

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

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Abstract. Release characteristics of four different polymer-coated fertilizers (Multicote, Nutricote, Osmocote, and Polyon) were studied over a 47-week period in a simulated outdoor, containerized plant production system. The 2.4-L containers, filled with high-fertility, neutral-pH substrate, were placed on benches outdoors to simulate the environmental conditions often used for sun-tolerant, woody perennials grown in the southwestern United States. Container leachates were collected weekly and monitored for electrical conductivity, pH, and concentrations of NH_4^+N , NO_3^-N , total P, and total K. Concentrations of most nutrients in leachates were relatively high, but fluctuated frequently during the first third of the study period, and then gradually decreased and stabilized during the last 27 weeks. Osmocote often resulted in greater NH_4^+ and total inorganic N concentrations in leachates than other fertilizers during weeks 1 through 5, whereas Multicote produced higher NH_4^+ in leachates than most of the other fertilizer types during weeks 9 through 12. Overall, total P concentrations were greater with Multicote during a third of the experimental period, especially when compared with Osmocote and Polyon. Differences were also observed among treatments for leachate concentrations of K, with Polyon and Multicote fertilizers producing greater K concentrations in leachates compared with Osmocote during several weeks throughout the experimental period. Leachate concentrations of NO_3^-N and P from all fertilizer types were usually high, especially from week 5 through week 30.

Federal regulations and guidelines have been in place since 1972 to reduce pollutants entering surface water bodies contaminated

from point and nonpoint sources. Section 101(a) of the Clean Water Act provides a list of chemicals that, at certain levels, are considered pollutants for different types of water bodies (U.S. Environmental Protection Agency, 1976). Many of the chemicals listed in these guidelines are associated with waste from heavy industry. However, there are several chemicals that are closely associated with nursery fertility management, two of the most notable being nitrate (NO_3^-) and phosphate (PO_4^{2-}) (Rathier and Frink, 1989). For two reasons, NO_3^-N is the most likely nutrient to appear as a contaminant in runoff. First, it is applied at the highest rate relative to other essential nutrients (Rathier and Frink, 1989). Second, as an anion, NO_3^- does

not bind readily to the predominantly negatively charged soil and substrate colloids. Likewise, because P is also present as the PO_4^{2-} anion, it may also leach readily from the negatively charged soil-substrate fractions. Even though NO_3^- and PO_4^{2-} are commonly used in the nursery industry, little is known regarding the dynamics of these nutrients during a typical 1-year production period for containerized woody ornamentals. In order for the nursery industry to comply with regulations pertaining to the runoff of NO_3^- and PO_4^{2-} , it is crucial that nutrient dynamics of growing crops are understood so that fertilizer availability coincides with crop needs. This would optimize nutrient use efficiency while simultaneously minimizing nutrient runoff.

In an effort to improve nutrient use efficiency and reduce nutrient runoff, coated fertilizers have been developed that allow a slow release of nutrients into the substrate throughout crop development. Most of the commonly used controlled-release fertilizers (CRFs) are coated with polymers, which release nutrients through osmosis at a rate that is generally positively correlated with increasing soil temperature, within a certain range of temperatures. During the past decade, several studies (Broschat, 1996, 2005; Handreck, 1997; Huett, 1997a, 1997b; Huett and Gogel, 2000; Huett and Morris, 1999; Husby et al., 2003) have been conducted on nutrient release patterns from CRFs. However, most of these studies were relatively short term. In addition, these studies were usually conducted under environmentally controlled laboratory conditions. Although these types of experiments are suitable for fast-growing herbaceous plants and foliage crops being grown in climate-controlled greenhouses, these conditions do not reflect the highly variable conditions typically experienced during the outdoor production of containerized woody perennials.

A more recent 11-month study (Blythe et al., 2006; Merhaut et al., 2006) was conducted with CRFs in a greenhouse using low fertilizer rates typically used for the production of salt-sensitive crops such as rhododendron and camellia. The purpose of that study was to determine CRF nutrient release characteristics when used for relatively slow-growing, shade-requiring crops. Results indicated variable release rates from CRFs that were not always correlated with air temperature, even though the study was conducted in a greenhouse in which high temperatures were moderated by shade cloth and swamp coolers.

In the current study, nutrient release patterns of four types of CRFs were quantified for a 1-year production scenario typically used for the production of most containerized, sun-requiring, fast-growing woody perennials: (1) near-neutral pH substrate, (2) high fertilizer rates, and (3) outdoor conditions in which low and high temperatures were not moderated by artificial means. As in the previous study (Blythe et al., 2006; Merhaut et al., 2006), plants were not included, so that nutrient release characteristics could be monitored through measurement of nutrient concentrations in leachates.

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Trade names are mentioned throughout this manuscript, but this does not imply product endorsement by the authors and their associated institutions.

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Materials and Methods

Substrate. Substrate consisted of a 5:3:1 (by volume) mixture of composted forest products (Scott-Sierra Horticultural Products Co., Marysville, Ohio), pine bark (6.4–9.5 mm), and washed builder's sand. The substrate was amended with dolomite 65 (Chemical Lime Co., Scottsdale, Ariz.) at a rate of 1.77 kg·m⁻³ and ultrafine calcium sulfate (Western Mining and Minerals, Apex, Nev.) at a rate of 0.59 kg·m⁻³. Substrate, dolomite, and calcite were mixed together using a model MB20L5 Batch Mixer (Measured Marketing, Kankakee, Ill.). Prepared substrate had a pH of 6.5 at the beginning of the study. For analysis of nutrients, substrate was air-dried and ground to 0.420 mm with a Wiley Mill model #3 (Arthur H. Thomas Co., Philadelphia, Pa.). The ground samples were extracted using the 1:2 dilution method (Lang, 1996), in which a 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 substrate N was quantified by combustion on a LECO-FP528 Nitrogen Gas Analyzer (Leco Corp., St. Joseph, Mich.) (Sweeney, 1989). Total P and K concentrations in extracts were quantified with an inductively coupled plasma optical emission spectrometer (ICP-OES) (model IRIS 1000 HR; Thermo Electron Corp., Franklin, Mass.). Substrate nutrient concentrations before the addition of CRFs were as follows: 0.20% total N, 0.01% extractable P, and 0.05% extractable K.

Fertilizer treatments. Treatments consisted of four different 365-d-release CRFs: Multicote 17–5–11 + minors (Haifa Chemicals, Ltd., Haifa Bay, Israel), Nutricote 18–6–8 Total (Chisso-Asahi Fertilizer Co., Tokyo), Osmocote 24–4–9 (Scott-Sierra Horticultural Products Co., Marysville, Ohio), and Polyon 17–5–11 + micros (Pursell Technologies, Inc., Sylacauga, Ala.). These four CRFs are polymer-coated formulations that release nutrients from prills through water diffusion, the rate of which is positively correlated with increasing temperature. However, the 1-year longevity of each fertilizer is based on different temperatures: 27 °C for Osmocote and Polyon, 21 °C for Multicote, and 21 to 27 °C for Nutricote. Element concentrations and compounds used in each fertilizer were different (Table 1); however, the amount of fertilizer added was calculated so that all treatments contained 2.34 kg N·m⁻³ (6.2 g N per container), which is an average rate for fast-growing woody ornamentals, as recommended by the four fertilizer manufacturers. The content of other nutrients varied (Table 2). Osmocote did not contain micronutrients; therefore, Micromax (Scott-Sierra Horticultural Products Co., Marysville, Ohio), an uncoated, granular micronutrient fertilizer, was incorporated at a rate of 1.06 kg·m⁻³. All CRFs were blended into the substrate using a portable cement mixer, and the resulting substrates were used to fill

Table 1. Sources and amount (percent by weight) of N, P, and 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 |

^zOsmocote 24–4–9. Nitrogen, P, and K are derived from ammonium nitrate, ammonium phosphate, polymer-encapsulated sulfur-coated urea, calcium phosphate, and potassium sulfate.

^yPolyon 17–5–11. Nitrogen, P, and K are derived from ammonium nitrate, ammonium phosphate, potassium sulfate, and potassium nitrate.

^xMulticote 17–5–11 + minors. Nitrogen, P, and K are derived from ammonium nitrate, monoammonium phosphate, potassium nitrate, and potassium sulfate.

^wNutricote 18–6–8 total. Nitrogen, P, and K are derived from ammonium nitrate, ammonium phosphate, calcium phosphate, and potassium nitrate.

Table 2. Amount (in grams) of N, P, and K incorporated into each no. 1 container (2.4 L) of substrate.

| Treatment (fertilizer) | NH ₄ ⁺ N | NO ₃ ⁻ N | Urea-N | Total N | P | K |
|------------------------|--------------------------------|--------------------------------|--------|---------|------|------|
| Osmocote | 1.66 | 1.48 | 3.08 | 6.22 | 0.44 | 1.92 |
| Polyon | 3.30 | 2.92 | 0.00 | 6.22 | 0.74 | 3.24 |
| Multicote | 3.30 | 2.92 | 0.00 | 6.22 | 0.76 | 3.32 |
| Nutricote | 2.98 | 3.24 | 0.00 | 6.22 | 0.88 | 2.28 |

Fertilizer rates were normalized for the same amount of nitrogen (6.22 g/no. 1 container), because different brands of fertilizers contained different ratios of nutrients.

no. 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 containers of each treatment for each of the 11 months of leachate monitoring. Containers were placed in a randomized complete block design.

Cultural practices. Treatments were prepared on 1 Aug. 2001. The experiment was conducted from 1 Aug. 2001 through 27 June 2002. Containers were placed on wooden benches outdoors on the University of California, Riverside, campus (lat. 33°53'30"N, long. 117°15'00"W). Containers were irrigated with municipal tap water that contained an average of 0.05 mg·L⁻¹ NH₄⁺ N, 2.32 mg·L⁻¹ NO₃⁻ N, 0.02 mg·L⁻¹ P, and 2.94 mg·L⁻¹ K, and had a pH range of 7.31 to 8.50 and an electrical conductivity (EC) ranging from 0.31 to 0.65 mS·cm⁻¹. Polyethylene, 6.35-mm diameter DRT4–36 ring drippers (Dramm Corporation, Manitowoc, Wis.) with six drip holes spaced every 2 cm were used to irrigate each container. Containers were irrigated about every 2 d, providing an average water volume of ≈1 L/week and an average leachate volume of ≈775 ml/week. Additional water was received by several rain events throughout the experimental period (Table 3). This irrigation program reflected the water requirements of *Ligustrum japonicum* (Thunb.) being grown during the same time period on adjacent benches.

Leachate collection. Leachate was collected from each container according to methods previously described (Merhaut et al., 2006). In brief, leachate from each container drained into a plastic 2.45-L (152 mm top diameter, 127 mm bottom diameter, and 152 mm high) bucket. All leachates drained into the collection buckets during the course of the week and were collected from buckets twice per week, and volumes from each bucket were combined so that

Table 3. Total rainfall for each week during the experimental period of 1 Aug. 2001 (beginning of week 1) through 27 June 2002 (end of week 47).

| Week ^z | Precipitation (mm) |
|-------------------|--------------------|
| 8 | 0.25 |
| 9 | 0.25 |
| 11 | 0.76 |
| 12 | 0.25 |
| 13 | 0.76 |
| 15 | 8.89 |
| 17 | 23.37 |
| 18 | 2.03 |
| 20 | 4.06 |
| 21 | 6.35 |
| 22 | 5.33 |
| 26 | 8.38 |
| 29 | 4.06 |
| 31 | 2.29 |
| 33 | 5.84 |
| 34 | 0.25 |
| 36 | 0.25 |
| 37 | 0.51 |
| 38 | 5.08 |
| 39 | 2.03 |
| 42 | 0.25 |
| Total | 81.24 |

^zWeek represents time after the initiation of the study (1 Aug. 2001). Weeks without precipitation were not included.

there was one leachate sample per container per week. Each week, leachate 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.). Leachates were chemically stabilized with 4 mL 2 N sulfuric acid per bucket and stored at 4 °C until volumes were measured. 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 refrigerated or frozen until analysis. Solutions were analyzed for NH₄⁺N and NO₃⁻N

with a Technicon TRAAC 800 Autoanalyzer (Technicon Instruments Corp., Tarrytown, N.Y.). Total P and K were determined using an ICP-OES (Thermo Electron Corp., model IRIS 1000 HR).

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. 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 test with an experimentwise α level of 0.10 covering all six simultaneous pairwise comparisons. Statistical analyses were conducted using the GLM procedure of SAS (SAS version 9.1; SAS Institute, Cary, N.C.).

Results and Discussion

Air temperature. Weekly average air temperature ranged between 24 °C and 35 °C during the first 8 weeks (Aug. through Sept. 2001), gradually declined during the next 10 weeks, and then fluctuated between 6 °C and 19 °C during the third 10-week period of the study (Fig. 1). During the last 17 weeks of the study (March through May), average air temperatures gradually increased from 10 to 32 °C. Maximum air temperatures ranged between 10 °C and 42 °C during the entire study, with the highest maximum temperatures occurring during the first and last 10 weeks. Minimum temperatures were usually less than 20 °C and always more than 2 °C.

The air temperatures during the first 10 and last 10 weeks of the study were usually at or more than the optimum temperature for all CRF treatments. However, from week 15 to week 40, average and maximum temperatures were usually less than the temperature threshold listed for the CRFs. Because the nutrient release rates of the CRFs are positively correlated with increasing temperature, the greatest likelihood of high nutrient release rates was during the first and last 10 weeks of the study. In other experiments, nutrient release rates from CRF prills increased by 15% (Huett and Gogel, 2000) to 200% (Husby et al., 2003; Kochba et al., 1990; Lamont et al., 1987; Oertli and Lunt, 1962) for every 10 °C increase in temperature above the labeled substrate temperature for the CRF. The relatively lower temperatures measured from weeks 15 to 40 suggest that nutrient release rates may have been lower,

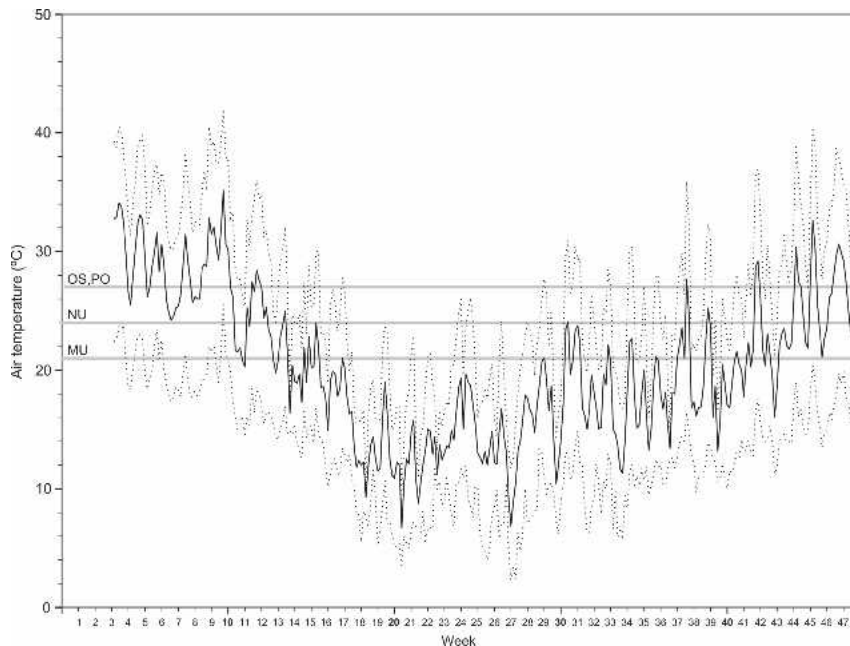


Fig. 1. Daily average (solid line), minimum (lower dotted line), and maximum (upper dotted line) outdoor air temperatures over a 47-week period (1 Aug. 2001 to 27 June 2002), with gray horizontal lines indicating optimal media temperatures for 12-month fertilizer release as specified by the respective manufacturers of Osmocote (OS), Polyon (PO), Multicote (MU), and Nutricote (NU).

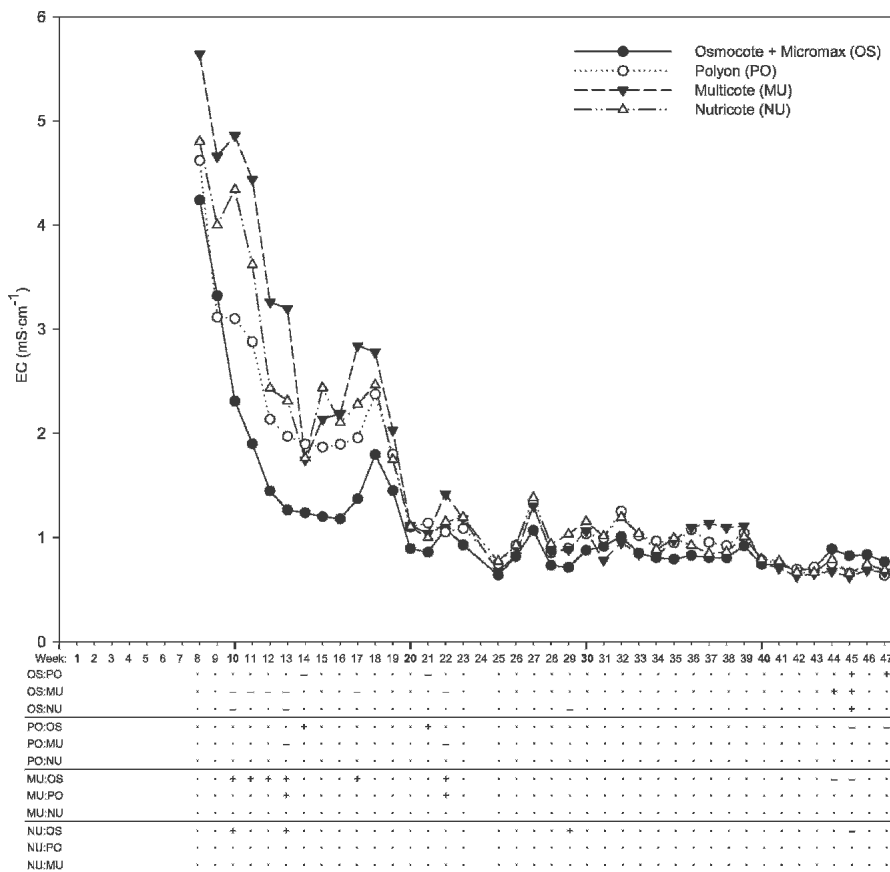


Fig. 2. Electrical conductivity (EC) of irrigation leachate collected weekly over a 47-week period (1 Aug. 2001 to 27 June 2002) from a composted forest products/pine bark substrate prepared with four controlled-release fertilizers at equal rates of total N. Plotted points (top) represent least squares 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 ($P \leq 0.10$). Pots of 2.4L containing substrate without plants were located outside during the experiment and irrigated with drip emitters using municipal tap water (EC, 0.5 mS·cm⁻¹).

and fluctuated often during the first half of the study, then decreased to near 0.0 mg·L⁻¹ for the remainder of the experimental period (Fig. 4). More specifically, NH₄⁺N concentrations were less than 25 mg·L⁻¹ during the first 4 weeks for all treatments, with the exception of Osmocote, then increased to ≈200 mg·L⁻¹ for Osmocote, Multicote, and Nutricote, and 60 mg·L⁻¹ for Polyon. Subsequently, NH₄⁺ decreased for all treatments, somewhat gradually for Osmocote and Polyon treatments, but more erratically for Multicote and Nutricote, which was reflected in the significantly lower NH₄⁺ concentrations for Osmocote and Polyon treatments compared with the Multicote and Nutricote treatments on several occasions during the first 20 weeks. Other differences in leachate NH₄⁺ concentrations were noted during the last half of the study and, although significant, concentrations were low, ranging between 0.5 mg·L⁻¹ and 7.0 mg·L⁻¹. The generally high and then decreasing NH₄⁺ concentrations did not reflect the relatively high–low–high air temperatures that were measured during the same 47-week period. This general pattern of relatively moderate NH₄⁺ concentrations in leachates during the first months and gradually less during later months, irrespective of changing air temperatures, was observed in a previous greenhouse study (Merhaut et al., 2006). This phenomenon may be associated with three factors: 1) initial binding of NH₄⁺ to the substrate (Foster et al., 1983; Thomas and Perry, 1980), 2) nitrification of NH₄⁺, and 3) rapid release of NH₄⁺ from prills. Although NH₄⁺ binding to substrate and NH₄⁺ nitrification may explain some of the observations, the rapid release of NH₄⁺ from prills is probably a significant factor, as was demonstrated by Broschat (2005). In Broschat's experiments with 8- to 9-month release formulations, held at constant temperature (23 °C), prills were analyzed for remaining nutrients, and it was shown that only half of the NH₄⁺ remained in the prills by the end of the second month. Therefore, the lower NH₄⁺ concentrations measured in leachates during the later stages of the current study and the previous study (Merhaut et al., 2006) were most likely the result of the low amounts of NH₄⁺ remaining in the prills during the later stages of the experiment. Contrary to the current and previous studies (Merhaut et al., 2006), a very short-term (20-h) study (Husby et al., 2003) showed NH₄⁺ release rates that were closely associated with temperature, with greater release of NH₄⁺ from Osmocote compared with Nutricote or Polyon at high temperatures (>35 °C), but lower release rates at low temperatures (<35 °C).

No federal guidelines exist for NH₄⁺. However, NH₃ should not exceed 0.02 mg·L⁻¹ for freshwater aquatic life (U.S. Environmental Protection Agency, 1976). Research by Thurston et al. (1974) indicates a total ammonium and ammonia (NH₄⁺ + NH₃) concentration of 16 mg·L⁻¹ or greater, when pH is between 6.0 and 7.0 at a temperature of 5 °C, would likely produce an NH₃ concentration of 0.02 mg·L⁻¹ or greater. Therefore, it is

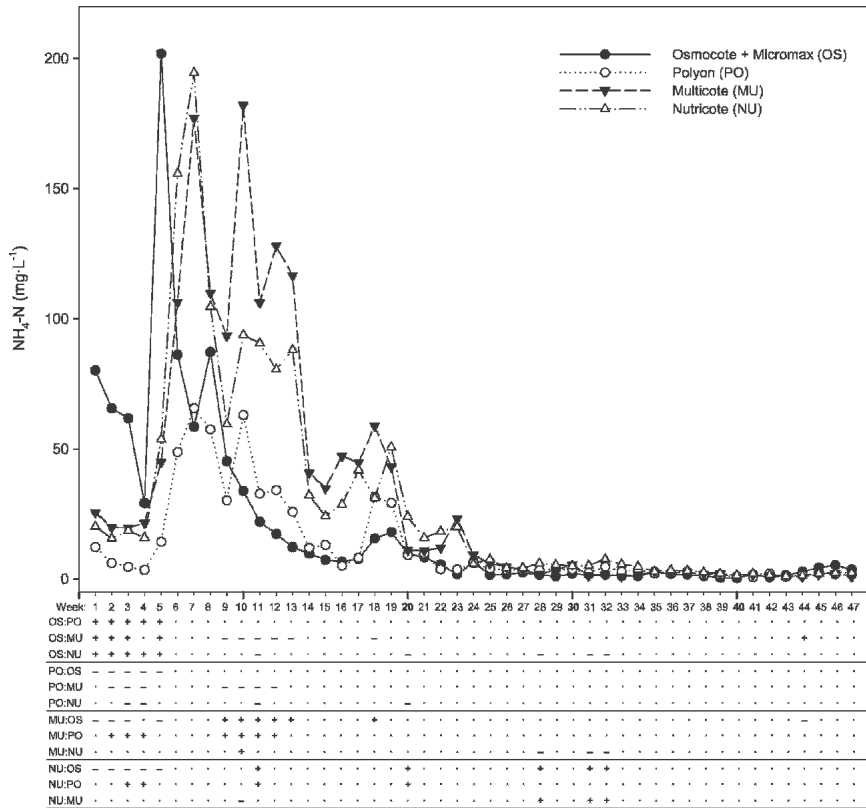


Fig. 4. Concentration of NH₄ N (in milligrams per liter) in irrigation leachate collected weekly over a 47-week period (1 Aug. 2001 to 27 June 2002) from a composted forest products/pine bark/sand substrate prepared with four controlled-release fertilizers at equal rates of total N. Plotted points (top) 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 ($P \leq 0.10$). Pots of 2.4L containing substrate without plants were located outside during the experiment and irrigated with drip emitters using municipal tap water.

feasible that NH₃ concentrations were more than the federal limits, especially during the first half of the experiment.

Nitrate N concentration. Leachate concentrations of NO₃⁻N for all CRFs fluctuated throughout the 47-week period, with significant differences observed among treatments (Fig. 5). Like NH₄⁺, concentrations of NO₃⁻N were relatively low (<25 mg·L⁻¹) during the first 4 weeks, with the exception of Osmocote, which was at ≈60 mg·L⁻¹. Thereafter, all treatments, except Osmocote, rapidly increased to concentrations more than 250 mg·L⁻¹ and then fluctuated between 100 mg·L⁻¹ and 200 mg·L⁻¹ until about week 20, after which time all the treatments produced leachates with NO₃⁻N concentrations less than 100 mg·L⁻¹. During the last 7 weeks of the study, NO₃⁻ concentrations of all treatments declined further (<50.0 mg·L⁻¹).

The general trends in NO₃⁻ leaching observed in the current study are similar to those observed in other studies (Broschat, 2005; Merhaut et al., 2006; Prasad and Woods, 1971). The initially low NO₃⁻ recovered in leachates of most treatments during the first 5 weeks of the study has been observed in another study (Prasad and Woods, 1971) and, in both cases, may be associated with physical or chemical reactions such as mineralization,

binding, or denitrification. During the later half of the current study, the elevated concentrations of NO₃⁻ relative to NH₄⁺ may have been associated with the nitrification of NH₄⁺ in addition to the release of NO₃⁻ from the fertilizer prills. Other studies have demonstrated significant nitrification of NH₄⁺ in soils and substrates of acidic to neutral pH (Dancer et al., 1973; Niemiera and Wright, 1986).

From the standpoint of NO₃⁻ concentrations in leachates of the different fertilizer treatments, it appears that Osmocote resulted in a more stable release pattern than the other CRFs. However, some of the differences may be partially explained by the fertilizer formulations, because Osmocote contained about half the amount of NO₃⁻ as the other CRFs. Our results of more stable NO₃⁻ release from Osmocote compared with the other CRFs differ from the results of Broschat (2005), who found that the degree of NO₃⁻ released from Osmocote was greater than from Nutricote. The differences in results of the current study with those of Broschat (2005) may be associated with differences in N types in the formulations; however, the N compounds in Broschat's experiment were not indicated and different fertilizer blends under the same brand name can contain different N sources.

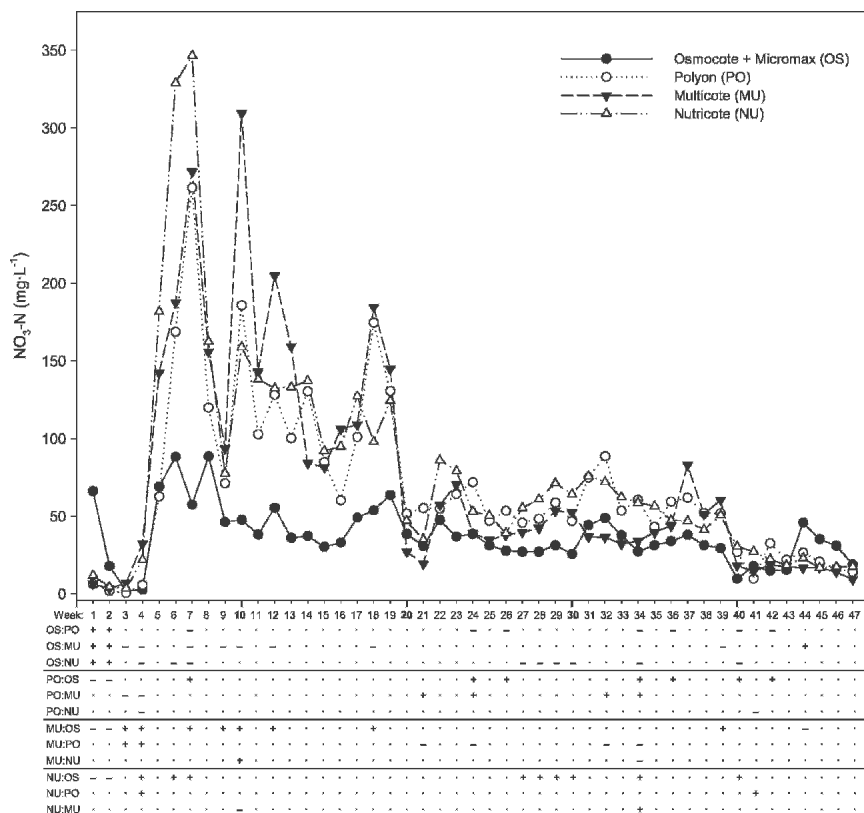


Fig. 5. Concentration of NO_3N (in milligrams per liter) in irrigation leachate collected weekly over a 47-week period (1 Aug. 2001 to 27 June 2002) from a composted forest products/pine bark/sand substrate prepared with four controlled-release fertilizers at equal rates of total N. Plotted points (top) 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 ($P \leq 0.10$). Pots of 2.4L containing substrate without plants were located outside during the experiment and irrigated with drip emitters using municipal tap water.

The maximum concentration level for $\text{NO}_3^- \text{N}$ is $10 \text{ mg}\cdot\text{L}^{-1}$ for domestic water use (U.S. Environmental Protection Agency, 1976). Leachate $\text{NO}_3^- \text{N}$ concentrations exceeded permissible levels during most of the experiment. However, if plants had been included in the current study, the likelihood of $\text{NO}_3^- \text{N}$ leaching in excess of $10 \text{ mg}\cdot\text{L}^{-1}$ would probably be more likely to occur during the first 12 weeks of the experiment, when total concentrations of $\text{NO}_3^- \text{N}$ were more than $100 \text{ mg}\cdot\text{L}^{-1}$. The only fertilizer product in exception to this was Osmocote, which had relatively low $\text{NO}_3^- \text{N}$ concentrations during the entire period of the study.

Total inorganic N concentrations. When NH_4^+ and NO_3^- are combined, it is clearly evident that there was a notable release of total inorganic N from all CRF treatments, especially between weeks 4 and 20 (Fig. 6), with some treatments having total inorganic N concentrations in leachates near $500 \text{ mg}\cdot\text{L}^{-1}$. After week 20, leachate concentrations of total inorganic N from all fertilizer types were less than $100 \text{ mg}\cdot\text{L}^{-1}$. Osmocote performed differently from the other CRFs, initially causing significantly higher total inorganic N concentrations in leachates than

the other fertilizer types during the first 3 weeks of the study. However, during the remaining term of the experiment, Osmocote resulted in lower total inorganic N concentrations compared with the other fertilizer types, which was significant for 5, 6, and 8 weeks for Polyon, Nutricote, and Multicote respectively.

Overall, the elevated then lower pattern of inorganic N release did not reflect the changes in air temperature during the same time period. These N release characteristics are similar to other CRF studies (Huett, 1997b; Huett and Gogel, 2000; Merhaut et al., 2006; Prasad and Woods, 1971; Patel and Sharma, 1977), but differ from other experiments in which temperatures were regulated (Cabrera, 1997; Handreck, 1997). The relatively low N concentrations in the beginning of the study may be associated with the release characteristics of the CRFs or may be ascribed to N binding on substrate colloids (Foster et al., 1983; Thomas and Perry, 1980), or N consumption through microbial activity (Gartner et al., 1971; Handreck and Bunker, 1996; Sharman, 1993). The relatively low total inorganic N observed for Osmocote may be associated with the release characteristics

of the fertilizer, or may be the result of half of the Osmocote N formulation consisting of urea, which was not measured in the study.

Total P concentrations. Total P concentrations in leachates were initially low during the first 4 weeks of the study, then fluctuated between $5 \text{ mg}\cdot\text{L}^{-1}$ and $35 \text{ mg}\cdot\text{L}^{-1}$ during the next 26 weeks, with the exception of Multicote, which had total P concentrations that ranged between $20 \text{ mg}\cdot\text{L}^{-1}$ and $110 \text{ mg}\cdot\text{L}^{-1}$ (Fig. 7). During the last 17 weeks, leachates from all CRFs were $15 \text{ mg}\cdot\text{L}^{-1}$ or less. When comparing fertilizer types, total P concentrations in leachates from Multicote were significantly greater than the other CRFs for one third to one half of the experimental period. The differences between Multicote and Osmocote can be explained to some extent by: 1) the amount of P used, and 2) the solubility of the P sources. The Multicote treatment ($0.76 \text{ mg}\cdot\text{L}^{-1}$) contained nearly twice as much P as the Osmocote treatment ($0.44 \text{ mg}\cdot\text{L}^{-1}$), because treatments were normalized only for the N amount. Second, the solubility of the P source, monoammonium phosphate, used for both Multicote and Osmocote is 13 times greater than the solubility of calcium phosphate, which is the other P source used in Osmocote formulations. However, the amount of P added with Multicote was similar to Nutricote ($0.88 \text{ mg}\cdot\text{L}^{-1}$) and Polyon ($0.74 \text{ mg}\cdot\text{L}^{-1}$), and the form of P used (ammonium phosphate) was the same for all three CRFs. Therefore, differences between these treatments must be associated with other factors such as release characteristics of the prills.

The overall pattern of initially low P concentrations recovered in leachates, followed by high P concentrations, then a gradual decline, is somewhat similar to the results obtained in other studies (Huett, 1997b; Huett and Gogel, 2000; Merhaut et al., 2006). However, only the current study measured low P concentrations during the beginning of the experiment, a characteristic that may be associated with binding of P by the substrate, which has been documented in another study (Handreck, 1996). If P binding to substrate is the cause of delayed P recovery in leachates, it may be specifically associated with the composted forest products, because that substrate was not used in the previous greenhouse study (Merhaut et al., 2006) in which no lag in P leaching was observed. The significantly higher P concentrations in leachates from Multicote compared with Nutricote and Polyon are similar to the previous greenhouse study (Merhaut et al., 2006). No other studies have compared the P release of Multicote with other CRFs. When comparing Polyon, Osmocote, and Nutricote, others have measured faster release of total P from Osmocote versus Nutricote (Broschat, 2005), or no significant difference between CRF types (Huett, 1997b; Huett and Gogel, 2000). Based on the P concentrations measured in the current study, in conjunction with the general recommendation of $\approx 10 \text{ mg}\cdot\text{L}^{-1}$ P for optimum production of containerized

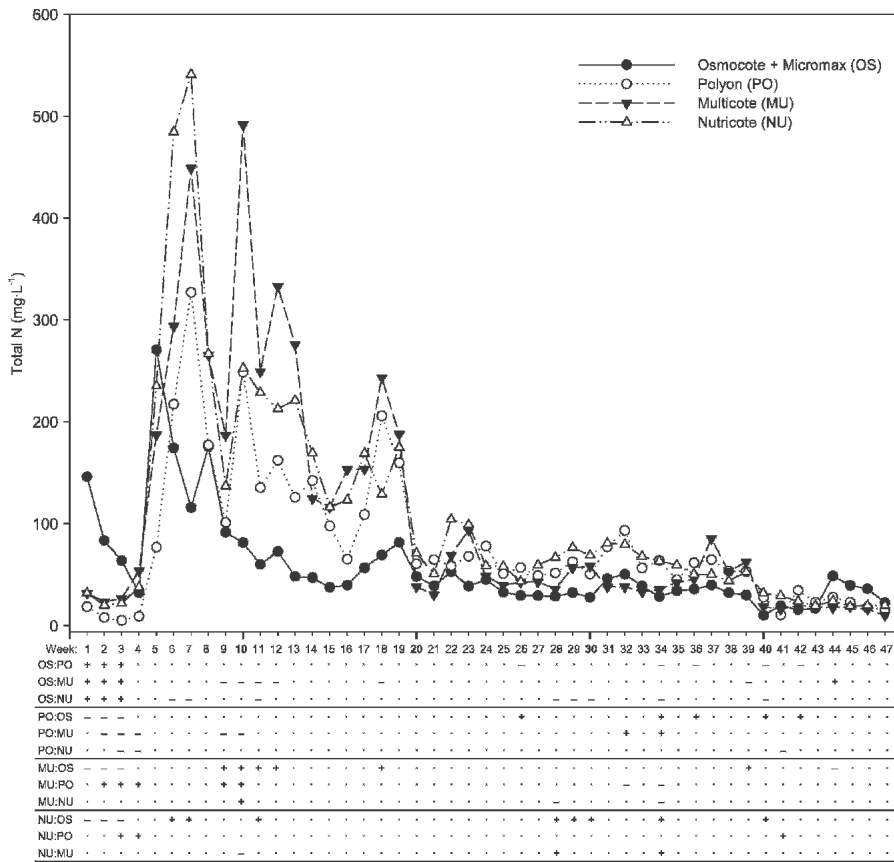
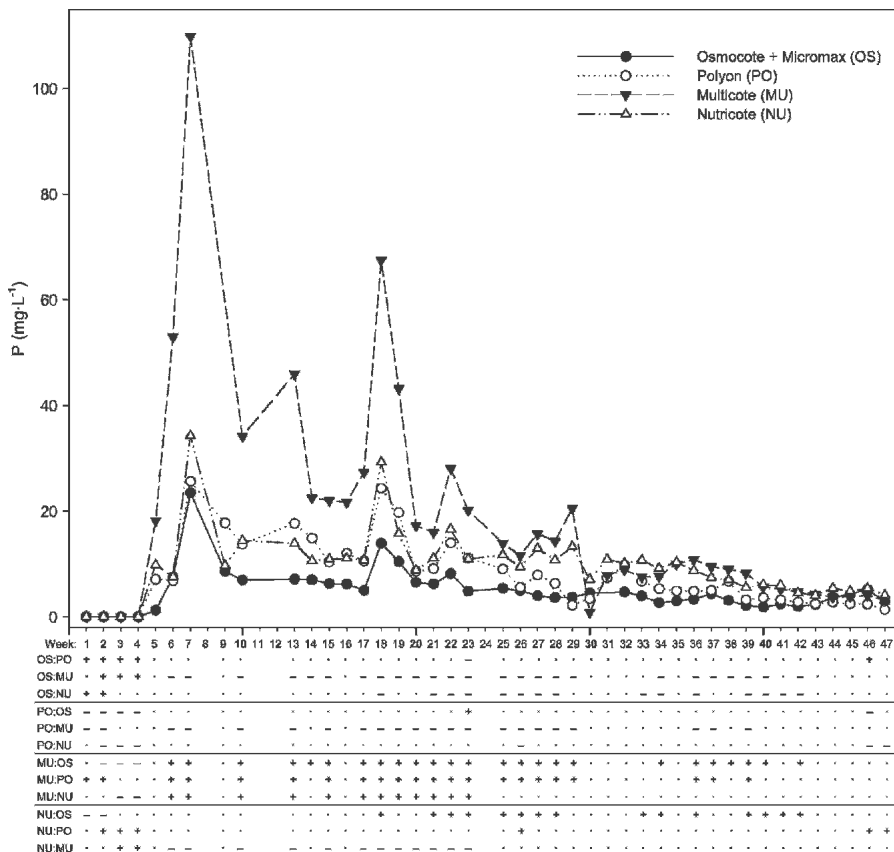


Fig. 6. Concentration of inorganic N ($\text{NH}_4\text{N} + \text{NO}_3\text{N}$; in milligrams per liter) in irrigation leachate collected weekly over a 47-week period (1 Aug. 2001 to 27 June 2002) from a composted forest products/pine bark/sand substrate prepared with four controlled-release fertilizers 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 ($P \leq 0.10$). Pots of 2.4L containing substrate without plants were located outside during the experiment and irrigated with drip emitters using municipal tap water.



plants (Flint, 1962; Handreck, 1996; Havis and Baker, 1985a, b; Wright, 1984; Yeager and Wright, 1982), the greatest risk of P leaching is during the first half of a 1-year production cycle. Of the CRFs tested, there is the greatest risk of P leaching from Multicote.

Physiologically, all CRFs exhibited sufficient P release ($\geq 10 \text{ mg}\cdot\text{L}^{-1}$) for adequate plant growth throughout the 47-week period. Environmentally, because the U.S. Environmental Protection Agency has established a limit of $0.01 \mu\text{g}\cdot\text{L}^{-1}$ for elemental P (U.S. Environmental Protection Agency, 1976), there may be a risk of P leaching if a portion of the total P measured was in the elemental form. There are no federal guidelines for orthophosphate or total phosphorus. However, in areas such as southern California, watersheds are being monitoring for ortho-P and total P in runoff from nonpoint sources such as nurseries (Harris and Dasker, 1994). However, no studies have been conducted to determine elemental P concentrations under nursery conditions.

Total potassium concentrations. Total K concentrations of all leachates ranged between 0.0 and slightly more than $400 \text{ mg}\cdot\text{L}^{-1}$ (Fig. 8). The greatest fluctuations and the highest concentrations occurred during the first 22 weeks, then stabilized between $50.0 \text{ mg}\cdot\text{L}^{-1}$ and $75.0 \text{ mg}\cdot\text{L}^{-1}$ during the remainder of the study. Potassium concentrations were significantly lower for the Osmocote treatment compared with the Polyon and Multicote treatments for 13 and 11 weeks of the

Fig. 7. Concentration of total P (in milligrams per liter) in irrigation leachate collected weekly over a 47-week period (1 Aug. 2001 to 27 June 2002) from a composted forest products/pine bark/sand 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 ($P \leq 0.10$). Pots of 2.4L containing substrate without plants were located outside during the experiment and irrigated with drip emitters using municipal tap water.

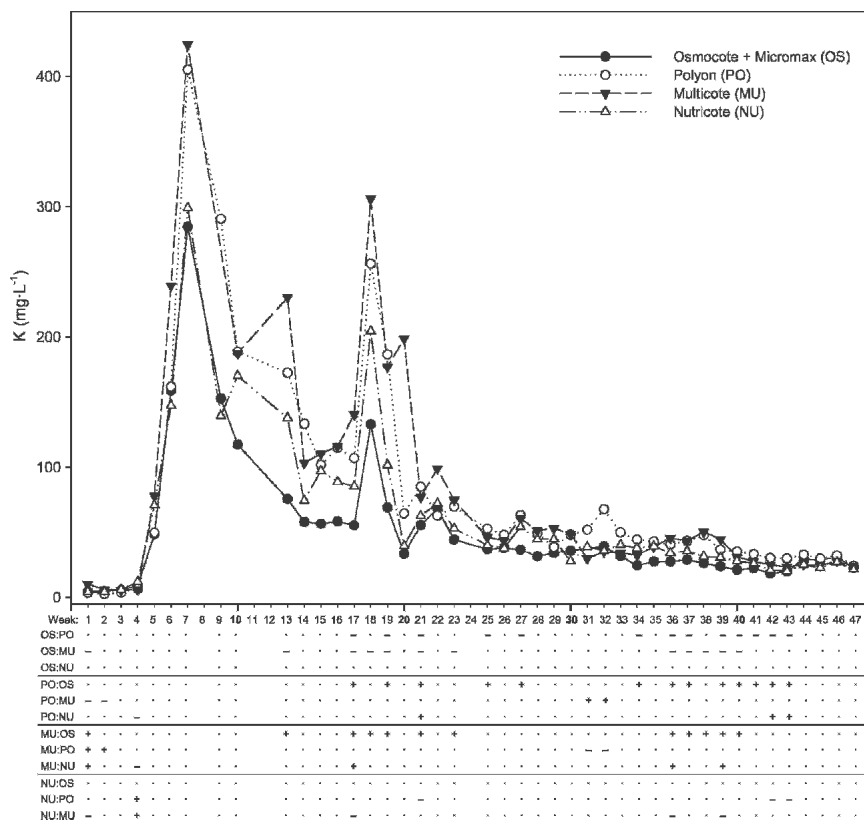


Fig. 8. Concentration of K (in milligrams per liter) in irrigation leachate collected weekly over a 47-week period (1 Aug. 2001 to 27 June 2002) from a composted forest products/pine bark/sand substrate prepared with four controlled-release fertilizers at equal rates of total N. Plotted points (top) 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 ($P \leq 0.10$). Pots of 2.4L containing substrate without plants were located outside during the experiment and irrigated with drip emitters using municipal tap water.

study respectively. These differences may be associated with the nearly 40% lower K amounts added in the Osmocote treatment compared with the Multicote and Polyon treatments. There were a few significant differences among the other treatments, but there appeared to be no pattern or trend in these differences. The initially low K concentrations of leachates observed during the first 4 weeks may be associated with the binding of K with the substrate, as observed in other studies (Brown and Pokorny, 1977; Foster et al., 1983). The relatively high and fluctuating K concentrations measured during the first half of the experiment are similar to a study conducted in a greenhouse (Merhaut et al., 2006) and studies conducted in more controlled environmental conditions (Broschat, 1996, 2005; Huett, 1997b). There are no federal guidelines nor known state regulations regarding K concentrations for runoff waters.

Conclusion

Under the environmental conditions of the current study, leachate chemical parameters of EC, and NH_4^+ , NO_3^- , K, and P concentrations of all CRF treatments were relatively high during the first half of the

study and then decreased during the remainder of the experimental period—a trend that was not correlated with the seasonal fluctuations of air temperature. When comparing CRF types, Osmocote tended to have a more stable release pattern than the other fertilizer types, and Multicote had a more erratic release pattern than the other fertilizer types during the 47-week period. From a horticultural perspective, the nutrients released during the first half of the study would probably be in excess of plant needs, even for fast-growing woody ornamentals. This would especially be the case in container production, in which small plant “plugs” are transplanted into larger containers. Plants in this situation initially would not have a sufficient root system established to absorb nutrients released from prills during the beginning stages of a crop production cycle. This lack of an established root system would also explain why the high EC measured at the beginning of the study would not be an issue. During the last half of the production period, most if not all nutrients released from prills would probably be absorbed by the mature plants. When comparing treatments, significant differences did occur throughout the study. However, the most notable differ-

ences occurred with the P concentrations of the leachates from the Multicote treatment, which were significantly greater than with the other CRF types during almost half the experimental period.

Environmentally, the high nutrient release during the first half of the study suggests that the first few months of a plant production period would be the most likely period of excess nutrient leaching under the typical cultural conditions, and thus could impair water bodies if allowed to runoff from nursery production sites. Of the fertilizers studied, Multicote could result in the greatest risk of polluting runoff water as a result of the erratic and excess concentrations of nutrients, especially total P, exhibited throughout the study. The leachate nutrient concentrations, as measured during the later stages of the experiment, would probably not be of environmental concern, because plants at this stage of the production period should be large enough to absorb the amounts of nutrients released during this time period. Although the likelihood of nutrient runoff during the later stages of this type of production system are low, similar studies with typical plant systems would be required to determine the extent, if any, of nutrient leaching.

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