Cyclic Irrigation Increases Irrigation Application Efficiency and Decreases Ammonium Losses[1]

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Abstract

Cyclic irrigation using pressure compensated drip emitters was evaluated for irrigation application efficiency, nutrient efficacy, and plant growth. The experiment, a RCBD with four replications was conducted in a simulated nursery using high volumes of irrigation which are common in container-grown ornamental nurseries in the southeastern United States. A container-grown plant production area, subdivided into 16 separate plots, allowed for the collection of all irrigation water leaving each plot. *Rudbeckia fulgida* Ait. 'Goldsturm' and *Cotoneaster dammeri* Schneid. 'Skogholm' plants were potted into 3.8 liter (#1) containers in a pine bark:sand substrate (8:1 by vol) and irrigated with either 900 ml (1.2 in) of water applied once a day [900 ml (1×)], 450 ml (0.62 in) applied in two cycles [450 ml (2×)], 300 ml (0.41 in) applied in three cycles [300 ml (3×)], or 150 ml (0.21 in) applied in six cycles [150 ml (6×)]. A cycle consisted of a one-hour rest interval between each irrigation allotment. At 8:00 AM daily, volume of effluent from each plot was measured and a sub-sample of the effluent was analyzed for NO_3-N, NH_4-N, and P. Cycled irrigation (2×, 3×, 6×) reduced volume of effluent, increased irrigation application efficiency [(irrigation volume applied – volume leached) ÷ volume applied], and decreased total NH_4-N (mg) losses compared to the 900 ml (1×) application. Cycled irrigation (2×, 3×, 6×) did not differ in effluent volume or irrigation application efficiency. However, the 450 ml (2×) treatment had greater total NH_4-N losses compared to 300 ml (3×) and 150 ml (6×) treatments. Irrigation treatments did not affect NO_3 or P losses. Irrigation application efficiency over the course of the experiment averaged 0.52 for cyclic irrigation applications (2×, 3×, 6×), a 38% improvement over the 900 ml (1×) standard application. Depending on irrigation treatment, 89% to 104% of the 3.0 g of N applied was recovered. Nitrogen efficiency averaged 89% and 88% for cotoneaster and rudbeckia, respectively. Of the 0.34 g of P applied, 43.4% was recovered. Phosphorus efficiency averaged 29% for both species. Growth, nutrient concentration, and nutrient content of cotoneaster or rudbeckia were not affected by irrigation treatments.

Index words: runoff, effluent, nutrient contamination, container production, plant growth, nitrogen, phosphorus, and nutrient budgets.

Species used in this study: cotoneaster (*Cotoneaster dammeri* Schneid. 'Skogholm') and rudbeckia (*Rudbeckia fulgida* Ait. 'Goldsturm').

Significance to the Nursery Industry

Even with high irrigation volumes, cycled irrigation improved irrigation application efficiency and NH_4-N retention in the containerized plant production system used in this experiment. Irrigation application efficiency was improved 38% with cycled irrigation over a one-time application. Dividing daily water allotments into two applications with one hour between each application maximized irrigation application efficiency when 900 ml (1.2 in) of water was applied to a 3.8 liter (#1) container. Two one-hour rest intervals were required between irrigation applications to minimize NH_4-N losses. Thus, it appears that growers in the southeastern United States can increase irrigation efficiency and reduce NH_4 losses with minimal changes in their current irrigation practices. However, to reduce leaching losses of mobile anions such as NO_3 and P will require a reduction in irrigation volume.

Introduction

Pine bark based container substrates, common in the southeastern United States, have low moisture retention properties; therefore, one or more daily irrigations are required to maximize plant growth during the growing season. Restrictions that reduce or eliminate irrigation runoff may be forthcoming for the nursery industry. Thus, concerns with water-use and nutrient contaminated runoff have forced many nurseries to search for 'best management practices' to improve irrigation efficiency (17).

Pine bark substrates have low cation exchange capacities (CEC) and anion exchange capacities (AEC) which can lead to nutrient leaching losses. Demonstrating the low CEC and AEC of pine bark substrates, Foster et al. (4) concluded that 90% of leachable NH_4 and NO_3 was lost after four applications of 2.5 cm (1 in.) of water. To reduce N losses many growers have switched to controlled release fertilizers (CRFs), however, N losses from CRFs can vary from 12% to 29% depending upon nutrient sources, control release mechanisms, and irrigation regime (5, 11). Phosphorus is also readily leached from container substrates (8, 19). Warren et al. (16) reported P losses from 8% to 27% depending upon the P source. Complete nutrient budgets which account for the fate of applied nutrients are lacking for the container-grown nursery crop industry. These budgets are needed to address environmental concerns over the efficiency of current water and fertilization practices. In addition, recommendations for alterations in current irrigation and fertilization management practices need to be supported by balance sheets charting the fate of applied N and P.

Research has shown that cyclic irrigation, where the daily water allotment is applied in a series of cycles comprised of an irrigation and a resting interval (6, 9), can improve irrigation application efficiency and nutrient efficacy (retention). Cyclic irrigation may improve irrigation application efficiency by allowing time for water to move through the

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micropore system of container substrate (6). Lamack and Niemiera (7) reported cyclic irrigation improved irrigation application efficiency by 24% compared to applying the water allotment in one application. Concurrent with increased irrigation application efficiency, Karam (6), working in a laboratory, reported a 30% decrease in NO_3 and NH_4 leached with cyclic irrigation compared to a single application. Data reported by Lamack and Niemiera (7) and Karam (6) were based on low volumes of irrigation and liquid fertilizer applications. This research was conducted in a stimulated nursery using high volumes of irrigation water and CRF, management practices common to the southeastern United States, to evaluate the effects of cyclic irrigation on irrigation application efficiency, nutrient efficacy, and plant growth.

Materials and Methods

The experiment, a RCBD with four replications and two species, *Rudbeckia fulgida* 'Goldsturm' and *Cotoneaster dammeri* 'Skogholm', was conducted at the North Carolina State University Horticulture Field Laboratory in Raleigh during the summer (June to September) of 1993. A container-grown plant production area, subdivided into 16 separate plots, allowed for the collection of all irrigation water leaving each plot. Plots were 7.6 × 1.8 m (25 × 6 ft) with a 2% slope and were lined with black plastic. Fifteen containers of each species were grouped together in each plot for a total of 60 containers of each species in each treatment. Treatments included 900 ml (1.2 in) of water applied once a day [900 ml (1×)], 450 ml (0.62 in) applied in two cycles [450 ml (2×)], 300 ml (0.41 in) applied in three cycles [300 ml (3×)], and 150 ml (0.21 in) applied in six cycles [150 ml (6×)]. A cycle consisted of a one-hour rest interval between each irrigation allotment. Total volume of irrigation was divided into increasingly smaller volumes of application based on previous research which indicated that cyclic irrigation application efficiency increased with decreasing application volume and increasing time between applications (6). Irrigation water was applied via pressure compensated drip emitters (Woodpecker, WPC8; Netafim Irrigation Inc., Valley Stream, NY) at a rate of 150 ml/min (0.21 in/min). Irrigation was applied between 12:00 and 5:00 AM.

Plants were potted into 3.8 liter (#1) containers in a pine bark:sand (8:1 by vol) substrate, top dressed with 13 g (0.46 oz) of an experimental CRF 23N–2.6P–8.4K (23–6–10) (The Scotts Company, Marysville, OH), and amended on a m^3 (yd^3) basis with 1.8 kg (4 lbs) dolomitic limestone and 0.9 kg (1.5 lbs) micronutrient fertilizer (Micromax, The Scotts Company). The N and P sources were polymer coated urea and uncoated monoammonium phosphate, respectively. Fertilizer applications resulted in 3.0 g N and 0.34 g P_2O_5 being applied to each container. Fertilizer was top dressed at initiation (Day 0; June 1, 1993) and the study was terminated 100 days later. Physical properties of the substrate (percent volume at drainage) were total porosity: 78%, air space: 16%, container capacity: 62%, unavailable water: 31%, and available water: 30%. Physical properties were determined as described in Tyler et al. (15).

Chemical properties. At 8:00 AM daily, volume of effluent from each plot (four per treatment) was measured and a sub-sample of the effluent was collected, filtered, and analyzed for NO_3-N (1), NH_4-N (2), and P (10) using a spectrophotometer (Spectronic 1001 Plus, Milton Roy Co., Rochester, NY). Urea in effluent was hydrolyzed to NH_4 with urease (Sigma Chemical Company, St. Louis, MO) prior to NH_4-N analysis (2).

At harvest, all fertilizer prills from five randomly chosen containers per species per plot (total of 20 containers/species/treatment) were removed and a sample of the substrate was collected. Fertilizer prills were mixed in a blender with 100 ml (3.5 oz) distilled, deionized water for one minute. This solution was diluted to 500 ml (17.5 oz) total volume with distilled, deionized water. Nitrate-N, NH_4-N, and P analyses were conducted as described for effluent analysis. Substrate samples were dried at 62C (144F) for 5 days, ground in a hammer mill and sieved through a 18 mesh (1 mm) screen. Each substrate sample (1.25 g) was combusted at 490C (914F) for 6 hr. The resulting ash was dissolved in 10 ml (0.03 oz) 6 N HCl and diluted to 50 ml (1.5 oz) with distilled, deionized water. Phosphorus concentrations were determined with an inductively coupled plasma emissions spectrophotometer (P-2000, Perkin Elmer, Norwalk, CT). Nitrogen concentrations were determined using 10 mg (0.03 oz) samples in a CHN elemental analyzer (Perkin Elmer 2400).

Substrate solution was extracted from two cotoneaster and two rudbeckia containers per plot (total of eight containers/species/treatment) via the pour-through nutrient extraction method (18) 28 days after initiation (DAI) (June 29), 51 DAI (July 27), and 99 DAI (September 8). The pour-through sample was obtained by pouring 150 ml (5 oz) of distilled water on the substrate surface 2 hr after irrigation and collecting leachate. Leachates were filtered through Whatman #1 paper and analyzed for NO_3-N, NH_4-N, and P as described for effluent analysis.

Plant growth. At harvest, shoots (aerial tissue) from five randomly chosen containers per species per plot (total of 20 containers/species/treatment) were removed and roots were placed over a screen and washed with a high pressure water stream to remove substrate. Shoots and roots of each species were dried at 62C (144F) for 5 days and weighed. After drying, shoots and roots were ground in a Wiley mill to pass a 40 mesh (0.425 mm) screen. At treatment initiation (Day 0), 10 plants were harvested and separated into shoots and roots. These plants were handled as previously described to determine initial shoot dry weight, root dry weight and nutrient concentration. Tissue analyses were conducted as described for substrate analysis.

All variables were tested for differences using analysis of variance procedures (ANOVA) (12). All treatment comparisons were made by single degree of freedom linear contrast tests and were considered significant at $p \leq 0.05$. The following variables were determined as follows: plant nutrient content = plant part dry weight (g) × plant part nutrient concentration (percent dry weight); nutrient efficiency = [plant nutrient content (g) ÷ (nutrient content (g) in effluent + plant + substrate)]. Nutrient content of fertilizer prills was not included in nutrient efficiency calculations since this is related to remaining nutrient supplying power of the fertilizer. Initial N and P contents of cotoneaster and rudbeckia shoots and roots were subtracted from plant nutrient content data prior to nutrient efficiency calculations. Irrigation application efficiency = [(irrigation volume applied − volume leached) ÷ volume applied]. This definition of irrigation application efficiency relates volume of irrigation water retained by the container substrate to volume of irrigation applied.

Table 1. **Effect of irrigation treatment on cumulative effluent losses, fertilizer prill, and irrigation efficiency, 100 days following fertilization. All data presented on a 3.8 liter container basis.**

Irrigation[z] treatment	Effluent[y] Volume (liters)	Effluent[y] NH_4-N (mg)	Prill[x] NH_4-N (g)	Irrigation efficiency[w]
900 ml (1×)	43.9	51.2	1.64	0.38
450 ml (2×)	33.8	32.1	1.46	0.52
300 ml (3×)	31.8	26.0	1.34	0.55
150 ml (6×)	36.1	25.6	1.34	0.49
Contrast[v]				
900 vs. 450	0.002	0.001	0.050	0.002
900 vs. 300	0.001	0.001	0.005	0.001
900 vs. 150	0.009	0.001	0.005	0.009
450 vs. 300	NS	0.050	NS	NS
450 vs. 150	NS	0.040	NS	NS
300 vs. 150	NS	NS	NS	NS

[z]Treatments included 900 ml of water applied once a day [900 ml (1×)], 450 ml of water applied in two cycles [450 ml (2×)], 300 ml of water applied in three cycles [300 ml (3×)], and 150 ml of water applied in six cycles [150 ml (6×)]. A cycle consisted of a one hour rest interval between each irrigation allotment.

[y]Average of 120 containers per irrigation treatment.

[x]Average of 40 containers per irrigation treatment.

[w][(ml applied – ml lost) ÷ ml applied].

[v]Treatment comparisons made by single degree of freedom linear contrast tests and were considered nonsignificant (NS) at $p > 0.05$, p value stated otherwise.

Data for days where rainfall events ≥ 0.13 cm (0.05 in.) were deleted from the cumulative effluent ANOVA analyses as volume of effluent generated by irrigation could not be distinguished from that generated by rainfall. As a result, data for 17 days out of the 100 day experiment were deleted from the cumulative effluent data set.

Results and Discussion

Irrigation application efficiency and nutrient efficacy. The 900 ml (1×) treatment produced a greater volume of effluent, higher total NH_4-N losses, and lower irrigation efficiency compared to cycled irrigation (2×, 3×, 6×) (Table 1). Cycled irrigation (2×, 3×, 6×) did not differ in volume of effluent or irrigation efficiency. For the 100 days, irrigation efficiency averaged 0.52 for the cycled irrigation treatments (2×, 3×, 6×), an improvement of 38% over the 900 ml (1×) standard application. Thus, it appears, under these experimental conditions, one one-hour rest interval between two 450 ml applications was sufficient to allow for movement of water through the micropore system of the substrate, maximizing irrigation application efficiency. This is in contrast to Lamack and Niemiera's (7) and Karam's (6) results where irrigation application efficiency increased with increasing cycled applications. These differences could be related to volume of irrigation and method and rate of irrigation application.

Cumulative NH_4-N in the effluent increased linearly for each treatment over the 100 days, suggesting rates of fertilizer release always exceeded plant uptake (Fig. 1). Working

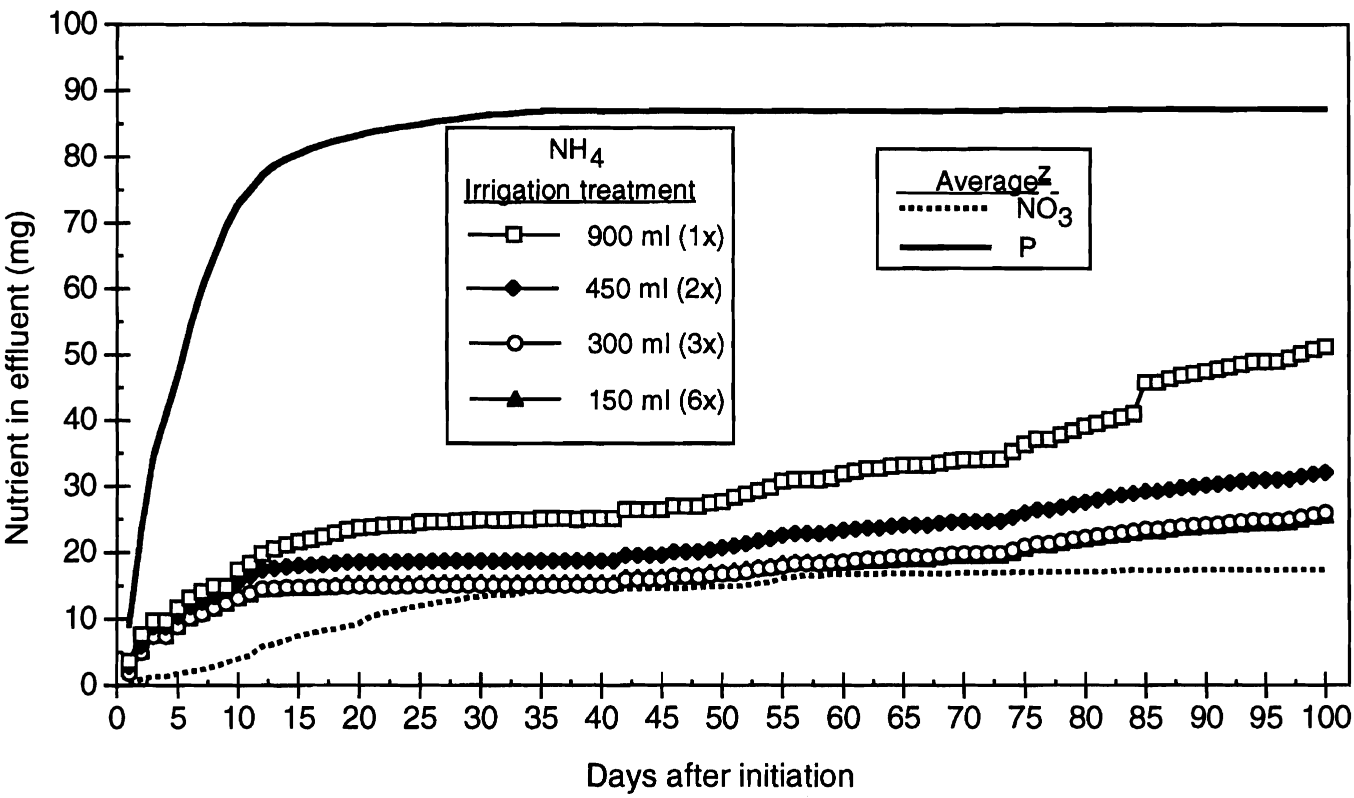

Fig. 1. **Cumulative nutrient losses per 3.8 liter container in effluent through 100 days after initiation (rain events excluded). Irrigation treatments included 900 ml of water applied once a day [900 ml (1×)], 450 ml of water applied in two cycles [450 ml (2×)], 300 ml of water applied in three cycles [300 ml (3×)], and 150 ml of water applied in six cycles [150 ml (6×)]. A cycle consisted of a one hour rest interval between each irrigation allotment [NH_4: 900 ml (1×), $y = 0.36x + 12.36$, $r^2 = 0.93$; 450 ml (2×), $y = 0.19x + 12.01$, $r^2 = 0.91$; 300 ml (3×), $y = 0.15x + 10.0$, $r^2 = 0.90$; 150 ml (6×), $y = 0.15x + 10.36$, $r^2 = 0.89$; NO_3: $y = -0.003x^2 + 0.45x + 0.99$, $r^2 = 0.96$; and P: $y = -0.01x^2 + 1.27x + 51.85$, $r^2 = 0.62$].**

[z]NO_3-N and P content were not effected by irrigation treatment. Therefore, NO_3-N and P content were averaged over irrigation treatment.

Table 2. Effect of irrigation treatment on grams of N recovered in effluent, substrate, irrigation water, fertilizer prills, and plant shoots and roots, 100 days after fertilizer application. All data presented on a 3.8 liter container basis.

Variable	Irrigation treatment[z] 900 ml (1×)		450 ml (2×)		300 ml (3×)		150 ml (6×)	
	Nitrogen							
	g	%[y]	g	%	g	%	g	%
Effluent								
NH_4-N	0.11	8	0.10	7	0.09	6	0.09	7
NO_3-N	0.04	2	0.03	2	0.03	2	0.03	2
Substrate	0		0		0		0	
Irrigation water	0.03	2	0.02	1	0.02	1	0.02	2
Fertilizer prills	1.64		1.46		1.34		1.34	
Cotoneaster								
shoots	1.11	75	1.07	74	1.10	76	0.98	74
roots	0.21	14	0.21	15	0.21	14	0.20	16
Recovered N[x]	3.13		2.90		2.79		2.67	
N efficiency[w]		89		89		90		90
Rudbeckia								
shoots	0.61	54	0.68	54	0.67	51	0.69	53
roots	0.35	31	0.42	33	0.52	39	0.48	37
Recovered N	2.77		2.71		2.67		2.66	
N efficiency[w]		85		88		90		89

[z]Treatments included 900 ml of water applied once a day [900 ml (1×)], 450 ml of water applied in two cycles [450 ml (2×)], 300 ml of water applied in three cycles [300 ml (3×)], and 150 ml of water applied in six cycles [150 ml (6×)]. A cycle consisted of a one hour rest interval between each irrigation allotment.

[y]Percentage based on N (g) measured in effluent + substrate + irrigation water + plant.

[x]Total recovered N (effluent + substrate + irrigation water + plant + fertilizer prill) (N in rainfall included).

[w]N efficiency = [g N in plant ÷ (g N in effluent + substrate + irrigation water + plant)] × 100.

with composted turkey litter (an organic fertilizer) and two commercial synthetic CRFs (a resin-coated NH_4NO_3 and a urea), Warren et al. (16) reported similar linear cumulative NH_4 losses in effluent from days 18 to 100. Total NH_4-N lost over the 100 days was greater for the 900 ml (1×) treatment compared to any of the cycled applications (2×, 3×, 6×) (Table 1). In addition, the 450 ml (2×) treatment had greater total NH_4-N losses than 300 ml (3×) and 150 ml (6×) treatments. This suggests that two one-hour rest intervals (300 ml 3×) were required to recharge the cation exchange of the substrate, minimizing NH_4-N leaching. This is supported by the nonsignificant contrast between 300 ml (3×) and 150 ml (6×) treatments.

Table 3. Grams of P recovered in effluent, substrate, irrigation water, fertilizer prills, and plant shoots and roots, 100 days after fertilizer application. All data presented on a 3.8 liter container basis.

Variable	P g	%[z]
Effluent	0.102	68
Substrate	0.005	3
Irrigation water	0	
Fertilizer prills	0	
Cotoneaster		
shoots	0.029	19
roots	0.010	7
Recovered P[y]	0.150	
P efficiency[x]		26
Rudbeckia		
shoots	0.039	26
roots	0.004	3
Recovered P	0.150	
P efficiency		29

[z]Percentage based on P (g) measured in the effluent + substrate + irrigation water + plant.

[y]Total recovered P (effluent + substrate + irrigation water + plant + fertilizer prill + rainfall).

[x]P efficiency = [g P in plant ÷ (g P in effluent + substrate + irrigation water + plant)] × 100.

Irrigation treatment did not affect total NO_3-N or P effluent losses (data not shown). Average cumulative NO_3-N and P losses are shown in Fig. 1. In addition, irrigation treatment did not affect substrate solution concentration of NO_3 or P as determined by the pour-though extraction at any sampling date (28 DAI, 51 DAI, and 99 DAI) (data not shown). Nitrogen and P remaining in the substrate at 100 DAI was also not affected by irrigation treatments (Tables 2 and 3). Even though cyclic irrigation increased irrigation application efficiency, with high irrigation volumes leaching of mobile anions such as NO_3 and P still occurred resulting in similar losses in the effluent. This is supported by results reported by Tyler et al. (14) who stated that NO_3 and P losses were decreased if daily irrigation volume was reduced to match daily water losses from the substrate.

Ammonium and P remaining in fertilizer prills were not affected by the species × irrigation treatment interaction; therefore, data were averaged over species. Irrigation treatment affected NH_4 remaining in the fertilizer prills at 100 DAI (Table 1) but did not affect P (Table 3). More NH_4 remained in the fertilizer prills of 900 ml (1×) irrigated containers compared to cycled irrigated (2×, 3×, 6×) containers. This difference may be due to a lower water potential in the upper zone of the 900 ml (1×) irrigated substrate which reduced movement of water into the fertilizer prill. Cycled irrigation (2×, 3×, 6×) did not affect the NH_4 content of the fertilizer prills at 100 DAI. Nitrate content in fertilizer prills was below detection limits as the N source was urea (data not shown).

Plant response. Irrigation treatment did not affect shoot or root dry weight of cotoneaster or rudbeckia (data not shown). In addition, tissue N and P concentrations (data not shown) and contents (Tables 2 and 3) for both species were not affected by irrigation treatment, suggesting that nutrient uptake was similar regardless of irrigation treatment.

N and P budgets. Depending on irrigation treatment, 89% to 104% of the 3.0 g of N applied to the substrate of cotoneaster and rudbeckia plants was recovered (Table 2). Nitrogen from rainfall and mineralization of organic substrate was not deducted from N recovery calculations which may have resulted in percentages > 100. Even though irrigation treatment affected total NH_4-N losses, it did not affect N efficiency which averaged 89% and 88% for cotoneaster and rudbeckia, respectively. This is further supported by the nonsignificant treatment effect for tissue N content in both species. Thus, even though cyclic irrigation improved water retention by 38%, it did not enhance nutrient accumulation by the plant. Using our definition of N efficiency and data collected by Stewart et al. (13), a 15% N efficiency was calculated when ligustrum (*Ligustrum japonicum*) was grown with liquid fertilization. In a simulated nursery situation with 1.2 cm of water applied daily by overhead irrigation, Warren et al. (16) reported resin-coated NH_4NO_3 and urea, both CRF's, provided a 56% N efficiency for azalea (*Rhododendron* sp. 'Sunglow'). Nitrogen efficiency will vary depending upon irrigation volume, method of irrigation application, form of nutrient and fertilizer applied, effectiveness of controlled release technology, and efficiency of plant uptake.

Of the N released from fertilizer prills, 8% to 10% was lost in the effluent (Table 2). Fare (3) reported 63% of 6.0 g N applied as Osmocote 17N–3.0P–10K (17–7–12, resin-coated NH_4NO_3) was lost as NO_3-N in the effluent with a single irrigation application compared to 46% for cycled irrigation. Differences in NO_3-N lost in effluent may be due to fertilizer rate and source. Shoots of cotoneaster contained about five times the N found in roots (Table 2). Rudbeckia had a more equal distribution of N between shoots and roots.

In contrast to N, only 43% and 44% of the 0.34 g of P applied was recovered for cotoneaster and rudbeckia, respectively (Table 3). This was surprising, since P does not volatilize and has been reported to leach readily from pine bark substrates which have low P fixation capacities. However, Warren et al. (16) working in a simulated nursery also reported low P recovery percentages. The effluent fraction contained about two-thirds of the recovered P (Table 3). The P source was uncoated monoammonium phosphate resulting in the majority of P being lost within 15 DAI (Fig. 1). Although cycled irrigation reduced total cumulative volume of effluent, P efficiency (average = 29%) was not improved over the 900 ml (1×) treatment suggesting that leaching was still adequate to remove P from the substrate solution. Warren et al. (16) reported 43% P efficiency with ammonium and calcium phosphates where P sources were contained in a resin-coated prill. Tyler et al. (14) demonstrated that P efficiency can be improved by reducing irrigation volume.

Cycled irrigation improved irrigation application efficiency and NH_4-N efficacy in the container-grown production system used in this experiment. With high irrigation volumes, irrigation application efficiency was improved 38% with cycled irrigation over the one-time application. In contrast to previous reports, dividing the plant's daily water allotment into two cycles of irrigation maximized irrigation application efficiency. However, two one-hour rest intervals [300 ml (3×)] were required to maximize NH_4-N efficacy. Nutrient contaminated effluent leaving a nursery site can be reduced with the use of cyclic irrigation. However, reduction in leaching losses of mobile anions such as NO_3 and P requires lower irrigation volumes.

Literature Cited

1. Calaldo, D.A., M. Haroon, L.E. Schrader, and V.L. Youngs. 1975. Rapid colorimetric determination of nitrate in plant tissue. Commun. Soil Sci. Plant Anal. 6:71–80.

2. Chaney, A.L. and E.P. Marbach. 1962. Modified reagents for determination of urea and ammonia. Clin. Chem. 8:130–132.

3. Fare, D.C. 1993. The influence of irrigation practices on nitrate-nitrogen leached from container-grown ornamentals. Ph.D. Dissertation. Auburn University, Auburn, AL.

4. Foster, W.J., R.D. Wright, M.M. Alley, and T.H. Yeager. 1983. Ammonium adsorption on a pine-bark growing medium. J. Amer. Soc. Hort. Sci. 108:548–551.

5. Hershey, D.R. and J.I. Paul. 1982. Leaching-losses of nitrogen from pot chrysanthemums with controlled-release or liquid fertilization. Scientia Hortic. 17:145–152.

6. Karam, N.S. 1993. Overhead sprinkler irrigation strategies to reduce water and nitrogen loss from container-grown plants. Ph.D. Dissertation. Virginia Polytechnic Institute and State University, Blacksburg.

7. Lamack, W.F. and A.X. Niemiera. 1993. Application method affects water application efficiency of spray stake-irrigated containers. HortScience 28:625–627.

8. Marconi, D.J. and P.V. Nelson. 1984. Leaching of applied phosphorus in container media. Scientia Hortic. 22:275–285.

9. Mostaghimi, S. and J.K. Mitchell. 1983. Pulsed irrigation effects on soil moisture distribution. Water Resources Bul. 19:605–612.

10. Murphy, J. and J.P. Riley. 1962. A modified single solution method for the determination of phosphate in natural waters. Anal. Chim. Acta. 27:31–36.

11. Rathier, T.M. and C.R. Frink. 1989. Nitrate in runoff water from container grown juniper and Alberta spruce under different irrigation and N fertilization regimes. J. Environ. Hort. 7:32–35.

12. SAS Institute. 1985. SAS User's Guide: Statistics. Version 5 Edition. SAS Institute, Cary, NC.

13. Stewart, J.A., L.J. Lund, and R.L. Branson. 1981. Nitrogen balances for container-grown privet. J. Amer. Soc. Hort. Sci. 106:565–569.

14. Tyler, H.H., S.L. Warren, and T.E. Bilderback. 1996. Reduced Leaching Fractions Improve Irrigation Use Efficiency and Nutrient Efficacy. J. Environ. Hort. 14:199–204.

15. Tyler, H.H., S.L. Warren, T.E. Bilderback, and W.C. Fonteno. 1993. Composted turkey litter: I. Effect on chemical and physical properties of a pine bark substrate. J. Environ. Hort. 11:131–136.

16. Warren, S.L., T.E. Bilderback, and H.H. Tyler. 1995. Efficacy of three nitrogen and phosphorus sources in container-grown azalea production. J. Environ. Hort. 13:147–151.

17. Williams, R. 1990. A quick look at solutions to nitrate runoff. Greenhouse Grower 8:112, 114.

18. Wright, R.D. 1986. The pour-through nutrient extraction procedure. HortScience 21:227–229.

19. Yeager, T.H. and R.D. Wright. 1982. Phosphorus requirements of *Ilex crenata* Thunb. cv. Helleri grown in a pine bark medium. J. Am. Soc. Hort. Sci. 107:558–562.