Nutrient Release from Controlled-release Fertilizers in a Neutral-pH Substrate in an Outdoor Environment: II. Leachate Calcium, Magnesium, Iron, Manganese, Zinc, Copper, and Molybdenum Concentrations

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Additional index words. Micromax, micronutrients, Multicote, nursery, Nutricote, Osmocote, polymer, Polyon, woody ornamentals

Abstract. Nutrient release characteristics of four different controlled-release fertilizers (Osmocote, Nutricote, Polyon, and Multicote) were monitored during an 11-month period in a simulated outdoor nursery production facility. Although no plants were used in the experiment, fertilization rates, irrigation regimes, and cultural practices simulated those typically used to produce fast-growing, high-nutrient-requiring containerized woody ornamentals. Fertilizer prill release characteristics were monitored through analyses of leachates, which were collected weekly. Concentrations of Mg, Mn, Zn, Cu, and Mo were relatively high during the first 5 to 10 weeks of the experiment, then declined and usually stabilized during the remainder of the study. However, Mn and Zn displayed erratic increases in concentrations several times throughout the study. Calcium concentrations did not increase until the fifth week, rapidly peaked to about 300 mg·L⁻¹, and then decreased and leveled off to ≈80 to 100 mg·L⁻¹ during the remainder of the study. Several significant differences were observed between treatments. The Osmocote treatment had significantly greater Ca and Mg concentrations in the leachate than the other fertilizer types during the last 6 weeks of the study, whereas the Nutricote treatment often had significantly greater Fe concentrations than leachates from other treatments, especially during the last 26 to 35 weeks of the study, and significantly greater Zn concentrations than the other CRFs during the last 21 weeks of the study. Based upon U.S. Environmental Protection Agency guidelines, concentrations of Fe were often more than the allowable limit of 0.3 mg·L⁻¹ with all fertilizer types, but especially with Nutricote. Concentrations of Mn and Cu also exceeded federal guidelines, particularly during the first several weeks of the study.

studies have been conducted to determine the fate of other essential plant nutrients derived from polymer-coated controlled-release fertilizers (CRFs) when used in a typical nursery production scenario.

In earlier studies (Blythe et al., 2006; Merhaut et al., 2006), release and leaching characteristics of plant essential nutrients from CRFs were determined in a greenhouse production system using the cultural practices of low N fertilizer (1.17 kg·m⁻³) rates and an acid pH, peat/pine bark/sand substrate. In the current study, the nutrient release characteristics of the same CRFs were studied using cultural practices (relatively high fertilizer rates, neutral pH, composted forest products/pine bark/sand substrate, and an outdoor climate) commonly used for sun-tolerant, fast-growing woody ornamentals. With this information, we hope to determine the patterns of release and leaching of plant essential nutrients from the CRFs and substrate so that CRF formulations or fertilizer and substrate management practices typically used for outdoor production practices can be manipulated to optimize nutrient uptake efficiency and simultaneously reduce the likelihood of nutrient runoff from nursery production facilities.

Materials and Methods

Experimental procedures are described by Newman et al. (2006). However, an abbreviated description follows, emphasizing the protocols associated with the use and measurement of Ca, Mg, Fe, Mn, Cu, Zn, and Mo.

Substrate. Substrate consisted of a 5:3:1 mixture of composted forest products (Scott-Sierra Horticultural Products Co., Marysville, Ohio), pine bark (6.4–9.5 mm), and washed builder's sand (by volume). The substrate was amended with dolomite 65 (Chemical Lime Co., Scottsdale, Ariz.) at a rate of 1.78 kg·m⁻³ and ultrafine calcium sulfate (Western Mining and Minerals, Apex, Nev.) at a rate of 0.59 kg·m⁻³. This provided ≈0.50 g Mg/no. 1 container and 0.97 g Ca/no. 1 container from dolomite and 0.42 g Ca/no. 1 container from the calcium sulfate. Random samples of air-dried substrate was ground to 0.420 mm and extracted in water for nutrient analyses. Calcium, Mg, Fe, Mn, Zn, Cu, and Mo in extracts were quantified using an inductively coupled plasma optical emission spectrometer (ICP-OES; model IRIS 1000 HR; Thermo Electron Corp., Franklin, Mass.). Nutrient concentrations of substrate before the addition of CRFs were 25.98 mg·L⁻¹ Ca, 9.27 mg·L⁻¹ Mg, 7.16 mg·L⁻¹ Fe, 1.78 mg·L⁻¹ Mn, 5.14 mg·L⁻¹ Zn, 0.20 mg·L⁻¹ Cu, and 0.01 mg·L⁻¹ Mo.

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.), and Polyon 17–5–11 + minors (Pursell Technologies, Sylacauga, Ala.). All CRFs are polymer-coated formulations that

Received for publication 2 June 2006. Accepted for publication 9 July 2006.

This research was funded in part by grants from the Hansen Trust Fund and the California Department of Food and Agriculture Fertilizer and Research and Education Program (CDFA-FREP).

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

Special thanks are given to Shahram Ahmadian and Harold D. Ewing for their technical assistance.

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As previously discussed in the literature (Blythe, et al., 2006; Merhaut, et al., 2006), plant nutrients, other than nitrate (NO₃⁻) and P, are listed under the Clean Water Act (U.S. Environmental Protection Agency, 1994) as potential pollutants of impaired water bodies. Some state agencies, such as the Regional Water Quality Control Board for Los Angeles, have already listed Mn, Cu, and Zn as potential pollutants that need to be monitored (Harris and Dasker, 1994). However, aside from monitoring N, P, and K, few

release nutrients from prills through water diffusion, the rate of which is positively correlated with increasing temperature. However, the longevity of each type is based on different temperatures.

Nutrient concentrations and compounds used in each fertilizer were different (Table 1); however, the amount of fertilizer added was calculated so that all treatments contained N at 2.34 kg·m⁻³ (6.2 g/no. 1 container). The content of other nutrients varied (Table 2). Osmocote did not contain micronutrients; therefore, micronutrients were added by the incorporation of Micromax (Scott-Sierra Horticultural Products Co.)—an uncoated, granular fertilizer—at a rate of 1.06 kg·m⁻³. All CRFs and Micromax were blended into the substrate, and the resulting substrates were used to fill no. 1 black polyethylene containers (2.4 L; 157 mm top diameter, 127 mm bottom diameter, 178 mm tall; Farrand Enterprises, Chino, Calif.). There were five containers (replications) 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 and the study was conducted from 1 Aug. 2001 through 27 June 2002. Containers were placed on wooden benches outdoors. Containers were irrigated with municipal tap water, which contained an average of 64.3 mg·L⁻¹ Ca, 9.48 mg·L⁻¹ Mg, 0.01 mg·L⁻¹ Fe, 0.00 mg·L⁻¹ Mn, 0.00 mg·L⁻¹ Cu, 0.004 mg·L⁻¹ Zn, and 0.003 mg·L⁻¹ Mo. Irrigation was supplied through polyethylene, 6.35-mm-diameter ring drippers (DRT4-36; Dramm Corporation, Manito-

woc, Wis.). Containers were irrigated about every 2 d, which provided an average irrigation volume of ≈1 L/week and an average leachate volume of ≈775 mL/week. Additional water was received by several rain events that occurred throughout the experimental period (Newman et al., 2006).

Leachate collection and analyses. Leachate was collected twice per week from each container according to methods described previously (Merhaut et al., 2006), and solutions from each container were combined so that there was one sample from each container per week. Leachates were chemically stabilized with 4 mL 2 N sulfuric acid per bucket and stored at 4 °C until volumes were measured. Collection buckets were washed weekly with 10% bleach to prevent algal growth. Leachate solutions were analyzed for Ca, Mg, Fe, Mn, Zn, Cu, and Mo using an ICP-OES (model IRIS 1000 HR; Thermo Electron Corp.).

Statistical analysis. Preliminary analysis of the data was conducted by regressing each of the dependent variables (Ca, Mg, Fe, Mn, Zn, Cu, and Mo) 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 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

Calcium concentration. Leachate Ca concentrations were usually more than the 10 to 15 mg·L⁻¹ levels recommended for optimum plant growth (Dunham and Tatnall, 1961; Edwards and Horton, 1981; Starr and Wright, 1984; Wright, 1984). There were only two occasions when notable treatment differences occurred (Fig. 1). During the first 4 weeks of the study, Ca concentrations were near zero; however, concentrations rapidly increased during the next 5 weeks to the maximum levels (≈350–375 mg·L⁻¹) measured in the study. Thereafter, Ca concentrations from all treatments decreased, and usually ranged between 100 mg·L⁻¹ and 200 mg·L⁻¹ during the next 10 weeks. Concentrations then leveled off to near 100 mg·L⁻¹ during the remainder of the study. In a similar study (Blythe et al., 2006), comparable patterns were observed in Ca concentrations in leachates, except that Ca concentrations were lower during the first month of the current study. The initially low Ca concentrations in leachates observed in the current study may be associated with the neutral pH of the substrate, which may have slowed the solubilization process of the Ca relative to the rate that may have occurred in the lower pH (4.5) substrate used by Blythe et al. (2006), even though the current study had twice as much Ca as the previous experiment. Solubilization and release of Ca from substrates have been shown to increase at lower solution pH (Whitcomb, 1988).

Concerning treatment effects, there were two notable periods when significant differences occurred between treatments: 1) the first 3 weeks when leachate Ca from the Multicote treatment was significantly greater than the other CRFs, and 2) the last 5 weeks when the Osmocote treatment produced significantly greater Ca concentrations than the other fertilizer types. These differences were quite unexpected, because all the Ca from all treatments, with the exceptions of the Polyon and Osmocote treatments, were derived from Ca in the irrigation water, dolomite, and calcium sulfate. Also, when comparing CRF types, the greenhouse study by Blythe et al. (2006) did not show any extended period of continuous significant differences between fertilizer types, like those that occurred in the current study. The differences observed between treatments in the current study are difficult to explain, because Ca sources were not derived from the CRF treatments, but rather from the water and calcium sulfate and dolomite, which were added equally to the substrates. Although differences between treatments were significant, there was probably no

Table 1. Sources and amount (percent by weight) of Mg, Ca, Fe, Mn, B, Mo, Zn, and Cu in Polyon 17–5–11 + micros, Multicote 17–5–11 + minors, Nutricote 18–6–8 total, Osmocote 24–4–9, and Micromax.

Fertilizer type	Mg	Ca	Fe	Mn	B	Mo	Zn	Cu
Osmocote ^z	0.00	0.00	0.00	0.00	0.00	0.02	0.015	0.00
Polyon ^y	0.90	1.10	0.44	0.18	NA	0.009	0.050	NA
Multicote ^x	0.60	0.00	0.20	0.06	0.25	0.01	0.060	0.06
Nutricote ^w	1.20	0.00	0.20	0.06	0.02	0.02	0.015	0.05
Micromax ^v	3.00	5.00	16.00	2.50	0.10	0.05	1.000	1.00

^zOsmocote 24–4–9. Nutrients are derived from calcium phosphate.

^yPolyon 17–5–11. Nutrients are derived from magnesium sulfate, iron sulfate, manganese sulfate, zinc sulfate, molybdc oxide, and calcium phosphate.

^xMulticote 17–5–11 + minors. Nutrients are derived from calcium phosphate, magnesium oxide, sodium borate, copper sulfate, iron EDTA, manganese sulfate, sodium molybdate, and zinc sulfate.

^wNutricote 18–6–8 total. Nutrients are derived from calcium phosphate, copper sulfate, Fe ethylenediaminetetraacetic acid (EDTA), magnesium sulfate, manganese sulfate, sodium borate, sodium molybdate, and zinc sulfate.

^vMicromax. Nutrients are derived from dolomite, ferrous sulfate, manganese sulfate, zinc sulfate, copper sulfate, sodium borate, and sodium molybdate.

Table 2. Amount (in grams) of Mg, Ca, Fe, Mn, B, Mo, Zn, and Cu added to each no. 1 container (2.4 L) of substrate for four controlled-release fertilizer treatments. 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.

Treatment (fertilizer)	Mg ^z	Ca ^z	Fe	Mn	B	Mo	Zn	Cu
Osmocote + Micromax ^y	0.08	0.14	0.448	0.070	0.002	0.002	0.028	0.028
Polyon	0.32	0.40	0.160	0.066	0.000	0.004	0.018	0.000
Multicote	0.22	0.00	0.074	0.022	0.010	0.004	0.022	0.022
Nutricote	0.42	0.00	0.070	0.020	0.006	0.006	0.006	0.018

^zAn additional 1.50 g Ca and 0.55 g Mg were included in each no. 1 container through the incorporation of 1.77 kg·m⁻³ dolomite and 0.59 kg·m⁻³ calcium sulfate into the substrate before preparation of the four controlled-release fertilizer treatments.

^yMicromax (1.47 kg·m⁻³) was added to the Osmocote fertilizer treatment only, because Osmocote 24–4–9 contains no Mg, Ca, or micronutrients.

Fig. 1. Concentration of Ca (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.

physiological and environmental importance for the Multicote treatment effect, because the Ca concentration and ranges were low ($2.5\text{--}4.7\text{ mg}\cdot\text{L}^{-1}$); however, the differences with the Osmocote treatment may be of concern because concentrations and ranges were greater ($49\text{--}64\text{ mg}\cdot\text{L}^{-1}$). Overall, the Ca concentrations measured in the current study, irrespective of fertilizer type, were often two to four times greater than Ca concentrations measured in runoff from other production systems (Chen et al., 2003). From an environmental perspective, no guidelines have been established directly related to Ca concentrations.

Magnesium concentrations. Magnesium concentrations for all treatments were at their highest levels ($\approx 200\text{--}275\text{ mg}\cdot\text{L}^{-1}$) at the initiation of the study, rapidly decreased to $\approx 50\text{ mg}\cdot\text{L}^{-1}$ by week 20, and then gradually decreased to near $12\text{ mg}\cdot\text{L}^{-1}$ during the last 27 weeks (Fig. 2). Regarding treatments, the Osmocote treatment produced significantly greater Mg in leachates than did the Polyon or Multicote treatments during the first 2 weeks and significantly greater Mg in leachates than with the Polyon, Multicote, and Nutricote treatments. The greater Mg in leachates between the Osmocote and Polyon treatments was unexpected, because the Polyon treatment provided nearly three times as much Mg as the Osmocote treatment. Similarly, the differences between the Osmocote treatment and the other treatments would appear unlikely, because there was little

Fig. 2. Concentration of Mg (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.

variation in Mg application rates between Osmocote + Micromax, Multicote, and Nutricote (Table 2). The Mg release/leaching characteristics and Mg concentrations ob-

served in the current study are somewhat similar to other studies (Blythe et al., 2006; Chen et al., 2003; Huett, 1997; Huett and Morris, 1999) and are probably associated with

the solubilization of Mg from the dolomite. Even though the Mg and a major percentage of the Ca are derived from dolomite, the faster dissolution of Mg compared with Ca is expected, because $MgCO_3$ is 100 times more soluble than $CaCO_3$ (Whitcomb, 1988). Based on plant requirements for Mg (≈ 10 – $15\text{ mg}\cdot\text{L}^{-1}$) that have been estimated in other studies (Mankin and Fynn, 1996; Starr and Wright, 1984; Wright, 1984), it appears that Mg availability would be sufficient for plant growth in the current production scenario during the first 30 weeks, but may become limiting during the later stages of the production process.

Iron concentrations. Iron concentrations in leachates from all treatments fluctuated somewhat throughout the experimental period, but usually remained less than $2.0\text{ mg}\cdot\text{L}^{-1}$ (Fig. 3). Significant differences occurred between all treatments throughout the study; however, the most obvious difference being that the Nutricote treatment resulted in significantly higher Fe concentrations during one half to three quarters of the experimental period. The patterns and differences noted between treatments are similar to a previous study (Blythe et al., 2006) conducted in a greenhouse using an acid-type substrate. However, in the current study, the degree of fluctuations in Fe concentrations were almost one half of what was measured in the greenhouse experiment during the first 20 weeks, even though Fe application rates were twice as high in the

current study. Based on these two studies, it seems likely that chelated forms of Fe, such as the Fe-ethylenediaminetetraacetic acid (EDTA) used in the Nutricote and Multicote treatments, may have an impact on the leaching of Fe, particularly for Nutricote, even at the two pH regimes (4.5 and 6.5) that have been studied. It appears that chelated forms of Fe are more likely to leach from containers than the less soluble mineral forms and could present an environmental concern if not taken up by the plant. Similar leaching characteristics of chelates have also been demonstrated in a study by Broschat and Donselman (1985). Regarding the lower Fe concentrations recovered in the current study compared with the previous study (Blythe et al., 2006), it has been determined that substrates consisting of bark or sawdust immobilize more iron than peat-based substrates (Handreck, 1989). Because the substrate in the current study consisted of pine bark and wood chips, and the substrates of the greenhouse study consisted mostly of peat, it is possible that the greater amounts of Fe were immobilized in the current study than the previous study. Based on the current and previous experiments (Blythe et al., 2006), Fe concentrations recovered in leachates were similar to other production systems (Chen et al., 2003), and in all cases Fe concentrations were always more than the U.S. Environmental Protection Agency guideline of $0.3\text{ mg}\cdot\text{L}^{-1}$ for domestic use (U.S. Environmental Protection Agency, 1976, 1994). However, only

during the first 20 weeks of the study were Fe concentrations more than $1.0\text{ mg}\cdot\text{L}^{-1}$, the maximum concentration considered safe for freshwater aquatic life (U.S. Environmental Protection Agency, 1976, 1994). Based on these criteria, environmental concern regarding Fe leaching would probably be only during the first 2 months of a 1-year production cycle. Thereafter, it is likely that most of the free Fe would be absorbed by plant roots in a typical production system.

Manganese concentrations. Manganese concentrations in leachates were initially high (30 – $60\text{ mg}\cdot\text{L}^{-1}$), and then declined rapidly to near $0.0\text{ mg}\cdot\text{L}^{-1}$ by week 5 for all treatments (Fig. 4). Thereafter, Mn concentrations were low, usually fluctuating between $0.25\text{ mg}\cdot\text{L}^{-1}$ and $1.00\text{ mg}\cdot\text{L}^{-1}$. Few treatment differences occurred, and they did not appear to be physiologically notable. On several different occasions, all treatments showed spikes in Mn concentrations resulting from a high Mn concentration in the leachate of one of the five replications. The periodic spikes in Mn concentrations and the elevated concentrations during the beginning of the experiment may be associated with the substrate, which contained composted forest products. In other research (Pokorny, 1979), Mn concentrations more than 100 ppm were determined in ashed pine bark, even though water-extracted levels were often less than 1.0 ppm. It is less likely that high levels were associated with the CRFs, because the highest rate of Mn applied was $70\text{ mg}/\text{no. 1}$ container for the Osmocote treatment. In a similar study (Blythe et al., 2006) with the same CRFs at half the rate, but different substrates, such noticeable spikes in Mn concentrations were not observed.

In a physiological sense, the high Mn concentrations in the beginning of the study could be toxic to the plant system; however, because roots were probably mostly confined to the liner plug located near the top of the container at this early stage of development, it is unlikely roots would be exposed to the elevated concentrations recovered in leachates from the bottom of the container. During the rest of the experiment, Mn concentrations were low, but would be adequate based on the low Mn requirements of plants, as determined by others (Tinus and McDonald, 1979).

Fig. 3. Concentration of Fe (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. 4. Concentration of Mn (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 in a controlled-environment greenhouse during the experiment and irrigated with drip emitters using municipal tap water.

Fig. 5. Concentration of Zn (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 previous study compared with the current study. This difference between the two studies may be associated with the substrates used, as one study (Pokorny, 1979) has shown that

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been measured, and in the experiments by Broschat and Donselman (1985), leachate Zn concentrations were greatest during the first 4 to 10 weeks of the study for some of the products tested, whereas other products exhibited no initial high leaching pattern during the same time period. The leachate Zn concentrations observed in the current study would probably be sufficient for most crops, because other studies (Carroll and Loneragan, 1969; Tinus and McDonald, 1979) showed healthy plant growth when zinc concentrations were ≈ 0.02 to $0.20 \text{ mg}\cdot\text{L}^{-1}$. In comparison with EPA guidelines, Zn concentrations were usually more than the limit of $5.00 \text{ mg}\cdot\text{L}^{-1}$ for drinking water only during the first 4 to 8 weeks of the study for all fertilizer types tested.

Copper concentrations. Leachate Cu concentrations were initially more than $100 \text{ mg}\cdot\text{L}^{-1}$ for all treatments, then rapidly declined and stabilized to $\approx 0.20 \text{ mg}\cdot\text{L}^{-1}$ for the remainder of the study, with the exception of weeks 14 and 15 (Fig. 6). Few treatment differences occurred, with the most notable differences being the higher Cu concentrations in leachates collected from the Osmocote treatment compared with the Polyon and Multicote treatments during the first 3 weeks. These differences may be partly attributed to the use of granular, uncoated Micromax in the Osmocote treatment, which may have allowed a more rapid solubilization and leaching of Cu compared with the polymer-coated Cu found in the Multicote and Nutricote fertilizers. The high Cu concentrations in leachate during the first 4 weeks for all

treatments is more likely the result of the release of Cu from the substrate, because the Cu derived from the fertilizer sources was relatively low (0.00 – $28.0 \text{ mg/no. one container}$). During weeks 14 and 15, Cu concentrations increased for all treatments, indicating a likely Cu contamination of the water source during those 2 weeks, a phenomenon that also occurred in another study (Blythe et al., 2006) that was conducted concurrently using the same water source. In another study (Broschat and Donselman, 1985), Micromax also exhibited a high release of Cu into the leachate during the first 10 weeks of the experimental period. The elevated recovery of Cu in the leachates observed in the current research and other studies may be attributed to rapid release of Cu from some organic fractions, some of which contain as much as 77 ppm Cu (Pokorny, 1979). Other studies have indicated that some substrates, such as peat, have a high affinity for micronutrients, a chemical association that is pH dependent (Schnitzer and Skinner, 1966). With respect to U.S. Environmental Protection Agency guidelines (U.S. Environmental Protection Agency, 1976), Cu concentrations exceeded acceptable levels ($1.0 \text{ mg}\cdot\text{L}^{-1}$) for domestic water supplies only during weeks 1 through 4 and weeks 14 and 15 for all CRF types studied.

Molybdenum concentrations. Molybdenum concentrations in leachates were relatively high during the first 4 weeks of the experiment (Fig. 7). Significant differences occurred between treatments, with Nutricote producing greater Mo concentrations in

leachates compared with leachates collected from all other fertilizers during weeks 7, 16, 17, and 47. Aside from the first 4 weeks, Mo concentrations were usually at or near $0.0 \text{ mg}\cdot\text{L}^{-1}$ for most of the experimental period. No federal guidelines have been established for Mo in surface waters.

Conclusion

With the exceptions of Ca and Fe, leachate concentrations of Mg and the other micronutrients measured for the four fertilizer treatments were elevated during the first 4 weeks of the experimental period. Thereafter, nutrient concentrations declined and leveled off for the remainder of the study. Calcium and Fe concentrations exhibited a more gradual and variable decline throughout the 11-month period. The sudden release of Mg, Mn, Zn, Cu, and Mo during the first month may be the result of these nutrients being released from the substrate rather than from the incorporated fertilizer. This pattern of micronutrient release did not reflect the results of the previous experiment (Blythe et al., 2006), in which a pine bark and peat-based substrate was used. Differences between results in the current and previous studies may be associated with 1) substrate type, 2) substrate pH, 3) environmental conditions, and 4) fertilizer rates.

From a plant health perspective, the high concentrations of micronutrients recovered in leachates would normally be toxic to plants. However, in a typical production scenario for woody ornamentals, root growth into the substrate during the first month of plant production would usually be minimal. Therefore, root systems would not have been exposed to the nutrient concentrations experienced during this stage of production. In addition, the nutrient concentrations in leachates recovered from the upper portion of the containerized substrate, where most new roots would be located, would probably not be as high as the concentrations measured from leachates collected from the lower portion of the containerized substrate.

Regarding water quality regulations and guidelines, only Fe concentrations were often at or more than the U.S. Environmental Protection Agency guidelines ($1.0 \text{ mg}\cdot\text{L}^{-1}$ for Fe), especially with fertilizers that contained

Fig. 6. Concentration of Cu (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. 7. Concentration of Mo (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.

Fe-EDTA. Copper, Mn, and Zn concentrations of all CRF types were also more than U.S. Environmental Protection Agency guidelines of 1.0, 0.10, and 5.0 mg·L⁻¹ respectively, but only during the first 4 weeks of the study. Thereafter, concentrations of these nutrients were low. Therefore, the greatest environmental risk from these nutrients in the production system described would be during the first month of a 1-year production cycle for woody ornamentals. If regulations are developed regarding the runoff of plant micronutrients, the content and release of these elements from different organic sources should be investigated to mitigate their release during the initial stages of the plant production process.

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