket which was filled with water at approximately 1800 HR. When the substrate was fully saturated, after approximately 2 hr (as evidenced by a glossy sheen of water at the substrate surface), the containers were placed on the load cells and allowed to drain until 0000 HR (12 am) the following morning. At 0000 HR the computer recorded weights for each of the 16 containers, and this was assumed to be equivalent to CM.

Substrate temperatures were measured at two locations in one container in every replication (total of 8 thermocouples

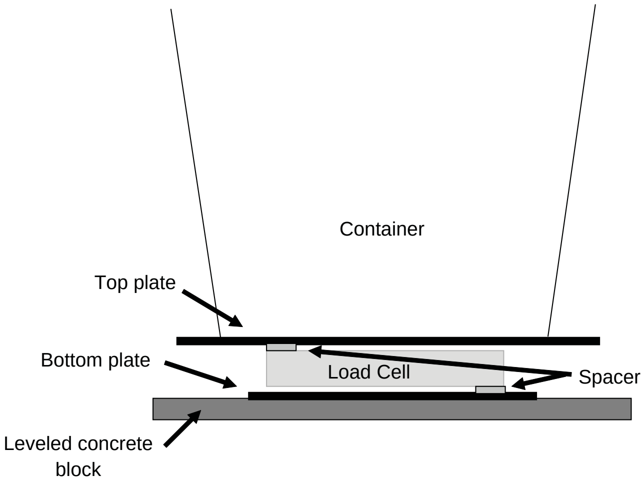

Fig. 1. Load Cell Configuration.

per treatment) for the entire study to determine if irrigation method affected substrate temperature. The copper-constantan thermocouples were positioned in the substrate ≈ 8 cm (3.2 in) down the container profile 2.5 cm (1 in) from the container wall on the southern and northern exposure in each container. Thermocouples were connected to the CR3000 micrologger® via an AM32 multiplexer (2). Temperature was recorded every 5 min and averaged over each 60-min interval. Maximum, minimum, and average temperature along with time of maximum and time of minimum were recorded every 60 min.

Electrical conductivity (EC) and pH of the substrate solution were measured every 3 weeks after treatment initiation via the pour-through nutrient extraction procedure (12). Net photosynthesis (P_n) and stomatal conductance (g_s) were measured on July 24, 2007. One plant from each of the replications was measured between 1030 and 1130 HR. The measurements were taken using a portable photosynthesis system containing a LI-6400 open, portable gas exchange system with a LI-6400-05 conifer chamber (LI-COR, Lincoln, NE). Measurements were conducted on the intact terminal 5 cm (2 in) of stem with approximately 5 fully expanded leaves [5.55 cm^2 ± 0.29 SE (2.2 in^2)] under natural light in which photosynthetic active radiation remained > 1600 $\mu mol \cdot mol^{-1}$. These data were used to calculate water use efficiency of photosynthesis (WUE_{Pn} = CO_2 assimilation ÷ stomatal conductance).

The experiment was initiated on June 7, 2007, and terminated after 95 days. At termination, shoots (aerial tissue including stem and leaves) were removed from two plants from each plot (total of 8 containers per treatment). Roots were placed over a screen and washed with a high pressure water stream to remove substrate. Shoots and roots were dried at 65C (149F) until reaching a stable weight and weighed. Total plant dry weight = shoot dry weight + root dry weight. Root:shoot ratio (RT:S) = root dry weight ÷ top dry weight.

After drying, the tops and roots were first ground using a Model 4 bench, 1 HP Wiley Mill® (Thomas Scientific, Swedesboro, NJ), to pass ≤ 6 mm (0.24 in) screen and then through a Foss Tecator Cyclotec 1093 sample mill (Analytical Instruments, LLC, Golden Valley, MN) to pass a ≤ 0.5 mm (0.02 in) screen. Roots and tops were analyzed for nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), sulfur (S), iron (Fe), manganese (Mn), zinc (Zn), copper (Cu), boron (B), molybdenum (Mo), and sodium (Na) by the North Carolina Department of Agriculture, Agronomic Division. Total N concentrations were determined by oxygen combustion with an elemental analyzer (NA 1500; CE Elantech Instruments, Milan, Italy) (2). Phosphorus, K, Ca, Mg, S, Fe, Mn, Zn, Cu, B, and Na concentrations were determined by EPA Method 200.7 with an ICP spectrophotometer (Optima 3300 DV ICP Emission Spectrometer; Perkin Elmer Corporation, Wellesley, MA), following open-vessel HNO_3 digestion in a microwave digestion system (CEM Corp., Matthews, NC) (4).

Statistical analysis. All variables were analyzed using analysis of variance (ANOVA) Proc GLM in SAS version 9.01 (SAS Inst. Inc., Cary, NC). Treatment comparisons were made by F test, $P \leq 0.05$.

Results and Discussion

Plant response. Shoot dry weight, root dry weight, total dry weight, and RT:S ratio were unaffected by the treatments (Table 1). This is in contrast to an earlier study where Skogholm cotoneaster grown with On Demand irrigation had a significantly larger top and total dry weight than PM 0.2 LF (8). The summer of 2008, during which this experiment took place, was uncharacteristically hot and dry for North Carolina, and it can be speculated that no matter how much water was applied, all plants in the study were under an atypically high amount of stress during this period.

Water use. Total irrigation volume applied per container over the life of the study was not significantly affected by the treatments (Table 2). However, when examined as daily water volume (weight gained) per container in early, midway and late in the season, the treatments significantly affected daily irrigation volume (Table 3). Early in the study (June), when evapotranspiration was the lowest, On Demand applied a daily average of 0.5 liter (0.14 gal) per container, whereas PM 0.2 LF required 0.9 liters (0.25 gal), or 42% more water. This demonstrates the power of gravimetric-based irrigation applications in contrast to a fixed LF in which superfluous water was applied. As the plants grew and temperature increased which increased evapotranspiration, On Demand increased to an average daily application of 2.1 liters (0.55

Table 1. Effect of irrigation treatments on plant dry weight (g) and root:shoot ratio.

Treatment	Shoot dry weight	Root dry weight	Total dry weight	Root:shoot ratio[z]
	(g)			
PM 0.2 LF	96.7 ± 3.8[y]	11.7 ± 0.8	108.4 ± 4.4	0.12 ± 0.01
On Demand	90.5 ± 7.9	10.2 ± 0.9	100.7 ± 8.7	0.11 ± 0.01
Significance	0.684[w]	0.426	0.650	0.437

[z]Root:shoot ratio = root dry weight ÷ shoot dry weight.
[y]Each mean ± standard error is based on four observations.
[w]*P*-value.

Table 2. Effect of irrigation treatments on total water volume applied, leaching fraction, and irrigation water use efficiency of productivity (WUE_p).

Treatment	Total volume applied (liters)	Leaching fraction[z]	WUE_p[y] ($mL \cdot g^{-1}$)
PM 0.2 LF	74.1 ± 1.6[x]	0.14 ± 0.02	577.0 ± 1.5
On Demand	77.3 ± 1.1	0.06 ± 0.01	715.6 ± 2.8
Significance	0.772[w]	0.010	0.004

[z]Leaching fraction = water leached (liters) ÷ water applied (liters).

[y]WUE_p = total irrigation volume retained in substrate (mL) ÷ total plant dry weight (g).

[x]Each mean ± standard error is based on four observations.

[w]*P*-value.

gal) in mid-season (July), an increase of 74% compared to only a 39%, 1.5 liter (0.4 gal) increase for 0.2 LF. By late season (August) both irrigation treatments were applying similar daily irrigation volumes, with On Demand applying just 20% more water than 0.2 LF.

The number of cycles per day between treatments were remarkably similar early and midway during the study, whereas later in the study when evapotranspiration was at a maximum, On Demand irrigated seven or more times a day to remain within the given upper and lower CM limits. As the number of cycles increased throughout the study, the first irrigation event in the On Demand treatment was initiated earlier in the day. Early in the Season (June) the first irrigation event was initiated on average at 1155 HR for On Demand compared to the fixed 1200 HR for PM 0.2 LF. Midway in the study the first irrigation event started around 0953 HR and by late in the study was at 0738 HR for On Demand. In contrast, the last irrigation event was similar for On Demand and PM 0.2 LF midway (1804 HR versus 1800 HR) and late in the study (1909 HR versus 1800 HR). The combination of these events (total run time, number of cycles, total weight gain per day) also decreased the average TAAR throughout the study for On Demand versus PM 0.2 LF. In early, mid-, and late season TAAR was significantly less for On Demand compared to PM 0.2 LF (a smaller TAAR is more desirable).

Leaching fraction was significantly affected by treatments, with On Demand averaging 0.06 and PM 0.2 LF averaging 0.14 for the entire study (Table 2). This shows that equivalent growth can be produced with significantly reduced LF compared to the recommended 0.2 LF. However, it would be very difficult for a grower to maintain this very low LF without some form of real-time substrate moisture monitoring equipment.

Water application efficiency averaged 94% for On Demand versus 85% for PM 0.2 LF. This very high level of WAE probably resulted from the decreased TAAR produced by On Demand compared to PM 0.2 LF (Table 3). According to Lamack and Niemiera (6), low TAAR is highly correlated with high WAE. Warren and Bilderback (11) stated that low TAAR values and resulting high WAE should be a target of every irrigation operator. Therefore On Demand irrigation is a further improvement on the cyclic method of irrigation application.

Interestingly, the previously discussed results produced significantly different WUE_p (Table 2). On Demand required 139 more mL (0.04 gal) of water to produce one g of dry mass, which is 19% more than PM 0.2 LF. By maintaining what would appear to be a more consistent substrate water environment, evapotranspiration increased without increasing plant biomass. This was surprising, and is in conflict with results by Prehn et al., 2008. It can be speculated that an uncharacteristically hot and dry summer in Raleigh, NC, during the summer of 2007 may have contributed to these results (7).

Photosynthesis and stomatal conductance. Even though WUE was significantly affected by the treatments, P_n, g_s and WUE_{Pn}, were unaffected (Table 4). To find no differences when P_n and g_s are measured on individual leaves is not un-

Table 3. Average values for start time, stop time, run time, number of cycles, weight gain of container mass, and TAAR of two irrigation treatments.

Treatment	Start time (HR)	Stop time (HR)	Total run time (min)	Number of cycles	Weight gain per cycle (mL)	Weight gain per day (mL)	TAAR[z] ($mL \cdot min^{-1}$)
				Early season (June)			
PM 0.2 LF	1200[y]	1800	360	3.0	311	922	2.7a[x]
On Demand	1155	1652	296	2.0	271	544	1.6b
				Midseason (July)			
PM 0.2 LF	1200[y]	1800	360	3.0	504	1510	4.1a
On Demand	0953	1804	613	3.5	315	2081	2.2b
				Late season (August)			
PM 0.2 LF	1200[y]	1800	360	3.0	670	2009	5.4a
On Demand	0738	1909	811	7.5	308	2278	3.3b

[z]Time averaged application rate = water applied daily (mL) ÷ total run time (min).

[y]Dictated by treatment selection.

[x]Means within a column and season not followed by the same letter are significantly different as determined by F test, $P \leq 0.05$.

Table 4. Effect of irrigation treatment on net photosynthesis (P_n), stomatal conductance (g_s) and water use efficiency of photosynthesis (WUE $_{Pn}$) of *Cotoneaster dammeri* 'Skogholm' at 1000 HR 47 days after initiation.

Treatment	P_n ($\mu mol \cdot m^{-2} \cdot s^{-1}$)	g_s ($\mu mol \cdot m^{-2} \cdot s^{-1}$)	WUE_{Pn} [z] (mmol $H_20 \cdot \mu mol\ CO_2^{-1}$)
PM 0.2 LF	15.1 ± 0.52[y]	0.22 ± 0.01	0.01 ± 0.000
On Demand	17.0 ± 1.54	0.25 ± 0.05	0.02 ± 0.003
Significance	0.318[x]	0.351	0.134

[z]$WUE_{pn} = g_s \div P_n$

[y]Each mean ± standard error is based on four observations on four separate plants.

[x]*P*-value.

Table 5. Effect of irrigation treatments on substrate pH and electrical conductivity (EC) at 13, 29, 48, and 64 days after treatment initiation (DAI).

Treatment	DAI 13	DAI 29	DAI 48	DAI 64
	pH			
PM 0.2 LF	6.0 ± 0.10[z]	6.3 ± 0.09	5.9 ± 0.10	6.3 ± 0.12
On Demand	6.1 ± 0.15	6.1 ± 0.10	5.9 ± 0.10	6.1 ± 0.21
Significance	0.715[y]	0.236	0.715	0.383
	EC ($mS \cdot cm^{-1}$)			
PM 0.2 LF	0.50a ± 0.02	0.39a ± 0.09	0.38b ± 0.04	0.34a ± 0.01
On Demand	0.54a ± 0.07	0.57a ± 0.09	0.49a ± 0.03	0.47a ± 0.07
Significance	0.542	0.086	0.025	0.111

[z]Each mean ± standard error is based on four observations of four different plants.

[y]*P*-value.

usual (10) and the quantitative larger values for On Demand found in Table 4 may have resulted in higher water losses when expressed on a whole plant basis.

EC and pH. Electrical conductivity was higher in every instance in the On Demand treatment but was only significantly greater than PM 0.2 LF at 48 DAI (Table 5). This may have been due to the decreased LF allowing more salts to remain in the substrate. There were no significant differences or trends in substrate for irrigation treatments, but pH values were within the range considered acceptable (13).

Nutrients. There were no significant differences among macronutrient concentrations in the roots of either of the treatments (Table 6). There were, however, significant differences between P and K macronutrient concentrations in

Table 6. Effect of irrigation treatments on root and shoot nutrient concentration.

Treatment	N	P	K	Ca	Mg	S
	($mg \cdot g^{-1}$)					
Root						
PM 0.2 LF	23.6 ± 0.09[z]	1.9 ± 0.002	10.3 ± 0.03	5.3 ± 0.02	2.6 ± 0.01	2.2 ± 0.02
On Demand	23.3 ± 0.16	2.2 ± 0.02	10.4 ± 0.06	5.7 ± 0.05	2.6 ± 0.02	1.8 ± 0.03
Significance	0.901[y]	0.284	0.890	0.527	0.842	0.376
Shoot						
PM 0.2 LF	14.8 ± 0.26	1.4 ± 0.01	4.5 ± 0.03	2.3 ± 0.02	1.5 ± 0.02	2.1 ± 0.04
On Demand	14.0 ± 0.22	1.9 ± 0.02	5.7 ± 0.03	2.7 ± 0.04	1.6 ± 0.01	2.1 ± 0.04
Significance	0.832	0.048	0.034	0.492	0.677	0.914

[z]Each mean ± standard error is based on four observations.

[y]*P*-value.

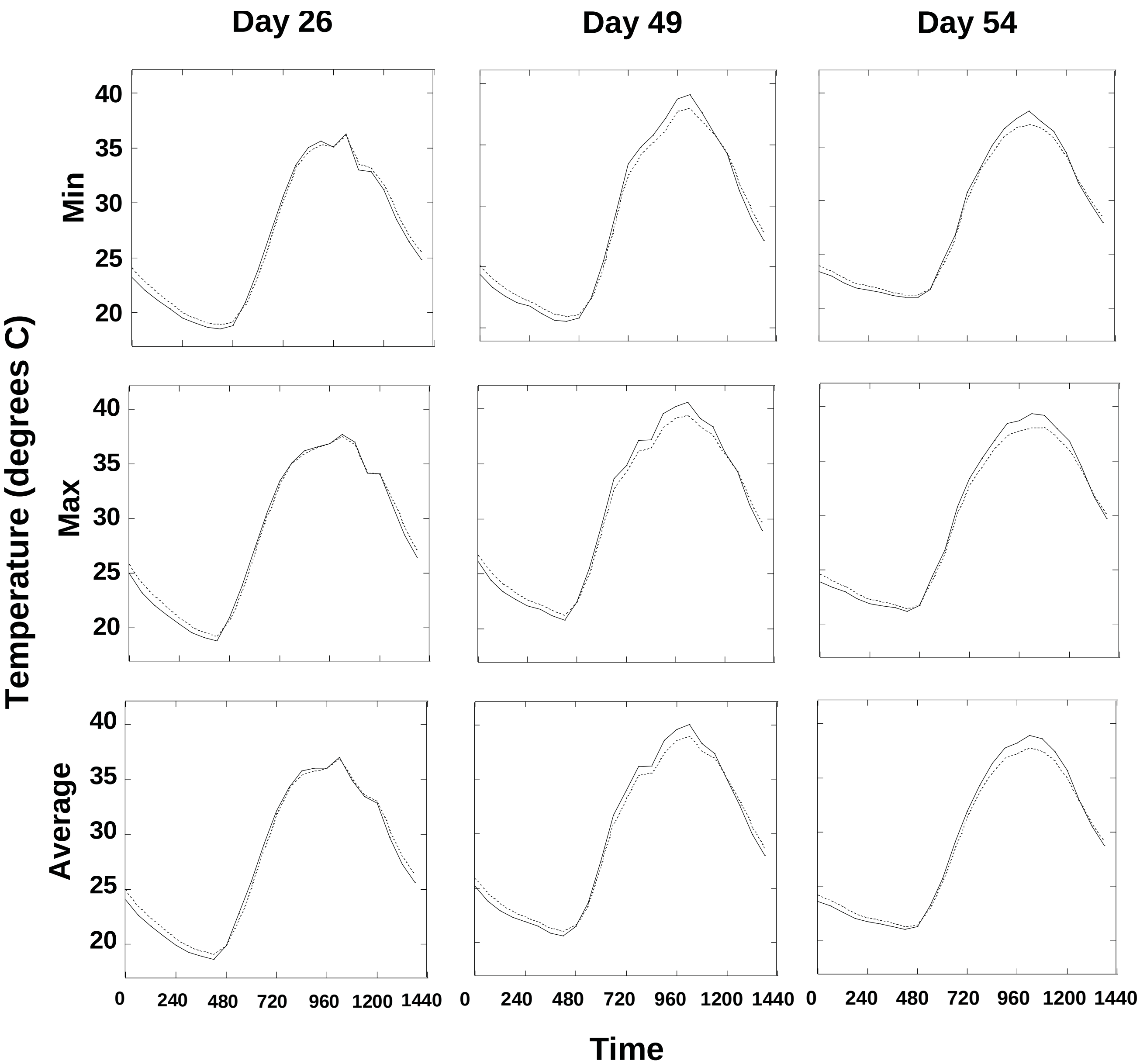

Fig. 2. **Substrate temperature on selected days (26, 49, 54 DAI) for Skogholm cotoneaster irrigated at 1200, 1500, and 1800 HR to maintain 0.2 leaching fraction (———) or irrigated on demand regardless of time to maintain weight between set upper and lower container capacity parameters (········).**

plant shoots. There was less P and K in the plant tissue of PM 0.2 LF (by 26 and 21%, respectively) than On Demand. Phosphorous and K leach readily from containerized plants (1) and so the reduced LF for On Demand (Table 6) may have produced these results. In this case, with an average LF of only 0.06, On Demand was able to retain more P and K in the substrate and these nutrients may therefore have been more available for uptake by the plants. Nitrogen is also readily leached; however, there was no difference in plant top concentration of nitrogen. None of the other shoot mineral nutrient concentrations differed between treatments (Table 6).

Substrate temperature. Substrate temperatures between the two treatments differed during some parts of the day over the entire experiment (Fig. 2). At 49 DAI, maximum temperature was greater for On Demand between 0300 and 0700 HR. This is when the last irrigation event for both treatments started at about the same time, so it is difficult to explain why PM 0.2 LF was cooler during the early morning hours, except that the last irrigation event the day before may have been longer for the PM 0.2 LF as run-time was based on time rather than weight. The average temperatures were significantly different from 0500 to 0700 HR, when PM 0.2 LF was cooler, and 1000 to 1200 HR, when On Demand was cooler. On day 54 the maximum (1100 HR) temperatures were significantly greater for PM 0.2 LF (Fig. 2). Thus, it appears that On Demand did maintain lower substrate temperatures throughout the day. This decreased substrate temperature is believed to be a result of the increased number of irrigation cycles and the increased total run time. Even though the decreased substrate temperature did not result in increased growth of Skogholm cotoneaster there may be more heat-sensitive species that would respond positively to the decreased substrate temperature.

On Demand gravitational irrigation can reduce the average season-long LF to less than 0.1. Dry weight between On Demand and traditional PM irrigation did not result in different-sized plants, contrary to the findings in Prehn et al. (8), where On Demand irrigation grew a much larger plant. Time-averaged application rate was better (less) for On Demand irrigation at all points in the season, and also kept the substrate temperature cooler for the entire study. Data herein indicate the On Demand method of irrigation has great potential as a commercial method to monitor and control irrigation application of containerized nursery crops.

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