HortScience 53(8):1197–1202. 2018. https://doi.org/10.21273/HORTSCI13030-18

Integrating Moisture Characteristic Curves with Gravimetric Data in the Management of Substrate Moisture Content for Annual Vinca

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Additional index words. volumetric water content, gravimetric water content, *Catharanthus roseus* irrigation, matric potential

Abstract. **Greenhouse growers must use water more efficiently. One way to achieve this goal is to monitor substrate moisture content to decrease leaching. A systems approach to irrigation management would include knowledge of substrate matric potentials and air-filled pore space (AS) in addition to substrate moisture content. To study the relationship between substrate moisture and plant growth, annual vinca (*Catharanthus roseus* L.) was subject to a 2 × 2 factorial combination of two irrigation treatments and two substrates with differing moisture characteristic curves (MCCs). A gravimetric on-demand irrigation system was used to return substrate moisture content to matric potentials of −2 or −10 kPa at each irrigation via injected drippers inserted into each container. Moisture characteristic curves were used to determine gravimetric water content (GWC), volumetric water content (VWC), and AS at target substrate matric potential values for a potting mix consisting of sphagnum moss and perlite and a potting mix consisting of sphagnum moss, pine bark, perlite, and vermiculite. At each irrigation event, irrigation automatically shut off when the substrate-specific weight of the potted plants associated with the target matric potential was reached. Irrigation was triggered when the associated weight for a given treatment dropped 10% from the target weight. VWC and AS differed between substrates at similar matric potential values. Irrigating substrates to −2 kPa increased the irrigation volume applied, evapotranspiration, plant size, leaf area, shoot and root dry weight, and flower number per plant relative to irrigating to −10 kPa. Fafard 3B had less AS than Sunshine LB2 at target matric potential values. Plants grown in Fafard 3B had greater leaf area, shoot dry weight, and root dry weight. Leachate fraction ranged from 0.05 to 0.08 and was similar across all treatment combinations. Using data from an MCC in conjunction with gravimetric monitoring of the container–substrate–plant system allowed AS to be determined in real time based on the current weight of the substrate. Closely managing substrate matric potential and AS in addition to substrate water content can reduce irrigation and leachate volume while maintaining plant quality and reducing the environmental impacts of greenhouse crop production.**

Nutrient leaching and runoff due to excessive irrigation have detrimental environmental impacts, and emerging regulations require growers to minimize these impacts (Beeson et al., 2004; Majsztrik et al., 2011). Because of limited container size, greenhouse crops must be irrigated frequently. Therefore, greenhouse production managers face the challenge of irrigating frequently and efficiently while applying adequate water to maintain optimum crop growth.

Automated on-demand irrigation systems that apply irrigation based on water use have been used successfully to provide adequate irrigation to bedding plants and nursery crops with little to no leachate in research trials (Burnett and van Iersel, 2008; Chappell et al., 2013; Lea-Cox et al., 2017). Such on-demand systems can use container weight or capacitance sensor readings to estimate substrate water content (Nemali and van Iersel, 2006; Owen et al., 2008; Sammons and Struve, 2008). Many studies have been conducted that evaluate effects of substrate VWC on growth of bedding plants (Alem et al., 2015; Burnett and van Iersel, 2008; van Iersel et al., 2010; Zhen and Burnett, 2015; Zhen et al., 2014). However, substrate physical properties such as AS and matric potential at any given VWC are dependent on the substrate. To better understand plant responses to irrigation management, the effects of matric potential and AS in addition to VWC should be determined. A MCC can be used to determine substrate matric potential and AS at a given VWC or GWC (Raviv and Lieth, 2008). The objective of this experiment was to determine the effects of two substrates and two substrate matric potential ranges on annual vinca growth, applied irrigation, leachate volume, and plant water use.

Materials and Methods

Forty-eight 12.7-cm-diameter plastic containers (Dillen Products, Inc., Middlefield, OH) were filled with a uniform weight of either Sunshine LB2 (Sunshine; Sun Gro Horticulture Canada Ltd., Vancouver, British Columbia, Canada) or Fafard 3B (Fafard; Conrad Fafard Inc., Agawam, MA) commercial potting mixes. Sunshine was composed of Canadian sphagnum moss and coarse perlite and was amended with dolomitic limestone and gypsum. Fafard was composed of Canadian sphagnum moss (50% by volume), pine bark, perlite, and vermiculite and was amended with dolomitic limestone. Other than the peatmoss in Fafard, the ratios of components in both substrates are proprietary information. Both substrates contained proprietary wetting agents, but neither substrate was amended with starter nutrients. Sunshine had a standard bulk density from the factory of 112–160 $kg \cdot m^{-3}$, whereas Fafard had a standard bulk density from the factory of 176–224 $kg \cdot m^{-3}$.

Substrate samples taken during container filling were used to determine an estimate of substrate dry weight in each container so that GWC could be tracked using gravimetric

data. On 7 Mar. 2012, finished seedlings of *C. roseus* (L.) 'Cora Lavender' (Green Circle Growers, Oberlin, OH) were transplanted one per container from 288-cell plug flats and hand-watered. The plants were placed in a glass roof greenhouse at the Columbus campus of the Ohio State University with a high temperature set point of 32 °C and a low temperature set point of 13 °C. After transplanting, containers were watered to the container capacity with 1200 ppm SOAX wetting agent (Smithers-Oasis Company, Kent, OH). Two days after transplanting, the containers were top-dressed with 2 g of a 15N–3.9P–10K controlled release fertilizer of 3- to 4-month longevity at 21 °C (Osmocote Plus 15–9–12; The Scotts Company LLC, Marysville, OH). The containers were drenched with 3336F (thiophanate-methyl; Cleary Chemicals Corp., Dayton, NJ) at a concentration of 7.8 $mL \cdot L^{-1}$ on 13 Mar. The plants were watered uniformly as needed until 16 Mar., 9 d after transplanting, when containers were placed in tubs filled with water to substrate level and allowed to saturate for 6 h. The substrate was then allowed to drain overnight. Before sunrise on 17 Mar., four containers were placed within a tray on each one of 12 DigiTOL 8213-0025 digital bench scales (Mettler-Toledo, LLC, Columbus, OH). The trays were elevated on one end so that leachate would drain through the holes in the trays into a collection pan next to the balance. Balances were tared with a tray and four empty containers beforehand so that only the weight of the substrate and seedling were represented by gravimetric data. Each balance with a tray of four plants represented a plot in the experiment. The balances were connected to a personal laptop computer, via RS-232 cables, running Microsoft Windows XP Professional operating system and Microsoft Office Excel 2007 (version 12.0; Microsoft Corp., Redmond, WA). The computer was also connected to three solid-state relay modules each with five optically isolated solid-state relay switches (Weeder Technologies, Fort Walton Beach, FL). Each solid-state relay switch supplied 5 VDC power to a PC relay switch (Model QUA-SS-105D; TE Connectivity Ltd., Berwyn, PA) when closed. Each PC relay switch supplied 24 VDC to a normally closed 2.5-cm solenoid valve (Model 100DV; Rain Bird Corporation, Azusa, CA) when actuated. Each solenoid valve supplied irrigation water to four plants on a designated balance when activated via a 3.8-$L \cdot h^{-1}$ pressure-compensated Xeri-Bug emitter (XB-10PC; Rain Bird Corp., Glendora, CA), split four ways by a 4-way manifold (Netafim USA, Fresno, CA) and four microirrigation tubes. A 2.3-$L \cdot h^{-1}$ arrow angle injected dripper (Netafim USA) was fitted at the end of each microirrigation tube and inserted into each container. A macro written in Visual Basic for Applications retrieved and logged the weight reading of each balance every 15 min. If the weight readout of an individual balance was below a user-defined lower set point, then the solenoid valve supplying irrigation to the plants on that balance was opened. Once irrigation was turned on, the macro retrieved and logged the weight readout of the balance every 5 s until a user-defined upper weight set point was reached that triggered the solenoid valve to turn off. The macro additionally logged the date and time of each weight retrieval in a Microsoft Excel spreadsheet.

MCCs were developed for each substrate using the Modified Long Columns (MLC) method (Altland et al., 2010). The method was replicated four times for each substrate; however, one replication of Fafard 3B was unusable because of air pockets that developed in the column. Curve fitting was performed using SigmaPlot 13.0 (Systat Software, Inc., San Jose, CA). To test for differences between the MCCs of each substrate, data from each replication column were individually fit to a four-parameter log-logistic function. Two-sample *t* tests were used to determine differences between the two substrates for each of the parameters using PROC TTEST in SAS version 9.4 (SAS Institute, Cary, NC) at $\alpha = 0.05$. Total pore space was also compared using two-sample *t* tests. In addition, prediction curves were fit for each substrate (one curve for each substrate) along with the associated 95% confidence bounds using PROC NLIN in SAS.

The relationship between GWC and matric potential tensions was also fit to a four-parameter log-logistic function using SigmaPlot. The function was used to estimate GWC at matric potential tensions of –2 kPa (irrigation termination of wet treatment) and –10 kPa (irrigation termination of dry treatment). The irrigation system was programmed to end an irrigation event at the substrate weight associated with these tensions. The weight reading at which irrigation was started was set to 10% below the weight reading of irrigation termination for each replication. GWC and VWC data from the MLC method were subjected to regression analysis. Over the range of values tested, response was linear. The function was used to estimate VWC using the substrate weight.

The experiment was ended on 7 May (51 d after irrigation treatment initiation). Cumulative irrigation volume retained per plant by the substrate over the course of the experiment was calculated using SAS version 9.2 (SAS Institute Inc., Cary, NC) as the sum of all the differences in plot weight before and after each irrigation event and averaged over the four plants within each plot. Leachate accumulation from each plot was collected and measured in a graduated cylinder every 1–2 d and totaled for the experiment. Individual leachate volume per plant was estimated by dividing plot leachate volume by four (four plants per plot). Cumulative irrigation volume applied per plant over the course of the experiment was calculated by adding irrigation volume retained per plant and irrigation volume leached per plant. Leachate fraction was calculated by dividing cumulative irrigation volume leached by cumulative irrigation volume applied. Plant water use per plant was calculated using SAS version 9.2 using gravimetric data to daily water use per plot for the duration of irrigation treatments and dividing by four. The equation used to calculate daily water use for a plot was as follows: {[(g plot weight at end of irrigation event – g plot weight at beginning of irrigation event) × (number of

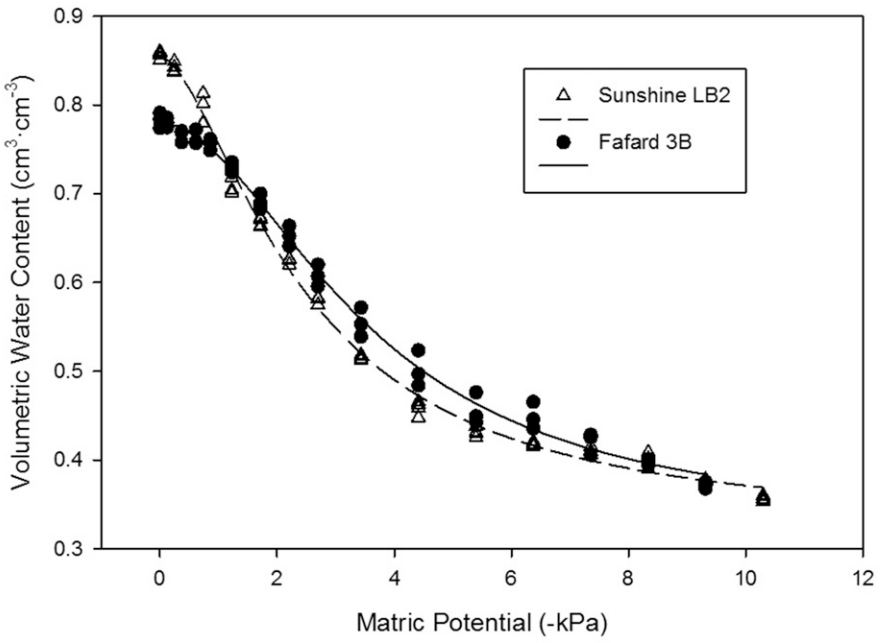

Fig. 1. Moisture characteristic curves of Sunshine LB2 and Fafard 3B generated by the modified long column method (Altland et al., 2010). Data were fit to a log-logistic four-parameter function $[F(x) = y_0 + a/(1 + |(x/x_0)|^b]$ with $R^2 = 0.996$ for Sunshine LB2 and $R^2 = 0.994$ for Fafard 3B.

Received for publication 1 Mar. 2018. Accepted for publication 11 June 2018.

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irrigation events)] – [g plot weight at beginning of day – g plot weight at end of day]}. This equation takes into account changes in plant weight as the plants grew.

At termination, all plants were irrigated to container capacity, and substrate pH and electrical conductivity (EC) were determined using the Virginia Tech Extraction Method (Wright, 1986). Size index [(height + width + width)/3] and flower numbers were recorded for all plants. Leaf area was measured on two randomly selected plants per replication. Leaf greenness was measured on each plant using a SPAD-501 portable leaf greenness meter (Minolta Corp., Ramsey, NJ). Three SPAD measurements of randomly selected mature leaves and three nodes from the shoot tip were averaged for each plant. Shoots of all plants were harvested. Roots of three randomly selected plants per plot were harvested and washed free of substrate. Shoots and roots were dried in a forced-air oven at 55 °C until a constant weight was reached. Whole plant water use efficiency (WUE), shoot WUE, and root WUE were calculated for all 48 plants by dividing the corresponding plant dry weight by the average milliliters of plant water use per plant (milliliters of plant water use per plot divided by four plants per plot).

An analysis of variance was performed on all responses using PROC GLIMMIX in SAS version 9.4 (SAS Institute). The experimental design was a generalized randomized complete block design for all responses except water retained per plant, leachate per plant, water applied per plant, water use per plant, leachate fraction, and irrigation event number. The design for these responses was a randomized complete block design. All designs had three blocks. The treatment design was a two-way factorial of substrate and irrigation. The Gaussian probability distribution was used with all responses, except flower, branch, and irrigation event numbers, and chlorosis rating. Where residual plots and a significant covariance test for homogeneity indicated heterogeneous variance among treatments, a RANDOM statement with the GROUP option was used to correct heterogeneity. Differences between main effects means and differences between interaction simple effects means were determined using F tests. The generalized Poisson probability distribution was used for flower numbers, branch numbers, and irrigation event numbers. Differences between interaction simple effects means for flower counts were determined using the simulated method. The multinomial probability distribution was used for chlorosis rating. Presented are treatment medians for chlorosis rating. Differences between irrigations were determined using the main effect F test. All significances were at $\alpha = 0.05$.

Results and Discussion

The four-parameter log-logistic function used to create MCCs fit data with R^2 values of 0.996 for Sunshine and 0.994 for Fafard (Fig. 1). *t* tests determined that the fitted x_0 parameter significantly differed between substrates (Pr < 0.026). The fitted four-parameter log-logistic curves and their 95% confidence bounds are plotted in Fig. 2. The confidence bounds rarely overlap, suggesting that the substrate MCCs are significantly different from one another.

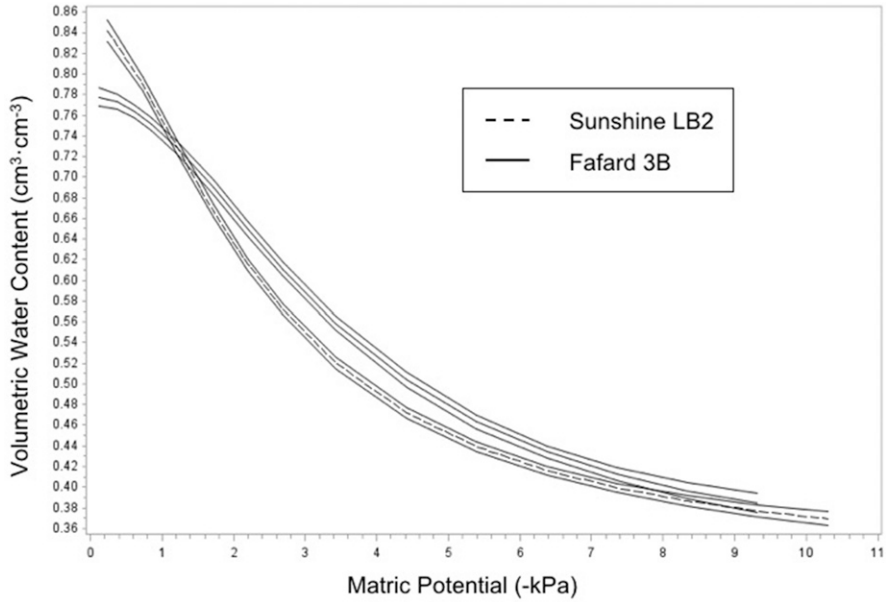

Fig. 2. Moisture characteristic curves for Sunshine LB2 and Fafard 3B with fitted prediction curves and associated 95% confidence bounds.

Table 1. Estimated substrate properties at upper and lower irrigation set points for *Catharanthus roseus* L. 'Cora Lavender' growing in 13-cm pots from 17 Mar. to 6 May.

Treatments		Irrigation	Substrate matric		VWC	Air-filled pore
Substrate	Irrigation[z]	set points[y]	potential (–kPa)	GWC (%)[x]	($cm^3 \cdot cm^{-3}$)[w]	space (%)
Fafard 3B	Wet	Upper	2.0	85	0.66	12
		Lower	3.1	83	0.59	20
	Dry	Upper	10.0	77	0.35	43
		Lower	21.5	75	0.23	55
Sunshine LB2	Wet	Upper	2.0	85	0.66	19
		Lower	2.8	83	0.59	27
	Dry	Upper	10.0	77	0.37	49
		Lower	28.0	74	0.29	56

[z]Irrigation treatments were applied to a substrate water tension of –2 kPa (wet treatment) or –10 kPa (dry treatment) at each irrigation event.
[y]The points at which irrigation was started (lower) and ended (upper).
[x]Gravimetric water content (GWC) expressed as percentage of substrate mass attributed to water.
[w]Volumetric water content (VWC) expressed as fraction of substrate volume attributed to water.

Table 2. Main effects of irrigation treatments on irrigation volume applied, leached, and retained and number of irrigation events for *Catharanthus roseus* (L.) 'Cora Lavender' growing in 13-cm pots from 17 Mar. 2012 to 6 May 2012.

	Irrigation (mL)			
Treatment[z]	Applied[y]	Leached[x]	Retained[w]	Irrigation events
Dry	2633 b[v]	145 NS	2488 b	73 b
Wet	4181 a	274 NS	3907 a	90 a
Main effects		Significance (Pr > F)		
Substrate	0.1525	0.6054	0.0702	0.8798
Irrigation	0.0004	0.1800	0.0003	0.0137
Substrate × Irrigation	0.8596	0.7326	0.9580	0.2941

[z]Irrigation treatments were maintained at water tension ranges of 2.0–2.8 kPa or 10.0–28.0 kPa (wet and dry treatments, respectively) for Sunshine LB2 and 2.0–3.1 kPa or 10.0–21.5 kPa (wet and dry treatments, respectively) for Fafard 3B.
[y]Total irrigation volume applied in mL per plant.
[x]Total irrigation volume leached in mL per plant.
[w]Total applied irrigation volume not leached in mL per plant.
[v]Least squares means comparisons between irrigation treatments using the main effect F test at $P < 0.05$.
NS = not significant.

The four-parameter log-logistic function used to estimate GWC at a given matric potential fit data with R^2 values of 0.995 for Sunshine and 0.993 for Fafard.

Based on MCCs, substrate total porosity was 85.5% for Sunshine and 78.3% for Fafard and differed between substrates. Less total porosity was expected in the Fafard

Table 3. Main effects of substrate and irrigation treatments on water use per plant for *Catharanthus roseus* (L.) 'Cora Lavender' growing in 13-cm pots from 17 Mar. 2012 to 6 May 2012.

Substrate	Water use (mL)	Irrigation[z]	Water use (mL)
Fafard 3B	3078 b[y]	Dry	2298 b
Sunshine LB2	2666 a	Wet	3446 a
Main Effects	Significance (Pr > F)		
Substrate	0.0428		
Irrigation	0.0002		
Substrate × Irrigation	0.9896		

[z]Irrigation treatments were maintained at water tension ranges of 2.0–2.8 kPa or 10.0–28.0 kPa (wet and dry treatments, respectively) for Sunshine LB2 and 2.0–3.1 kPa or 10.0–21.5 kPa (wet and dry treatments, respectively) for Fafard 3B.
[y]Least squares means comparisons between irrigation treatments using the main effect F test at $P < 0.05$.

Table 4. Effects of substrate and irrigation treatment interaction on size index of *Catharanthus roseus* (L.) 'Cora Lavender' growing in 13-cm pots from 17 Mar. 2012 to 6 May 2012.[z]

	Irrigation[y]	
Substrate	Dry	Wet
Fafard 3B	21.3 a NS[x]	22.2 b NS
Sunshine LB2	18.2 b B	24.7 a A
Main Effects	Significance (Pr > F)	
Substrate	0.6317	
Irrigation	<0.0001	
Substrate × Irrigation	<0.0001	

[z]The substrate by irrigation interaction was significant at $P < 0.0001$.
[y]Irrigation treatments were maintained at water tension ranges of 2.0–2.8 kPa or 10.0–28.0 kPa (wet and dry treatments, respectively) for Sunshine LB2 and 2.0–3.1 kPa or 10.0–21.5 kPa (wet and dry treatments, respectively) for Fafard 3B.
[x]Least squares means comparisons between substrates (lower case in columns) and between irrigations (upper case in rows) using the F tests at $P < 0.05$.
NS = not significant.

because it had a higher listed bulk density by the manufacturer. According to the MCCs, the GWC at substrate matric potential values of –2 and –10 kPa were 85% and 77%, respectively, for both substrates (Table 1). The estimated VWC at a GWC of 85% was estimated to be 0.66 $cm^3 \cdot cm^{-3}$ for both substrates. The estimated VWC at a GWC of 77% was estimated to be 0.35 $cm^3 \cdot cm^{-3}$ for Fafard and 0.37 $cm^3 \cdot cm^{-3}$ for Sunshine. Because the irrigation initiation set point was set 10% lower than the substrate weight reading at irrigation termination, the substrate matric potential values at irrigation initiation varied by substrate. In Fafard, irrigation initiated at GWC measurements of 83% (wet treatment) and 74% (dry treatment) which correlated with matric potential measurements of –3.1 and –21.5 kPa, respectively. In Sunshine, irrigation initiated at GWC measurements of 83% (wet treatment) and 74% (dry treatment) which correlated with matric potential measurements of –2.8 and –28 kPa, respectively. Because the method used to create the MCC for each substrate only measured substrate tensions up to 10 kPa, the estimated substrate matric potential measurements for the dry treatments are projected tensions. Air-filled pore space was determined by subtracting VWC from total pore space. Air-filled pore space in Fafard was maintained between 12% and 20% in the wet treatment and between 43% and 55% in the dry treatment, whereas AS of Sunshine was maintained between 19% and 27% in the wet treatment and between 49% and 56% in the dry treatment.

Substrate had no effect on the irrigation volume applied, leached, or retained, or the number of irrigation events (Table 2). However, irrigation volumes applied and retained were affected by irrigation treatments. Irrigation volume applied per plant was 59% higher in the wet treatment than the dry treatment. Irrigation retained per plant was 57% higher in the wet treatment than the dry treatment. Although leachate volume in the wet treatment was 89% higher than that in the dry treatment, differences in leachate volume per plant between dry and wet treatments were not significant. The reason leachate volumes were statistically similar between irrigation treatments is probably because of variability in the leachate data. Because leachate volume per plot was low, small differences in the data created high variability. Hoskins et al. (2014) demonstrated that water moves more quickly through a dry pine bark: sand substrate than a saturated one because of high pore water velocity in the macropores of the substrate. As a result, water channels through a dry pine bark:sand substrate more quickly than a wet one. However, the fact that the increase in leachate volume in the wet treatment compared with the dry treatment (89%) was actually greater than the increase in irrigation volume applied (59%) or retained (57%) in this experiment indicates that water channeling did not occur in the dry substrates. This may be due to the smaller pore sizes found in peat-based substrates compared with pine bark–based substrates. The wet treatment also had a 23% increase in the number of irrigation events during the 51 d of irrigation treatments compared with the dry treatment. Leachate fraction was unaffected by substrate or irrigation treatments and ranged from 0.05 to 0.08.

Plant water use was affected by irrigation treatments and substrate treatments as main effects. Maintaining substrate moisture at or close to –2 kPa in the wet treatment increased plant water use by 50% when compared with the dry treatment (Table 3). Growing annual vinca in Fafard resulted in a 15.4% increase in plant water use compared with Sunshine. Greater water use among plants grown in Fafard is likely due to differences in plant growth between substrates.

Plant size index was affected by the interaction of substrate and irrigation treatments. Among plants grown in Fafard, irrigation treatment had no effect on plant size, whereas among plants grown in Sunshine, plants in the wet irrigation treatment were 36% larger than plants grown in the dry treatment (Table 4). Furthermore, annual vinca grown under the dry treatment in Fafard were 17% larger than those grown in Sunshine, and those grown under the wet treatment in Sunshine were 11% larger than those grown in Fafard. Although annual vinca grown in Fafard under the dry treatment were larger than those grown in Sunshine, those grown in Sunshine under the wet treatment were 11% larger than those grown in Fafard under the wet treatment. Under the wet treatment, airspace might have been ideal for plants growing in Sunshine. Airspace in Fafard ranged between 12% and 20% under the wet treatment, whereas airspace in Sunshine ranged between 19% and 27%. The recommended airspace range for greenhouse crop substrates after watering is 10% to 20% (Nelson, 1998). Annual vinca require high-porosity during production (Thomas et al., 2012), so an airspace volume of 12% after watering is low.

Plant dry weight and leaf area were affected by substrate and irrigation treatments as main effects. Growing plants in Fafard resulted in heavier plant dry weight and more leaf area compared with plants grown in Sunshine (Table 5). Annual vinca grown in Fafard had 19.6% greater shoot dry weight, 31.9% greater root dry weight, 21.4% greater whole plant dry weight, and 19% greater leaf area that those grown in Sunshine. As stated, water use per plant was 15.4% higher among plants grown in Fafard. The reasons for these differences are unclear. Fafard contained vermiculite which has a high cation exchange capacity (Raviv and Lieth, 2008). Higher nutrient availability in Fafard may account for growth differences. Differences in substrate matric potential between substrates in the dry irrigation treatment may also explain differences in plant dry weight and water uptake because substrate matric potential reached –28.0 kPa in Sunshine and –21.5 kPa in Fafard.

Annual vinca grown under the dry treatment had a 27% lower shoot dry weight, 14% lower root dry weight, 28% lower whole plant dry weight, and 29% lower leaf area than those under the wet treatment (Table 6). These results are similar to those in which plant biomass and leaf area decreased proportionally with decreasing substrate water content (Burnett and van Iersel, 2008; Khalil et al., 2008; Kim and van Iersel, 2009; van Iersel and Nemali, 2004; Zhen and Burnett, 2015). Annual vinca grown under the dry treatment also had a 21% higher root:shoot ratio than those grown under the wet treatment. It is generally understood that water deficits typically promote greater allocation of photosynthate to root growth (Kozlowski and Pallardy, 2002).

Plant WUE was unaffected by treatments. Annual vinca is a drought-tolerant species. Annual vinca dry weight and leaf area were

Table 5. Main effects of substrate and irrigation treatments on shoot, root, and whole plant dry weight, root-to-shoot ratio, and leaf area of *Catharanthus roseus* L. 'Cora Lavender' grown in 13-cm pots from 17 Mar. 2012 to 6 May 2012.

Main effects of substrate					
Substrate	Shoot dry wt (g)	Root dry wt (g)	Whole plant dry wt (g)	Root:shoot ratio	Leaf area (cm^2)
Fafard 3B	5.99 a[z]	0.95 a	6.78 a	0.15 NS	650.4 a
Sunshine LB2	5.01 b	0.72 b	5.50 b	0.16 NS	546.6 b
Main effects of irrigation treatments					
Irrigation[y]	Shoot dry wt (g)	Root dry wt (g)	Whole plant dry wt (g)	Root:shoot ratio	Leaf area (cm^2)
Dry	4.63 b	0.77 b	5.22 b	0.17 a	496.8 b
Wet	6.38 a	0.91 a	7.27 a	0.14 b	700.2 a
Main Effects			Significance (Pr > F)		
Substrate	0.0007	0.0008	0.0043	0.1538	0.0482
Irrigation	<0.0001	0.0391	<0.0001	0.0133	0.0006
Substrate × Irrigation	0.3171	0.7711	0.5001	0.2231	0.8274

[z]Least squares means comparisons between irrigation treatments using the main effect F test at $P < 0.05$.
[y]Irrigation treatments were maintained at water tension ranges of –2.0 to –2.8 kPa or –10.0 to –28.0 kPa (wet and dry treatments, respectively) for Sunshine LB2 and –2.0 to –3.1 kPa or –10.0 to –21.5 kPa (wet and dry treatments, respectively) for Fafard 3B.
NS = not significant.

Table 6. Effect of substrate and irrigation treatment interaction on number of flowers per plant of *Catharanthus roseus* (L.) 'Cora Lavender' grown in 13-cm pots from 17 Mar. 2012 to 6 May 2012.

	Irrigation[z]	
Substrate	Dry	Wet
Fafard 3B	17 a NS[y]	20 ns NS
Sunshine LB2	11 b B	21 ns A
Main effects	Significance (Pr > F)	
Substrate		0.0580
Irrigation		0.0001
Substrate × Irrigation		0.0114

[z]Irrigation treatments were maintained at water tension ranges of 2.0–2.8 kPa or 10.0–28.0 kPa (wet and dry treatments, respectively) for Sunshine LB2 and 2.0–3.1 kPa or 10.0–21.5 kPa (wet and dry treatments, respectively) for Fafard 3B.
[y]Least squares means comparisons between substrates (lower case in columns) and between irrigations (upper case in rows) using the F tests at $P < 0.05$.
NS = not significant.

similar between control and drought treatments in a study by Niu et al. (2006).

Flower number per plant at treatment termination was affected by the interaction of irrigation and substrate treatments. Annual vinca grown in Sunshine in the wet irrigation treatment had more flowers than those grown under the dry irrigation treatment. These results are consistent with previous research in which petunia, impatiens, and zonal geranium had fewer flowers in drier substrates (Blanusa et al., 2009; Sánchez-Blanco et al., 2009). As with size index, irrigation treatment had no effect on flower number of annual vinca grown in Fafard. However, plants grown in Fafard under the dry treatment had 55% more flowers than those grown in Sunshine under the dry treatment. The fact that irrigation treatment affected flower number of plants grown in Sunshine but not in Fafard provides further evidence that airspace, matric potential, or both limited growth in plants grown in Sunshine under the dry treatment.

Substrate pH at experiment termination was affected by substrate but not by irrigation treatments. Substrate pH averaged 5.9 in Fafard and 6.5 in Sunshine. The recommended pH for during annual vinca production is 5.5–6.3 (Hamrick, 2003). Ca, P, Fe, Mn, and Zn nutrient solubility is highly pH dependent (Raviv and Lieth, 2008). Differences in the availability of these nutrients may be partly responsible for the effects of substrate on plant growth discussed earlier. EC was unaffected by treatments and averaged 1.07 $mS \cdot cm^{-1}$. The recommended EC for annual vinca during production is 1.0 $mS \cdot cm^{-1}$ (Hamrick, 2003).

Conclusion

Although many studies have explored the effect of substrate VWC on plant growth, differences in plant response have usually been attributed to treatment differences in substrate water content. The results of our study demonstrate that differences in airspace between substrate mixes affect plant response even when VWC between the substrate mixes is similar and that airspace could be controlled in real time through irrigation management. Although VWC was very similar between the two substrates used in our study, differences in plant size, plant dry weight, and flower number occurred depending on substrate.

A limitation in this study was the absence of a measurement of substrate properties in the container at the end of the study to determine how those properties changed over time. Porosity of soilless substrates typically decreases over time because of settling and segregation of particles (Bures et al., 1993). However, Allaire-Leung et al. (1999) demonstrated that gas relative diffusivity remained unchanged in five substrate mixes containing various ratios of mostly peat, composted bark, or both for over a year when used in a 5-L container, whereas growing *Prunus ×cisterna* (Hansen) Koehne despite decreases in total porosity and air-filled porosity over time. In addition, more information on nutrient availability throughout the study may further explain differences in growth responses between substrates. As noted, substrate nutrient retention likely differed between substrates because of the differences in components. Substrate EC was measured only at the end of the study as irrigating substrates to container capacity to collect adequate leachate would have had a deleterious effect on irrigation treatments. However, nutrient analysis of leaf tissue and of leachate samples collected at termination would help determine if nutrient availability confounded the study.

Although the relationship between VWC and matric potential has been well documented in previous studies, our study demonstrates how MCCs can be used to better understand the effects of matric potential and airspace on crop growth. In practical application, MCCs of substrates can be used to estimate AS and matric potential in real time so that these properties can be managed during production as easily as water content. The use of sensors to measure VWC in real time is becoming more common (Lea-Cox et al., 2017). Information from MCCs could be used to estimate AS in real time. Although growers may not have the means to produce MCCs, commercial potting mix manufacturers could provide MCC information for specific mixes to growers.

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