Water and Nutrient Uptake and Use Efficiency with Partial Saturation Ebb and Flow Watering

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Abstract. Subirrigation for production of potted ornamental plants reduces the waste of water and fertilizer inherent to conventional overhead watering systems used in greenhouses. Ebb and flow watering systems for flooded floors typically operate slowly so that the substrate takes up water to near effective water-holding capacity during each irrigation event. We used a system that rapidly delivered water to and removed water from the production surface to restrict the water provided to the plants. We examined several parameters that vary between this fast-cycle ebb and flow watering on a flooded floor compared with slow-cycle watering. Water and fertilizer use was reduced by 20% to 30% with fast- compared with slow-cycle watering. Biomass and stem height at bloom were also reduced by 10% to 20% under fast-cycle saturation. This watering method did not affect the rate of flower development or plant nutrient composition. Volumetric water content of the substrate was the only measure that was affected by location on the flooded floor. Despite the fast ebb and flow on pitched floors, none of the aspects of plant growth was affected by location on the floor. This method of watering shows promise as a means to produce uniform crops of container-grown plants while conserving water and fertilizer.

Conventional overhead watering uses excess water to ensure complete coverage of the entire crop to the point of effective saturation of the root medium or substrate. Under certain conditions, up to 75% of the water and fertilizer applied by overhead irrigation may be wasted or leached from potted plants (Yelanich and Beirbaum, 1994). Even with drippers that deliver water only to the substrate, overwatering by 10% to 30% is recommended to prevent salt buildup (Argo and Beirbaum, 1995; Mastalerz, 1977). The runoff of water, fertilizer, and pesticides resulting from these irrigation methods is a potential risk to the quality of the environment in proximity to a greenhouse operation.

Subirrigation, and in particular ebb and flow, systems are more efficient than overhead watering (Dole et al., 1994; Morvant et al., 2001) and also more efficient in terms of nutrient use (Haley and Reed, 2004; Purvis et al., 2000; Zheng et al., 2004). The benefits of ebb and flow, as it is currently applied, is

that no water is lost to the environment and very little is lost to evaporation. In ebb and flow systems, the bench or floor holding potted plants is flooded to a depth of 2 to 10 cm. Capillary action in the substrate takes up water or nutrient solution through the base of the pots (Nelson, 1998). Then the solution is drained from the bench or floor to a reservoir. In most commercial ebb and flow systems, the duration of watering is relatively long, 20 to 30 min, and the substrate may take up water to 90% or more of effective water-holding capacity. It should be noted that subirrigation results in a lower effective water-holding capacity than when pots are watered from overhead (Elliot, 1992) as a result of the limitation of capillary action compared with percolation for watering the medium. Geremia Greenhouse (Wallingford, CT), in collaboration with True Leaf (Petaluma, CA), developed a method for rapid ebb and flow watering for production of potted ornamental plants that can complete an ebb and flow cycle in as short as 4 min. This short cycle restricts water uptake. From here on we refer to this short cycle irrigation process as the partial saturation ebb and flow watering (PSEFW).

There are numerous benefits that could derive from PSEFW. Water stress may be used to control plant growth and quality. A constant low volumetric water content can control both biomass and height growth of ornamental plants (Burnett et al., 2005; Van Iersel et al., 2004), although the extent of restriction of height, rather than biomass, growth depends

on plant species. If the substrate is only partially saturated, the oxygen content is higher than with full saturation, which can benefit the metabolic activity of roots (Nemati et al., 2002). Partial saturation may alter the microenvironment in which both beneficial and disease-causing microbes grow. In contrast to PSEFW, pots watered to their effective water-holding capacity tend to leak some of the water back out onto the floor. Pathogens can spread from pot to pot through the irrigation water (George et al., 1990; Hong and Moorman, 2005; Stanghellini et al., 2000).

There are some other characteristics of ebb and flow irrigation systems that could cause problems. Because there is no leaching of the medium with subirrigation, nutrients tend to accumulate. In particular, a vertical gradient of nutrients develops in the substrate with a high electrical conductivity (EC) in the upper-most layer, which may affect the distribution of roots (Morvant et al., 2001). This can inhibit growth of plants unless the fertilizer supply is adjusted to maintain EC in the medium within a target range (Kang and van Iersel, 2009). A dryer substrate would also exacerbate any deleterious effect of high EC on plant growth as a result of an excessive fertilizer supply.

To determine the benefits and drawbacks to partial saturation ebb and flow watering, we compared PSEFW with a control treatment of slow-cycle ebb and flow watering applied to grow geranium and chrysanthemum in pots on a flooded floor. We measured water uptake per irrigation cycle and water and nutrient content of the root medium after repeated irrigation cycles. We also measured the vertical gradient and distribution of water and nutrients in the substrate. We determined biomass and height growth and tissue nutrient composition as a function of watering treatment and location of pots across a flooded floor.

Materials and Methods

Substrate composition and volume. Ten-, 15-, and 20-cm pots were used in this study. The 10-cm pots had upper and lower widths of 8.5 and 7.0 cm and were filled to a height of 7.5 cm for a total volume of 0.42 L. The 15-cm pots had upper and lower diameters of 13.0 and 10.5 cm and were filled to a height of 8.5 cm for a total volume of 0.88 L. The 20-cm pots had upper and lower diameters of 17.5 and 16.0 cm and were filled to a height of 9.5 cm for a total volume of 2.1 L. The peat-lite substrate used in all experiments was TG1 (Lafaille and Beaver Peat Co., Quebec, Canada). This mix was 83% peat (30%, 20%, and 40% coarse, medium, and fine fibers and 10% other) and 17% perlite by volume supplemented with 7.5 kg·m⁻² limestone and a complete starter fertilizer with EC of 1.3 dS·m⁻¹ measured in a saturated extract. Dry density was 76 g·L⁻¹ with a water retention capacity of 10.2 times dry weight. The effective maximum water-holding capacity with subirrigation was 68% of medium volume.

Ebb and flow benches. Benches were used as independent irrigation units to examine the

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relation between duration of contact of water in the range from 2 to 20 min and uptake of water into dry medium in pots. The benches had a plastic liner with a furrowed surface. Each bench was 2.5×2.9 m (7-m^2 area) and could be filled to ≈ 5 cm above the bottom of the pots. There were separate water delivery and return points. The benches drained continually both while water was supplied and after the supply was shut off. The time for water to clear the benches after the supply cutoff was about the same as the duration of supply. Water uptake into the substrate was measured in separate experiments with 10- and 15-cm pots filled with dry medium without plants. The pots covered the benches uniformly at alternate spacing (half maximum density). Water content was determined for 16 pots uniformly distributed across each bench by weighing each pot before and after watering. Water uptake was expressed as volumetric water content (VWC) using the following equation:

$$\text{VWC} = \frac{(\text{Pot and medium wt after watering} - \text{Pot and medium dry wt})}{\text{Total volume (g equiv of water)}}$$

Ebb and flow floors. Crops of potted plants were grown on flooded floors. A (9×18 m) single-truss greenhouse covered with a double layer of polyethylene film covered two separate but similar flooded floors. Each floor was 5.5×6.7 m in area with a smooth concrete surface. The floors were carefully prepared with a uniform slope from a high elevation at opposite sides to low elevation running parallel to these sides. The difference between low and high elevations was ≈ 2 cm. There were 16 5-cm diameter ports, or holes that penetrated the concrete, spaced at 38-cm intervals in a line across the lowest elevation. High-capacity pumps supplied water from a reservoir to these ports through a manifold under each floor. The floors were drained to a sump through the same ports. Drainage was by gravity with a drop of ≈ 0.6 m. The content of each sump was pumped through a debris filter and back to the reservoir for each floor. The fastest practical cycle for uniform watering of all pots was 2 min to flood the floor with water immediately followed by 2 min to drain the water off the floor. It took 1 min from the start of flooding to completely wet all areas of the floor. The pump continued to supply water for 3 min, by which time the depth of water was 4 to 6 cm.

For the control or slow-cycle irrigation, the water was held on the floor for 10 to 15 min followed by 3 min to drain the floor. For the PSEFW or fast-cycle irrigation, water was held on the floor for 3 to 5 min before a valve released water to the sump. All except a surface coating of water drained in 2 min. All unused solution was completely recycled in these closed watering systems. A flow meter measured the volume of water required to return each reservoir to a set volume as determined by a float switch. This was recorded as total volume of water taken up in the watering

cycle. The initial nutrient solution in each reservoir was a 1:1 mix of calcium nitrate and magnesium sulfate, both added at $0.6 \text{ g}\cdot\text{L}^{-1}$. The solution used to fill each reservoir up to volume after each watering cycle was a complete soluble fertilizer, 21N–2.2P–16.6K, at a concentration of $1.2 \text{ g}\cdot\text{L}^{-1}$.

These experiments were run with simultaneous watering of the control and PSEFW treatments. The VWC that triggered an irrigation cycle was ≈ 0.1 , because that was the content when leaves started to flag. The pots were never watered by overhead watering with the rare exception of some chrysanthemum plants that served as non-data guard rows around the perimeter of each floor and wilted before any interior plants.

Environment. The environmental control set points for the flooded floor greenhouse were 17°C for heating and 25°C for ventilation. Daily maximum temperatures varied between 20 and 34°C . From 6 May to 6 June 2007, during growth of geranium, mean air temperatures were $24.5/19.1^\circ\text{C}$ day/night; mean soil temperatures were $26.3/21.4^\circ\text{C}$ day/night. Mean irradiance was $28 \text{ mol}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$ photosynthetically active radiation (PAR). From 20 Aug. to 20 Sept. during growth of chrysanthemum, mean air temperatures were $24.5/20.2^\circ\text{C}$ day/night; mean soil temperatures were $24.6/22.9^\circ\text{C}$ day/night. Mean irradiance was $21 \text{ mol}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$ PAR.

Plant material. The experiments were conducted on zonal geranium (*Pelargonium xhortorum* L. H. Bailey) grown in 15-cm pots. ‘Allure Red Passion’ (Ball Seed Company) was the cultivar grown in 2007. A total of 750 plants was placed on each floor on 9 May 2007 at 20 plants/ m^2 . Flower buds started to open by 22 May, and 100% of the plants were in full bloom by 13 June. On 15 June, plants were harvested for analysis. The PSEFW regime supplied water for 3 min, and this was drained from the floor in the next 2 min. The control floor supplied water for 10 min and required 3 min to drain. In 2008, geranium cultivar Allure Hot Coral was placed on the flooded floors on 7 Mar. Twelve Echo-EC5 moisture sensors (Decagon Devices, Pullman, WA) were calibrated in fresh substrate. Six sensors were placed in pots on each floor; two each near the edge, midway between the edge and the center, and near the centerline of each floor. This crop was grown until it was in full flower and harvested for analysis on 4 June 2008. The floor watered with PSEFW had a 4-min supply and 2-min drain cycle. The floor for control watering had a 12-min supply and 3-min drain cycle. The plants were never watered by overhead irrigation during the experiments nor were growth regulators or supplemental fertilizer applied by watering or spraying.

In summer and early fall of 2007 and 2008, crops of chrysanthemum (*Chrysanthemum morifolium* L.) were grown as three rooted cuttings per 20-cm pot. All cultivars were from Syngenta Flowers (Boulder, CO). The midseason cultivar Donna and the late-season cultivar Nancy were grown in 2007. On 22 Aug. 2007, when leaves started to

overlap the sides of the pot, a total of 450 plants was placed on each floor at 12 plants/ m^2 . The cultivars were divided with ‘Nancy’ on the east and ‘Donna’ on the west of each floor. Flowers were in a tight-bud stage by 20 Sept. and began to open on 24 Sept. 2007. Plants were harvested for analysis on 10 Oct. 2007. All plants of ‘Donna’ had reached the initial bloom stage by this date, whereas only 50% of ‘Nancy’ was at initial bloom. For each irrigation event in 2007, water remained on the PSEFW floor for 6 min and on the control floor for 15 min. The cultivars Beth and Hannah were grown in 2008. The plants were set in 16×15 staggered rows on each floor at 10 plants/ m^2 . By 25 July, the cuttings were 10 cm tall and covered the surface of the pots. The final harvest of ‘Hannah’ was on 24 Sept. 2008. On 1 Oct. 2008, ‘Beth’ was harvested using the same procedure. In 2008, the duration of watering was increased to achieve $\approx 0.45 \text{ L}\cdot\text{L}^{-1}$ VWC after a PSEFW watering cycle. Water remained on the PSEFW floor for 7 min and on the control floor for 17 min.

Uptake and distribution of water and nutrients. A similar experimental design was used to determine uniformity of water uptake for each crop. A set of 18 labeled pots with plants was used to gravimetrically determine medium water content and uptake for each watering cycle on each floor. These pots were placed near the edge, midway between the edge and center, or near the centerline and otherwise representative of all positions on each floor. They were completely surrounded by other plants. Each labeled pot was weighed before and after irrigation.

When the crop was considered salable, each labeled plant was measured and the root medium was collected. The average height from the soil surface to the flower base was measured as well as the diameter of the crown. The shoots were broken off at the soil surface and weighed. The shoots were dried at 75°C for 3 d and reweighed to determine dry weight and dry matter fraction. Plant material was ground and subsampled to determine elemental composition. Substrate in the labeled pots was stored at -10°C in plastic bags. The substrate was cut into four horizontal layers separated at 25%, 50%, and 75% of the full height of the pot. These vertical layers of substrate were weighed, dried, and reweighed to determine the vertical gradient in water content in the pot. The dried material was combined into samples corresponding to a similar position on each floor (edge, midway, or center). These samples were mixed together. A subsample of 500 mL was extracted with distilled water by the saturated extract method (Warneke, 1986). The aqueous phase was filtered through a $0.45\text{-}\mu\text{m}$ filter. The filtrate was stored at 4°C until analysis or mixed 1:1 with 8% v/v H_2SO_4 for spectrometric analysis of elements. The pH, EC, nitrate, and potassium were measured with electrodes as described subsequently.

Twelve plants representing a distribution of locations on each floor were selected from each watering treatment and held for 2 to 4

weeks under simulated retail sales conditions in a shaded greenhouse. Plants were held in shipping trays for the duration of the post-harvest period. Geraniums were harvested at initial color and 1 week later and held for 2 weeks under postharvest conditions. Leaf color change, leaf chlorophyll concentration, and flower quality were measured weekly. Chrysanthemums were held in a simulated retail environment greenhouse with 15/21 °C day/night temperatures and watered as needed but not fertilized. Plants were held in shipping trays for the duration of the post-harvest period. Five flower buds on chrysanthemum plants were tagged that were not yet at Stage 1 and post-harvest bud maturity was recorded each day. Bud maturity was assessed on a five-stage scale as follows: S-1 = first petal lifted 90° off the floral disc; S-2 = first petal fully reflexed to 180° (full open petal); S-3 = 100% of perimeter ray petals reflexed to 180° (full open flower); S-4 = first petal senesced (evidenced by drying or brown discoloration); and S-5 = 25% of petals senesced (full flower senescence).

Sampling and chemical analysis. Composition of the nutrient solution was measured with electrodes immersed in a stirred sample of solution. The sensors were: Thermo Scientific model 9256BN combination pH/AgCl reference; Fisher Catalog 093262 Conductivity/Resistivity/TDS meter; and the nitrate- and potassium-selective electrodes, Thermo Scientific Models 970701 and 931901, respectively (all probes from Fisher Scientific, Pittsburgh PA). Solution samples were diluted 2:1 with 8% w/v H₂SO₄ for analysis of a variety of elements by inductively coupled plasma spectrometry (Gent, 2008). Chlorophyll concentration was measured in a 0.8-cm² disk of tissue from individual leaves. Each disk was extracted in 2 mL of N, N-dimethylformamide for 24 h in the dark. Absorbance of leaf extracts was measured using a Shimadzu UV160U spectrophotometer. Chlorophyll concentration was determined from the following equation:

$$\text{Chlorophyll (mg/liter)} = 17.9 \text{ A}_{647} + 8.08 \text{ A}_{664.5}.$$

Statistical analysis. The watering treatment, location on the floor, and cultivar and/or year were fixed effects in analysis of all data for one pot size or species. The vertical layers of substrate (depth) were a continuous variable for which linear and quadratic effects were included in analysis. Variation between plants was the source of error within treatment and year or cultivar. These data were subject to analysis of variance for all main effects and interactions. None of the three- and four-way interactions were significant. The error from these statistical analyses was used to determine least significant difference.

Results

Water supply and uptake. The uptake of water into dry substrate in pots on ebb and

flow benches was a function of the duration of water contact with the base of the pot (Fig. 1). There was a remarkable uptake of 0.27 and 0.24 L·L⁻¹ VWC for 10- and 15-cm pots, respectively, even when this duration was only 2 min. Uptake of water in 10 min was 0.47 and 0.43 L·L⁻¹ for 10- and 15-cm pots, respectively. The amount of water taken up increased more slowly as the watering duration was increased to 20 min when 10-cm pots took up 0.60 L·L⁻¹ and 15-cm pots took up 0.54 L·L⁻¹ VWC (Fig. 1). Other experiments indicate that it takes two water cycles of 30-min duration to achieve 90% of effective water-holding capacity for pots that were initially dry (Elliot, 1992). Thus, a minimum of 0.2 and a maximum of ≈0.6 L·L⁻¹ VWC were the practical limits to adding water with a single ebb and flow watering cycle. Pot-to-pot variation in uptake of water was greatest at the shortest watering duration for 15-cm pots. The SD was 0.1 L·L⁻¹ compared with 0.06 L·L⁻¹ overall. Some pots did not take up any water within the 2-min duration of water contact. There was also more variation for a long duration of watering, because some

pots were near effective water-holding capacity and others were not.

Water uptake during crop production. Medium water content was measured before and after each irrigation event while crops were grown on flooded floors. The substrate water content was measured gravimetrically in 2007. In 2008, the substrate water content was measured with ECH2O probes. For the 2007 and 2008 geranium crops, an irrigation event was initiated when the medium water content was 0.05 to 0.15 L·L⁻¹ for control and 0.05 to 0.10 L·L⁻¹ for PSEFW regimes, respectively (the mean ± SD observed over all watering cycles; see Table 1). The pots took up less water per irrigation event in 2008 than in 2007 under both watering treatments. Water uptake per pot for an irrigation event under the PSEFW regime was only 75% and 77% of that for the controls in 2007 and 2008, respectively. Except for one cycle when plants were watered when medium water content was relatively high, the difference in water content between PSEFW and control regimes diminished over the drying cycle between irrigation events (Fig. 2).

Fig. 1. Water uptake into dry substrate as a function of duration of contact with water on ebb and flow benches. Symbols represent mean volumetric water content for each of two pot size, and error bars indicate the SD. The curves are fitted to the data for 10- and 15-cm pots.

Table 1. Root medium volumetric water content before and after irrigation and amount of water added under control or partial saturation ebb and flow watering (PSEFW) regimes.^z

Yr	Watering	Duration (min)	Volumetric water content		Water added (L/pot)
			Before	After	
Geranium		15-cm pots			
2007					
	Control	13	0.10 ± 0.05	0.59 ± 0.02	0.57 ± 0.05
	PSEFW	5	0.07 ± 0.02	0.48 ± 0.02	0.43 ± 0.02
2008					
	Control	15	0.10 ± 0.05	0.55 ± 0.04	0.49 ± 0.09
	PSEFW	6	0.05 ± 0.03	0.45 ± 0.04	0.38 ± 0.10
Chrysanthemum		20-cm pots			
2007					
	Control	18	0.15 ± 0.08	0.54 ± 0.03	0.98 ± 0.04
	PSEFW	6	0.09 ± 0.06	0.38 ± 0.06	0.75 ± 0.03
2008					
	Control	17	0.15 ± 0.10	0.52 ± 0.04	0.98 ± 0.12
	PSEFW	7	0.12 ± 0.06	0.44 ± 0.04	0.82 ± 0.06

^zValues are mean ± SD overall watering cycles.

The substrate water content after an irrigation cycle was less for 20-cm pots with chrysanthemum than for 15-cm pots with geranium in 2007 (Table 1). This trend is consistent with our previous observations on 10- and 15-cm pots (Fig. 1), namely that larger pots accumulated lower water content for a given contact time with water. However, in 2008, the water content for geranium in 15-cm pots was less than in 2007 and similar to that for 20-cm pots with chrysanthemum. Irrigation events were initiated at higher water content for chrysanthemum than for geranium, in part because leaves of geranium were more resistant to wilting than those of chrysanthemum. The time course of water content of 20-cm pots with chrysanthemum during drying cycles (Fig. 3) was similar to that for 15-cm pots with geranium, except chrysanthemum dried down faster than geranium, and they were irrigated approximately every 3 d. This was probably the result of several factors, including species differences in transpiration, larger plants and wider pot spacing, and differences in seasonal climatic conditions. Water uptake per irrigation event for pots with chrysanthemum under the PSEFW regime was 76% and 84% of that for the controls in 2007 and 2008, respectively.

Distribution of water and nutrients. The distribution of water in the substrate was measured at the final harvest for geraniums grown in 2007, 3 d after they were last watered. There were significant effects of irrigation regime and depth within the pot (Table 2). The lowest layer had the greatest water content, and other layers were similar to each other. The PSEFW treatment reduced the water content of each layer of substrate compared with the controls. The water content of lower and upper layers was reduced more than that of middle layers. The location of pots on the floor did not affect water content (data not shown).

A saturated medium extract of nutrients from the substrate showed there was a strong vertical gradient in nutrient concentrations decreasing from the top to the bottom of each pot (Table 2). EC was very high in the top layer of substrate. The concentration of the sum of all nutrients was much less in the lower layers. Pots under both PSEFW and control watering developed this gradient. Potassium contributed more than nitrate to the high EC in the top layer of substrate for geranium grown in 2007. This did not seem to be harmful to the growth or quality of the plants. The average concentration of nutrients in the vertical substrate profile as measured by EC was unaffected by watering treatment.

The root medium of chrysanthemum was sampled on 10 Oct. 2007, 1 d after an irrigation event. The water content varied less with depth than for geranium (Table 3). In each layer, the water content was $\approx 0.20 \text{ L} \cdot \text{L}^{-1}$ higher for control than for PSEFW. The water content for pots containing 'Donna' was 0.10 units greater than for pots of 'Nancy'. Location on the floor had an effect on water content for pots under PSEFW but not for those under the control regime. The pots with the highest

Fig. 2. Variation with time in volumetric water content of root medium in 15-cm pots of a geranium crop grown in 2008. Control had 15-min contact with water compared with 6 min for partial saturation ebb and flow watering (PSEFW).

Fig. 3. Variation with time in volumetric water content of root medium in 20-cm pots of a chrysanthemum crop grown in 2008. Control had 17-min contact with water compared with 7 min for partial saturation ebb and flow watering (PSEFW).

water content were located at the lowest elevation on the PSEFW floor (midway to the center). The effect of watering regime on the concentration of nutrients in the substrate varied among cultivars. Effects were significant for 'Hannah' in 2008 but not for 'Donna' or 'Nancy' in 2007. There was a stratification of nutrients, as measured by EC, and for nitrate and potassium. The concentrations of salts in the upper layer were up to fourfold higher than in the lower layers. Nitrate contributed more than potassium to the gradient of nutrients in the substrate of chrysanthemum. The EC was less in 2008 than in 2007 as was the gradient in EC among vertical sections or height in the pot (data not shown).

Nutrient solution composition. The composition of the nutrient solution remaining in the reservoirs was measured four times in May 2007 and twice in Sept. 2007. The EC was 1.14 and $1.03 \text{ dS} \cdot \text{m}^{-1}$ for control and PSEFW treatments, respectively, during growth of geranium in May. Both nitrate nitrogen (N) and potassium were higher in control than PSEFW reservoirs, 86 and $77 \text{ mg} \cdot \text{L}^{-1}$ for nitrate-N and 80 and $66 \text{ mg} \cdot \text{L}^{-1}$ for potassium. The EC of solution in the reservoirs was lower during growth of chrysanthemum, 0.77 compared with $0.55 \text{ dS} \cdot \text{m}^{-1}$ in control

and PSEFW treatments, respectively. Nitrate-N was higher in control than PSEFW, 54 and $42 \text{ mg} \cdot \text{L}^{-1}$, respectively, but potassium was the same, $20 \text{ mg} \cdot \text{L}^{-1}$. The reservoirs contained 2000 L of solution, enough for four or five watering cycles. The difference in concentration of nutrients remaining in solution represents a substantial increase in the amount of nutrients taken up per liter of solution in the PSEFW regime compared with the controls. To some extent this compensated for the smaller volume of water supplied to the crop under PSEFW irrigation.

Biomass, height, and flowering. Compared with controls, the PSEFW treatment provided a greater but variable water stress on the crops. This affected the growth of geranium plants throughout the experiment in 2007. The fresh weight per plant, and the difference in weight between watering treatments, increased with time until the stage of maximum flower development (Fig. 4). At the final harvest on 15 June, the control plants weighed 20% more than those grown under PSEFW (Table 4). The watering regimes had a significant effect on all measures of growth. Relative differences were greatest for stem height in 2008 and for biomass in 2007, but interactions between year and watering

Table 2. Effect of watering regime and depth on characteristics of the root medium for geranium grown in 15-cm pots on flooded floors in 2007.^z

Factor	Watering	Water content (L·L ⁻¹)		pH		Electric conductivity (dS·m ⁻¹)		Nitrate-N (mg·L ⁻¹)		Potassium (mg·L ⁻¹)	
		Control	PSEFW	Control	PSEFW	Control	PSEFW	Control	PSEFW	Control	PSEFW
Substrate depth											
	Lower	0.50 a ^y	0.36 a	5.30	5.24	1.49 c	1.45 b	152 b	146 c	77 c	68 b
	Low-mid	0.35 b	0.29 b	5.24	5.16	1.31 c	1.02 b	132 c	98 c	66 c	49 b
	Upper-mid	0.39 b	0.32 ab	5.22	5.34	2.83 b	1.69 b	286 b	178 b	150 b	89 b
	Upper	0.43 b	0.27 b	5.33	5.22	9.52 a	11.64 a	434 a	346 a	659 a	847 a
Significance											
	Watering (W)	***		NS		NS		*		*	
	Depth (D)	*		NS		***		**		***	
	Interactions	W × D*		NS		NS		NS		NS	

^zControl had 13-min contact with water compared with 5 min for partial saturation ebb and flow watering (PSEFW).^yValues within a column followed by different letters differ at $P < 0.05$.^zNS = non-significant; *significant at $P \leq 0.05$; **significant at $P \leq 0.01$; ***significant at $P \leq 0.001$.Table 3. Effect of cultivar, watering regime, location on floor, and substrate depth on characteristics of the root medium for chrysanthemum grown in 20-cm pots on flooded floors.^z

Factor	Watering	Water content (L·L ⁻¹)		pH		Electric conductivity (dS·m ⁻¹)		Nitrate-N (mg·L ⁻¹)		Potassium (mg·L ⁻¹)	
		Control	PSEFW	Control	PSEFW	Control	PSEFW	Control	PSEFW	Control	PSEFW
Cultivar											
	Donna/2007	0.60 a ^y	0.43 a	5.19	5.18	2.78 a	2.86 a	250 a	268 a	161 a	172 a
	Nancy/2007	0.50 b	0.29 b	5.20	5.14	2.72 b	2.58 a	260 a	262 a	151 a	165 a
	Hannah/2008	NA	NA	5.31	5.87	2.37 c	1.79 b	243 b	173 b	97 b	79 b
Substrate depth											
	Lower	0.64 a	0.41 a	5.01 c	5.36 b	1.26 c	1.45 c	113 c	136 b	124 b	167 a
	Low-mid	0.53 b	0.35 b	4.83 d	5.05 c	1.33 c	1.24 d	125 c	107 c	107 c	113 c
	Upper-mid	0.49 b	0.35 b	5.49 b	5.52 a	2.27 b	2.17 b	208 b	126 b	126 a	129 c
	Upper	0.53 b	0.33 b	5.60 a	5.65 a	5.64 a	5.06 a	559 a	489 a	189 a	144 b
Location											
	Edge	0.54 a	0.31 b	5.24	5.43	2.67	2.43	258	235	144	129
	Midway	0.55 a	0.41 a	5.19	5.34	2.54	2.29	241	221	126	144
	Center	0.55 a	0.35 b	5.27	5.42	2.67	2.48	254	244	138	142
Significance											
	Cultivar (C)	****		NS		***		***		***	
	Watering (W)	***		NS		**		**		**	
	Depth (D)	***		***		***		***		***	
	Location (L)	**		NS		NS		NS		NS	
	Interactions	W × D* W × L**		NS		C × D*** C × W**		C × D*** C × W**		C × D*** C × W* W × L*	

^zControl had 17- to 18-min contact with water compared with 6 to 7 min for partial saturation ebb and flow watering (PSEFW).^yValues within a column followed by different letters differ at $P < 0.05$.^zNS = non-significant; *significant at $P \leq 0.05$; **significant at $P \leq 0.01$; ***significant at $P \leq 0.001$.

NA = not available.

Fig. 4. Shoot fresh weight of geranium grown in 2007. Control had 13-min contact with water compared with 5 min for partial saturation ebb and flow watering (PSEFW). Symbols are mean values for each harvest date, and lines show a linear trend with time.

regime were not significant. Location of pots on the floor had no effect on biomass or plant size (data not shown).

The PSEFW treatment had slowed the growth of chrysanthemum compared with control watering as early as 6 Sept. 2007 (Fig. 5). Linear fits to the data for each cultivar showed no further increase in the effect of the irrigation regimes, because the buds developed up to the final harvest on 10 Oct. 2007. At the final harvest in both 2007 and 2008, watering regime had a significant effect on both height and fresh weight biomass (Table 5). The effect on dry weight was less significant. Differences in biomass resulting from watering were greater in 2008 than in 2007. Cultivar or year had significant effects for all measures of growth, but there was no interaction with watering regime. Location of pots on the floor had no effect on growth (data not shown).

The water use efficiency (WUE) for dry matter accumulation could be calculated from the increase in biomass of the entire

Table 4. Effect of year and watering regime on shoot height and biomass of geranium grown in 15-cm pots on flooded floors.^z

Factor	Watering	Shoot ht (cm)		Fresh wt (g)		Dry wt (g)	
		Control	PSEFW	Control	PSEFW	Control	PSEFW
Year							
2007		13.7	12.3	123	101	14.0	11.3
2008		17.8	15.3	179	152	20.9	15.6
Significance							
Year		***y		***		***	
Watering		***		***		***	
Interactions		NS		NS		NS	

^zControl had 13- to 15-min contact with water compared with 5 to 6 min for partial saturation ebb and flow watering (PSEFW).

^yNS = non-significant; *significant at $P \leq 0.05$; **significant at $P \leq 0.01$; ***significant at $P \leq 0.001$.

Fig. 5. Shoot fresh weight for two cultivars of chrysanthemum grown in 2007. Control had 18-min contact with water compared with 6 min for partial saturation ebb and flow watering (PSEFW). Symbols are mean values for each harvest date, and lines show linear trends with time.

Table 5. Effect of cultivar and watering regime on shoot height and biomass of chrysanthemum grown in 20-cm pots on flooded floors.^z

Factor	Watering	Shoot ht (cm)		Fresh wt (g)		Dry wt (g)	
		Control	PSEFW	Control	PSEFW	Control	PSEFW
Cultivar/year							
Donna/2007		35.9 c ^y	32.3 c	511 a	493 a	86.5 b	84.7 a
Nancy/2007		29.4 d	27.3 d	466 b	446 b	84.9 b	83.5 a
Beth/2008		38.4 b	34.1 b	415 c	369 d	90.2 a	83.8 a
Hannah/2008		40.4 a	36.1 a	462 b	402 c	90.8 a	85.2 a
Significance							
Cultivar		***x		***		NS	
Watering		***		***		*	
Interactions		NS		NS		NS	

^zControls had 17- to 18-min contact with water compared with 6 to 7 min for partial saturation ebb and flow watering (PSEFW).

^yValues within a column followed by different letters differ at $P < 0.05$.

^xNS = non-significant; *significant at $P \leq 0.05$; **significant at $P \leq 0.01$; ***significant at $P \leq 0.001$.

crop over the period that the watering treatments were applied divided by the total volume of water used to refill the reservoirs for each floor over that period. The WUE did not differ consistently as a result of watering regime over the 5-week period used to grow geranium. The values were 4.3 compared with 4.5 g·L⁻¹ in 2007, and 6.4 compared with 6.1 g·L⁻¹ in 2008, for control and PSEFW regimes, respectively. However, the WUE did differ for the crops of chrysanthemum averaged over the response for the two cultivars grown in each year. The values were 6.6

compared with 8.7 g·L⁻¹ in 2007 and 7.6 compared with 8.3 g·L⁻¹ in 2008 for control and PSEFW regimes, respectively. This corresponds to a 20% increase in WUE for PSEFW compared with control watering. There was negligible loss of water from either irrigation system as a result of evaporation from the floor or leakage as determined by comparing the total volumes taken up by the pots compared with the volumes used to refill the reservoirs. Thus, the increased WUE resulting from the PSEFW irrigation of chrysanthemum must have been the result of reduced plant

transpiration and evaporation from the surface of the medium.

At full flower in 2007, 'Nancy' under PSEFW was just filling in the allocated space, whereas under the control irrigation, plants of 'Nancy' had become crowded at this spacing and began to stretch. 'Donna', a more vigorous cultivar, began to elongate before first color under both irrigation regimes. There were modest variations in flower longevity when plants were maintained in a post-harvest environment. For 'Donna' harvested at first color, flower development to the first petal fully reflexed stage (S-2) took 9.5 d under both control and PSEFW irrigation regimes (Table 6) but under control irrigation, plants took progressively longer to reach fully open flower (S-3), first petal senescence stage (S-4), and full senescence (S-5). This difference was smaller for plants harvested at the early flower stage. For 'Nancy' harvested at first color, each stage up to senescence (S-5) was synchronous for both irrigation regimes. However, 'Nancy' harvested at the early flower stage, the time to first petal reflex (S-2), full open flower (S-3), and first petal senescence (S-4) was slower for plants grown under PSEFW than controls. For plants harvested at the early flower stage, the interval from S-1 to S-4 averaged over both cultivars was 1.8 d longer under PSEFW than control irrigation ($P < 0.01$). When plants were selected in 2008, both cultivars of chrysanthemum had become crowded in the production spacing regardless of irrigation regime. Irrigation regime had no significant effect on post-harvest flower longevity (data not shown).

Plant tissue composition. There were few differences resulting from watering treatments in the concentration of elements in plant tissue on a dry weight basis (data not shown). The nutrient content of geranium plant shoot tissue did not differ as a result of watering in 2007. For chrysanthemum grown in 2007, watering regime only affected phosphorus; the concentration was higher for plants grown under PSEFW than controls, 5.1 compared with 4.7 mg·g⁻¹. The quantities of nutrients delivered to the plants differed as a result of the different volumes of water supplied in the two watering regimes. However, this was not sufficient to affect plant composition. Any differences in uptake of nutrients between PSEFW and control watering were apparently in the same ratio as the differences in biomass.

Chlorophyll concentration was measured in samples of plants maintained in a post-harvest environment. There was no difference resulting from irrigation for geranium in 2007 either at the time of harvest or 1- or 2-weeks post-harvest (data not shown). In 2008, chlorophyll concentrations in bottom-most leaves at harvest was slightly higher under PSEFW compared with controls, 48 and 38 µg·cm⁻², respectively ($P = 0.07$). There was a similar effect on chlorophyll resulting from watering in chrysanthemum cultivar Nancy harvested at the first color stage in 2007. However, differences in chlorophyll content were no longer apparent after 1 or more weeks in the post-harvest environment.

Table 6. Effect of watering regime on days post-harvest to reach various stages of flower maturity for chrysanthemum cultivars Nancy and Donna grown in 2007.²

Plants harvested at first color stage						
Irrigation	Cultivar	Flower maturity stage				
		S-1	S-2	S-3	S-4	S-5
Days post-harvest to attain each stage of flower maturity						
Control	Nancy	3.8	10.5	13.0	20.3	34.3
	Donna	4.5	9.5	12.8	21.1	38.1
PSEFW	Nancy	4.3	10.4	13.7	21.9	34.4
	Donna	4.1	9.5	11.9	18.6	34.2
Significance						
Watering		NS ^y	NS	NS	NS	NS
Cultivar		NS	***	**	NS	NS
Interaction		**	NS	*	*	NS
Plants harvested at early flower stage						
Control	Nancy	3.1	9.5	12.5	17.1	36.8
	Donna	2.5	8.2	11.5	16.5	35.1
PSEFW	Nancy	3.5	10.9	13.5	20.6	37.7
	Donna	2.9	8.3	10.7	17.5	32.5
Significance						
Watering		NS	*	NS	***	NS
Cultivar		*	***	***	**	***
Interaction		NS	*	***	NS	*

²Control had 18-min contact with water compared with 7 min for partial saturation ebb and flow watering (PSEFW).

^yNS = non-significant; *significant at $P \leq 0.05$; **significant at $P \leq 0.01$; ***significant at $P \leq 0.001$.

Discussion

In the flooded floor system examined here, it is likely that watering durations of 2 to 4 min would result in substantial variation in substrate water content according to location or height above the lowest elevation on the floor. We observed small but consistent differences in substrate water content with location on the floor for chrysanthemum watered for 6 to 7 min but not when they were watered for 17 to 18 min. However, any variation in water content resulting from location on the floor did not have an effect on biomass or chemical composition of these crops. The variation in substrate water content with location observed for short duration irrigation cycles underscores the need for precision in design and construction of PSEFW systems so that water can be added and removed quickly, but also uniformly.

These experiments were run with simultaneous watering of the control and PSEFW treatments. There are several alternatives to this protocol that could have been followed. Watering could have been triggered more often, for instance daily, so that neither treatment was exposed to a very low VWC. The water content for the control would be substantially higher than for PSEFW at all times. Alternatively, watering could have been initiated at a higher preset VWC. In this experiment, the VWC that triggered an irrigation cycle was ≈ 0.1 , because that was the content when leaves started to flag. It could be considerably higher, for instance $0.25 \text{ L} \cdot \text{L}^{-1}$ VWC. More frequent watering would reduce the variability between the minimum and maximum water content but would not eliminate it entirely. Some dry-down period is required to maintain a VWC below the effective water-holding capacity (Elliot, 1992). This variability over time in water content distinguishes the irrigation method examined here

from various other irrigation protocols to maintain relatively constant water content. These other protocols include small-volume drip irrigation triggered at a specific VWC (Van Iersel et al., 2010) or watering using capillary mat with a height gradient (van Iersel and Nemali, 2004) and other methods.

One particular benefit of the system examined here is that soil moisture sensors are not necessary or critical for the operation. Another benefit is that ebb and flow irrigation is robust to variation in water uptake from one cycle to another. The rate of uptake of water is inversely related to the water content of the substrate at the start of irrigation (Otten et al., 1999). This is a valuable characteristic that leads to remarkable crop uniformity with ebb and flow watering over time. If pots that take up less water in one watering cycle have a drier substrate, they are likely to take up more water in the next. The measurements reported here showed some variation in substrate water content with location on the floor but never showed differences in biomass and height growth, or tissue composition, as a result of location.

The watering protocol had more of an effect on biomass of geranium than chrysanthemum. Geranium was grown in spring under a period of less temperature stress than chrysanthemum, which was grown in late summer. Watering intervals were more widely separated for geranium than chrysanthemum. The difference in substrate water content between watering regimes, which was established during each irrigation event, was maintained over a longer duration for geranium than for chrysanthemum. In addition, an irrigation event for geranium was typically initiated at lower substrate water content than for chrysanthemum. Leaves of chrysanthemum started to flag at a higher water content, triggering a watering cycle. Several studies have shown that plant growth is slowed when substrate water content

falls below 0.20 to $0.25 \text{ L} \cdot \text{L}^{-1}$. There was a quadratic growth response to VWC for petunia grown under constant moisture regimes varying from 0.05 to $0.40 \text{ L} \cdot \text{L}^{-1}$ with a greater response from 0.05 to $0.25 \text{ L} \cdot \text{L}^{-1}$ compared with the response from 0.25 to $0.40 \text{ L} \cdot \text{L}^{-1}$ (Van Iersel et al., 2010). Three of six annual species grew faster when watered at 0.25 compared with $0.18 \text{ L} \cdot \text{L}^{-1}$ VWC (Niu et al., 2006). A study of growth and gas exchange of four species during a 10-d drying cycle found transpiration was reduced relative to controls only when medium water content was at or below $0.2 \text{ L} \cdot \text{L}^{-1}$ (Starman and Lombardini, 2006). Thus, the time spent at relatively low water content, from 0.10 to $0.25 \text{ L} \cdot \text{L}^{-1}$, may have the largest effect on plant growth. In particular, geranium spent a longer duration than chrysanthemum with the substrate water content in this range.

Although there were differences in water content between treatments immediately after an irrigation event, these differences may have relatively little effect on growth, because in all cases, water content was above $0.38 \text{ L} \cdot \text{L}^{-1}$. This would also suggest that if plants in the PSEFW regime had been watered more frequently, there would have been less difference in growth response compared with the controls.

Some of the benefits of PSEFW when applied on flooded floors were greater use efficiency of water and fertilizer and reduced plant height. The increase in water and nutrient use efficiencies under PSEFW were in addition to those resulting from the ebb and flow itself (Kent and Reed, 1996; Purvis et al., 2000). The increased water and nutrient use efficiency will result in the use of less fertilizer and water when PSEFW is used for the production of ornamental crops in greenhouses. This will benefit growers by lowering production costs.

Another benefit of PSEFW, compared with slow-cycle ebb and flow watering, is that the substrate never approaches the effective water-holding capacity. Thus, plants are not exposed, even temporarily, to a high water content that may encourage root disease. We have noted previously the ability of PSEFW to prevent disease expression in poinsettia when disease was evident in plants watered with slow-cycle ebb and flow (Gent et al., 2009). This ability to repress disease should encourage growers to adopt ebb and flow methods that recycle all the excess water applied to the plant. This will benefit society and protect natural resources and the environment from pollution resulting from the application of excess fertilizer.

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