Controlled-release Fertilizer Placement Affects the Leaching Pattern of Nutrients from Nursery Containers during Irrigation

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Abstract. Maximizing nutrient use efficiency while minimizing nutrient leaching and non-point source contributions from containerized crop production systems are goals of researchers and growers. These goals have led to irrigation and crop nutrition management practices that reduce fertilizer and irrigation expenditures and reduce the nutrient load into the environment. However, one area that has received little attention, and may lead to the further refinement of crop management practices, is how dissolved nutrients (solutes) move through a substrate while water is being applied during irrigation. A study was conducted to characterize the effect of a controlled-release fertilizer (CRF) placement method on changes in leachate nutrient concentration throughout an irrigation event and to evaluate these changes at different times throughout a production season. A pine bark:sand (9:1, by volume) substrate was placed in 2.7-L nursery containers (fallow) and was treated with topdressed, incorporated, and dibbled CRF or did not receive CRF. The nutrient leaching pattern was evaluated at 3, 9, and 15 weeks after potting (WAP). Leachate nutrient concentration was the highest in the first 50 mL of effluent and steadily diminished as irrigation continued for the topdressed, incorporated, and the no CRF treatments. Effluent nutrient concentration from containers with dibbled CRF generally increased throughout the first 150 mL of effluent, plateaued briefly, and then diminished. The nutrient load that leached with higher volumes of irrigation water was similar between incorporated and dibbled CRF placements. However, the unique nutrient leaching pattern observed with the dibbled CRF placement method allowed for a lower effluent nutrient load when leaching fractions are low. Dibble may be an advantageous CRF placement method that allows for the conservation of expensive fertilizer resources and mitigates non-point source nutrient contributions by reducing undesired nutrient leaching during irrigation.

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Maximizing nutrient use efficiency and minimizing leaching and non-point source contributions through runoff have been persistent challenges in containerized crop production that drive both researchers and growers to develop new technologies and methods to manage crop nutrition. CRFs are a recommended (Bilderback et al., 2013) and widely adopted (Dennis et al., 2010) nutrient delivery method for containerized crops. CRFs contain encapsulated, solid mineral nutrients that, in the presence of water, slowly dissolve and release into the surrounding substrate solution over an extended period of time; dissolution and release are dictated by factors such as coating technology (Adams et al., 2013) and temperature (Adams et al., 2013; Husby et al., 2003).

The performance of CRFs throughout a typical production season has been extensively studied (Alam et al., 2009; Broschat and Moore, 2007; Cabrera, 1997; Colangelo

and Brand, 2001) and their use has been demonstrated to be an effective fertilizer application method in reducing nitrogen (N) and phosphorus (P) runoff as compared with systems where dissolved nutrients are applied through irrigation water (i.e., fertigation or liquid feed) (Wilson and Albano, 2011). However, the movement of dissolved nutrients (solutes) through a soilless substrate during the application of water (i.e., during irrigation) has received little attention in the current body of literature. Hoskins (2014) found that the movement of applied irrigation water through pine bark-based substrates was not uniform as a result of the formation of channels in dry regions of the substrate profile. It is not clear how this uneven movement of applied irrigation water affects the leaching of mineral nutrients from the substrate. Hoskins (2014) also conducted solute transport experiments using pine bark-filled columns and demonstrated that the soluble anion fertilizer species nitrate (NO_3^-) and phosphate (PO_4^{3-}) moved through the substrate very quickly as compared with the cation potassium (K^+). The application of these principles to a system where CRF is the solute source may provide valuable insight into the nutrient leaching processes that occur during irrigation.

Research has shown that when a lower volume of effluent is generated during irrigation, measured by practitioners as a leaching fraction ($\text{LF} = \text{volume leached} \div \text{volume applied}$) less total nutrients are leached (Owen et al., 2008; Tyler et al., 1996). Niemiera and Leda (1993) found similar results with regard to total nutrient load leached, but also reported that NO_3^- and NH_4^+ concentrations in the substrate solution, collected using a pour through procedure, were higher at reduced LFs. Collectively, these findings suggest that before irrigation, an initially high, CRF-derived nutrient concentration resides in the pore-water solution and is flushed out to an extent that is dependent on the volume of water leached. However, the mechanisms behind leaching of mineral nutrients, how that relates to leachate volume, and how solutes move from the substrate solution and leave a container during irrigation are not fully understood. Current knowledge on solute transport is based on work in mineral soils or sands, where physiochemical properties can be quite different from bark-based soilless substrates.

There are two key attributes of CRFs that are important in understanding the principles of solute transport during irrigation. First is the seasonal variability in the rate of nutrient release, which is higher in the early portion of a CRF's life (Merhaut et al., 2006). Furthermore, the nutrient release rate is affected by choice of CRF placement in the container. For example, the maximum release rate occurs later in the season for the topdressed method (i.e., surface-applied) than for the incorporated method (i.e., distributed throughout soilless substrate) (Alam et al., 2009). As a result of the inherent seasonal variability in CRF nutrient release rates, we hypothesize that solute

transport dynamics also change. The second attribute to consider is the non-uniform nutrient distribution throughout a substrate. This distribution would be affected by CRF placement (topdressed, incorporated, or dibbled), type (liquid vs. solid), and irrigation management. Brown and Pokorny (1977) demonstrated the variability in K distribution throughout a substrate profile when applied in soluble form to the substrate surface. Altland et al. (2004) and Broschat and Moore (2003) evaluated the effect of fertilizer placement on crop quality and weed growth in containers. They found a species-specific response in crop growth to the placement of CRFs and less weed growth in treatments using dibbled CRF (i.e., all fertilizer placed directly in the center of the substrate). As a whole, these studies suggest that nutrient availability and distribution are variable throughout a substrate profile and are affected by CRF placement.

By studying how factors such as the length of time that CRF prills have been in production and CRF placement method affect nutrient leaching patterns, researchers and growers may gain a better understanding of the nutrient load generated during a single irrigation event. A study was conducted with the following objectives: 1) characterize the changes in leachate nutrient concentration throughout an irrigation event using the manufacturers' recommended CRF application rate (Expt. 1) and matched N rates (Expt. 2) for given CRF placement methods; 2) evaluate the variability in leachate nutrient concentration changes (objective 1) at different times in a production season; and 3) relate the within-irrigation changes in leachate nutrient concentration changes to cumulative nutrient load leached with increasing leachate volumes. This information was used to make inferences about solute transport in pine bark substrates during irrigation. We hypothesize that nutrient distribution throughout a substrate profile is affected by the placement of CRF in the container and that this distribution affects the pattern in which nutrients are leached from the container during individual irrigation events. The results may be used by researchers to improve nutrient models such as that developed by Majsztrik (2011) and recommendations for fertilizer and irrigation management in container nurseries.

Materials and Methods

On 21 June 2013, pine bark:sand (9:1, by volume; Carolina Bark Products LLC, Seaboard, NC) substrate was amended with 1.8 kg·m⁻³ (3 lb/yd³) crushed dolomitic lime (Rockydale Quarries Corp., Roanoke, VA) and an equal quantity of pelletized dolomitic lime (Kelly's Limestone LLC, Kirksville, MO) and was placed into trade gallon (2.7 L) nursery containers (Myers industries, Middlefield, OH). Porometers were used to determine the following static physical properties of the substrate: total porosity = 78.7% vol.; container capacity = 52.3% vol.; air space = 26.4% vol.; and bulk density = 0.325 g·cm⁻³. Particle size

distribution (percent by weight), as determined by a 5-min mechanical agitation with oven-dried substrate, was as follows: greater than 6.3 mm = 8.0; 6.3 to 2 mm = 27.6; 2 to 0.71 mm = 37.9; less than 0.71 mm = 26.5.

Expt. 1. A pre-weighed quantity of 16N–2.6P–9.1K CRF (16N–6P₂O₅–11K₂O with 7.2% N–NO₃, 8.8% N–NH₄ with micronutrients; 5–6 month or 20–24 week; Harrell's, Lakeland, FL) was applied at the manufacturer's recommended rate of 11.0, 15.9, 15.9, and 0.0 g per container for topdressed, incorporated, dibble, and a control (no CRF) placement methods, respectively. Topdressed CRF was distributed evenly over the substrate surface. Incorporated CRF was pre-mixed into the substrate on an individual container basis. Dibbled CRF was placed in a 3-inch deep, hand-formed hole in the substrate surface that was backfilled after CRF placement. All treatments were fallow (i.e., not containing a plant).

The percentage of original fertilizer remaining in the CRF was approximated at the time of data collection. For each treatment, an extra container was potted in which the respective quantity of CRF was enclosed in a packet made from standard mesh window screen. Topdressed packets were placed in a single circular pouch that covered the entire substrate surface. Incorporated packets were partitioned into three circular pouches that were placed at 1, 3, and 5 inches from the container base. Dibbled packets were enclosed in a small square pouch and were placed in the middle of the vertical and horizontal container profile. These packets were collected throughout the duration of the study, and their CRF was analyzed to determine the quantity nutrients remained (Table 1).

All containers were placed in an open-air research nursery at the Hampton Roads Agricultural Research and Extension Center in Virginia Beach, VA (lat. 36° 53' 31" N; long. 76° 10' 45" W) where they received a daily,

15-min overhead irrigation (12.7 mm·h⁻¹). Data were collected at 3, 9, and 15 WAP. At each WAP, containers were brought into the laboratory before data collection and weighed repeatedly until an average volumetric water content (VWC) of 37.1% ± 0.4 SE (n = 36) was reached to simulate the field conditions in which water would be applied. Data collection began once the target VWC had been reached. Each container was nested into a custom irrigation platform (Fig. 1), where it was irrigated with deionized water through a diffuser-mounted 27 cm (10.6 in) above the substrate surface. Irrigation was applied at a rate of 300 mL·min⁻¹, which was comparable to a 19-L·h⁻¹ spray stake but inherently faster than most overhead irrigation systems. During irrigation, effluent (leachate) from every container was collected and fractionated in the following increments, in sequence: 3 × 50 mL

Table 1. Observed, non-replicated, percent of ions remaining in an ≈20- to 24-week longevity controlled-release fertilizer at 3, 9, and 15 weeks after potting (WAP) by fertilizer placement method (Expt. 1) in a pine bark:sand (9:1, by volume) substrate.

Placement	WAP			R ²
	3	9	15	
N-NO ₃				
Topdressed	87.7	70.6	54.1	1.00
Incorporated	88.9	42.9	23.4	0.95
Dibble	86.6	42.2	20.9	0.96
N-NH ₄				
Topdressed	87.2	76.8	63.5	0.99
Incorporated	92.5	58.2	34.3	0.99
Dibble	93.6	56.7	34.5	0.98
P-PO ₄				
Topdressed	81.9	84.4	82.9	0.25
Incorporated	90.5	72.3	57.8	0.99
Dibble	94.2	73.9	49.2	1.00
Potassium				
Topdressed	90.1	85.0	75.6	0.97
Incorporated	93.6	64.4	43.1	0.99
Dibble	91.9	65.0	42.5	1.00

Fig. 1. Physical setup of the irrigation platform depicting the application of deionized irrigation water through a diffuser with constant head and the collection of effluent throughout the irrigation event.

(total = 150 mL), 3 × 100 mL (total = 300 mL), 3 × 200 mL (total = 600 mL), and 3 × 400 mL (total = 1200 mL). This produced a total of 12 samples totaling 2.25 L of effluent. Using the time when leaching was first observed ($56 \text{ s} \pm 2 \text{ SE}$, $n = 36$) and the irrigation application rate, the volume of water applied at each cumulative effluent volume was calculated and used to approximate the LF [Eq. (1)] at each effluent volume.

$$LF = \frac{\text{cumulative effluent vol. (mL)}}{5 \times \text{leaching time (s)} + \text{cumulative effluent vol. (mL)}} \quad [1]$$

Irrigation ended once the effluent for all samples had been collected. Hoskins (2014) found that water moved as a relatively even front through pine bark in fallow nursery containers when the moisture distribution was even throughout the container profile. Therefore, the effect of channeling (downward movement of water through specific flow paths) was thought to be minimal in this study. After irrigation, each container was allowed to drain for 1 h, at which point the substrate moisture content was at container capacity (CC). All effluent was collected during this period of post-irrigation drainage and analyzed in the same manner as other effluent samples to determine the post-irrigation nutrient load in drainage water. The height of substrate in the container was measured at 9 and 15 WAP to determine the amount of substrate shrinkage.

An aliquot of each effluent sample was analyzed for electrical conductivity (EC; $\mu\text{S}\cdot\text{cm}^{-1}$) and pH using an Orion 4-Star benchtop meter equipped with a DuraProbe™ 4-Electrode Conductivity Cell (Thermo Fisher Scientific, Beverly, MA). The average pH of the first 50 mL effluent collected was $5.35 \pm 0.07 \text{ SE}$. Nitrate (NO_3), NH_4 , PO_4 , SO_4 , K, magnesium (Mg), and calcium (Ca) concentrations in effluent were determined using a separate, filtered ($0.2 \mu\text{m}$) aliquot through an ICS-1600 ion chromatography system (Thermo Scientific, Madison, WI) equipped with a $4 \times 250\text{-mm}$ (i.d. $\times$ length) AS22 anion-exchange column, a $4 \times 250\text{-mm}$ CS12A cation-exchange column, and an AS-AP autosampler on a $25\text{-}\mu\text{L}$ sample loop driven by an isocratic pump.

The experiment was a four (CRF placement) $\times$ three (WAP) factorial that used a completely randomized design with three replicates per treatment level and resulted in 36 total containers used in the study (not counting the containers with CRF packets). Separate sets of 12 experimental units (containers) were used for each WAP. The relationship between EC and individual leachate nutrient concentrations was evaluated using Pearson's correlation coefficient and linear regression. Slopes and intercepts of these regression lines were pooled and blocked by CRF placement method. Data were subjected to analysis of variance ($\alpha = 0.1$) (Marini, 1999) and means separation by way of Tukey's

honestly significant difference when appropriate. All data were processed using JMP® Pro Version 10.0.2 (SAS Institute Inc., Cary, NC).

Expt. 2. On 15 Aug. 2013, a similar co-experiment was initiated using equal N rates (15.9 g of the same CRF used in Expt. 1) for both topdressed and incorporated CRF placement methods to ensure that the same nutrient leaching patterns held true when the quantity of CRF applied to topdressed containers was equal to that of incorporated CRF. All materials and management practices used in this experiment were the same as Expt. 1, except for the different CRF application rate. Treatments included only topdressed and incorporated CRF placements and data were collected at only one time in the season (6 WAP). The experiment was a completely randomized design with two CRF placement levels (topdressed and incorporated) and three replicates per treatment level ($n = 6$). Data collection procedures and analysis methods were the same as Expt. 1.

Results and Discussion

Analysis of the EC values, nutrient concentrations, and nutrient load at each effluent collection volume indicated an interaction between CRF placement method and WAP. Therefore, the simple effects (i.e., the effect of one treatment within only one level of the other treatment) of CRF placement and WAP are discussed.

Nutrient leaching pattern. Fertilizer placement affected the pattern in which nutrients leached (changes in effluent concentration

with effluent volume) from the base of a container during irrigation. In Expt. 1, effluent EC (Fig. 2) was the highest in the first 50 mL of effluent and steadily diminished as irrigation continued for topdressed, incorporated, and the control (no CRF). However, the pattern was quite different for the dibbled CRF placement and was much more variable. Effluent EC from containers with dibbled CRF increased for the first 150 mL of leachate, plateaued briefly, and then diminished as irrigation continued. The Expt. 1 leaching pattern of N-NO_3 and P-PO_4 (Fig. 2) followed similar trends as EC. However, nitrate release curves (RCs) were more similar in shape to the EC than P-PO_4 RCs. In Expt. 1, N-NO_3 was the predominant ion present in leachate (reflective of the CRF formulation) and likely contributed to most of the EC. Overall, each ion exhibited a strong linear correlation with EC (Table 2). Comparison of the mean slopes from each linear regression line allowed the authors to infer individual ion contribution to the bulk EC ($P < 0.0001$) was as follows: $\text{NO}_3 > \text{SO}_4$, $\text{K} > \text{Mg}$, Ca , PO_4 , and NH_4 . These results suggest that effluent EC may serve as a strong indicator of effluent NO_3 concentration and a moderate indicator of SO_4 and K.

The general pattern of nutrient leaching from containers with topdressed CRF generally followed the same trend as containers with incorporated CRF, although there was a reduced nutrient load (Table 3) for each ion as leachate volume increased. A similar trend was observed in Expt. 2 (Fig. 3). Effluent nutrient concentrations in containers with topdressed CRF was lower, throughout the

Fig. 2. Expt. 1 release curves showing changes in effluent electrical conductivity (EC), nitrogen (N-NO_3), and phosphorus (P-PO_4) concentration as a function of cumulative effluent volume at 3, 9, and 15 weeks after potting (WAP). Fallow, 2.7-L nursery containers with a pine bark:sand (9:1, by volume) substrate and controlled-release fertilizer (CRF) applied as (□) dibble, (●) incorporated, (○) topdressed or (■) without CRF during irrigated with deionized water (DI) at a rate of $300 \text{ mL}\cdot\text{min}^{-1}$.

irrigation event, as compared with containers with CRF that was incorporated at an equal rate. This illustrates the inherent differences in the solute transport mechanisms when CRF is concentrated on the substrate surface (topdressed) rather than dispersed throughout the substrate profile. Nutrient movement from inside the encapsulating membrane to the surrounding substrate environment requires water (Adams et al., 2013), and the reduced moisture content (MC) observed by Hoskins (2014) in the upper portion of the substrate profile likely reduced the capacity for nutrient release as compared with incorporated CRF, where individual prills were subject to higher MCs.

Nutrient load in effluent. In Expt. 1, the initial amounts of N-NH₄, N-NO₃, P-PO₄, and K were highest in the first 50 mL of effluent collected from treatments with incorporated CRF at 3 WAP as compared with

that of the other CRF placement methods (Table 3). However, later in the production season (9 and 15 WAP), differences in ion concentrations in the first 50 mL of effluent were not as prominent between CRF placement methods. The observation that the highest nutrient load was in the first 50 mL of effluent and the incorporated CRF placement produced was most likely a result of the close proximity of some CRF prills to the base of the container. Similarly, in containers with dibbled CRF, the observation the effluent nutrient concentration peaked after 150 mL of effluent had been collected (Fig. 2) is likely a result of the prills being located farther from the base of the container compared with incorporated prills. However, at 350 and 2250 mL cumulative effluent volume (≈0.5 and 0.9 LF) (Table 3), differences in nutrient load were not prominent between incorporated and dibble CRF placement methods. This suggests that with these placement methods, the CRF prills may have been exposed to similar moisture and temperature conditions and subsequently released a similar quantity of nutrients into the substrate solution. However, a benefit of dibbled CRF was revealed, in that when effluent volumes were low (0.15 LF), the potential for nutrient leaching was reduced despite a similar quantity of nutrient in the pore solution. This was consistent with the findings of Alam et al. (2009) who found improved growth of container-grown forsythia and less NO₃ in leachate with dibbled CRF and a low LF as compared with other placement methods and LFs.

The 2250-mL cumulative effluent volume can be considered a near maximal flush of all ions in the pore water solution and therefore represented the quantity of displaceable, non-bound ions in the substrate. Incorporated and

dibbled CRF released a similar quantity of displaceable ions into the substrate solution at 3 and 15 WAP (Table 3). Topdressed CRF released less leachable ions than incorporated or dibbled CRF and was the same as the no CRF treatment at 3 and 15 WAP. This illustrates a difference in the potential quantity of nutrients that may be released from CRF prills in the extreme moisture conditions (i.e., relatively wet during irrigation and dry between) of the substrate surface. Effluent volumes are not likely to be this high when using recommended irrigation practices. However, quantifying the nutrient load that may be leached with high volumes of water is an important measurement because, as Colangelo and Brand (2001) demonstrated, the often high precipitation amounts that occur throughout the production season in the eastern United States may induce significant amounts of leaching. Furthermore, Colangelo and Brand (2001) found that precipitation nullified the benefits of high-efficiency (microirrigation) irrigation systems and low LFs in terms of NO₃ load leached over two production seasons as compared with overhead irrigation and high LFs.

Post-irrigation drainage. The volume of post-irrigation drainage (Table 4) from Expt. 1 increased with WAP ($P = 0.0003$). This may be explained by the observation that irrigation water tended to pond on the substrate surface for a few containers at 9 WAP and to a greater extent at 15 WAP. Shrinkage induced by the decomposition and compaction of bark-based substrates with time (Altland et al., 2011) and an associated reduction in hydraulic conductivity (Nash and Laiche, 1981) may explain the increased frequency at which ponding was observed. Substrate shrinkage was observed between 9 and 15 WAP ($P < 0.0001$), as indicated by a reduction

Table 2. Pearson's correlation coefficient ($\alpha = 0.05$) and linear regression parameters describing the relationship between leachate electrical conductivity and individual ion concentrations during the irrigation (300 mL·min⁻¹ with deionized water) of fallow, 2.7-L nursery containers with pine bark:sand (9:1, by volume) substrate while blocking for controlled-release fertilizer placement (Expt. 1).

Ion	<i>r</i>	Slope	Y-intercept	R ²
NO ₃	0.99	0.29 a ^z	-5.87 c	0.99
SO ₄	0.99	0.11 b	-2.76 bc	0.99
Potassium	0.99	0.10 b	3.71 a	0.98
Magnesium	0.98	0.03 c	-2.06 abc	0.97
Calcium	0.99	0.03 c	-2.07 abc	0.99
PO ₄	0.96	0.03 c	1.94 ab	0.93
NH ₄	0.90	0.03 c	1.90 ab	0.81

^zMeans within column not sharing the same letter are significantly different according to Tukey's honestly significant difference ($P < 0.1$).

Table 3. Expt. 1 nutrient load (mg) in container effluent as a function of the cumulative effluent volume (mL) generated during the irrigation of a 2.7-L nursery container and pine bark:sand (9:1, by volume) substrate as affected by controlled-release fertilizer (CRF; ≈22-week longevity) placement at 3, 9, and 15 weeks after potting (WAP).

CRF placement	50 mL (0.15 LF ^a)			350 mL (0.5 LF)			2250 mL (0.9 LF)		
	3	9	15	3	9	15	3	9	15
<i>N-NH₄</i>									
No CRF	0.0 b ^y	0.0 b	0.0 c	0.0 c	0.0 c	0.0 b	0.0 b	0.0 c	0.0
Dibble	0.0 b B	0.6 a A	0.4 b A	1.3 ab B	7.0 a A	3.8 a AB	7.0 a	29.5 a	37.9
Incorporated	0.5 a	0.7 a	0.8 ab	2.3 a B	5.0 ab A	5.0 a A	5.3 a B	16.4 b AB	20.4 A
Topdressed	0.0 b B	0.3 ab B	0.9 a A	0.2 bc B	4.0 b A	4.7 a A	0.4 b B	12.6 b A	14.2 A
<i>N-NO₃</i>									
No CRF	0.0 c B	0.0 b B	0.0 b A	0.0 c B	0.0 b B	0.1 c A	0.0 b B	0.0 b B	0.2 c A
Dibble	0.5 b B	1.2 a AB	1.6 ab A	9.8 ab	11.3 a	12.4 b	37.3 a	39.3 a	57.8 ab
Incorporated	2.1 a AB	0.9 ab B	3.1 a A	12.5 a B	6.8 a C	18.5 a A	28.6 a B	23.0 a B	68.9 a A
Topdressed	0.4 bc B	1.7 a AB	2.7 a A	2.9 bc C	10.0 a B	15.6 ab A	8.6 b C	26.2 a B	45.5 b A
<i>P-PO₄</i>									
No CRF	0.1 b A	0.0 b B	0.0 c B	0.6 A	0.0 c B	0.0 c B	1.5 A	0.0 c B	0.1 c B
Dibble	0.0 b C	0.1 ab B	0.2 b A	0.9 B	2.0 a A	2.1 b AB	2.9	10.7 a	17.1 a
Incorporated	0.2 a B	0.2 ab B	0.5 a A	1.3 B	1.6 b B	3.1 a A	3.5 B	5.6 b B	13.6 ab A
Topdressed	0.1 b B	0.3 a AB	0.4 ab A	0.5 B	1.6 b A	2.3 ab A	1.4 C	4.4 b B	7.4 bc A
<i>K</i>									
No CRF	1.6 b A	0.3 B	0.3 b B	9.3 b A	2.0 b B	2.2 b B	27.8 b A	5.3 c B	7.3 b B
Dibble	1.8 b AB	0.9 B	2.6 ab A	16.1 ab	16.6 a	20.5 ab	57.7 a	55.5 a	118.4 a
Incorporated	3.7 a A	1.3 B	3.9 a A	22.5 a AB	9.3 a B	28.5 a A	61.0 a B	32.3 b B	133.3 a A
Topdressed	1.9 b	1.9	3.5 a	11.6 b	11.0 a	21.1 ab	38.4 ab	29.9 b	62.6 ab

^aLeaching fractions (LFs) are approximated based on the average time which leaching began (56 s ± 2 SE, n = 36), irrigation application rate (300 mL·min⁻¹) and the volume of effluent collected, not measured irrigation volumes.

^yMeans not sharing the same lower-case letter within columns or upper-case letters within row (delimited to 50-, 350-, or 2250-mL effluent groups) are significantly different according to Tukey's honestly significant difference ($P < 0.1$). The absence of letters indicates no significant difference.

Fig. 3. Expt. 2 release curves showing changes in effluent electrical conductivity (EC), nitrogen (N-NO_3), and phosphorus (P-PO_4) concentration as a function of cumulative effluent volume for fallow, 2.7-L nursery containers with pine bark:sand (9:1, by volume) substrate with a controlled-release fertilizer (CRF) applied as (O) incorporated or (●) topdressed CRF during irrigation with deionized water (DI) at a rate of $300 \text{ mL} \cdot \text{min}^{-1}$.

Table 4. Expt. 1 N-NO_3 load (mg) in post-irrigation drainage after the irrigation ($300 \text{ mL} \cdot \text{min}^{-1}$ with deionized water) of fallow, 2.7-L nursery containers with a pine bark:sand (9:1, by volume) substrate as affected by controlled-release fertilizer (CRF) placement at 3, 9, and 15 weeks after potting (WAP).

Placement	WAP		
	3	9	15
No CRF	0.0 b ²	0.0 c	0.0 b
Dibble	1.7 a A	2.4 a A	6.8 a B
Incorporated	0.9 ab A	1.5 ab A	5.6 a B
Topdressed	0.3 b A	1.0 bc AB	4.1 ab B
Volume (mL)	282.2 A	320.8 A	385.0 B

²Means not sharing the same lower-case letter within columns or upper-case letters within row (delimited to 50-, 350-, or 2250-mL effluent groups) are significantly different according to Tukey's honestly significant difference ($P < 0.1$). The absence of letters indicates no significant difference.

in the substrate height by $7.0 \text{ mm} \pm 0.6 \text{ SE}$ ($n = 12$). The highest N-NO_3 load in the post-irrigation drainage occurred in treatments with dibble and incorporated CRF followed by topdressed CRF (Table 4). Following the trends observed in Figure 2, the N-NO_3 load was highest at 15 WAP. Load values of N-NH_4 , P-PO_4 , and K (data not shown) followed the same general trends.

Weeks after potting. In Expt. 1, from 3 to 9 to 15 WAP, the predominant trend at 50-, 350-, and 2250-mL cumulative effluent volumes was for the total nutrient load to increase (Table 3). An exception to this trend was the N-NO_3 load leached when CRF was incorporated, in which the load tended to be highest at 15 WAP and least at 9 WAP. Potassium load in the control treatment was highest at 3 WAP for each of the 50-, 350-, and 2250-mL effluent volumes (Table 4) and was likely the result of an inherent amount of soluble K in pine bark (Raviv and Lieth, 2008) that was eventually leached from the bark with successive irrigations early in the

production season. Although the magnitude of the release curves in Figure 2, and subsequent nutrient load, for each CRF placement method changed among 3, 9, and 15 WAP, the pattern in which fertilizer salts moved through and leached from the substrate were similar for each placement method and is most likely resulted from the aforementioned differences in nutrient distribution throughout the substrate profile.

Conclusion

The concentration of ions in container effluent changed throughout the irrigation event and were affected by the CRF application method. Incorporated and topdressed CRF produced their highest effluent nutrient concentrations in the first 50-mL volume of effluent collected before steadily diminishing with increasing effluent volume. Dibbled CRF peaked after $\approx 150 \text{ mL}$ of effluent had been collected and resulted in a variable load of leached nutrients based on CRF placement and leachate volume.

Incorporated and dibbled CRF placement methods have the potential to produce the greatest quantity of leachable nutrients as compared with the topdressed method. However, a benefit of the dibbled over the incorporated method is that less of the leachable nutrients may leave the container when effluent volumes are kept low (low LF), leaving more residual nutrients in the substrate that are available for plant growth. This suggests that the dibble method may be a viable CRF placement method in terms of reducing nutrient leaching and the subsequent environmental impact in situations where growers are able to maintain a low LF, excluding the effect of rainfall. Additionally, the effect of fertilizer placement and effluent volume can be incorporated into models that predict nutrient leaching. Further research is warranted to determine the optimal method for adapting this placement method to containerized crop production systems.

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