Nutrient Release from Controlled-release Fertilizers in Acid Substrate in a Greenhouse Environment: I. Leachate Electrical Conductivity, pH, and Nitrogen, Phosphorus, and Potassium Concentrations

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Abstract. **Release characteristics of four types of controlled-release fertilizers (Osmocote, Nutricote, Polyon, and Multicote) were studied during a 47-week simulated plant production cycle. The 2.4-L containers containing a low-fertility, acid-based substrate were placed in an unheated greenhouse and subjected to environmental conditions often used for production of azaleas and camellias. Leachate from containers was collected weekly and monitored for pH, electrical conductivity, and concentrations of NH_4^+ N, NO_3^--N, total P and total K. Leachate concentrations of all nutrients were relatively high during the first 10 to 20 weeks of the study, and then gradually decreased during the remaining portion of the experiment. Differences were observed among fertilizer types, with Multicote often resulting in higher concentrations of N, P, and K in leachates compared to the leachates from the other fertilizer types during the first half of the study. Concentrations of NO_3^- and P from all fertilizer types were often above permissible levels as cited in the federal Clean Water Act.**

The Federal Water Pollution Control Act of 1948 was overhauled in 1972 with the addition of several amendments that directed regulations towards nonpoint sources of pollution, including commercial and private landscapes and nurseries. Since that time, the Act has been referred to as the Clean Water Act and, among other items, requires that all states must identify impaired waterbodies in their region and must implement regulations to mitigate pollutant runoff from any point and nonpoint sources. States are to use the U.S. Environmental Protection Agency (EPA) set of guidelines referred to as the Total Maximum Daily Loads (TMDLs) process described in §101(a), which provides a narrative list of physical and chemical parameters that should be considered as possible pollutants. Within this list are two major plant nutrients—nitrogen (N) and phosphorus (P). Other chemical parameters related to the horticultural industry, such as pH and salinity, are also listed in these federal guidelines.

Of the chemicals listed in these guidelines, N has the greatest risk for contaminating runoff, since N usage by the container nursery industry is relatively high (536 lb/acre each year) compared to other chemicals used on horticultural crops (Rathier and Frink, 1989) and various cultural practices of the industry are highly conducive to nitrate (NO_3^-) leaching. In order for the nursery industry to comply with these regulations, it is imperative that more efficient fertilization and irrigation guidelines be developed and more effective fertilizers be designed so that nutrient use efficiency (NUE) is optimized and nutrient leaching is minimized.

Controlled-release fertilizers (CRFs) are used extensively for the production of containerized woody ornamental plants, with the nursery and greenhouse industry accounting for almost 20% of all CRFs used in the U.S.

(Goertz, 1993). Most of the research related to nutrient release characteristics from CRFs have been undertaken using atypical substrates such as 100% sand, under controlled laboratory conditions (Broschat, 1996; 2005; Handreck, 1997; Havis and Baker, 1985a; Holcomb, 1981; Huett and Gogel, 2000; Husby et al., 2003; Lamont et al., 1987; Lunt and Oertli, 1962; Oertli and Lunt, 1962; Patel and Sharma, 1977), or by means of field studies (Gandeza et al., 1991), none of which reflects conditions experienced in container-production facilities. In addition, the duration of many experiments has been limited to ≤6 months, which is insufficient for measuring nutrient release from 12-month-release fertilizer formulations, as alluded to by Havis and Baker (1985a). The following study quantifies the nutrient release patterns of four types of CRFs, when blended into an acid substrate during an 11-month period in an unheated greenhouse environment, a production scenario often used for ericaceous crops such as azaleas and rhododendrons. Plants were not included in the study so that nutrient release characteristics could be easily monitored through leaching characteristics, without the influence of nutrient uptake into plants.

Materials and Methods

Substrate. Substrate consisted of a mixture of 5 sphagnum peatmoss (Premier Horticulture Inc., Red Hill, Pa.) : 4 pine bark (6.4 to 9.5 mm) : 1 washed builder's sand (by volume). The substrate was amended with dolomite 65 (Chemical Lime Co., Scottsdale, Ariz.) at a rate of 0.59 kg·m⁻³ and ultrafine calcium sulfate (Western Mining and Minerals, Apex, Nev.) at a rate of 0.59 kg·m⁻³. Substrate and amendments were blended together using a batch mixer (model MB20L5; Measured Marketing, Kankakee, Ill.). Substrate pH was 4.5 at the initiation of the experiment. For nutrient analyses, media were air-dried and ground to 0.420 mm with a Wiley Mill (model #3; Arthur H. Thomas Co., Philadelphia). The ground samples were extracted using the 1:2 dilution method as described by Lang (1996), where 50 mL volume of ground substrate was diluted with 100 mL deionized water, mixed, allowed to equilibrate for 30 min, and gravity filtered through Whatman 41 filter paper (Whatman Int., Ltd., Maidstone, England). Total P and K concentrations in extracts were quantitatively determined using an inductively coupled plasma–optical emission spectrometer (ICP–OES) (Thermo Electron Corp., model IRIS 1000 HR, Franklin, Mass.). Total N of the substrate was quantitatively determined by combustion on a N gas analyzer (LECO-FP528; Leco Corp., St. Joseph, Mich.) (Sweeney, 1989). Nutrient concentrations prior to incorporation of CRFs were as follows: 0.12% total N, 0.01% extractable P, and 0.02% extractable K.

Fertilizer treatments. Treatments consisted of four different CRFs: Osmocote 24–4–9 (Scott-Sierra Horticultural Products Co., Marysville, Ohio), Nutricote 18–6–8 Total (Chisso-Asahi Fertilizer Co., Tokyo), Multicote 17–5–11 + minors (Haifa Chemicals,

Table 1. Sources and amount (% by weight) of nitrogen (N), phosphorus (P), and potassium (K) in Osmocote 24–4–9, Polyon 17–5–11 + micros, Multicote 17–5–11 + minors, and Nutricote 18–6–8 total.

Fertilizer type	NH$_4^+$ N	NO$_3^-$ N	Urea N	Total N	P	K
Osmocote[z]	6.40	5.70	11.90	24.00	1.68	7.44
Polyon[y]	7.30	9.70	0.00	17.00	2.02	8.85
Multicote[x]	9.00	8.00	0.00	17.00	2.10	9.10
Nutricote[w]	8.60	9.40	0.00	18.00	2.52	6.62

[z]Osmocote 24–4–9. Nitrogen, phosphorus, and potassium are derived from ammonium nitrate, ammonium phosphate, polymer-encapsulated sulfur coated urea, calcium phosphate, and potassium sulfate.
[y]Polyon 17–5–11. Nitrogen, phosphorus, and potassium are derived from ammonium nitrate, ammonium phosphate, potassium sulfate, and potassium nitrate.
[x]Multicote 17–5–11 + minors. Nitrogen, phosphorus, and potassium are derived from ammonium nitrate, mono ammonium phosphate, potassium nitrate, and potassium sulfate.
[w]Nutricote 18–6–8 total. Nitrogen, phosphorus, and potassium are derived from ammonium nitrate, ammonium phosphate, calcium phosphate, and potassium nitrate.

Table 2. Amount (g) of nitrogen (N), phosphorus (P), and potassium (K) incorporated into each #1 container (2.4 L) of substrate. Fertilizer rates were normalized for the same amount of nitrogen (3.11 g/#1 container) since different brands of fertilizers contained different ratios of nutrients.

Treatment (fertilizer)	NH$_4^+$ N	NO$_3^-$ N	Urea N	Total N	P	K
Osmocote	0.83	0.74	1.54	3.11	0.22	0.96
Polyon	1.65	1.46	0.00	3.11	0.37	1.62
Multicote	1.65	1.46	0.00	3.11	0.38	1.66
Nutricote	1.49	1.62	0.00	3.11	0.44	1.14

Ltd., Haifa Bay, Israel), and Polyon 17–5–11 + micros (Pursell Technologies, Inc., Sylacauga, Ala.). All four fertilizers release nutrients based on water diffusion into prills, the rate of which is regulated by temperature. Osmocote did not contain micronutrients; therefore, micronutrients were provided by incorporation of Micromax (Scott-Sierra Horticultural Products Co., Marysville, Ohio), an uncoated, granular fertilizer at a rate of 0.53 kg·m^{-3}. All CRFs were 365-d release formulations; however, release rates of these CRFs are based on different temperature regimes: 27 °C for Osmocote and Polyon, 21ºC for Multicote, and 21 to 27 °C for Nutricote. Element concentrations and compounds used in each fertilizer were different (Table 1). Since the percentage of nutrients contained in the different fertilizers varied, the amount of fertilizer added was calculated so that all treatments contained 3.11 g N/container, which is equivalent to 1.17 kg N/m^3, an average rate which the four fertilizer manufacturers recommended for slow-growing woody ornamentals. While N content for all CRF treatments was the same, the content of other nutrients varied (Table 2). CRF prills were incorporated throughout the substrate using a portable cement mixer. Substrate with CRF was placed in #1 black polyethylene containers (2.4 L; 157 mm top diameter, 127 mm bottom diameter, 178 mm tall; Farrand Enterprises, Chino, Calif.) with side and bottom drainage holes. Each container represented one replication. There were five replications of each treatment for each of 11 months of leachate monitoring. Containers were placed in a randomized complete block design.

Cultural practices. Substrate and fertilizer treatments were prepared on 1 Aug. 2001. The experiment was conducted from 1 Aug. 2001 through 27 June 2002. Containers were placed in an unheated, poly-covered greenhouse on the University of California, Riverside campus (lat. 33°53'30'N, long. 117°15'00'W). Summer high temperatures were moderated with the use of an evaporative pad and fan cooling system, which was set to turn on at 30 °C. Winter low temperatures were moderated through the protection provided by the polyethylene cover. From 1 Aug. 2001 to 29 Oct. 2001 and 8 Apr. 2002 to 27 June 2002, the greenhouse was covered with an aluminum-coated polyester OLS50 screen (AB Ludvig Svensson, Kinna, Sweden), which provided 49% shade. Containers were irrigated with municipal tap water which contained an average of (mg·L^{-1}): 0.05 NH$_4^+$ N, 2.32 NO$_3^-$ N, 0.02 P, and 2.94 K, and had a pH range of 7.31 to 8.50 and an EC ranging from 0.31 to 0.65 mS·cm^{-1}. Irrigation water was distributed uniformly over the surface of the substrate using DRT4-36 ring drippers (Dramm Corporation, Manitowoc, Wis.) made of 6.35-mm-diameter polyethylene tubing with six drip holes spaced every 2 cm. Containers were irrigated about every 2 d, providing an average irrigation volume of about 1 L/week and an average leachate volume of about 750 mL/week. This irrigation program mirrored the water requirement of an adjacent azalea crop being grown during the same time period in the same greenhouse.

Leachate collection. Leachate was collected from each container by placing a plastic sleeve (140 mm bottom diameter and 165 mm top diameter) over each container; each container and sleeve were placed into a plastic 2.45 L (152 mm top diameter, 127 mm bottom diameter, and 152 mm high) bucket. The larger dimensions of the container compared to the collection bucket allowed the containers to be elevated above the level of the leachate. Leachate was collected from buckets twice per week, and volumes from each bucket were combined so that there was one leachate sample per container per week. Leachate electrical conductivity (EC) and pH were measured once per week after the first irrigation of the week. EC was measured with a Horiba conductivity meter (model B-173; Horiba Ltd., Minami-ku Kyoto, Japan), and pH was measured with a Horiba compact pH meter (model B-213; Horiba Ltd.). Immediately following EC and pH measurements, 2 mL of 2 N sulfuric acid were added to each bucket to chemically sta-

bilize the leachate. An additional 2 mL of 2 N sulfuric acid was then added to the emptied bucket, so that subsequent leachate collected from the container during the final part of the week was immediately stabilized. Leachate from the first collection of the week was stored at 4 °C until the end of the week, at which time leachate from the remainder of the week was added to the weekly sample. At the end of each week, collection buckets were washed with 10% bleach to prevent algal growth.

Leachate analysis. Total leachate volume from each container was measured at the end of each week. A 70-mL aliquot was taken and frozen until analysis. Solutions were analyzed for ammonium (NH$_4^+$) N and NO$_3^-$ N with a Technicon TRAAC 800 Autoanalyzer (Technicon Instruments Corp., Tarrytown, N.Y.). Total P and K were determined using an inductively coupled plasma optical emission spectrometer (ICP-OES) (Thermo Electron Corp., model IRIS 1000 HR, Franklin, Mass.).

Statistical analysis. Preliminary analysis of the data was conducted by regressing each of the dependent variables (EC, pH, and concentrations of individual nutrients) against time (weeks), along with the qualitative treatment and blocking factors, using a general linear model (PROC GLM). Preliminary results (not presented) indicated strong interaction between time and treatments, along with higher-level polynomial terms for the regression component of the model. To facilitate a useful interpretation of the experimental results, data were subsequently analyzed by modeling the dependent variables against only the qualitative treatment and blocking factors, with separate analyses for each week, permitting comparisons among CRF treatments at specific times during the 11-month period. Multiple comparisons among CRF treatments within a specific week were made using Tukey's Studentized range test with an experimentwise α-level of 0.10 covering all six simultaneous pairwise comparisons. Statistical analyses were conducted using SAS Version 9.1 (SAS Institute, Cary, N.C.).

Results and Discussion

Air temperature. Weekly average greenhouse air temperature ranged between 24 and 30 °C during the first 10 weeks (August through September 2001) and the last 10 weeks (May 2002 through June 2002) of the study (Fig. 1). Maximum air temperatures during this time period ranged from 28 to 46 °C, which are temperatures observed in other warm-temperate and subtropical growing regions (Ingram, 1981; Lamont et al., 1987). These temperatures were consistently above 21 °C, the labeled substrate temperature rating for 1-year longevity for Multicote. However, only weekly maximum air temperatures were typically above the average labeled media temperature ratings of 24 °C for Nutricote and 27 °C for Osmocote and Polyon. Since nutrient release from many CRFs, including those in the present study, is temperature dependent, any elevated temperatures that may occur can greatly impact nutrient release characteristics of CRFs. In studies related to
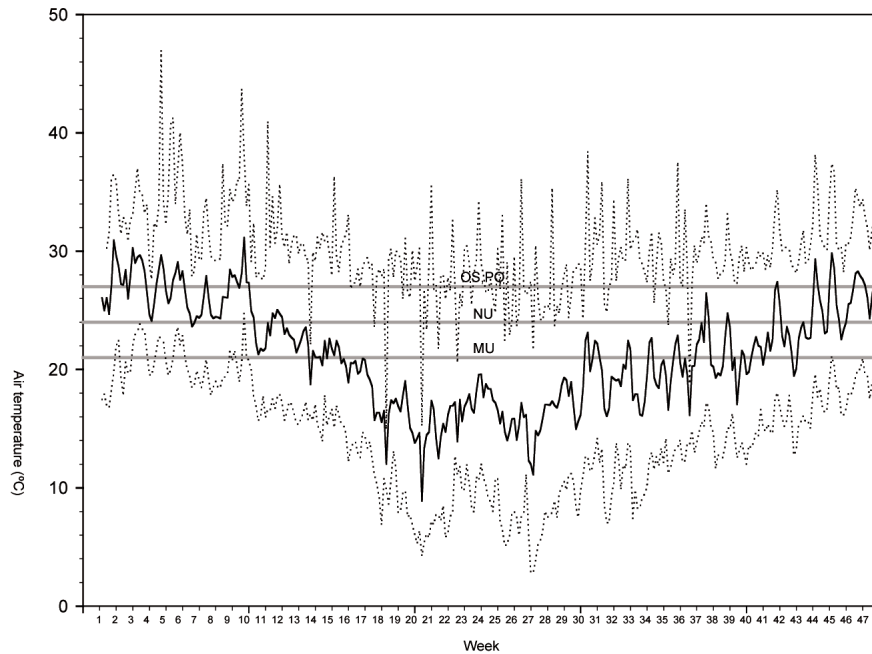
Fig. 1. Daily average (solid line), minimum (lower dotted line) and maximum (upper dotted line) greenhouse air temperatures over a 47-week period (1 Aug. 2001 to 27 June 2002), with gray horizontal lines indicating media temperatures for 12-month fertilizer release as specified by the respective manufacturers of Osmocote (OS), Polyon (PO), Multicote (MU), and Nutricote (NU).
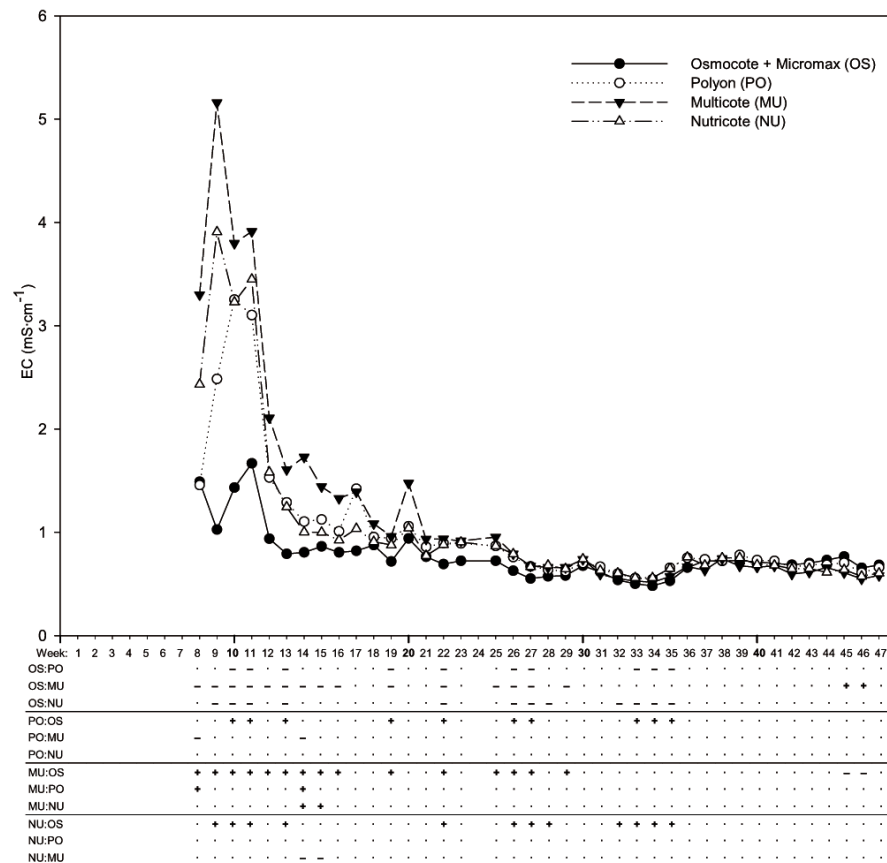

Fig. 2. Electrical conductivity (EC) of irrigation leachate collected weekly over a 47-week period (1 Aug. 2001 to 27 June 2002) from a pine bark and peat-based substrate prepared with four controlled-release fertilizers at equal rates of total N. One-gallon containers containing substrate without plants were located in a controlled-environment greenhouse during the experiment and irrigated with drip emitters using municipal tap water (EC 0.5 mS·cm⁻¹). Plotted points (**top**) represent least squares means for each fertilizer. Significant differences in least squares means for pairs of treatments for each week (**bottom**) are indicated with the first treatment listed in each pair being greater than (+), less than (−), or not different from (•) the second treatment listed in each pair according to Tukey's test ($P \le 0.10$).

environmental conditions and CRFs, nutrient release rates increased by up to 200% for every 10 °C increase in media temperature above optimum release temperature (Husby et al., 2003; Kochba et al., 1990; Lamont et al., 1987; Oertli and Lunt, 1962); however, other experiments (Huett and Gogel, 2000) showed only a 15% increase in release rates at higher media temperatures. At suboptimum temperatures, nutrient release characteristics have been shown to be inconsistent (Engelsjord et al., 1997); however, others (Kochba et al., 1990) have shown that the nutrient release rates are lower, but uniform.

Electrical conductivity. Leachate electrical conductivity (EC) was elevated during the first 5 months of the study, relative to the later time frame, regardless of fertilizer type, with significant differences observed among treatments (Fig. 2). Similar trends in EC fluctuations have also been observed in other studies (Lamont et al., 1987). During the entire study, the leachate EC of the Osmocote treatment was often significantly lower than the EC from the other treatments, especially Multicote. Both Polyon and Nutricote treatments also had leachate EC levels that were significantly lower than levels recorded for Multicote. Near the end of the study, (weeks 45 and 46), the leachate EC for Osmocote was significantly greater than the EC for Multicote. In diurnal studies (20 h) that compared Osmocote, Nutricote, and Polyon, Osmocote resulted in leachates with lower soluble salts than Nutricote or Polyon at temperatures between 20 and 25 °C; however, Osmocote had higher release rates at temperatures above 35 °C (Husby et al., 2003). In longer-term studies (Lamont et al., 1987), Osmocote exhibited higher release rates than Nutricote at all temperature regimes studied (5, 10, 15, 20, 25, 30, 35, 40, and 45 °C). Based on the present study and research by Husby et al. (2003) and Lamont et al. (1987), there are daily as well as weekly trends in nutrient release from CRFs which, in the case of diurnal fluctuations, closely reflect changes in temperature. However, over extended periods of time, the pool of nutrients remaining in the prills diminishes, which results in decreased quantities of nutrient release and thus decreased EC levels, even with increased temperatures during later parts of a production period.

From an environmental perspective, federal guidelines dictate that soluble salts should not exceed 250 mg·L⁻¹, based on chloride and sulfate concentrations only. Therefore, monitoring and control of EC, from a regulatory point-of-view, would be irrelevant, since EC takes into account all dissolved salts.

pH. During the first 20 weeks, leachate pH was variable, but consistently acidic (Fig. 3), even though irrigation water pH was 7.5, indicating that substrate and/or fertilizers used in the study influenced leachate pH more so than did the neutral irrigation water. Other studies (Chen et al., 2003) have demonstrated that a similar substrate containing pine bark, sand, and peat buffered irrigation water of pH 9.7 (with low alkalinity) to a measured substrate pH of about 6.5. In addition, a study by Ivy et al. (2002) showed that fertilizer type (Osmocote
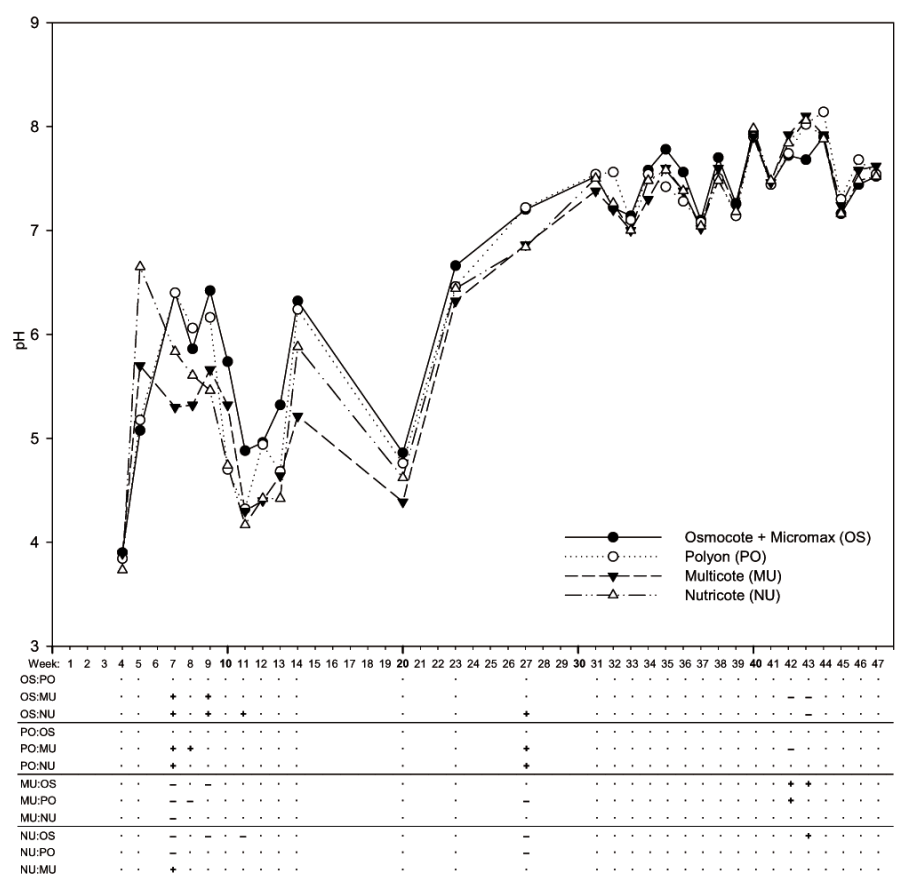
Fig. 3. The pH of irrigation leachate collected weekly over a 47-week period (1 Aug. 2001 to 27 June 2002) from a pine bark and peat-based substrate prepared with four controlled-release fertilizers at equal rates of total N. Plotted points (**top**) represent least squares means for each fertilizer. Significant differences in least squares means for pairs of treatments for each week (**bottom**) is indicated with the first treatment listed in each pair being greater than (+), less than (−), or not different from (•) the second treatment listed in each pair according to Tukey's test ($P \leq 0.10$). One-gallon containers containing substrate without plants were located in a controlled-environment greenhouse during the experiment and irrigated with drip emitters using municipal tap water (pH 7.5).

and Polyon) used does not influence pH.

Among fertilizer types, few significant differences were detected. Leachate pH from substrate containing Osmocote was higher compared to the leachate pH of Multicote and Nutricote treatments, 2 and 4 weeks, respectively, during the 47-week period. The pH readings in weeks 42 and 43 for Multicote and week 42 for Nutricote were significantly higher than the leachate pH for Osmocote. However, another study (Ivy et al., 2002) showed that fertilizer type (Osmocote and Polyon) did not influence pH but, in a different study (Argo and Biernbaum, 1997), it was determined that leachate pH is influenced by compounds used in fertilizers, especially in respect to the ratios of NH_4^+ to NO_3^-, with pH decreasing when the amount of NH_4^+ relative to NO_3^- increases. In the present study, the amount of N as NH_4^+ ranged between 43% and 53%, except for the Osmocote formulation that contained 76% of the N in the ammoniacal form (NH_4^+ and urea). These differences in N form may not have been different enough to cause significant changes in leachate pH among different fertilizer treatments. None of the changes in pH measured in the present study fell outside the critical ranges established by the U.S. EPA (pH of 5.0 to 9.0 for domestic water supplies, 6.5 to 8.5 for freshwater aquatic life, and 6.5 to 9.0 for marine aquatic life) (U.S. EPA, 1976).

Ammoniacal-nitrogen concentration. During the first 4 weeks of the study, NH_4^+ N concentrations in leachates in all treatments were below 10 mg·L^{-1} (Fig. 4). From week 5 to week 9, concentrations increased to above 150 mg·L^{-1}, followed by a decline from week 10 to week 30. During the last 17 weeks, leachate

Fig. 4. Concentration of NH_4^+ N (mg·L^{-1}) in irrigation leachate collected weekly over a 47-week period (1 Aug. 2001 to 27 June 2002) from a pine bark and peat-based substrate prepared with four controlled-release fertilizers at equal rates of total N. Plotted points (**top**) represent least squares means for each fertilizer. Significant differences in least squares means for pairs of treatments for each week (**bottom**) is indicated with the first treatment listed in each pair being greater than (+), less than (−), or not different from (•) the second treatment listed in each pair according to Tukey's test ($P \leq 0.10$). One-gallon containers containing substrate without plants were located in a controlled-environment greenhouse during the experiment and irrigated with drip emitters using municipal tap water.

NH_4^+ N concentrations were <1 mg·L^{-1}, except for the Osmocote treatment, which averaged about 3.0 mg during the last 3 weeks of the study, which was significantly greater than with the other fertilizer treatments. When making comparisons among treatments, leachate NH_4^+ N from the Multicote treatment was significantly greater than with the other treatments
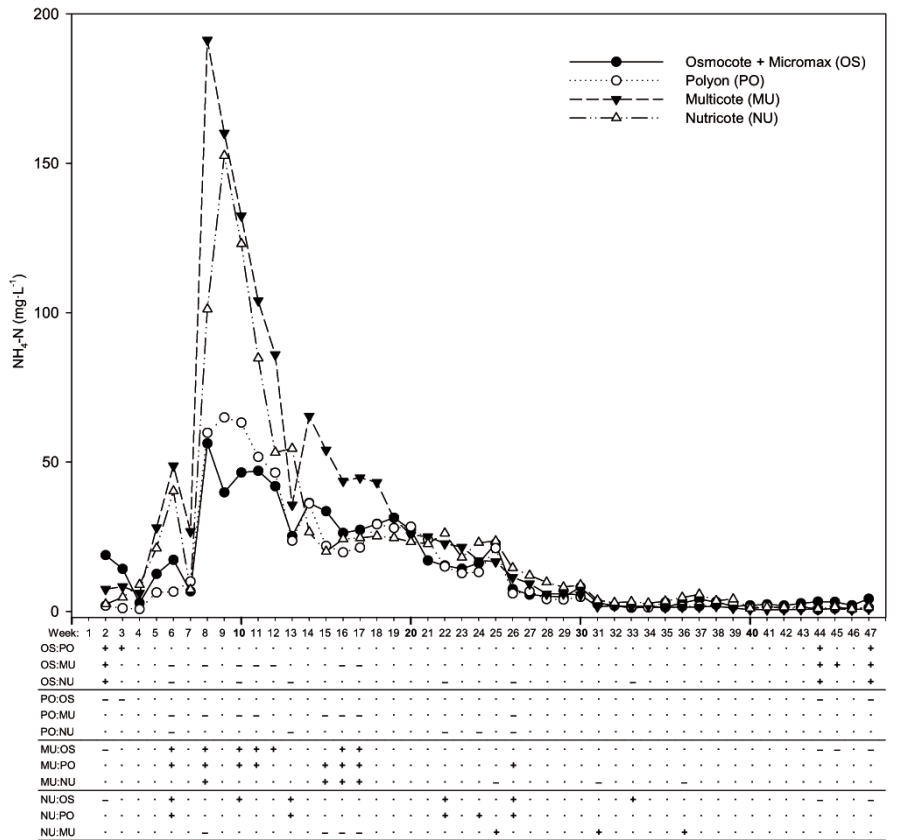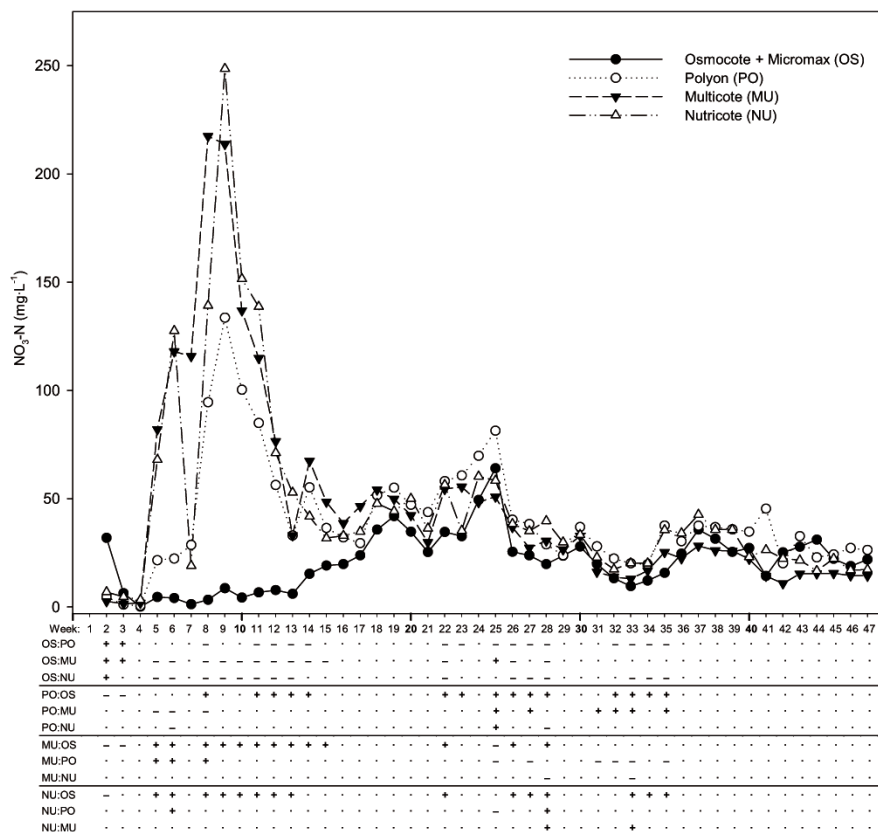
Fig. 5. Concentration of NO_3^--N (mg·L^{-1}) in irrigation leachate collected weekly over a 47-week period (1 Aug. 2001 to 27 June 2002) from a pine bark and peat-based substrate prepared with four controlled-release fertilizers at equal rates of total N. Plotted points (**top**) represent least squares means for each fertilizer. Significant differences in least squares means for pairs of treatments for each week (**bottom**) are indicated with the first treatment listed in each pair being greater than (+), less than (–), or not different from (•) the second treatment listed in each pair according to Tukey's test ($P \leq 0.10$). One-gallon containers containing substrate without plants were located in a controlled-environment greenhouse during the experiment and irrigated with drip emitters using municipal tap water.

(2005), the percentage of NH_4^+-N from the CRF recovered in the leachates in the present study were lower, which is probably due to the binding of NH_4^+-N to organic matter of the container substrate (Foster et al., 1983; Thomas and Perry, 1980). The decrease in NH_4^+-N concentrations of leachates during the later stages of the present study may be partly accounted for by lower quantities of NH_4^+-N that remained in the prills (Broschat, 2005). In addition, there was probably nitrification of NH_4^+ to NO_3^- in the present study. In studies associated with nitrification of NH_4^+, it was determined that most of the NH_4^+ is converted to NO_3^-, with a slower rate of nitrification when soil pH was lower (Dancer et al., 1973; Niemiera and Wright, 1986) or when substrate temperatures exceed 46 °C (Walden and Wright, 1995). In a diurnal study (Husby et al., 2003), NH_4^+-N release was closely associated with temperature, with greater release of NH_4^+ from Osmocote compared to Nutricote or Polyon at high temperatures (>35 °C), but lower release rates at low temperatures (<35 °C). In the present study, air temperatures were seldom above 35 °C, which may explain the fairly level NH_4^+-N release patterns.

Federal guidelines do not mention NH_4^+-N concentration, but do state that concentrations of unionized ammonia, expressed as NH_3, should not exceed 0.02 mg·L^{-1} for freshwater aquatic life (U.S. EPA, 1976). Based on other research (Thurston et al., 1974), this would mean that total ammonia (NH_4^+ + NH_3) concentration, which was measured in the present

several times during the first 17 weeks of the study. Similar release patterns were observed in other experiments (Broschat, 2005) using 8- to 9-month-release formulations of Osmocote and Nutricote. Broschat (2005) found that 30% to 50% of the NH_4^+-N was released from prills of these fertilizers by the end of month 2, and by month 7, <20% of the NH_4^+-N remained in the prills. While patterns of NH_4^+-N leaching were similar to release rates measured by Broschat

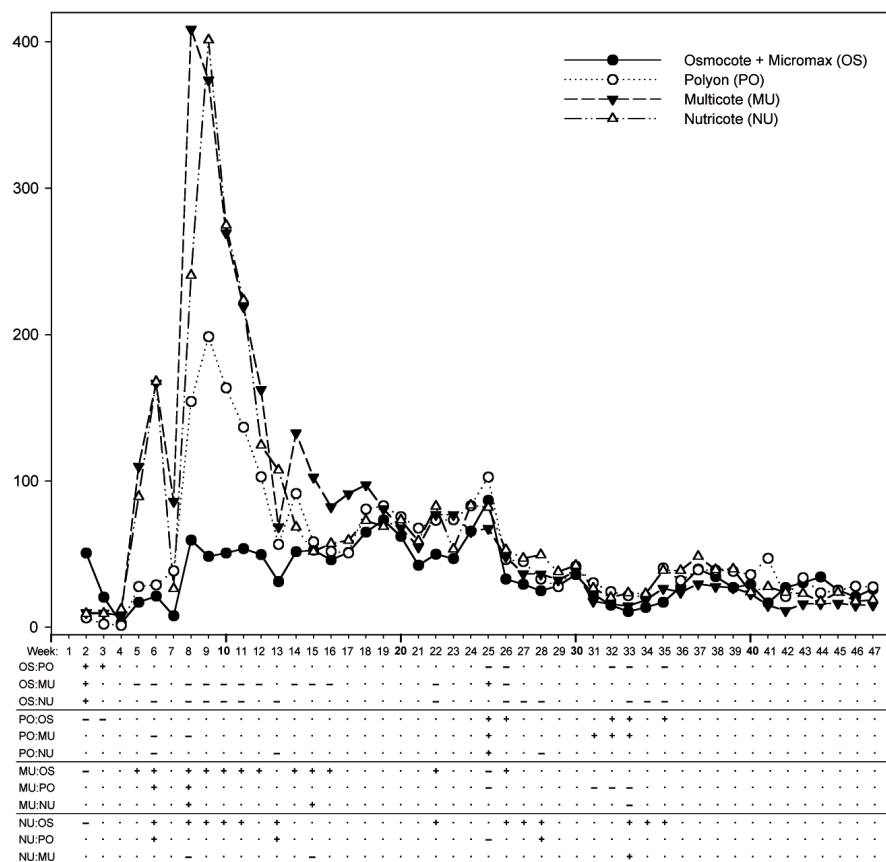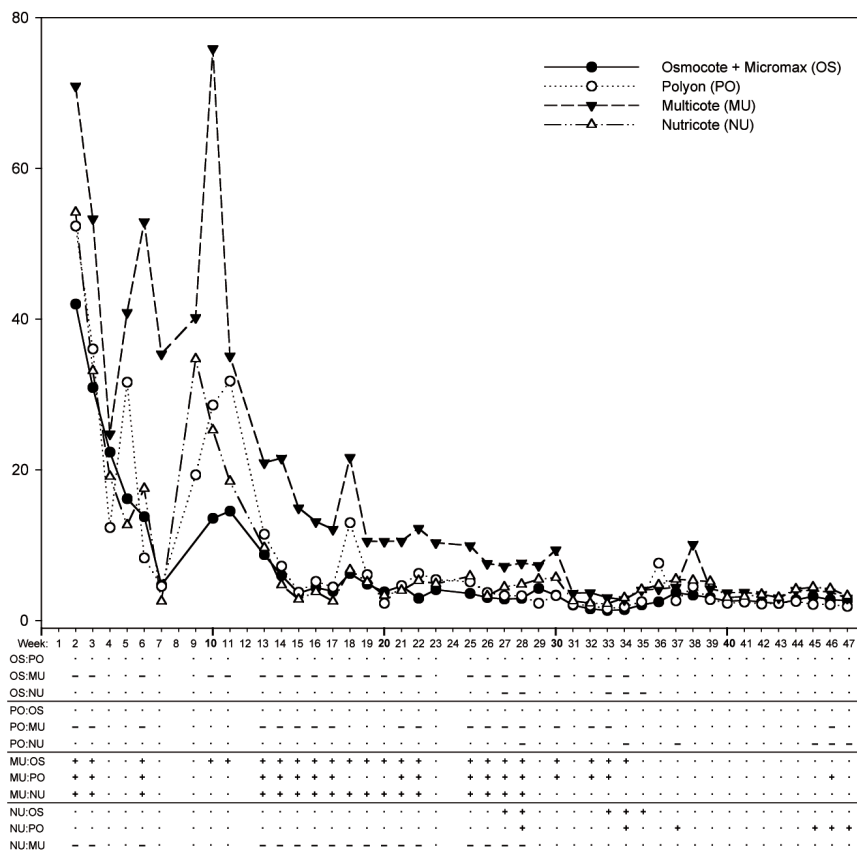Fig. 6. Concentration of inorganic N (NH_4^+-N + NO_3^--N) (mg·L^{-1}) in irrigation leachate collected weekly over a 47-week period (1 Aug. 2001 to 27 June 2002) from a pine bark and peat-based substrate prepared with four controlled-release fertilizers at equal rates of total N. Plotted points (**top**) represent least squares means for each fertilizer. Significant differences in least squares means for pairs of treatments for each week (**bottom**) are indicated with the first treatment listed in each pair being greater than (+), less than (–), or not different from (•) the second treatment listed in each pair according to Tukey's test ($P \leq 0.10$). One-gallon containers containing substrate without plants were located in a controlled-environment greenhouse during the experiment and irrigated with drip emitters using municipal tap water.

Fig. 7. Concentration of total P (mg·L⁻¹) in irrigation leachate collected weekly over a 47-week period (1 Aug. 2001 to 27 June 2002) from a pine bark and peat-based substrate prepared with four controlled-release fertilizers at equal rates of total N. Plotted points (**top**) represent least squares means for each fertilizer. Significant differences in least squares means for pairs of treatments for each week (**bottom**) are indicated with the first treatment listed in each pair being greater than (+), less than (−), or not different from (•) the second treatment listed in each pair according to Tukey's test ($P \leq 0.10$). One-gallon containers containing substrate without plants were located in a controlled-environment greenhouse during the experiment and irrigated with drip emitters using municipal tap water.

study, would have to be in the range of 16 to 160 mg·L⁻¹ for a solution pH range of 7.0 to 6.0, but is also dependent on solution temperature. Given these criteria, it is likely that NH₃

concentrations could have exceeded federal limits several times throughout the course of the experiment.

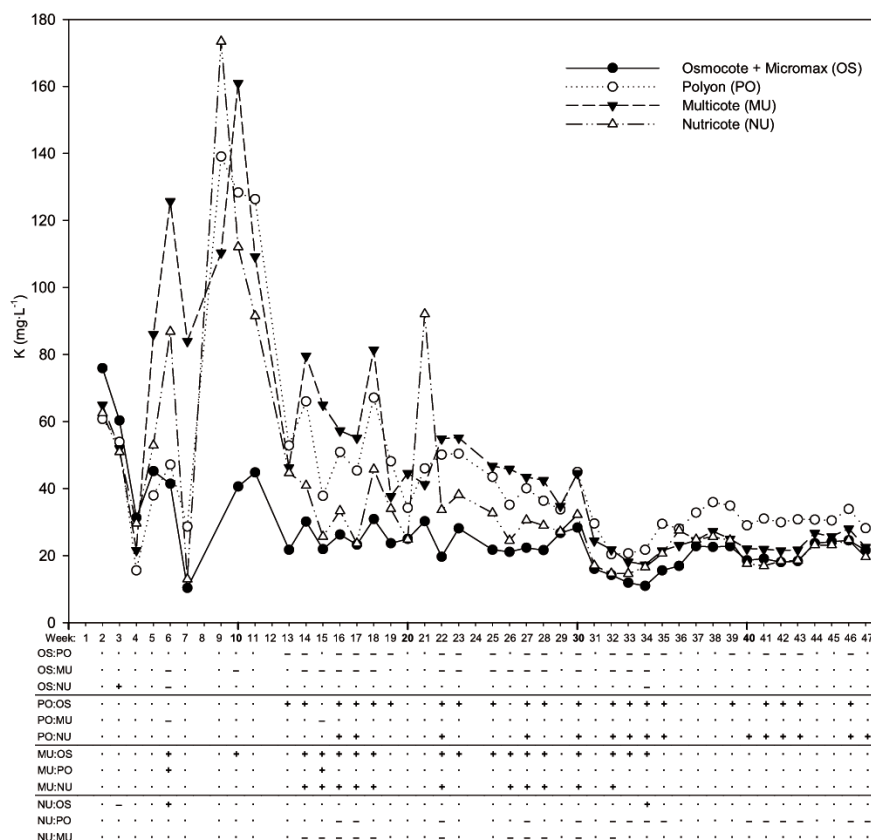*Nitrate nitrogen concentration.* In all fertilizer treatments, NO_3^- N concentrations were below 10 mg·L⁻¹ during the first 4 weeks of the study, with the exception of week 2, when leachate from the Osmocote treatment averaged 32 mg·L⁻¹ (Fig. 5). From week 4 to week 9, NO_3^- N concentrations increased to over 100 mg·L⁻¹ for all treatments except Osmocote. From week 10 to the end of the study, NO_3^- N concentration decreased and leveled off to about 30 mg·L⁻¹ for leachates from treatments containing Nutricote, Polyon, or Multicote. However, for Osmocote, leachate NO_3^- N concentrations gradually increased to about 50 mg·L⁻¹ and then decreased to about 30 mg·L⁻¹ during the remaining 20-week period. Of the fertilizers tested, Osmocote appeared to produce the most stable release pattern of NO_3^- N. During one-third of the weeks of the study, NO_3^- N concentrations were lower for Osmocote compared with the leachate collected from the other fertilizer types. Similarly, the NO_3^- N concentration in leachates collected from the Polyon treatment was significantly lower than for Multicote 6 weeks out of ten during weeks 25 through 35. The release pattern of NO_3^- in leachates from Osmocote and Nutricote treatments are similar to the release characteristics determined by others (Broschat, 2005; Prasad and Woods, 1971), except that, on a weekly basis, the data from the present study indicated that Osmocote may have a lower, but more stable, NO_3^- release pattern from the prills compared to Nutricote. In general, the elevated concentrations of NO_3^- relative to NH_4^+, especially during the later half of the study, are probably associated with the nitrification of NH_4^+ in addition to the release of NO_3^- from the fertilizer prills. Other stud-

Fig. 8. Concentration of K (mg·L⁻¹) in irrigation leachate collected weekly over a 47-week period (1 Aug. 2001 to 27 June 2002) from a pine bark and peat-based substrate prepared with four controlled-release fertilizers at equal rates of total N. Plotted points (**top**) represent least squares means for each fertilizer. Significant differences in least squares means for pairs of treatments for each week (**bottom**) are indicated with the first treatment listed in each pair being greater than (+), less than (−), or not different from (•) the second treatment listed in each pair according to Tukey's test ($P \leq 0.10$). One-gallon containers containing substrate without plants were located in a controlled-environment greenhouse during the experiment and irrigated with drip emitters using municipal tap water.

ies have demonstrated significant nitrification of NH_4^+ in soils and substrates of acidic to neutral pH (Dancer et al., 1973; Niemiera and Wright, 1986).

Based on federal guidelines of a maximum of 10 mg·L^{-1} of NO_3^--N for domestic water use (U.S. EPA, 1976), NO_3^--N concentrations exceeded permissible levels during most of the experiment. However, if plants had been included in the present study, the likelihood of NO_3^--N leaching in excess of 10 mg·L^{-1} would probably only have existed during the first 12 weeks of the study when total concentrations of NO_3^--N were above 100 mg·L^{-1}. The only fertilizer product in exception to this was Osmocote, which had relatively low NO_3^--N concentrations during the entire period of the study.

Total inorganic N concentrations. Release characteristics as indicated by total inorganic-N concentrations (ammonium + nitrate) showed significant release of N during the first 9 weeks of the study, then a decrease and leveling off period during the remaining 36 weeks for Polyon, Nutricote, and Multicote (Fig. 6). The exception to this pattern was Osmocote, which had more consistent leachate inorganic N concentrations between 30 and 50 mg·L^{-1} throughout the entire experimental period. The pattern of high then low N release during the beginning and end of the experiment, respectively, are similar to other studies (Huett, 1997b; Huett and Gogel, 2000; Prasad and Woods, 1971; Patel and Sharma, 1977). The initial lag in N appearance in leachate in the present study may be partially due to chemical and biological immobilization of N in the organic substrate, which has been documented by others (Foster et al., 1983; Gartner et al., 1971; Handreck and Bunker, 1996; Thomas and Perry, 1980). In addition, concentrations of NH_4^+ relative to NO_3^- were similar during the first half of the study, but NO_3^- was the predominant inorganic N form during the later half of the study, regardless of fertilizer type. This phenomenon is probably associated with the nitrification of NH_4^+, as demonstrated in other studies (Dancer et al., 1973) and possibly the faster release rate of NH_4^+-N from the prills, relative to NO_3, as measured by Broschat (2005). In shorter-term studies (6 months), NO_3^- was the predominant N form during the entire experimental period (Cabrera, 1997). Regardless of fertilizer type, the present study did not detect any significant correlation of inorganic N release with air temperatures. These results differ from studies conducted by Cabrera (1997) and Handreck (1997), where N release characteristics of Osmocote, Nutricote, and Polyon were closely associated with temperature. However, the experiments conducted by Cabrera lasted 9 months, during which time temperatures slowly increased then decreased, and the studies conducted by Handreck were in a temperature-controlled (21 °C) laboratory. In the present study, temperatures fluctuated, with relatively high temperatures during the first 2 months, then decreasing during the winter, and then increasing again during the following spring.

Total phosphorus concentrations. Since fertilizer additions were normalized for N content, total P content added differed among fertilizer treatments, with an average P content of 0.40 g/container for Polyon, Nutricote, and Multicote, but 50% less for Osmocote (0.22 g/container). Phosphorus concentrations in leachates of all treatments fluctuated throughout the study, but were higher (15 to > 60 mg·L^{-1}) during the first 10 weeks compared to the last 27 weeks of the study, when concentrations averaged below 10 mg·L^{-1} (Fig. 7). The pattern of high then low P release in the present study is similar to other studies with Osmocote, Nutricote, and Polyon (Huett, 1997b; Huett and Gogel, 2000). When comparing treatments, Multicote tended to produce the highest P concentrations in leachates compared to the other fertilizers types, primarily during the first 37 weeks. For the most part, total P concentrations of other treatments were somewhat similar throughout the study. In another experiment (Broschat, 2005), release of P from Osmocote prills during the first 5 months was significantly greater than that measured from Nutricote; however, by month 7, differences in release were not significant. In shorter-term studies (10 weeks), there were no differences in P release rates between Osmocote and Nutricote (Huett, 1997b). According to field and container experiments (Flint, 1962; Handreck, 1996; Havis and Baker, 1985a; 1985b; Wright, 1984; Yeager and Wright, 1982), solution P concentrations of about 10 mg·L^{-1} are required for optimal growth of woody ornamentals. A fraction of this P is tied in organic substrates, as demonstrated by Handreck (1996). Based on the present study and the experiments of others, it appears that a high release of P from CRFs may elevate the risk of P leaching during the early parts of the production cycle, but a lower release of P may limit plant growth during the later part of a production cycle.

Regarding P, the U.S. EPA has established a concentration limit of 0.01 µg·L^{-1} for elemental P (U.S. EPA, 1976). There are currently no federal guidelines for ortho-phosphate or total phosphorus. Based on the criterion for total P, the greatest risk of P leaching would be during the first 20 weeks of the production cycle, especially if any fraction of the total P determined was elemental in nature.

Total potassium concentrations. Total K concentrations of leachates from all treatments ranged between 10 and 170 mg·L^{-1}, with higher concentrations during the first 20 weeks of the study compare to the last 27 weeks (Fig. 8). When comparing CRF types, K concentrations in leachates from Osmocote and Nutricote treatments were similar, but both were significantly lower than K concentrations of leachates collected from containers containing Polyon or Multicote. These differences may be attributed to the amount of K added, since fertilizer additions were normalized for N. Osmocote and Nutricote contained about 36% less K than the Polyon and Multicote treatments. While not measured, a portion of the K released from the prills was probably tied up by the organic fraction, which has been shown to occur with organic substrate (Brown and Pokorny, 1977; Foster et al., 1983). Elevated K release from CRFs during the early part of the production cycle observed in the present study is similar to other studies (Broschat, 1996, 2005; Huett, 1997b) that compared K release from Osmocote, Nutricote, and Multicote. In other research (Holcomb, 1981) with Osmocote, K release rates were linear throughout the 63-d study period. Even though K concentrations were elevated in leachates during the first portion of the experiment, there is no concern of K concentrations exceeding federal recommended guidelines, since no guidelines have been established for K.

Conclusions

Under unheated greenhouse conditions, the release characteristics of NH_4^+, NO_3^-, K, and P from all CRFs tested were elevated during the first half of the study, followed by lower release during the later half of the 11-month period. The nutrient release rates do not appear to be associated with ambient temperature, as high temperatures were moderated with evaporative cooling pads and fans, and there was a general increase in temperature during the spring. Based on the results of this study and data from other long term studies, it appears that nutrient release from all the CRFs tested may be in excess of plant requirements during the first half of the production period (Huett, 1997b; Huett and Gogel, 2000), but may be insufficient during later stages of production (Huett, 1997a), depending on the nutrient demands of the crop being grown and the temperature profiles during production.

Patterns of leachate EC reflect somewhat the leachate concentrations of N, P, and K. These correlations have also been measured by others (Cabrera, 1997; Huett and Morris, 1999; Husby et al., 2003). Leachate EC is probably associated with both nutrient release from CRF and soluble salts leached out of the substrate during the first few weeks of the study.

Differences were noted among fertilizer types, with Multicote often exhibiting a higher nutrient release than the other CRFs tested during the first 20 weeks of the study. However, during the last half of the study, nutrient concentrations in Multicote leachates were sometimes less than the nutrient concentrations recovered from the other fertilizer treatments, suggesting that the high release rates measured for Multicote during the first half of the experiment resulted in a noticeably smaller pool of nutrients available for release during the last half of the study.

From an environmental perspective, risk of water impairment when using the CRFs employed in the present study would be greatest during the first 20 weeks of crop production when EC, NH_4^+-N, NO_3^--N, total P, and total K were elevated. Based on guidelines established by the U.S. EPA (1976), the chemical parameters of pH, EC, NH_4^+-N, NO_3^--N, and P, as observed in the present study, were not within acceptable limits during various time frames throughout the 11-month period. However, concentrations of nutrients in leachates would probably be reduced if plants were present in the containers. For this reason, additional

research regarding leaching characteristics of CRFs is required, particularly for a typical plant production scenario using woody ornamentals commonly grown in the nursery industry.

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