Cyclic Sprinkler Irrigation and Pre-irrigation Substrate Water Content Affect Water and N Leaching from Containers[1]

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Abstract

A series of sprinkler irrigation experiments were conducted to determine the influences of water application rate (WAR), pre-irrigation substrate water content (PSWC), and cyclic irrigation on water and N leaching from container-grown plants. Prior to experiments, Marigold (*Tagetes erecta* L. 'Apollo'), were glass house-grown in pine bark-filled 3.8 liter (1 gal) containers. Prior to treatment, substrate was dried via evapotranspiration (ET) to targeted PSWCs. A simulated overhead irrigation system applied the daily water allotment in a single continuous application or cyclically (multiple applications); in most cases the respective ET volumes were applied to the substrate. Water application efficiency (WAE; water vol retained in substrate ÷ water vol applied to substrate) was determined, and in some experiments, leachates were analyzed for EC, NO_3-N and NH_4-N. A negative linear relationship existed between WAR and WAE. Leachate NO_3-N and NH_4-N concentrations were unaffected by WAR, however, total N leached increased with increasing WAR. WAE of cyclic irrigation was 4% higher (absolute basis) than with continuous irrigation; WAE increased as the time interval between cyclic applications increased from 20 to 60 min. Regardless of how water was applied, WAE was inversely related to PSWC and application volume. These experiments showed that the most effective method to increase WAE is to irrigate at relatively low PSWCs; if irrigation occurs at relatively high PSWCs, then relatively low volumes should be applied.

Index words: $N0_3$-N, leachate, water application efficiency, marigold (*Tagetes erecta* 'Apollo'), irrigation scheduling.

Significance to the Nursery Industry

This study demonstrated that, regardless of how water was applied, water application efficiency (WAE) was primarily related to pre-irrigation substrate water content (PSWC) and application volume. Water application efficiency was highest when the PSWC and application volume were relatively low. Thus, by scheduling irrigation according to PSWC and controlling application volume relative to PSWC, WAE can approach 100% thereby reducing water and nutrient leaching from container production areas. Reducing the overall water application rate (WAR), either by cyclic irrigation or a low WAR irrigation system, increased WAE by about 4% to 10%.

Introduction

Overhead sprinkler irrigation generally delivers water at rates of 0.7 to 2.9 cm/hr (0.3–1.2 in/hr) (2, 3) and is relatively inefficient due to water falling between containers and leaching from the container substrate (1, 16, 17). Currently, this is the only economically feasible method of irrigating plants in small containers (≤ 12 liter; ≤ 3 gal). Container water loss is related to irrigation frequency, volume, WAR, and substrate physical characteristics.

Limited information is available on factors affecting WAE for sprinkler-irrigated container-grown crops. Welsh and Zajicek (18) showed that scheduling irrigation according to PSWC was a feasible method to reduce irrigation frequency and maximize growth of *Photinia* x *fraseri* (Dress.). The influence of WAR on water flow and distribution in mineral soil has been documented (12, 13, 14, 21) but findings may not be applicable to porous soilless substrates. A trickle irrigation study (11) provided limited information on WAR on WAE; however, there are no reports on the influence of sprinkler WAR on WAE.

With cyclic irrigation, a plant's daily water allotment is subdivided into more than one application with prescribed intervals between applications which contrasts with conventional irrigation practices whereby the daily water allotment is applied in a single (continuous) application. Cyclic irrigation was first proposed by Karmeli and Peri (7) working with mineral soil and was referred to as 'pulse irrigation.' However, the term pulse irrigation has been adopted by the commercial irrigation industry and refers to an irrigation mechanism in which water is emitted when the irrigation line water pressure increases to a critical value. To avoid the confusion between Karmeli and Peri's term and the commercial adaptation, we will use cyclic irrigation.

Use of cyclic irrigation by a nursery was first reported in 1986 (19). In response surface water runoff problems, cyclic irrigation reduced water and fertilizer use by 30% and 50%, respectively, and water and NO_3-N runoff by 77% and 90%, respectively, without affecting crop quality (19). In a spray stake irrigation study (11) using 11 liter (3 gal) pine bark-filled containers, WAE of cyclic irrigation was 11 to 17% greater compared to continuous irrigation. However, extrapolation of the results from this spray stake work to sprinkler irrigation may not be appropriate since the WAR of spray stake irrigation is generally higher than with a sprinkler system. Objectives of this sprinkler irrigation study using pine bark-filled containers were to determine how WAE was influenced by 1) PSWC; 2) cyclic irrigation including factors of interval duration between applications; and 3) WAR.

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Table 1. Physical properties of substrates.[z]

Substrates	Drainage[y]	Solids[x]	Total porosity[w]	Air space[v]	Container capacity[u]	Unavailable water[t]	Available water[s]	Bulk density[r]
	(ml)	(% vol)						(g/cc)
PB	70.4a	16	84a	20a	64a	39a	24c	0.19c
9PB:1S	39.2b	25	75b	11b	64a	37b	27b	0.38b

[z]Analyses performed using standard aluminum soil sampling cylinders (7.6 cm ID, 7.6 cm h). Mean separation in columns by Waller-Duncan k-ratio t-test (k-ratio = 100), P = 0.05. Each value represents the mean of 5 cylinders.

[y]Drainage = Amount (ml) water drained from each cylinder after saturation before container capacity was reached.

[x]Solids = Total porosity – 100. Represents the total % volume of solids in each medium.

[w]Total porosity is equal to container capacity + air space.

[v]Air space was the volume of water drained from the sample ÷ volume of the sample.

[u]Container capacity was (wet weight – oven dry weight) ÷ volume.

[t]Percent volume at 1.5 MPa.

[s]Calculated as the difference between container capacity and unavailable water.

[r]Grams per cubic centimeter after drying samples in a forced-air drying oven at 110°C for 24 hours.

We also determined how irrigation regime influenced container N effluent.

Materials and Methods

General procedure. All containers were irrigated by a simulated overhead sprinkler system to avoid the variability of a commercial system. In this system, each of 12 circular platforms (13 cm (5 in) diameter) held a single container and rotated at 13 rpm (motor driven). Three irrigation tubes (0.16 cm (0.06 in) inner diameter) were positioned over the container radius. Water was applied via peristaltic pumps so that each tube discharged water equally to one-third of the substrate surface area. This system uniformly wet the substrate surface.

Physical characteristics of commercial grade, milled pine bark, were determined at the Horticultural Substrates Laboratory at North Carolina State University, Raleigh (Table 1). Plastic containers with a volume, height, and diameter of 3.8 liter (1 gal), 17 cm (6.7 in), and 15 cm (6 in), respectively, were filled with 1.6 kg (3.5 lb) moist bark/container (≈ 3.5 liter; 3.7 qt). Containers were dropped on a hard surface from a height of 10 cm (4 in) three times to allow bark to settle. Marigold (*Tagetes erecta* 'Apollo') seedlings, selected for its rapid growth and large size, were transplanted into bark-filled containers and grown under natural photoperiod on raised benches in a glass house which was heated at 18°C (65°F) and ventilated at 24°C (75°F). Depending on the experiment, plants were top-dressed with 20 g/container (0.7 oz/container) Osmocote 14N-6.2P-11.6K (14-14-14), or liquid fertilized with ≈ 400 ml (three times weekly) with 150 mg N/liter (NH_4NO_3), 10 mg P/liter (H_3PO_4), and 100 mg K/liter (K_2SO_4). Liquid fertilization or hose irrigation for the Osmocote-fertilized plants occurred according to plant need for water. Plants were glass house-grown for about 30 days until experiments began. Substrate container capacity (CC) was expressed on a weight basis and was determined at the beginning of experiments by submerging containers in a water-filled trough for 0.5 hr, then draining for 1 hr, and weighing; plant and container weights were taken into consideration. Unless otherwise noted, container substrate was dried via evapotranspiration (ET) to targeted water contents after which plant shoots were severed at the substrate surface. When the substrate reached the targeted water contents, containers (and container with plants for multi-day experiments) were covered in white plastic bags to prevent water loss until irrigation treatment commencement. In most experiments, the water volume applied was equal to ET loss. After irrigation treatment, containers were covered to prevent evaporation (or ET in case of intact plants) and drained for 1 hr, weighed, and leachate volume measured. WAE was computed using the formula: WAE (%) = [(vol applied – vol leached) ÷ vol applied] × 100.

Evapotranspiration during irrigation was calculated (mass basis) and subtracted from the volume applied value (in numerator and denominator of efficiency equation). Due to this accounting and for agreement between efficiency and leachate volume for the stated application volumes, actual leachate volumes were adjusted for ET by solving for volume leached using the above formula. Adjusted leachate volumes values differed from actual values in a minor way and trends in data relative to treatment were unaffected. PSWC was expressed as a percentage of CC and calculated as follows: (substrate weight before irrigation treatment ÷ substrate weight at CC) × 100.

Unless noted otherwise, experiments were conducted in a completely randomized design with one container per block (number of blocks will be noted). The General Linear Model procedure of SAS was used in the analysis of variance (ANOVA). Treatments were replicated six times with one container per replication unless noted otherwise. Since the irrigation system applied water to 12 plants per irrigation event, the number of replications treated per event depended on the number of treatments and replications. The General Linear Model procedure of the Statistical Analysis System (SAS Institute) was used in analysis of variance (ANOVA). Contrast analysis was performed for linear and quadratic trend significance tests.

Water application rate. Pine bark dried to water contents of 89%, 81%, or 74% of CC which corresponded to drying volumes of 150, 300, or 450 ml (0.16, 0.32, or 0.48 qt); these PSWCs encompassed the range of daily ET losses from a 3.8-liter (1-gal) container-grown plant under various environmental conditions (4, 9). WARs were 0.7, 1.4, or 2.1

cm/hr (0.28, 0.55, 0.84 in/hr) which encompassed the WAR commonly used in nurseries (3, 4). The leachate from each container was analyzed for EC, and NO_3-N and NH_4-N using ion-selective electrodes. The experiment was conducted in a split-plot design with WAR as a whole-plot factor and PSWC as a split-plot factor, and with a factorial arrangement of WAR and PSWC. In a second experiment designed to study even lower WARs, WARs were 0.1, 0.4, or 0.7 cm/hr (0.04, 0.16, or 0.28 in/hr); PSWC was 81% CC. Only WAE was measured.

Cyclic versus continuous irrigation. Three hundred ml water was applied at 0.7 cm/hr (0.28 in/hr) continuously (single application) or cyclically in which there were three 100 ml (≈ 0.11 qt) applications with 40 min intervals between applications. PSWC was 81%. Treatments were replicated nine times. ANOVA was performed on transformed efficiency data. The initial weight of the container was used as a covariate and weighted means of efficiencies reported. This experiment was repeated on another set of containers with treatments replicated ten times.

Time interval between cyclic applications and pre-irrigation substrate water content. Plants, grown in pine bark:sand (9:1, by vol), received seven irrigations during August 15 through August 28. Containers were weighed before irrigation (BI) and after irrigation and drainage (AI). The volume of water applied in each irrigation was the difference between AI and BI. During the experiment, PSWC ranged from 95% to 70% of CC (equivalent to 168 to 900 ml (≈ 0.18–0.95 qt) from CC), and volume of water applied (= ET) ranged from 66 to 663 ml (≈ 0.07–0.7 qt). WAR was 1.4 cm/hr (0.55 in/hr) continuously (single application) or cyclically in which three applications (each of one-third of ET) were applied with 20, 40, or 60 min intervals between applications. The experiment was conducted in a repeated measure design over seven irrigations with treatments replicated six times. Transformed efficiency data were analyzed as repeated measures. Multiple regression analysis was performed for continuous and cyclic with the 60 min intervals using leachate volume as the dependent variable. Linear, quadratic, and interaction terms of PSWC and volume of water applied were tested as independent variables. A similar experiment but with only one irrigation was conducted in which 200 ml (≈ 0.21 qt) of water, which represented an average daily water allotment applied to a 3.8-liter (1-gal) container-grown plant (3), was applied at 1.4 cm/hr (0.55 in/hr) continuously (single application) or cyclically in which three 67 ml (0.07 qt) applications were applied with 60, 90, or 120 min intervals between applications. PSWC was 89% CC.

Results and Discussion

Application rate. There was no interaction between WAR and PSWC in either experiments (data not shown) but there was an inverse linear relationship between WAR and WAE (Table 2). WAE increased by 7% (absolute basis) as WAR decreased from 2.1 to 0.7 cm/hr in the first experiment and in the second experiment WAE increased by 5% as rate decreased from 0.7 to 0.1 cm/hr (Table 2). These findings were in general agreement with mineral soil studies which showed that rate of water movement through soil increased as WAR increased (12, 13, 14). However, Lamack and Niemiera (11)

Table 2. Influence of water application rate on leachate volume and water application efficiency in a 100% pine bark substrate (first application rate expt).

Application rate	Leachate volume	Application efficiency
(cm/hr)	(ml)	(%)
First expt.[z]		
0.7	114	62[y]
1.4	126	58
2.1	135	55
Significance		
Linear	—	0.05
Quadratic	—	0.10
Second expt.		
0.1	66	78[x]
0.4	75	75
0.7	81	73
Significance		
Linear	—	0.03
Quadratic	—	0.61

[z]pooled over pre-irrigation substrate water content.
[y]n = 18.
[x]n = 6.

using spray stake irrigation in a pine bark substrate showed that WAR had no influence on WAE; this discrepancy was most likely related to the higher spray stake WAR range (16–29 cm/hr; 6.3–11.4 in/hr) compared to the WARs (0.7–2.1 cm/hr) (0.28–0.84 in/hr) of the current study. Thus, relatively high WARs would most likely increase percolation through the substrate and result in less water adsorption to bark particles.

Leachate NO_3-N and NH_4-N concentrations and EC were unaffected by WAR (Table 3). Apparently, substrate solution displacement in the relatively porous pine bark was unaffected by the range of WARs of this experiment. In support of this contention, a study (6) investigating mixtures of pine bark, soil, and sand found a lower substrate salt removal efficiency (indicated by leachate EC) for a relatively porous mineral soil-pine bark mixture than in a less porous clay loam soil-sand mixture. The limited substrate ion displacement in porous substrates was attributed to a high percolation rate (6, 8) and a low piston flow index (6). Leachate volume increased as WAR increased (current study) resulting in 66% more total N (NO_3-N and NH_4-N) being leached when comparing the 2.1 cm/hr vs 0.7 cm/hr (0.28 in/hr) treatments (Table 3). Thus, growers can reduce water and nutrient loss from containers by reducing the WAR either by adapting the existing irrigation system for cyclic irrigation or by the use of low-volume irrigation through microsprinkler (mini-sprinkler) systems (5).

WAE (pooled over WAR) for PSWCs of 74%, 81%, and 89% was 71%, 63%, and 42%, respectively. This negative linear relationship (P = 0.001) was expected since a substrate with a low PSWC would have a relatively high proportion of unfilled-micropores and hence a high matric potential. In contrast, a spray stake irrigation study (11) showed a positive relationship between PSWC and WAE and attributed this to a greater channeling of water with a low PSWC.

Table 3. **Influence of water application rate on leachate EC, NO_3-N and NH_4-N concentrations, and total leachate NO_3-N and NH_4-N in a 100% pine bark substrate (first application rate expt.).**

Application rate[z]	EC	Leachate N concn (mg/l)		Total leachate N (mg)	
(cm/h)	(dS/m)	NO_3-N	NH_4-N	NO_3-N	NH_4-N
0.7	0.75	55	31	4.8	2.6
1.4	0.82	63	36	6.7	3.9
2.1	0.82	64	36	7.8	4.5
Significance[y]					
Linear	0.25	0.25	0.10	0.05	0.02
Quadratic	0.25	0.25	0.25	0.10	0.10

[z]Pooled over pre-irrigation substrate water content.
[y]n = 18.

Table 4. **Influence of pre-irrigation substrate water content on leachate EC, NO_3-N and NH_4-N concentrations, and total leachate NO_3-N and NH_4-N in a 100% pine bark substrate (first application rate expt.).**

Substrate water content[z]	EC	Leachate N concn (mg/l)		Total leachate N (mg)	
(%)	(dS/m)	NO_3-N	NH_4-N	NO_3-N	NH_4-N
74	0.99	69.0	42.4	8.8	5.3
81	0.72	56.5	32.5	6.1	3.5
89	0.69	56.2	27.8	4.4	2.2
Significance[y]					
Linear	0.005	0.05	0.001	0.001	0.001
Quadratic	0.05	0.10	0.10	0.10	0.10

[z]Pooled over pre-irrigation water application rate.
[y]n = 18.

This lack of agreement was most likely due to the spray stake WAR since the lowest spray stake WAR was about six times higher than the highest WAR of the current study.

There was a negative linear relationship between PSWC and leachate EC and N (NO_3-N and NH_4-N) concentrations (Table 4). At a 74% PSWC, EC, NO_3-N, and NH_4-N concentrations were 44%, 23%, and 53% higher, respectively, than at a 89% PSWC. Assuming that the substrate nutrient contents of the low and high PSWCs were the same prior to irrigation, the substrate solution of bark in the low PSWC would be more concentrated than a substrate with a high PSWC. Apparently, the higher leachate N concentration of the low PSWC was due to the irrigation water displacing and intermixing with the relatively concentrated substrate solution. Negative linear relationships were exhibited between PSWC and total leachate NO_3-N and NH_4-N leached (Table 4). At a 74% PSWC, total leachate NO_3-N and NH_4-N were ≈ 100% and 140% higher, respectively, than at 89% PSWC due to the higher leachate volume of the low PSWC treatment which was related to the higher volume of water applied.

Cyclic versus continuous irrigation. WAE was 86% (42 ml leached) for the cyclic irrigation treatment (three 100 ml applications with 40 min intervals) and 82% (55 ml leached) for continuous irrigation (300 ml) (different at P = 0.04); similar results occurred in the second experiment (data not shown). A method of expressing cyclic irrigation in terms of the overall WAR (including interval durations) is time averaged application rate (TAAR) (21). Applying water cyclically at a nominal application rate of 0.7 cm/hr and with 40 min intervals between applications resulted in a TAAR of 0.38 cm/hr. Thus, decreasing WAR either by applying water cyclically or by applying water at a low nominal rate increased WAE. Cyclic irrigation was shown to be 10% to 16% more efficient than continuous irrigation for spray stake-irrigated pine bark substrate (11). Apparently, low WARs allowed for more water to be adsorbed to extra- and intra-particle micropores than with continuous irrigation.

Time interval between cyclic applications and pre-irrigation substrate water content. There was a positive linear relationship between WAE (pooled over seven irrigations) and interval durations of 20, 40, or 60 min between cyclic applications (Table 5). WAE for the 60-min interval treatment (TAAR of 0.38 cm/hr) was 6% higher (absolute basis) than continuous irrigation in which water was applied at a nominal WAR of 1.4 cm/hr. A positive linear relationship was also exhibited between WAE and interval durations of 60, 90, and 120 min between cyclic applications (data not shown; TAARs of 0.29, 0.21, and 0.16, respectively). WAE increased by 7%, 10%, and 12% (absolute basis) with 60, 90, and 120 min intervals, respectively, compared to continuous irrigation. Results were in general agreement with a spray stake irrigation study (11) in which cyclic WAE increased by ≈ 10% (absolute basis) when interval duration increased from 20 to 40 min. Thus, growers can increase WAE by increasing the time between cyclic applications. Using data of the first interval experiment, the following correlation R^2 value demonstrated the strong relationship between cyclic irrigation WAE and TAAR:

$$WAE\ (\%) = 94.6 - (11 \times TAAR) \quad R^2 = 0.89$$

and is limited to a pine bark:sand (9:1, by vol) substrate and ≤ 1 h interval between applications.

Table 5. **Influence of continuous (single application) versus cyclic (three applications with 20, 40, or 60 min intervals between applications) irrigation on application efficiency and in a 9 pine bark:1 sand substrate; data are means of seven irrigations (first TAAR expt.).**

Irrigation treatment	Application efficiency	TAAR[y]
	(%)	(cm/h)
Continuous	85	1.40
20 min	87	0.73
40 min	89	0.50
60 min	91	0.38
Significance[z]		
Linear	0.001	—
Quadratic	0.10	—
Cubic	0.10	—

[z]n = 42.
[y]Time averaged application rate.

Regression models using data from the 60 min interval treatment (first interval expt.) showed that leachate volume increased as PSWC and volume of water applied increased for both irrigation methods. Models were:

Continuous:

$$VOL_L = (0.0662 \times PSWC^2) + (0.0075 \times PSWC \times VOL_A) - 594 \quad R^2 = 0.89,\ P = 0.0001$$

Cyclic:

$$VOL_L = (0.0643 \times PSWC^2) + (0.0063 \times PSWC \times VOL_A) - 567 \quad R^2 = 0.89,\ P = 0.0001$$

where

VOL_L = leachate volume (ml)
PSWC = PSWC (% of CC; mass basis)
VOL_A = volume of water applied (ml)

and are limited to a pine bark:sand (9:1, by vol) substrate, a PSWC range of 72 to 94%, and a VOL_A range of 125 to 610 ml. Predicted leachate volumes for a combination of PSWC and application volumes (Table 6) demonstrated the substrate-application volume relationship. These equations can also be used to predict the maximum volume of water to apply (for a particular PSWC) that results in a zero leaching fraction (LF; volume leached ÷ volume applied). Understanding and implementation of this relationship into irrigation schedules would allow growers to greatly reduce water and nutrient leaching from containers.

Irrigating at a low LF potentiates a toxic nutrient accumulation in the substrate. However, leachate EC values at the 300 ml (81% CC) deficit in our study were lower than values indicative of nutrient accumulation and plant injury (15). Ku and Hershey (10) showed a decrease in shoot dry mass for *Pelargonium* x *hortorum* (L.H. Baily) at a LF of 0 and 0.1 compared to 0.2 and 0.4, however, there were no differences in plant appearance. Yelanich and Biernbaum (20) reported that reducing LF and the fertilizer solution concentration resulted in poinsettia (*Euphorbia pulcherrima* Wild. ex Klotzsch) quality equivalent to conventional practices of a high LF and a high fertilizer solution concentration. Thus, the combination of low LF and low fertilizer application rates would result in the same nutrient supply to plants as with a high LF and high fertilization rates.

Table 6. Predicted volume of water leached for cyclic and continuous irrigation as influenced by irrigation volume and substrate pre-irrigation water content (% of container capacity).

Vol applied	Vol leached (ml)			
	Pre-irrigation water content (% CC)			
(ml)	73	80	87	94
	Cyclic			
125	0	0	0	75
250	0	0	57	149
375	0	34	125	223
	Continuous			
125	0	0	0	79
250	0	0	70	167
375	0	55	152	255

Results of the above experiments demonstrated that WAE was a function of PSWC, the volume of water applied, and WAR. Increases in WAE can be expected if growers decrease WAR by applying water cyclically or using a sprinkler system with a low application rate. WAE can also be increased if irrigation volume is adjusted on a daily basis according to the PSWC so that the amount applied does not exceed the substrate water holding capacity. When growers irrigate on a daily basis, irrespective of the PSWC, excessive water and nutrients exit the container.

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