Irrigation Volume, Application, and Controlled-release Fertilizer II. Effect on Substrate Solution Nutrient Concentration and Water Efficiency in Containerized Plant Production[1]

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Abstract

Rooted cuttings of *Cotoneaster dammeri* Schneid 'Skogholm' and seedlings of *Rudbeckia fulgida* Ait. 'Goldsturm' were potted into 3.8 liter (4 qt) containers in a pine bark:sand (8:1 by vol) substrate incorporated with 3.5 g (0.12 oz) N per container provided by one of the following five controlled-release fertilizers (CRFs): Meister 21N–3.5P–11.1K (21–7–14), Osmocote 24N–2.0P–5.6K (24–4–7), Scotts 23N–2.0P–6.4K (23–4–8), Sustane 5N–0.9P–3.3K (5–2–4) or Woodace 21N–3.0P–9.5K (21–6–12). Two hundred ml (0.3 in), 400 ml (0.6 in), 800 ml (1.1 in) or 1200 ml (1.7 in) of water was applied once daily (single) or in two equal applications with a 2 hr interval between applications (cyclic). Substrate solutions were collected from containers of cotoneaster 15, 32, 45, 60, 74, 90, 105, and 119 days after initiation (DAI). Irrigation efficiency [(water applied – water leached) ÷ water applied] was determined on the same days. Cyclic application improved irrigation efficiency at 800 ml (1.1 in) and 1200 ml (1.7 in) ≈ 27% compared to a single application. Irrigation efficiencies averaged over the season were 95%, 84%, 62%, and 48% for cotoneaster and 100%, 90%, 72%, and 51% for rudbeckia at 200 ml (0.3 in), 400 ml (0.6 in), 800 ml (1.1 in) and 1200 ml (1.7 in), respectively. NH_4-N and NO_3-N and PO_4-P concentrations in substrate solution decreased with increasing irrigation volume regardless of CRF. Substrate NH_4-N concentration decreased throughout the season with most CRFs below 5 mg/liter by 90 DAI. CRFs mainly affected substrate NH_4-N and NO_3-N concentrations when irrigated with 200 ml (0.3 in) or 400 ml (0.6 in). Substrate NH_4-N, NO_3-N, and PO_4-P solution concentrations were similar for all CRFs at irrigation volume of 1200 ml (1.7 in). Osmocote, Scotts, and Woodace maintained relatively constant substrate solution levels of PO_4-P through 60 DAI. By 90 DAI, substrate PO_4-P levels were similar regardless of irrigation volume or CRF. Substrate PO_4-P concentrations were never in the recommended range of 5 to 10 mg/liter when irrigated with 800 ml (1.1 in) or 1200 ml (1.7 in) regardless of CRF. Solution pH remained in the recommended range of 5.0 to 6.0 for all irrigation volumes and CRFs throughout the entire study with the exception of Sustane.

Index words: *Cotoneaster dammeri* 'Skogholm', *Rudbeckia fulgida* 'Goldsturm', nutrient content, irrigation efficiency, leaching, nitrogen, phosphorus.

Significance to the Nursery Industry

Growers of containerized nursery crops regulate irrigation and fertilization regimes to achieve maximum plant growth. Since the volume of water required to maximize growth of containerized plants is poorly understood, growers often utilize high volumes of irrigation resulting in low irrigation efficiency and reduced nutrient concentration of the substrate solution. In this study, increasing irrigation volume decreased substrate NH_4-N, NO_3-N, and PO_4-P solution concentrations regardless of CRF. However, decreasing substrate nutrient concentrations did not reduce plant growth for the better preforming CRFs. Our data supports the current substrate N recommendation of 15 to 25 mg/liter if total N is utilized in lieu of NO_3-N. Substrate PO_4-P concentrations were seldom in the recommended range of 5 to 10 mg/liter when irrigated with 800 ml (1.1 in) or 1200 ml (1.7 in) regardless of CRF suggesting that adequate substrate P concentration could be lowered without sacrificing growth. Osmocote, Scotts, and Woodace produced 90% of maximum top weight over a wide range of irrigation volumes [≈ 550 ml (0.8 in) to 1200 ml (1.7 in)] and subsequent substrate nutrient solution concentrations. This wide range of irrigation volume and substrate nutrient solution concentrations provides the grower much flexibility and suggests that adequate growth is possible with reduced resources.

Introduction

To maximize growth of containerized nursery crops, growers must maintain adequate water and nutrients (5, 24). Since the volume of water required to maximize growth of containerized plants is poorly understood, growers often utilize high volumes of irrigation. Due to low cation and anion exchange capacities of pine bark substrates, which is the common substrate in the southeastern United States, high irrigation volumes reduce the nutrient concentration of the substrate solution. Foster et al. (6) reported that 90% of NO_3-N and NH_4-N were leached from a pine bark substrate with four irrigations of 2.5 cm (1 in). Phosphorus is also leached easily from pine bark substrates (11, 19). Therefore, growers use controlled-released fertilizer (CRFs) that are designed to

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release nutrients over time to maintain adequate substrate nutrient concentrations and improve nutrient efficiencies (16). Resin-, polymer-, and sulfur-coated nutrients along with urea and isobutylidene-diurea comprise the majority of CRFs used by the nursery industry (16). There is currently little information, however, on the ability of CRFs to maintain adequate substrate nutrient concentrations over a range of irrigation volumes (9, 13).

Initial recommendations for substrate solution concentrations of N, P, and K were 50 to 100 mg/liter, 5 to 10 mg/liter, and 25 to 50 mg/liter, respectively with a pH of 5.0 to 6.0 (24). Although, little research has been reported on determining adequate substrate solution concentrations for CRFs (14, 17), N and K recommendations have been recently lowered to 15 to 25 mg NO_3-N/liter and 10 to 20 mg K/liter (18). Research using solution culture has demonstrated that plants meeting commercial growth expectations can be produced at very low nutrient concentrations if the levels are sustained, i.e., not allowed to deplete or fluctuate greatly (3, 4). Since CRFs are designed to maintain substrate nutrient solution concentrations, adequate substrate nutrient levels for CRFs might be expected to be even lower than the new recommendations (16, 24).

A companion paper (8) reported differences in growth and nutrient content of *Cotoneaster dammeri* Schneid 'Skogholm' and *Rudbeckia fulgida* Ait. 'Goldsturm' when grown with varying irrigation volume and CRFs. Maximum top dry weight of cotoneaster was obtained with 612 ml (0.8 in), 921 ml (1.3 in), 928 ml (1.3 in), 300 ml (0.6 in), or 909 ml (1.3 in), while maximum top dry weight of rudbeckia was found at 1160 ml (1.6 in), 931 ml (1.3 in), 959 ml (1.3 in), 1091 ml (1.5 in), or 1009 ml (1.4 in) grown with Meister 21–7–14, Osmocote 24–4–7, Scotts 23–4–8, Sustane 5–2–4 or Woodace 21–6–12, respectively. The objective of this research was to determine the effects of irrigation volume, application, and CRFs on irrigation efficiency, substrate nutrient solution concentration, and pH.

Materials and Methods

The experiment, a split-plot design with three replications and two cultivars, *Rudbeckia fulgida* 'Goldsturm' and *Cotoneaster dammeri* 'Skogholm', was conducted on a gravel pad at the North Carolina State University Horticulture Field Laboratory, Raleigh, during May to September 1994. Main plots were four volumes of irrigation and two methods of irrigation application. Irrigation volumes were chosen based on available water (AW = 783 ml) at container capacity held in a 3.8 liter (4 qt) container filled with a pine bark:sand (8:1 by vol) substrate amended per m^3 (yd^3) with 1.8 kg (4 lb) dolomitic limestone and 0.9 kg (1.5 lb) micronutrient fertilizer (MicroMax, The Scotts Co., Marysville, OH). Physical properties of the substrate are reported in Table 1. All physical property analyses were conducted at the Horticultural Substrates Laboratory according to the procedures outlined in Tyler et al. (20). Irrigation volumes of 0.25AW [200 ml (0.3 in)], 0.5AW [400 ml (0.6 in)], 1.0AW [800 ml (1.1 in)], or 1.5AW [1200 ml (1.7 in)] were applied once daily (single, 7:00 AM) or in two equal applications with a two hr interval between irrigation allotments (cyclic, 5:00 AM and and 7:00 AM). Irrigation was applied using pressure compensated spray stakes (Acu-Spray Stick, Wade Mfg. Co., Fresno, CA) at a rate of 200 ml/min (0.3 in/min). Within each main plot were five subplots consisting of two plants fertilized with one of five CRFs (two plants per replicate for a total of 6 plants per treatment).

Each plant was fertilized at potting (May 23) with 3.5 g N from one of the following fertilizers: Meister 21N–3.5P–11.1K (21–7–14, Helena Chemical Co., Tampa, FL) composed of 0.5% NO_3, 0.7% NH_4, 19.8% polymer-coated urea (referred to as polymer-coated urea), sulfur-coated ammonium phosphate and triple superphosphate (referred to as sulfur-coated P), and potassium nitrate and polymer-coated potassium sulfate (referred to as polymer-coated KS); Osmocote 24N–2.0P–5.6K (24–4–7, The Scotts Co.) consisting of resin-coated 6.6% NH_4, 5.9% NO_3, 11.5% urea (referred to as resin-coated NH_4NO_3), resin-coated ammonium phosphate and calcium phosphate (referred to as resin-coated P), and resin-coated potassium sulfate (referred to as resin-coated K); Scotts 23N–2.0P–6.4K (23–4–8, Southern formulation, The Scotts Co.) composed of polymer-coated urea and ammonium nitrate (referred to as polymer-coated N), polymer-coated ammonium phosphate and calcium phosphate (referred to as polymer-coated P), and polymer-coated potassium sulfate (referred to as polymer-coated K); Sustane 5N–0.9P–3.3K (5–2–4, Sustane Corp., Cannon Falls, MN) containing 0.8% NH_4, 4.2% organic N, organic P, and organic K (referred to as composted turkey litter); or Woodace 21N–3.0P–9.5K (21–6–12, Vigoro Industry, Inc., Fairview Heights, IL) composed of 1% NO_3, 16.5% urea, 3.5% water insoluble N (referred to as urea), noncoated magnesium potassium phosphate (referred to as MgKP), and sulfur-coated potassium sulfate and potassium nitrate (referred to as sulfur-coated K). Fertilizer was weighed for each container and incorporated into the substrate before transplanting.

A container received 400 ml (0.6 in) water daily until experiment initiation on day 0 (May 30). The study was terminated 120 days after initiation (DAI). Irrigation water averaged 0.2 mg NO_3-N/liter, 0.05 mg NH_4-N/liter, 0.06 mg PO_4-P/liter, and pH 6.02.

Substrate solutions were collected from one cotoneaster container per subplot via the pour-through nutrient extraction method (23) 15 DAI (June 14), 32 DAI (July 1), 45 DAI (July 14), 60 DAI (July 29), 74 DAI (August 12), 90 DAI (August 29), 105 DAI (September 12), and 119 DAI (September 26). Pour-through samples were obtained by pouring 150 ml (5 oz) of distilled water on the substrate surface 2 hr

Table 1. Physical properties of pine bark:sand (8:1 by vol) substrate.

Property	Volume (%)
Total porosity[z]	77.79
Air space[y]	16.32
Container capacity[x]	61.47 (1601 ml)[w]
Unavailable water[v]	31.40 (818 ml)[u]
Available water[t]	30.07 (783 ml)[u]
Bulk density (g/cm^3)	0.35

[z]Based upon percent volume of a 7.6 cm core at 0 kPa.

[y]Total porosity – container capacity.

[x]Measured as percent volume of a 7.6 cm core at drainage.

[w]Measured as percentage volume of a 3.8 liter container containing 3.0 liters of substrate.

[v]Based upon percent volume of a 7.6 cm core at 1500 kPa.

[u]Expressed as a percentage of the container capacity volume of a 3.8 liter container containing 3.0 liters of substrate.

[t]Container capacity – unavailable water.

after irrigation (9 AM) and collecting the leachate. Leachates were filtered and analyzed immediately for NO_3-N (2), NH_4-N (1), and PO_4-P (12) using a spectrophotometer (Spectronic 1001 Plus, Milton Roy Co., Rochester, NY). Any urea present in the solution was converted to NH_4 via urease prior to analysis.

Irrigation efficiency {[(water applied – water leached) ÷ water applied] × 100} was determined by collecting leachate from the container by placing a saucer under one plant per subplot for both species. Irrigation efficiency was measured on the same DAI as substrate solutions were collected.

All data were subjected to analysis of variance procedures and regression analysis where appropriate (15). Mean separations were performed via least significant difference (LSD) procedure at P = 0.05. Fertilizer by irrigation volume interaction was significant for all measured variables. All other interactions were nonsignificant.

Results and Discussion

Irrigation efficiency. Cyclic application increased irrigation efficiency ≈ 27% compared to a single application at 800 ml (1.1 in) and 1200 ml (1.7 in) (data not presented).

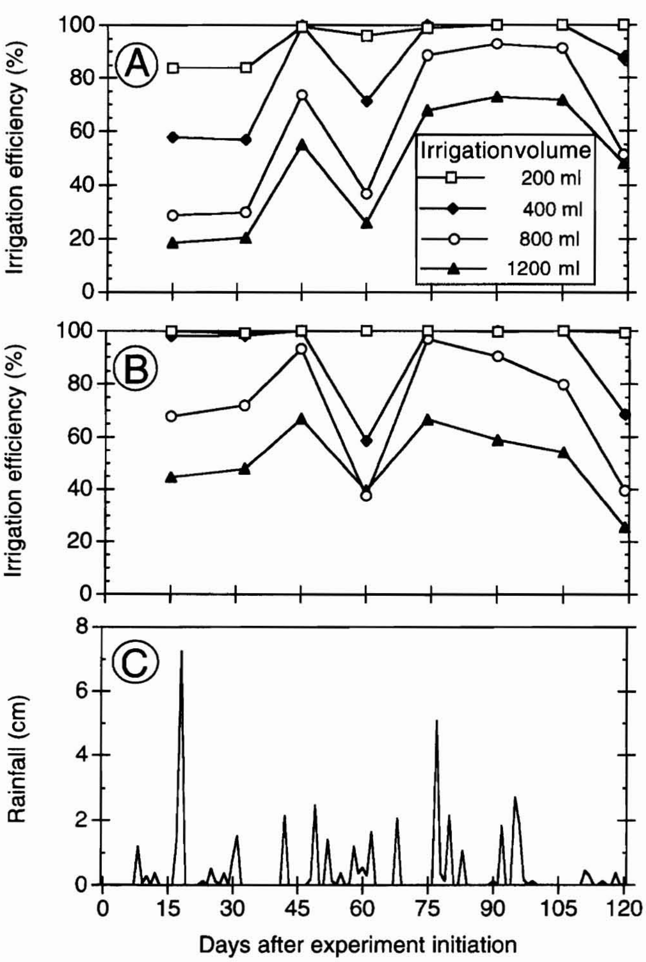

Fig. 1. A. Irrigation efficiency of *Cotoneaster dammeri* 'Skogholm' fertilized with Osmocote 24–4–7. B. Irrigation efficiency of *Rudbeckia fulgida* 'Goldsturm' fertilized with Osmocote 24–4–7. C. Rain events from 0 to 120 days after treatment initiation.

This is in agreement with other researchers (5, 10, 19) where cyclic irrigation improved irrigation efficiency 24% to 39% compared to a single application. Irrigation application (cyclic or single), however, did not affect any of the other measured variables nor were there any significant interactions; therefore, data were averaged over irrigation application and reanalyzed.

Irrigation efficiency for cotoneaster and rudbeckia followed similar trends at each irrigation volume and sample time (Figs. 1a and 1b); however, there were quantitative differences (P < 0.05). Irrigation efficiency with rudbeckia was greater than cotoneaster throughout the growing season illustrating differences in water usage between the two species. At 800 ml and 1200 ml, irrigation efficiencies of both species was low during the first 30 days presumably due to plants being small and newly transplanted. By 45 DAI, irrigation efficiencies increased. Irrigation efficiencies at a respective irrigation volume was relatively uniform throughout the study period except for periods of rainfall (Fig. 1c). As expected, irrigation efficiencies decreased with increasing volume of irrigation.

Substrate nutrient concentration. NH_4-N and NO_3-N concentrations in substrate solution decreased with increasing irrigation volume, presumably due to increased leaching regardless of CRF [represented by cotoneaster fertilized with resin-coated NH_4NO_3 (Figs. 2a and 2b)]. Even though increasing irrigation volume decreased NH_4-N and NO_3-N substrate concentration, N content of cotoneaster and rudbeckia were unaffected by irrigation volume indicating that similar quantities of N were absorbed regardless of irrigation volume (8). In addition, maximum dry weight of both species occurred at irrigation volumes greater than 800 ml (1.1 in) for the top preforming CRFs implying reduced substrate N concentration did not reduce growth (8). This may be a reflection of the difference between substrate nutrient concentration and substrate nutrient content. The plant's response to nutrient application is not a direct response to concentration in the substrate solution but to total nutrient supply (concentration × volume of solution) (24). Therefore, differences in substrate concentration could be nullified in nutrient content by differences in volume of substrate solution. Plants can also adjust N uptake kinetics for lower external N concentration, i.e., for K_m to decrease and V_{max} to increase (7).

Substrate NH_4-N concentration decreased throughout the season for all CRFs presumably due to increasing plant absorption, conversion to NO_3 and depletion of N from each CRF (Fig. 2a). Most CRFs were below 5 mg NH_4-N/liter by 90 DAI regardless of irrigation volume (data not presented).

Substrate NH_4-N concentration was also effected by CRF and followed a trend represented by samples collected 45 DAI and 119 DAI (Table 2). At 45 DAI, polymer-coated urea had the highest substrate NH_4-N concentration at 200 ml (0.3 in) even though it was not statistically different from all other CRFs. At 400 ml (0.6 in), resin-coated NH_4NO_3 had higher NH_4-N concentration compared to polymer-coated N and composted turkey litter. Throughout the experimental period, N sources and control-release mechanisms appeared to have the greatest impact on NH_4-N concentration when irrigated with 200 ml (0.3 in) or 400 ml (0.6 in); however, these differences were negated at higher irrigation volumes as NH_4-N concentrations were similar for all N sources at 800 ml (1.1 in) and 1200 ml (1.7 in).

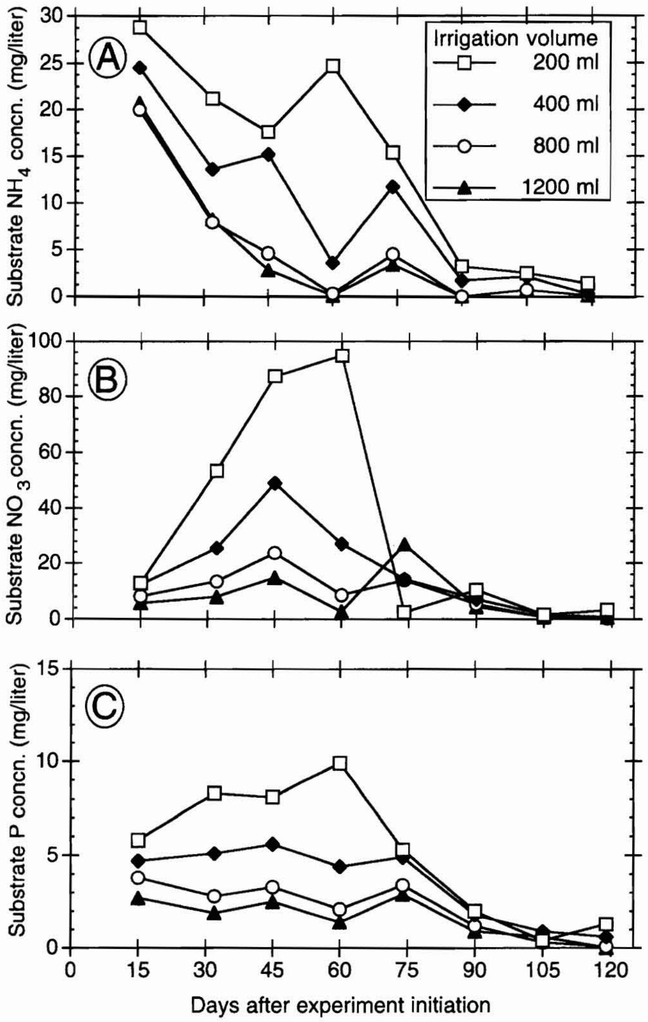

Fig. 2. A. Effect of irrigation volume on substrate NH_4-N concentration of *Cotoneaster dammeri* 'Skogholm' fertilized with resin-coated NH_4NO_3 (Osmocote 24–4–7). B. Effect of irrigation volume on substrate NO_3-N concentration of *Cotoneaster dammeri* 'Skogholm' fertilized with resin-coated NH_4NO_3 (Osmocote 24–4–7). C. Effect of irrigation volume on substrate P concentration of *Cotoneaster dammeri* 'Skogholm' fertilized with resin-coated P (Osmocote 24–4–7).

At 119 DAI, NH_4-N concentration was < 1 mg/liter for all N sources when irrigated with 400 ml (0.6 in), 800 ml (1.1 in), or 1200 ml (1.7 in), whereas at 200 ml (0.3 in) polymer-coated N maintained a higher concentration compared to all other N sources. Results from regression analysis suggest that all N sources, excluding possibly composted turkey litter, were still releasing N, but the rate of release was not adequate to replenish substrate solution at higher irrigation levels.

At all volumes of irrigation and N sources, substrate NO_3-N concentration increased through 45 DAI then decreased throughout the remainder of the experiment [represented by cotoneaster fertilized with resin-coated NH_4NO_3 (Fig. 2b)]. Nitrate released or converted from NH_4-N appeared to remain in solution with low irrigation volume of 200 ml (0.3 in) until ≈ 60 DAI then decreased presumably due to increased plant absorption. For all CRFs, substrate NO_3-N concentration was only in the recommended range of 15 to 25 mg/liter at 45 DAI when irrigated with 800 ml (1.1 in) which is the range of irrigation volume required to maximize growth (data not presented). However, total N (NH_4-N + NO_3-N) was above 20 mg/liter through 75 DAI when fertilized with Meister, Osmocote, and Scotts. This data supports the current substrate N recommendation of 15 to 25 mg/liter if total N is utilized. However, even though substrate NH_4-N and NO_3-N concentrations were the lowest at 1200 ml (1.7 in), top dry weight of cotoneaster and rudbeckia at 1200 ml (1.7 in) only decreased from 0% to 7% from the respective maximum dry weight for each CRF. This suggests that lower substrate N concentrations may produce adequate plant growth. In solution culture, Clements et al. (3) reported 0.11 mg N/liter was adequate for growth of ryegrass (*Lolium perenne* L.) while Elliot and Nelson (4) grew chrysanthemums (*Dendranthema* x *grandiflorum*) successfully at 0.42 mg N/liter. Data herein should also be considered in regards to current recommendations for fertilizer reapplication (18).

Leachate samples collected 32, 60, 90, and 119 DAI are presented for substrate NO_3-N concentration since these data are representative of the response of NO_3-N to irrigation volume and CRF throughout the experiment (Table 3). Nitrogen sources and control-release mechanisms (CRFs) affected NO_3-N concentration when irrigated with 200 ml (0.3 in) or 400 ml (0.6 in), however, substrate NO_3-N concentrations were not affected by CRFs at any sample time when irrigated with 1200 ml (1.7 in). Similar to NH_4-N concentra-

Table 2. Effect of irrigation volume and nutrient source on NH_4-N concentration in substrate solution of *Cotoneaster dammeri* 'Skogholm' 45 and 119 days after treatment initiation.

	NH_4 (mg/liter)				
	Nutrient source and control-release mechanism				
Irrigation volume (ml)	Polymer-coated urea[z]	Resin-coated NH_4NO_3	Polymer-coated N	Composted turkey litter	Urea
	45 days after initiation				
200	25.89a[y]	17.59ab	17.60ab	9.19b	14.96b
400	12.65ab	15.17a	6.94bc	0.15c	10.48ab
800	8.21a	4.57a	1.76a	1.01a	8.06a
1200	2.84a	2.81a	3.22a	0.25a	3.95a
Significance[x]					
Linear	0.001	0.004	0.001	0.048	0.010
Quadratic	NS	NS	0.001	NS	NS
	119 days after initiation				
200	3.37b	1.38c	5.69a	0.19c	1.54c
400	0.57a	0.31a	0.96a	0.11a	0.34a
800	0.33a	0.08a	0.81a	0.03a	0.11a
1200	0.25a	0.14a	0.51a	0.01a	0.23a
Significance					
Linear	0.006	0.001	0.008	NS	NS
Quadratic	0.023	0.006	0.029	NS	NS

[z]Polymer-coated urea = Meister 21–7–14, Resin-coated NH_4NO_3 = Osmocote 24–4–7, Polymer-coated N = Scotts 23–4–8, Composted turkey litter = Sustane 5–2–4, Urea = Woodace 21–6–12.

[y]Means within a row (irrigation volume) followed by the same letter or letters are not significantly different as determined by LSD, P = 0.05.

[x]Regression analysis of irrigation volume, NS = P > 0.05.

Table 3. **Effect of irrigation volume and nutrient source on NO_3-N concentration in substrate solution of *Cotoneaster dammeri* 'Skogholm' 32, 60, 90, and 119 days after treatment initiation.**

Irrigation volume (ml)	Polymer-coated urea[z]	Resin-coated NH_4NO_3	Polymer-coated N	Composted turkey litter	Urea
	NO_3 (mg/liter) — Nutrient source and control-release mechanism				
	32 days after initiation				
200	21.55c[y]	53.67a	29.00bc	33.12b	34.86b
400	16.09b	25.43a	14.79b	29.09a	30.04a
800	14.01a	13.36a	5.13a	10.70a	13.03a
1200	7.72a	7.85a	3.11a	5.62a	8.82a
Significance[x]					
Linear	0.001	0.001	0.001	0.001	0.001
Quadratic	NS	0.001	0.007	NS	NS
	60 days after initiation				
200	85.61a	94.75a	57.38b	9.97d	42.30c
400	34.85a	27.04ab	15.24bc	1.50c	28.12ab
800	13.40a	8.57a	3.73b	0.00b	4.13b
1200	3.49a	2.67a	2.81a	0.00a	0.23a
Significance					
Linear	0.001	0.001	0.001	0.002	0.001
Quadratic	0.001	0.001	0.001	0.002	0.001
	90 days after initiation				
200	6.12bc	10.44a	7.53ab	0.15d	2.74cd
400	9.18a	7.09a	4.61b	0.31c	7.46a
800	6.62a	5.38ab	4.44ab	0.09c	1.23bc
1200	4.36a	4.36a	2.69a	0.15a	0.51a
Significance					
Linear	NS	0.014	0.043	NS	0.048
Quadratic	NS	NS	NS	NS	NS
	119 days after initiation				
200	3.37a	3.29a	3.69a	0.82b	1.01b
400	1.13a	0.85a	1.27a	0.58a	0.47a
800	1.06a	0.36a	0.63a	0.21a	0.33a
1200	1.18a	0.70a	0.55a	0.49a	0.59a
Significance					
Linear	0.006	0.001	0.002	NS	NS
Quadratic	0.017	0.004	0.010	NS	NS

[z]Polymer-coated urea = Meister 21–7–14, Resin-coated NH_4NO_3 = Osmocote 24–4–7, Polymer-coated N = Scotts 23–4–8, Composted turkey litter = Sustane 5–2–4, Urea = Woodace 21–6–12.

[y]Means within a row (irrigation volume) followed by the same letter or letters are not significantly different as determined by LSD, P = 0.05.

[x]Regression analysis of irrigation volume, NS = P > 0.05.

tions, higher irrigation volumes masked the difference between CRFs. This is, in contrast, to the top dry weight response of cotoneaster to irrigation volume and CRF where the greatest difference between CRFs was evident between 800 and 1200 ml (1.7 in) (8).

At 32 DAI, resin-coated NH_4NO_3 had the highest NO_3-N concentration at 200 ml (0.3 in), whereas resin-coated NH_4NO_3, composted turkey litter, and urea had the highest concentration at 400 ml (0.6 in) (Table 3). Even though resin-coated NH_4NO_3 was the only fertilizer containing substantial quantities of NO_3-N, sufficient urea hydrolysis and nitrification occurred in the substrate such that these CRFs (resin-coated NH_4NO_3, composted turkey litter, urea) had similar substrate NO_3-N values. This is supported by various reports that urea is rapidly oxidized to NH_4-N in a pine bark substrate and nitrification of NH_4-N in the substrate solution is also a relatively rapid process (24). Jarrell et al. (9) and Warren et al. (21) also reported that substrate N solutions were similar in regards to NH_4 and NO_3 regardless of N source.

At 60 DAI, composted turkey litter had the lowest substrate NO_3-N concentration at each volume, excluding 1200 ml, although it was only statistically lower than all other N sources at 200 ml (0.3 in) (Table 3). At 200 ml (0.3 in) and 400 ml (0.6 in), substrate NO_3-N concentration increased from 32 to 60 DAI for all CRFs (except composted turkey litter). In contrast, substrate NO_3-N concentration from 32 to 60 DAI decreased at 800 ml (1.1 in) and 1200 ml (1.7 in) illustrating the impact of irrigation volume. Between 60 and 90 DAI, substrate NO_3-N concentration decreased greatly for all N sources at 200 ml (0.3 in) and 400 ml (0.6 in) probably due to plant uptake. Nitrate concentration between 60 and 90 DAI, however, had minimal changes at 800 ml (1.1 in) and 1200 ml (1.7 in) suggesting that high irrigation volume had a bigger impact on substrate NO_3-N concentration than plant uptake (Table 3).

By 90 DAI, composted turkey litter was no longer affected by irrigation volume implying the readily mineralized N was depleted (Table 3). Williams and Nelson (22) reported that various organic materials no longer released adequate N after 42 days. Resin-coated NH_4NO_3 had the greatest NO_3-N concentration at 200 ml (0.3 in), whereas polymer-coated urea, resin-coated NH_4NO_3, and urea had the greatest NO_3-N concentration at 400 ml (0.6 in). At 119 DAI, all N sources had similar NO_3-N concentrations within each irrigation volume except composted turkey litter and urea at 200 ml (0.3 in) suggesting that most of the N had been released (Table 3). This is also supported by minimum differences in substrate NH_4-N concentration at this time. Ruter (14) reported that Osmocote 17N–3P–9.9K (17–7–12), Osmocote 24N–1.7P–5.8K (24–4–7), and Sierrablen 17N–3P–8.3K (17–7–10) provided adequate concentration of nutrients for ≈ 90 days when irrigated (overhead) with 1.3 cm (0.5 in) per day.

Data herein combined with plant growth reported in Groves et al. (8) are supportive of the recent lowering of substrate N solution concentration when using CRFs. Our data, however, cannot discount that plant growth could have been due to luxury consumption of N from earlier in the season. An additional possibility could be that later in the season when roots had fully exploited the substrate, N levels were low due to plant uptake immediately after nutrients were released from CRFs. This possibility along with increased leaching with increasing volumes of water would produce low nutrient levels while the plants could potentially be absorbing adequate quantities of nutrients. However, reduced growth of cotoneaster when fertilized with polymer-coated urea, composted turkey litter, and urea at high irrigation volumes lend support to the original hypothesis (8).

Resin-coated P, polymer-coated P, and MgKP maintained relatively constant substrate solution levels of PO_4-P through 60 DAI, after which substrate PO_4-P concentration continually decreased [represented by cotoneaster fertilized with resin-coated P (Fig. 2c)]. By 90 DAI substrate PO_4-P levels were similar regardless of irrigation volume implying plant absorption was the major factor reducing PO_4-P concentra-

Table 4. Effect of irrigation volume and nutrient source on P concentration in substrate solution of *Cotoneaster dammeri* 'Skogholm' 32, 60, and 119 days after treatment initiation.

Irrigation volume (ml)	P (mg/liter) — Nutrient source and control-release mechanism: Sulfur-coated[z] P	Resin-coated P	Polymer-coated P	Composted turkey litter	MgKP
	---- 32 days after initiation ----				
200	8.99c[y]	8.29c	10.10c	19.11b	26.31a
400	7.70c	5.11c	5.80c	13.98b	22.27a
800	3.10c	2.80c	2.69c	7.42ab	11.54a
1200	1.65a	1.91a	1.82a	4.73a	5.07a
Significance[x]					
Linear	0.001	0.002	0.001	0.001	0.001
Quadratic	NS	0.031	0.007	NS	NS
	---- 60 days after initiation ----				
200	5.30b	9.91a	8.86a	9.26a	10.58a
400	2.56c	4.43ab	4.21b	6.22a	5.69ab
800	0.93a	2.12a	1.86a	2.48a	2.48a
1200	0.57a	1.43a	1.63a	1.67a	0.87a
Significance[y]					
Linear	0.001	0.001	0.001	0.001	0.002
Quadratic	0.003	0.001	0.007	0.002	0.034
	---- 119 days after initiation ----				
200	0.32b	1.26b	1.62b	4.51a	1.21b
400	0.03b	0.58ab	0.43ab	2.68a	0.35ab
800	0.00b	0.08b	0.08b	4.35a	0.03b
1200	0.00a	0.01a	0.00a	0.47a	0.00a
Significance[y]					
Linear	0.004	0.001	0.001	NS	0.006
Quadratic	0.015	0.005	0.001	NS	0.029

[z]Sulfur-coated P = Meister 21–7–14, Resin-coated P = Osmocote 24–4–7, Polymer-coated P = Scotts 23–4–8, Composted turkey litter = Sustane 5–2–4, MgKP = Woodace 21–6–12.

[y]Means within a row (irrigation volume) followed by the same letter or letters are not significantly different as determined by LSD, P = 0.05.

[x]Regression analysis of irrigation volume, NS = P > 0.05.

tion in lieu of increased leaching. In addition, these three P sources (resin-coated P, polymer-coated P, and MgKP) produced maximum P content in shoots of cotoneaster (8). In contrast, substrate PO_4-P concentration decreased over the entire period for sulfur-coated P and composted turkey litter at each irrigation volume (data not presented). Similar to NO_3-N and NH_4-N, substrate PO_4-P concentration decreased with increasing irrigation volume for all P sources. Phosphorus content of tops of cotoneaster also decreased with increasing irrigation volume suggesting reduced substrate PO_4-P concentration may have reduced P uptake (8). This is supported by a positive correlation (r = 0.48, P = 0.001) between P content of cotoneaster and substrate PO_4-P concentration (8).

Samples collected 32 DAI, 60 DAI, and 119 DAI for substrate PO_4-P concentration are presented since they represent P response to irrigation volume and CRF throughout the experiment (Table 4). Substrate PO_4-P concentrations were seldom in the recommended range of 5 to 10 mg/liter (24) when irrigated with 800 ml (1.1 in) or 1200 ml (1.7 in) regardless of P source suggesting that the adequate substrate PO_4-P concentration could be lowered without sacrificing growth. Similarly to NH_4-N and NO_3-N, all P sources responded similarly at 1200 ml (1.7 in) at all sample times implying P source and control-release mechanisms became secondary to irrigation at high irrigation volumes.

At 32 DAI, MgKP followed by composted turkey litter produced the highest substrate PO_4-P concentration at 200 ml (0.3 in), 400 ml (0.6 in), and 800 ml (1.1 in) (Table 4). The three coated P sources (sulfur-coated P, resin-coated P, and polymer-coated P) had the lowest levels. By 60 DAI all P sources had similar levels within each irrigation volume except sulfur-coated P which had reduced levels at 200 and 400 ml (0.6 in) implying the P source was nearing depletion. At 119 DAI, all substrate PO_4-P concentrations were < 1 mg/liter at 400 ml (0.6 in), 800 ml (1.1 in), and 1200 ml (1.7 in) except for composted turkey litter. Previous research has demonstrated the ability of composted turkey litter and other organic materials to supply adequate P throughout the growing season (20, 22). Even though organic materials do not release adequate N to maintain plant growth, these materials could play a prominent role in maintaining substrate P concentration.

Substrate solution pH of cotoneaster was affected by irrigation volume and CRF and followed a trend represented by 32 and 119 DAI (Table 5). Solution pH remained close to the recommended range of 5.0 to 6.0 (24) for all irrigation volumes and CRFs throughout the entire study with the exception of Sustane (composted turkey litter). Substrate amended with composted turkey litter and other organic materials has been shown to increase pH (20, 22). At 32 DAI, substrate pH of Scotts, Sustane, and Woodace increased linearly with increasing irrigation volume while Meister and Osmocote

Table 5. Effect of irrigation volume and controlled-release fertilizer on pH in substrate solution of *Cotoneaster dammeri* 'Skogholm' 32 and 119 days after treatment initiation.

Irrigation volume (ml)	pH — Controlled-release fertilizer: Meister 21–7–14	Osmocote 24–4–7	Scotts 23–4–8	Sustane 5–2–4	Woodace 21–6–12
	---- 32 days after initiation ----				
200	5.55ab[z]	5.49ab	5.37b	5.70a	5.46b
400	5.57a	5.59a	5.41a	5.67a	5.52a
800	5.62b	5.46b	5.67ab	5.88a	5.69ab
1200	5.66b	5.66b	5.72b	6.02a	5.82ab
Significance[y]					
Linear	NS	NS	0.001	0.018	0.014
Quadratic	NS	NS	NS	NS	NS
	---- 119 days after initiation ----				
200	5.67a	5.55a	5.72a	5.70a	5.54a
400	5.22c	5.23c	5.28bc	6.16a	5.50b
800	5.38bc	5.31c	5.42bc	6.28a	5.63b
1200	5.75b	5.37c	5.37c	6.44a	5.90b
Significance[y]					
Linear	0.021	NS	NS	0.001	0.020
Quadratic	0.012	NS	NS	NS	NS

[z]Means within a row (irrigation volume) followed by the same letter or letters are not significantly different as determined by LSD, P = 0.05.

[y]Regression analysis of irrigation volume, NS = P > 0.05.

were unaffected by irrigation volume. The increase in pH as irrigation volume increased could be due to nutrient leaching at higher volumes. Jarrell et al. (9) also reported a trend of increasing pH with increasing irrigation volume regardless of CRF. Sustane had the highest pH at all irrigation volumes but was not always statistically different from the other CRFs.

At 119 DAI, substrate pH with Sustane was higher than the other CRFs at all volumes except 200 ml (0.3 in) where all CRFs responded similarly. Substrate pH with Sustane and Woodace increased with increasing volume of irrigation; Osmocote and Scotts showed no trends; and Meister responded quadratically.

Increasing irrigation volume decreased substrate NH_4-N, NO_3-N, and PO_4-P solution concentrations regardless of CRF. However, decreasing substrate nutrient concentrations did not appear to reduce plant growth for the better performing CRFs. Osmocote, Scotts, and Woodace produced 90% of maximum top weight over a wide range of irrigation volumes [≈ 550 ml (0.8 in) to 1200 ml (1.7 in)] and subsequent substrate nutrient solution concentrations. This wide range of irrigation volume and substrate nutrient solution concentrations provides the grower much flexibility and may suggest that adequate growth is possible with reduced resources.

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