CALIFORNIA DEPARTMENT OF FOOD AND AGRICULTURE
FERTILIZER RESEARCH AND EDUCATION PROGRAM (FREP)

FINAL REPORT

Project Title

Minimizing nitrogen runoff and improving nitrogen use efficiency in containerized woody ornamentals through management of nitrate and ammonium-nitrogen

Project Number
00-0509

Project Location

UC Davis and UC Riverside

Project Duration

2.6 years

Project Leaders

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A. PROJECT SUMMARY

The main objectives of this research were to develop fertilization and irrigation guidelines for woody ornamental crop production that will minimize nitrate (NO_3) runoff and improve nitrogen (N) use efficiency (NUE). Two major experiments were done to characterize the dynamics of N cycling in the plants and the media.
University of California – Davis. A hydroponics study was conducted at Davis, California. By monitoring the rates of N and water depletion from nutrient solutions, the researchers were able to characterize the dynamics of N and water demand for several ornamental crops, as affected by physiological (stage of plant development) and environmental conditions (time of year).
University of California - Riverside. The study conducted at Riverside, California investigated the fate of different controlled-release fertilizers (CRF) and liquid fertilizers (LF) as affected by acid pH (5.0) media in a temperature-controlled

greenhouse setting and neutral pH (7.0) media in an outdoor setting (no temperature control). The dynamics of N cycling in the planting media and N uptake into the plants were determined by measuring nitrate (NO_3^-) and ammonium (NH_4^+) leaching from containers on a weekly basis and extractable NH_4^+, NO_3^- and total N in the planting media and total N in plants on a monthly basis. Plant response to fertilizers was determined by measuring total N accumulation in the plants on a monthly basis.

Specific Objectives:

1. Characterize the N and water demands of container-grown ornamental plants as influenced by plant growth rate, stage of plant development, and environmental conditions.

2. Determine the fate of NH_4^+ and NO_3^- from CRF and LF in containerized woody ornamentals growing in acid (5.0) or neutral (7.0) pH media during a 12-month period.

3. Develop fertilization and irrigation guidelines based on research results. Actively distribute guidelines to growers, CE advisors, consultants, fertilizer companies and educators through workshops, field days, seminars, lectures, and publications.

Added Objectives

In addition to the two well-known pollutants, nitrate (NO_3^-) and phosphate (PO_4^{-2}), other essential plant nutrients listed in §101(a) of the Clean Water Act (U.S. Environmental Protection Agency, 1994) are boron (B), copper (Cu), iron (Fe), manganese (Mn) and zinc (Zn). Although not receiving as much attention as NO_3^- and PO_4^{-2}, these plant micronutrients are chemicals that are used by the nursery industry and, therefore, are at risk of being regulated by state agencies. The likelihood of micronutrient contamination of surface waters from nursery runoff is unknown. Therefore, information regarding the movement of these nutrients in nursery production systems is needed so that the nursery industry is aware of any potential problems associated with micronutrient fertilization so that

Best Management Practices (BMPs) may be developed to mitigate the runoff of these nutrients. Since most essential plant nutrients are discussed as potential pollutants in EPA guidelines, and we were collecting samples of leachates, media and plant tissue, we decided to monitor all essential plant nutrients, with the exception of sulfur.

The results of the research funded by this grant are presented in two sections: (1) the first task presents the data and results regarding nitrogen and water use, which were conducted by Dr. Richard Evans at Davis, California and (2) the second task presents the data and results regarding the use of Controlled Release Fertilizers (CRF) and liquid fertilization programs.

Task 1

Water and Nitrogen Demand of Container-Grown Woody Plants

Month of initiation: 1/2001 Month of completion: 2/2002

Subtask 1.1: A static solution culture system was prepared in an outdoor nursery at the Environmental Horticulture Department at Davis, CA (Figure 1). An aeration system, consisting of a main manifold with individual air lines directed into each container, was constructed. Completed by 2/2001.

Figure 1. Static solution culture system at U.C. Davis.

Subtask 1.2: A modified, half-strength Hoagland's solution with full strength minor nutrients was prepared for the system. N form was adjusted as necessary to control pH. Completed by 2/2001.

Subtask 1.3: Five woody ornamental species (*Berberis thunbergii, Hydrangeaq macrophylla, Ilex aquifolium, Ligustrum lucidum and Rhododendron sp.*) were obtained as 2-inch liners. Roots were carefully cleaned of media and placed in nutrient solutions. Completed by 3/2001.

Subtask 1.4: Nitrogen and water uptake were monitored. Nutrient solutions were changed at three-day intervals, or as needed. Water use was determined gravimetrically on each container. N uptake was calculated by measuring N depletion from nutrient solutions each time solutions were changed. Nitrogen concentration of the solutions was determined by the diffusion-conductivity method (Carlson et al., 1990). Plant fresh weight and shoot elongation were measured weekly. Subtask was completed by 9/2001.

TASK 1 - RESULTS AND CONCLUSIONS

Five woody ornamental species (*Berberis thunbergii, Hydrangea macrophylla, Ilex aquifolium, Ligustrum lucidum, and Rhododendron sp.*) were obtained in Spring 2001 as 2-inch liners and planted into 4-L static solution culture containers and placed on benches in a lath-house at the Department of Environmental Horticulture. The composition of the nutrient solution used during most of the experimental period was 2 mM $MgSO_4$, 1 mM K_2SO_4, 1 mM KH_2PO_4, 2 mM NH_4NO_3, $CaSO_4$ at 0.43 g/L, and micronutrients at full-strength Hoagland's solution concentrations. Acidity was adjusted to pH 6, and solutions were changed every 3-4 days to maintain sufficient amounts of water and nutrients in the containers. From day 128 to day 138, the solution for half of the plants of each species was maintained between pH 4.5-5. The weight of the nutrient solution in each container was determined before and after each solution change for calculation of water use and N uptake. The concentration of NO_3-N and NH_4-N in the nutrient solution was determined before and after each change by the diffusion-conductivity method. Plant fresh weight was determined at each nutrient solution change after lightly blotting the roots to remove excess nutrient solution water.

Cumulative total N uptake varied greatly by species (Fig. 1). Total N uptake by *Hydrangea* was twice as great as uptake by any other species. This difference was even more pronounced for NO_3-N uptake (Fig. 2). With the exception of *Hydrangea*, all of the species under study took up more NH_4-N than NO_3-N (Fig. 3). Lowering the solution pH did not significantly affect plant preference for NH_4-N or NO_3-N.

During the first 50 days of growth, average daily water uptake of all five species was 50-75 mL per day (Fig. 4). After about 3 months of growth, average water uptake rates for most of the species were between about 160-225 mL per day (Table 1). The exception was *Hydrangea*, for which the average had increased to 470 mL per day. These rates of water use are lower than estimated irrigation application rates at most commercial nurseries.

The ratio of N uptake to water uptake yields a value for the ideal nutrient solution N concentration for a liquid feed system (Table 1). The highest ratio occurred in *Hydrangea* (54 mg/L) and the lowest in *Rhododendron* (23 mg/L). All of these values are substantially lower than the liquid feed N concentrations applied in most commercial nurseries.

The growth habits and soil preferences of the species studied are representative of the range typically found in commercial nurseries. The results will be useful to growers who seek finer adjustment of application rates of nitrogen and water, as well as to fertilizer companies and others who wish to match nitrogen application rates or release rates to woody ornamental crop needs.

Table 1. Average daily uptake of N (in mg), water (in mL), and the ratio of total N uptake to water uptake, in mg/L.

	mg N	mL water	mg N/L
Berberis	6.4	160	39.9
Hydrangea	25.3	470	54.0
Ilex	5.1	169	30.2
Ligustrum	11.0	226	48.7
Rhododendron	4.4	187	23.3

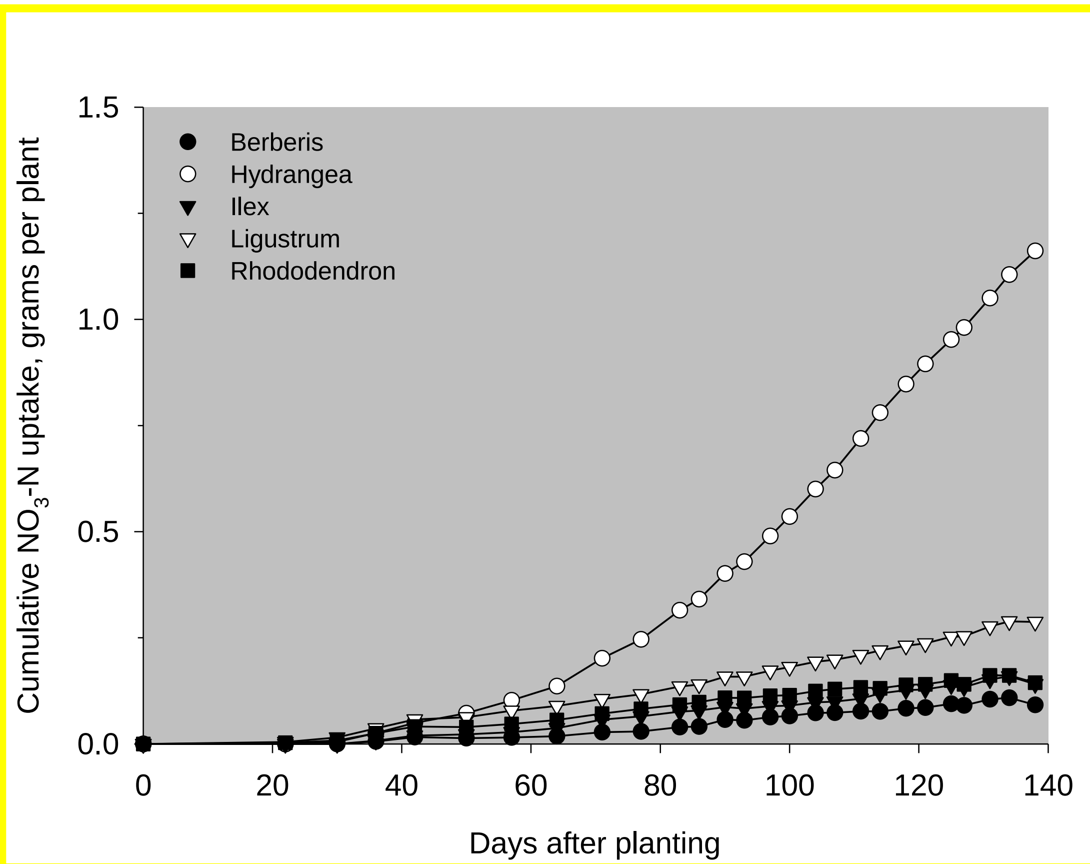

Figure 1. Cumulative nitrogen (N) uptake for *Berberis, Hydrangea, Ilex, Ligustrum,* and *Rhododendron*.

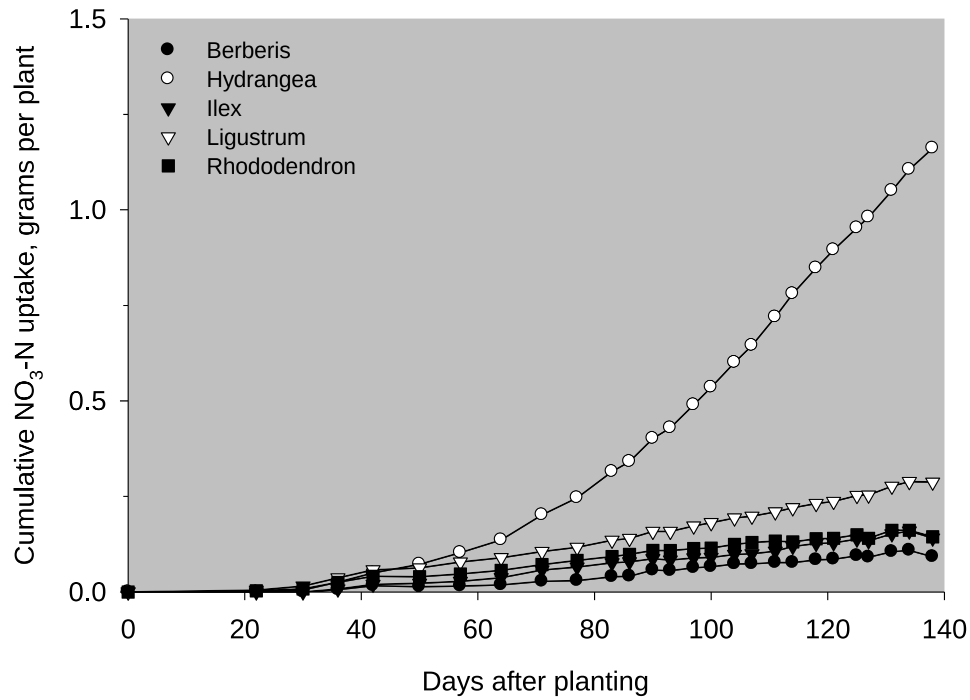

Figure 2. Cumulative NO_3—N uptake of *Berberis, Hydrangea, Ilex, Ligustrum,* and *Rhododendron.*

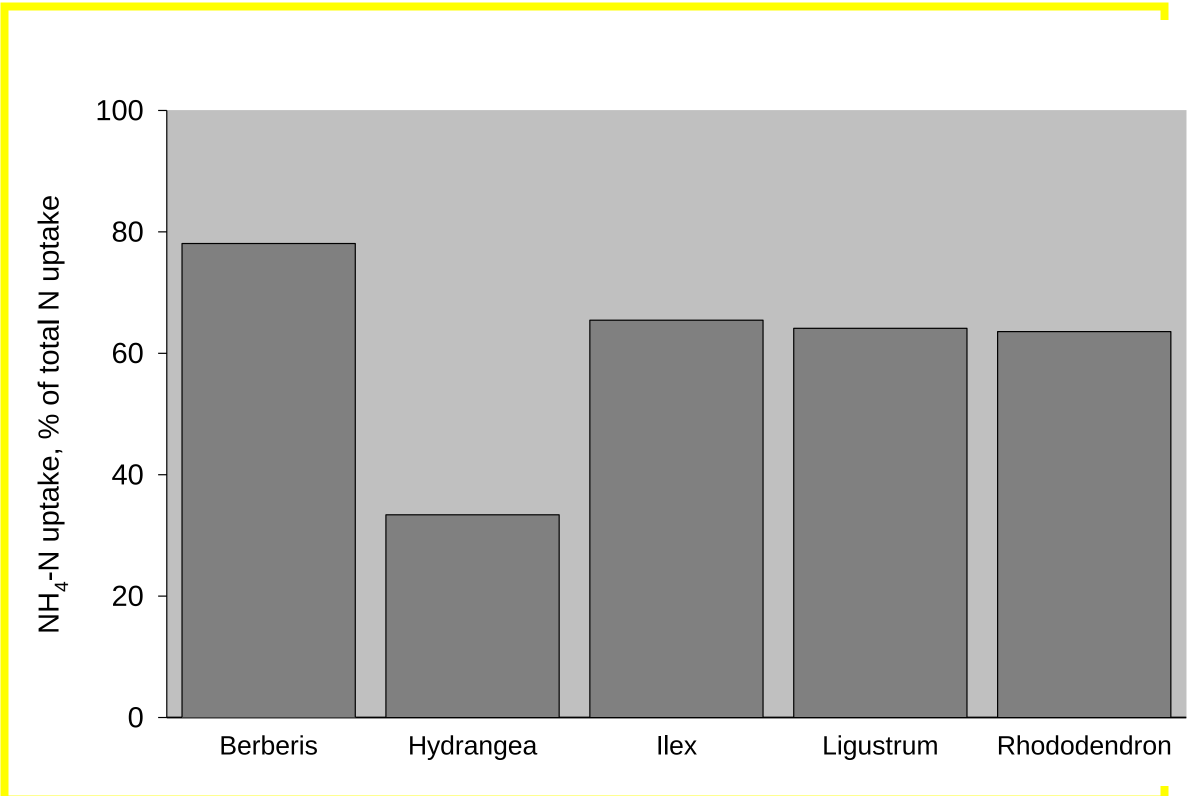

Figure 3. Ammonium (NH_4^+-N) uptake as a percentage of total N uptake in *Berberis, Hydrangea, Ilex, Ligustrum* and *Rhododendron.*

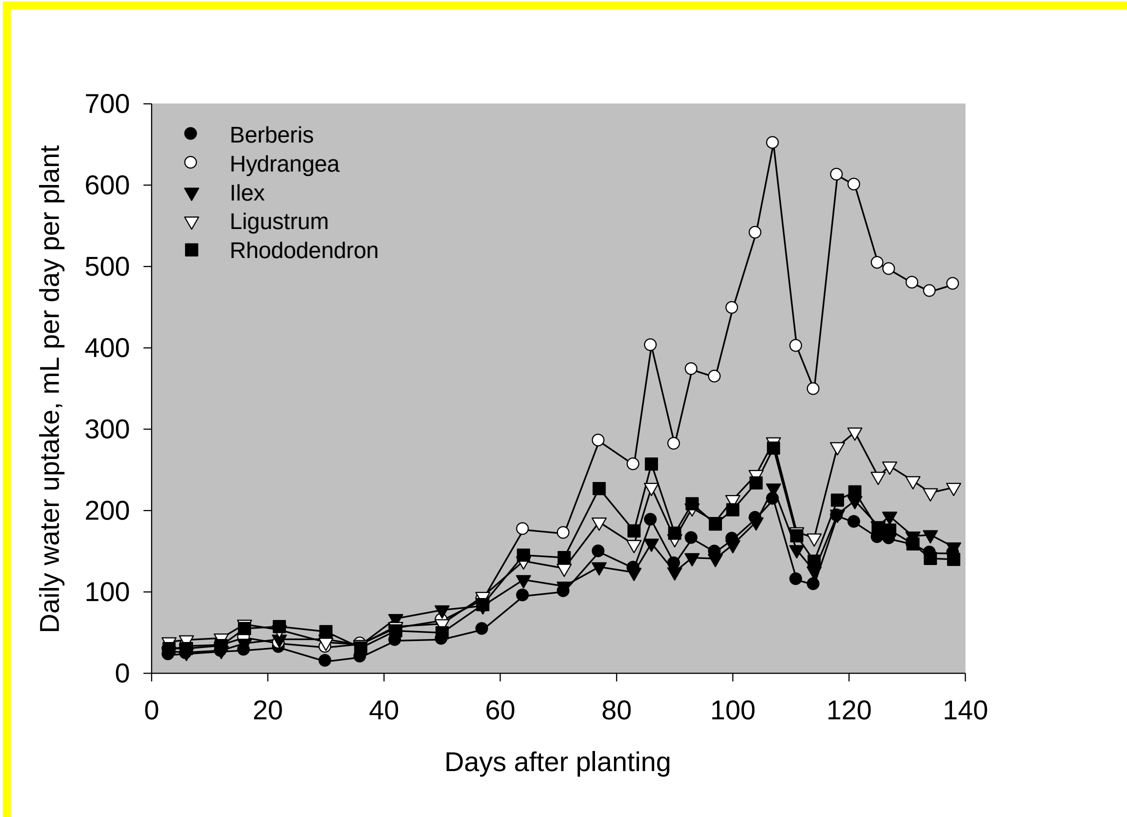

Figure 4. Daily water uptake rates in *Berberis, Hydrangea, Ilex, Ligustrum* and *Rhododendron*

Task 2

Ammonium, Nitrate, Phosphorus, Potassium, Calcium, Magnesium, Iron, Manganese, Copper, Zinc, and Molybdenum Release Characteristics from Containerized Acid Media in a Temperature-Regulated Greenhouse

Task 2. Determine the fate of NH_4^+ and NO_3^- from CRF and LF in containerized woody ornamentals growing in acid (5.0) or neutral (7.0) pH media throughout an 11-month period.

Month of Initiation: 1/2001 Month of completion: 7/2002

Subtask 2.1: Experimental plots were laid out and prepared for the installation of benches and the irrigation system. Treatments were set up into 10 blocks for the ligustrum crop (5 blocks for the plant study and 5 blocks for the controls – no plants) and 10 blocks for the azalea crop (5 blocks for the plant study and 5 blocks for the controls – no plants). Each of the 7 treatments was randomly assigned a position in each block (Figure 5). There were 11 replications of each treatment in each block, with one replication being harvested each month. Shade cloth was purchased. All fertilizer, irrigation equipment, and bench materials were purchased.

Completed by 2/2001

Osmo/7 B10L1	Nutri/7 B10L2	NO3/9 B10L3	NH4NO3/6 B10L4	NH4/9 B10L5	NH4NO3/11 B10L6	NH4/10 B10L7	NO3/5 B10L8
Apex/2 B10L9	Nutri/9 B10L10	Nutri/4 B10L11	Multi/7 B10L12	NH4/7 B10L13	Apex/10 B10L14	NH4NO3/3 B10L15	NO3/10 B10L16
Multi/1 B10L17	NH4NO3/9 B10L18	Apex/11 B10L19	Nutri/3 B10L20	NH4NO3/7 B10L21	NH4NO3/2 B10L22	Multi/8 B10L23	NH4/1 B10L24
Nutri/10 B10L25	NH4/8 B10L26	Multi/2 B10L27	NO3/8 B10L28	Osmo/3 B10L29	NH4NO3/5 B10L30	Nutri/11 B10L31	NO3/4 B10L32
NO3/11 B10L33	NH4NO3/10 B10L34	Osmo/8 B10L35	Multi/3 B10L36	Nutri/8 B10L37	Apex/6 B10L38	Osmo/11 B10L39	NO3/1 B10L40
NO3/6 B10L41	NH4/5 B10L42	Osmo/6 B10L43	Apex/3 B10L44	Osmo/2 B10L45	Osmo/4 B10L46	Nutri/2 B10L47	Apex/4 B10L48
NH4NO3/1 B10L49	Osmo/1 B10L50	Osmo/9 B10L51	NH4/2 B10L52	Multi/6 B10L53	Multi/4 B10L54	Multi/11 B10L55	Nutri/6 B10L56
Apex/5 B10L57	Apex/7 B10L58	Multi/5 B10L59	NO3/7 B10L60	NO3/3 B10L61	Apex/1 B10L62	Apex/9 B10L63	NH4NO3/4 B10L64
Nutri/1 B10L65	Nutri/5 B10L66	NH4NO3/8 B10L67	Multi/10 B10L68	NH4/3 B10L69	NH4/6 B10L70	NO3/2 B10L71	Apex/8 B10L72
Multi/9 B10L73	NH4/11 B10L74	Osmo/10 B10L75	NH4/4 B10L76	Osmo/5 B10L77	B10L78	B10L79	B10L80

Figure 5. A sample of a block, showing all of the treatments that were randomly assigned a location within the block. The layout description consisted of the treatment name: Osmocote (Osmo), Nutricote (Nutri), Multicote (Multi), Apex, liquid-fertilizer nitrate (NO_3^-), liquid-fertilizer ammonium (NH_4^+) and liquid-fertilizer ammonium nitrate ($NH_4^+NO_3^-$). Month of harvest is marked to the right of the treatment name (/1, /2, etc.). The letter and number code below the treatment name specifies the block and bench location. For example, B10L73 indicates the plant is at block 10 and location 73 on the bench.

Subtask 2.2: Benches, irrigation, and drainage systems were built and installed (Figures 6 and 7). The irrigation system was designed for automated irrigation of all treatments. There were four different irrigation lines (Figure 8) – city water was used for irrigating all CRF treatments, and three separate water lines represented the three different liquid fertilizer treatments (Figure 9). Materials needed to collect leachate were ordered and adapted to the system to collect leachate.

Completed by 3/2001.

Figure 6. Greenhouse benches that were used for azalea production. Photo shows Blocks 1-5, with Block 1 in the foreground and Block 5 in the background. Shade cloth (33% shade) covers the structure during the months of May to October.

Figure 7. Greenhouse benches that were used for ligustrum production. Photo shows Blocks 6-10, with Block 6 in the foreground and Block 10 in the background. Plants were not provided any protection from weather.

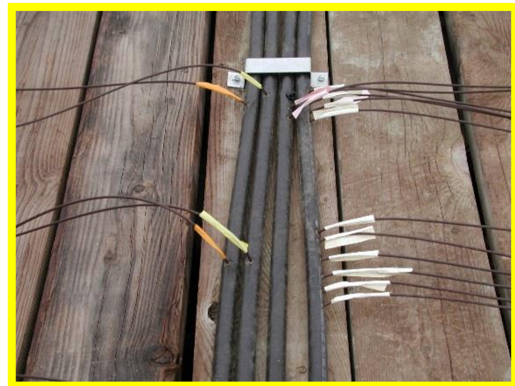

Figure 8. Four irrigation lines used to irrigate crops. Drippers extended out from each line to the pot to be irrigated. White-taped lines were water for the controlled-release fertilizer treatments and the orange, pink and yellow-taped lines represented the three liquid fertilizer treatments.

Figure 9. Three Dosatron pumps used
to portion out fertilizer for the three liquid fertilizer treatments.

Subtask 2.3: A total of 840 plants (Azalea Southern Indica 'Phoenicia', and *Ligustrum texanum*) at the liner-stage (Figure 10), were obtained from a commercial nursery. Plants were potted into 1-gallon containers containing the appropriate media (Figure 11). In the case of the Controlled Release Fertilizers (CRF), fertilizers were thoroughly mixed into the media with a cement mixer. Treatments were a 2 x 7 factorial of 2 different media pH (5.0 and 7.0) and seven different fertilizer treatments. The liquid-fertilizer study was initiated in March 2002. There were five replications of each treatment for each of the 11 monthly harvests. Substrates for the media were purchased and delivered. Completed by 4/2001.

Figure 10. Liners of plants prior to being planted into 1-gallon sized plastic containers.

Figure 11. Liners being planted into containers. All controlled-release fertilizers were mixed into media with a cement mixer.

List of fertilizer treatments for Task 2.

Treatment	Fertilizer
1	100 ppm N as 75% NH_4^+ and 25% NO_3^- Liquid fertilizer
2	100 ppm N as NH_4NO_3 Liquid Feed
3	100 ppm N as 75% NO_3 and 25% NH_4^+ Liquid fertilizer
4	Osmocote CRF
5	Apex CRF
6	Multicote CRF
7	Nutricote CRF

Subtask 2.4: Baseline measurements of media (without N fertilizer) and plants were taken. Five replications each of the acid and neutral pH media were measured for total KCL-extractable NH_4^+ and NO_3^-, total N, electrical conductivity (EC) pH and total nutrient content. Concentrations of NH_4^+ and NO_3^- were determined with a Technicon Continuous Flow Analyzer. Five each of the Azalea Southern Indica 'Phoenicia' and the *Ligustrum texanum* were harvested, separated into roots and shoots, dried and ground. Dry weights and N concentration of roots and shoots were measured. This data has been collected. This subtask for the controlled release fertilizers was completed by the end of 7/2001. The Liquid Fertilizer portion was completed by the end of 4/2002.

Subtask 2.5 and 2.6: Weekly tasks of leachate collection and analyses (EC, NO_3^--N content and NH_4^+-N content) were performed as planned.

TASK 2 – CURRENT RESULTS AND DISCUSSION

All experiments are completed. However, data is still being processed. Therefore, the results of the Controlled Release Fertilizer (CRF) studies and the Liquid Fertilization (LF) studies will be presented in 6 parts:

1. Release patterns of plant nutrients from four controlled release fertilizers in **Acid** media during an eleven-month period in a simulated greenhouse production facility – A control study (no plants).

The results of this study are presented in two manuscripts at the end of this document.

2. Release patterns of plant nutrients from four controlled release fertilizers in **Neutral** media during an eleven month period in a simulated outdoor production facility – A control study (no plants)

3. Release of plant nutrients from four **controlled release fertilizers** and leaching and plant uptake characteristics for **Greenhouse-Grown Azaleas** during an eleven month period.

4. Release of plant nutrients from four **controlled release fertilizers** and leaching and plant uptake characteristics for **Outdoor-Grown Ligustrum** during an eleven month period.

5. Nutrient leaching and uptake characteristics from three nitrogen **liquid fertilization** formulations for **Greenhouse-Grown Azaleas** during an eleven month period.

6. Nutrient leaching and uptake characteristics from three nitrogen **liquid fertilization** formulations for **Outdoor-Grown Ligustrum** during an eleven month period.

Nutrient Release Characteristics of Four Controlled-Release Fertilizers in Acid Substrate During an 11-Month Period in a Greenhouse Environment: I. Effects on Leachate Electrical Conductivity, pH, and Nitrogen, Phosphorus, and Potassium Concentrations.

Introduction

The Federal Water Pollution Control Act of 1948 was overhauled in 1972 with the addition of several amendments that directed regulations towards non-point sources of pollution such as commercial and private landscapes and nurseries. Since that time, the Act has been referred to as the Clean Water Act and, among other items, indicates that all states must identify impaired waterbodies in their region and must implement regulations to mitigate pollutant runoff from any point and non-point 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), which are used as fertilizers in the nursery industry. 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·A^{-1} 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 act in accordance 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 United States (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 reflect conditions experienced in container production facilities. In addition, the duration of many experiments has been limited to six months or less, which is insufficient for measuring nutrient release from 12-month-release fertilizer formulations, as alluded to by Havis and Baker (1985a). In the following study, nutrient release patterns of four types of CRFs, when blended into an acid substrate, were measured during an 11-month period in an unheated greenhouse environment to determine characteristics of nutrient release under a typical production scenario.

Materials and Methods

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, 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 $kg \cdot m^3$. All CRFs were 365-day release formulations. However, release rates of these CRFs are based on different temperature regimes: 27ºC for Osmocote and Polyon, 21ºC for Multicote, and 21-27ºC 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 per container, which is equivalent to 1.17 kg N·m^{-3}, a rate most fertilizer companies recommended for slow-growing woody ornamentals. While N content for all CRF treatments was the same, the content of other nutrients varied. 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.

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., Minami-ku Kyoto, Japan). Immediately following EC and pH measurements, 2 ml of 2 N sulfuric acid were added to each bucket to chemically stabilize 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.

Results and Discussion

Air temperature. Weekly average greenhouse air temperature ranged between 24 and 30ºC during the first ten weeks (Aug. through Sept. 2001) and last ten weeks (May 2002 through June 2002) of the study (Figure 1). Maximum air temperatures during this time period ranged from 28 to 46ºC, which are temperatures observed in other warm-temperate and subtropical growing regions (Ingram, 1981; Lamont et al., 1987). These temperatures were consistently above 21ºC, the labeled substrate temperature rating for 1-year longevity for Multicote. However, only weekly maximum temperatures were typically above the average labeled temperature ratings of 24ºC for Nutricote and 27ºC 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 environmental conditions and CRFs, nutrient release rates increased by up to 200% for every 10°C increase 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 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 five months of the study, relative to the later time frame, regardless of fertilizer type, with significant differences observed among treatments (Figure 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 hours) 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 $mg \cdot L^{-1}$, based on chloride and sulfate concentrations only. Therefore, monitoring and control of EC, from a nursery production 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 (Figure 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 approximately 6.5. In addition, a study by Ivy et al. (2002) showed that fertilizer type (Osmocote 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 (two and four times, 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 5.0-9.0 for domestic water supplies, 6.5 - 8.5 for freshwater aquatic life, and 6.5 – 9.0 for marine aquatic life) (U.S. EPA, 1976).

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

Osmocote treatment, which averaged ~3.0 mg during the last three 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 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 the second month, and by the seventh month, less than 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 (2005), the percentage of NH_4^+-N from the CRF recovered in the leachates in the present study were lower, which is probably associated with the binding of NH_4^+-N to organic matter of the container substrate, as described by others (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, as was determined by 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 the majority 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 rates.

Federal guidelines do not mention NH_4^+-N concentration, but do state that concentrations of un-ionized ammonia (NH_3), 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 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 NH_3 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 four weeks of the study, with the exception of week 2, when leachate from the Osmocote treatment averaged 32 mg·L^{-1} (Figure 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 approximately 30 mg·L^{-1} for leachates from treatments containing Nutricote, Polyon, or Multicote. However, for Osmocote, leachate NO_3^--N concentrations gradually increased to approximately 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 rate 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 six 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 studies 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^- leaching in excess of 10 mg·L^{-1} would probably only exist 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 nine weeks of the study, then a decrease and leveling off period during the remaining 36 weeks for Polyon, Nutricote, and Multicote. 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 rates 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 also accounted for by the 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 rate 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 (21ºC) 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). P concentrations in leachates of all treatments fluctuated throughout the study, but were higher (15 to > 60 $mg \cdot L^{-1}$) during the first 10 weeks compared to the last 27 weeks of the study, when concentrations averaged below 10 $mg \cdot L^{-1}$ (Figure 7). The pattern of high then low P release rates 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 to each other throughout the study. In another experiment (Broschat, 2005), release of P from Osmocote prills during the first five months was significantly greater than that measured from Nutricote; however, by the seventh month, 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 approximately 10 $mg \cdot L^{-1}$ 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 only established a concentration limit of 0.01 $\mu g \cdot L^{-1}$ 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 total 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 (Figure 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 approximately 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; however, Broschat (1996, 2005) did not detect differences among fertilizer types. In other research (Holcomb, 1981) with Osmocote, K release rates were linear throughout the 63-day 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 as of yet.

Conclusions

Under greenhouse conditions, where high temperatures were moderated with evaporative cooling pads and fans, 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 rates during the later half of the 11-month period, even when temperatures increased during the spring. Differences were noted among fertilizer types. 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 first few weeks of the study. Based on the results of this study and data from other long term studies, it appears that nutrient release from CRFs 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.

From an environmental perspective, risk of water impairment, when using the CRFs currently studied, would be greatest during the first 20 weeks of crop production**,** since EC, NH_4-N, NO_3-N, total P, and total K were elevated during this time period. 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.

Nutrient Release Characteristics of Four Controlled-Release Fertilizers in Acid Substrate During an 11-Month Period in a Greenhouse Environment II. Effects on Leachate Concentrations of Calcium, Magnesium, Iron, Manganese, Zinc, Copper, and Molybdenum

Introduction

In addition to the two well-known pollutants, nitrate (NO_3^-) and phosphate (PO_4^{-2}), other essential plant nutrients listed in §101(a) of the Clean Water Act (U.S. Environmental Protection Agency, 1994) are boron (B), copper (Cu), iron (Fe), manganese (Mn) and zinc (Zn). Although not receiving as much attention as NO_3^- and PO_4^{-2}, these plant micronutrients are chemicals that are used by the nursery industry and, therefore, are at risk of being regulated by state agencies. The likelihood of micronutrient contamination of surface waters from nursery runoff is unknown. Therefore, information regarding the movement of these nutrients in nursery production systems is needed so that the nursery industry is aware of any potential problems associated with micronutrient fertilization so that Best Management Practices (BMPs) may be developed to mitigate the runoff of these nutrients.

Controlled-release fertilizers (CRFs) are commonly used in the nursery industry. When used properly, these types of fertilizers can reduce the amount of nutrients in runoff compared to water-soluble fertilizers. However, little information is available regarding leaching of plant essential nutrients other than N and P. In the following study, the nutrient release patterns of four types of CRFs, when blended into a substrate, were measured during an 11-month period in an unheated greenhouse environment to determine characteristics of nutrient release under a typical production scenario.

Materials and Methods

The methodology of the experiment has been described in the first manuscript of this series. Therefore, methods are briefly described here, with emphasis on application, measurement and analyses of calcium (Ca), magnesium (Mg), Fe, Mn, Zn, Cu, and Mo.

Substrate. Substrate consisted of 5 sphagnum peatmoss (Premier Horticulture Inc., Red Hill, Penn.) : 4 pine bark (6.4-9.5 mm) : 1 washed builders sand (by volume). Substrate was amended with dolomite 65 (Chemical Lime Co., Scottsdale, Ariz.) at a rate of 0.59 $kg \cdot m^{-3}$ and ultrafine calcium sulfate (Western Mining and Minerals, Apex, Nev.) at a rate of 0.59 $kg \cdot m^{-3}$. Substrate and amendments were blended together using a Model MB20L5 Batch Mixer (Measured Marketing, Kankakee, Ill.). Substrate was analyzed for nutrient concentrations prior to incorporation of CRFs by grinding substrate to pass through a 40-mesh screen. The ground sample was then extracted by adding 100 ml deionized water to 50 ml volume of ground substrate and then filtered. Nutrient concentrations in extracts were quantitatively determined using an inductively coupled plasma (ICP) spectrometer (Thermo Electron Corp., model IRIS 1000 HR, Franklin, Mass.) Substrate nutrient concentrations prior to incorporation of CRFs were as follows ($mg \cdot L^{-1}$): 13.06 Ca, 10.19 Mg, 2.62 Fe, 0.59 Mn, 0.75 Zn, 0.11 Cu, 0.01 Mo.

Fertilizer treatments. Treatments consisted of four different types of 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, 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 the incorporation of Micromax (Scott-Sierra Horticultural Products Co., Marysville, Ohio). All CRFs were 365-day release formulations. However, release rates of the different products are based on different temperature regimes: 27ºC for Osmocote and Polyon, 21ºC for Multicote, and 21-27ºC for Nutricote. Element concentrations and the 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 per container, which is equal to 1.17 kg $N \cdot m^{-3}$, a rate most fertilizer companies recommend for slow-growing woody ornamentals. While N content for all CRF treatments were the same, the content of other nutrients varied. The CRF prills were incorporated throughout the substrate using a portable cement mixer. Substrate with CRF were 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 month 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).

Containers were irrigated with potable water, which contained ($mg \cdot L^{-1}$): 64.30 Ca, 9.48 Mg, 0.01 Fe, 0.00 Mn, 0.00 Cu, 0.004 Zn, and 0.003 Mo. Irrigation water was distributed uniformly over the surface of the substrate using DRT4-36 ring drippers (Dramm Corporation, Manitowoc, Wis.). Containers were irrigated approximately every 2 d, providing an average irrigation volume of ~1 L/week and an average leachate volume of ~750 ml/ week.

Leachate collection. All leachate was captured from each container, collected twice per week, and volumes from each collection bucket were combined so that there was one leachate sample per container per week. 2 ml of 2 N sulfuric acid were added to each collection bucket to chemically stabilize the leachate.

Results

Calcium concentration. During the first 13 weeks of the experiment, Ca concentrations in leachates from all treatments fluctuated, with concentrations reaching as high as 300 $mg \cdot L^{-1}$ (Figure 1). During the last 30 weeks of the study, Ca concentrations in leachates ranged between 25 and 50 $mg \cdot L^{-1}$, with few differences among treatments. During certain weeks, some treatments were significantly different from others; however, there did not appear to be any discernable pattern or trend in these differences. The lack of differences among treatments is expected since most of the Ca in all treatments was derived from calcium sulfate and dolomite that were blended into the substrate in addition to

Ca present in the potable water. Ca concentrations observed in the present study are similar to leachate readings observed in simulated production systems (Chen et al., 2003), where Ca concentrations ranged from 12 to 42 mg·L^{-1}. In shorter-term (1-2.5 months) studies (Huett, 1997b; Huett and Morris, 1999), the greatest loss of Ca occurred during the first week when testing Osmocote and Nutricote.

Based on other research, it does not appear that Ca would have been limiting to plant growth during any period of the study. In hydroponically-grown New Guinea impatiens (*Impatiens* 'Equinox'), maximum Ca uptake rate was achieved at a Ca concentration of approximately 95 mg·L^{-1} (Mankin and Fynn, 1996). However, in several other studies (Dunham and Tatnall, 1961; Edwards and Horton, 1981; Starr and, 1984; Wright, 1984), optimum plant growth was obtained with a Ca leachate concentration of 10-15 mg·L^{-1}. If similar uptake kinetics and Ca requirements can be generalized for most woody ornamentals, then sufficient Ca, under the fertilization regime described, should be available throughout the production period.

From an environmental perspective, there are no federal guidelines established for Ca. Significant Ca runoff may indirectly contribute to elevated electrical conductivity and pH. However, EPA criterion for salinity is 250 mg·L^{-1} and is based only on chloride and sulfates (U.S. EPA, 1976), not Ca or any other element. Present EPA criteria for pH are 5.0 to 9.0 (domestic water supply), 6.5

to 9.0 (freshwater aquatic life), and 6.5 to 8.5 (marine aquatic life) (U.S. EPA, 1976). The other water quality criterion associated with Ca is alkalinity, which is not to exceed 20 mg·L^{-1} of calcium carbonate ($CaCO_3$) for freshwater aquatic life, “except where natural concentrations are less”. (U.S. EPA, 1976).

Magnesium concentrations. Leachate concentrations of Mg fluctuated during the first 12 weeks of the study, with concentrations as low as 4 mg·L^{-1} for Osmocote (week 7) and as high as 70 mg·L^{-1} for Nutricote (week 9) (Figure 2). However, from week 13 to the conclusion of the experiment, Mg concentrations were relatively stable, falling within the range of 10-20 mg·L^{-1}. The range of Mg concentrations observed in the present study are similar to concentrations measured in simulated container production systems (Chen et al., 2003). In shorter-term studies (Huett, 1997b; Huett and Morris, 1999), Mg leaching was also greatest during the first week of the experiment. Several significant differences were measured among treatments, but there was no noticeable pattern in these differences. Other studies noted that Mg in the form of sulfates solubilized and leached from substrate more quickly than Mg derived from oxides and carbonates (Broschat and Donselman, 1985).

Based on plant requirements for Mg that have been established 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 production scenario studied. In hydroponically grown herbaceous plants, the maximum Mg uptake rate was achieved at a concentration of 30 mg·L^{-1} (Mankin and Fynn, 1996). In other studies (Starr and Wright, 1984; Wright, 1984), optimum plant growth in containerized plants was achieved when leachate Mg concentrations were maintained between 10 and 15 mg·L^{-1}. If the research by Mankin and Fynn (1996) and Wright (1984) can be applied to general containerized production practices, Mg availability from CRFs should not be limiting during a typical 11-month plant production cycle.

Environmentally, the greatest likelihood of Mg leaching from containers would only be during the first ten weeks of a production cycle; thereafter, plant roots should take up all Mg. However, since current federal policies (U.S. EPA, 1976) have no criterion for Mg concentration in runoff waters, Mg in runoff is not presently an environmental concern.

Iron concentrations. Iron concentrations in leachates from all treatments were relatively high and fluctuated during the first 12 weeks of the study (Figure 3). Fe concentrations in leachates were relatively stable during the last 30 weeks of the study, with significantly higher concentrations recovered in the leachates from the Nutricote treatment compared to the other three CRF treatments. This may be due to Fe leaching out of broken prills or, in the case of Micromax, Fe directly solubilizing from the fertilizer since Micromax is a non-coated form of micronutrient fertilizer. In other studies with uncoated granular fertilizers, a notable leaching of Fe occurred (Frost et al., 2003; Handreck, 1989) and, in some cases, the leaching rate from granular fertilizers was greater than that observed from soluble fertilizers (Frost et al., 2003). Overall, Fe concentrations measured in the present study, with the exception of the first 11 weeks, were similar to those observed in containerized production systems (Chen et al., 2003). The significant differences with Nutricote may be associated with the iron formulation, which was iron EDTA, a soluble iron form. Iron chelate was also the form of Fe used with Multicote; however, the Multicote treatment resulted in significantly greater leaching than all other CRFs during the first three weeks of the study, which may have resulted in less Fe available for release during the later part of the study. Broschat and Donselman (1985) noted that the leaching of Fe from organic-based substrate was greater with the use of chelated Fe compared to other mineral forms of Fe. It has also been determined that Fe is immobilized by organic substrate, up to 100 $mg \cdot L^{-1}$ for certain types of sawdust and bark products (Handreck, 1989).

Based on the present study and the results of other research (Broschat and Donselman, 1985; Chen et al., 2003; Frost et al., 2003, Handreck, 1989), it appears that sufficient Fe was probably available for normal plant growth in the simulated production system studied, with the environmental risk of high Fe concentrations (>0.3 $mg \cdot L^{-1}$) in leachates occurring during the first 20 weeks of the production cycle. The primary concern for Fe leaching would be with formulations using chelated iron, which have been found to be easily leached from organic substrates typically used in many containerized production systems.

Current federal guidelines indicate Fe concentrations are not to exceed 0.3 $mg \cdot L^{-1}$ for water for domestic use and 1.0 $mg \cdot L^{-1}$ for freshwater aquatic life.

Manganese concentrations. Managanese concentrations in leachates of all fertilizer treatments were relatively high (between 1.0 and 9.0 $mg \cdot L^{-1}$), but variable during the first twelve weeks of the study (Figure 4). During the last 30 weeks of the experiment, Mn concentrations were below 2.0 $mg \cdot L^{-1}$ for all treatments. In other studies, Mn leached from granular fertilizers, even more so than with the use of liquid fertilizers (Frost et al., 2003). The only significant differences observed were that the Osmocote treatment resulted in higher Mn concentrations in leachates compared to the other CRFs during the first two weeks of the study, then again from weeks 36 through 39 for Polyon and Multicote. Other differences were observed among fertilizer types throughout the experimental period, but no patterns or trends in these differences evolved. The lack of differences is not unexpected, since all fertilizer types contained manganese sulfate as their form of Mn. In other studies (Broschat and Donselman, 1985), it was shown that Mn might precipitate with other compounds at a substrate pH above 6.2; however, in the present study, the initial substrate pH was 4.5. Therefore, solubilization and possible leaching of Mn probably occurred during the beginning of the study. However, as leachate pH increased, and probably substrate pH as well, the solubilization, and therefore the leaching, of remaining Mn was minimized. Based on other research (Tinus and McDonald, 1979), a Mn concentration of 0.5 $mg \cdot L^{-1}$ is sufficient for healthy plant growth.

Therefore, the Mn concentrations observed in the present study should be adequate for plant requirements. Environmentally, Mn leaching, and therefore the potential for excess Mn in runoff, was high throughout the entire study since federal guidelines indicate that Mn concentrations are not to exceed 0.050 $mg \cdot L^{-1}$ for domestic waters and 0.100 $mg \cdot L^{-1}$ "for protection of consumers of marine mollusks" (U.S. EPA, 1976), levels which are below concentrations measured in the present study.

Zinc concentrations. Leachate concentrations of Zn were relatively high and variable during the first twelve weeks of the study (Figure 5). After week 13, Zn concentrations were below 0.5 $mg \cdot L^{-1}$, regardless of fertilizer type. These readings were higher than leachate measurements conducted in other studies (Chen et al, 2003) where Zn concentrations ranged between 0.01 and 0.04 $mg \cdot L^{-1}$. Leaching of Zn with granular micronutrients was also noted in other studies (Frost et al., 2003). Leachate Zn concentrations from the Nutricote treatment were significantly higher than with other fertilizer treatments during most of the study, despite the fact that the amount of Zn was three to four times less in the Nutricote treatment compared to the other CRF treatments. For plant growth, the Zn concentrations observed would probably be sufficient for most crops, as noted in other studies (Carroll and Loneragan, 1969; Tinus and McDonald, 1979). From an environmental perspective, Zn concentrations were usually below the critical limit of 5.000 $mg \cdot L^{-1}$ for domestic water supplies as established by the EPA.

Copper concentrations. Copper concentrations in leachates were usually below 1.00 mg·L^{-1}, regardless of fertilizer type (Figure 6). During weeks 14 and 15, concentrations of Cu increased for all treatments, then decreased and stabilized. There were some differences among treatments, most notable being the higher Cu concentrations with Nutricote relative to the other CRFs for eight weeks out of the 47-week period. In another study (Broschat and Donselman, 1985), copper concentrations in leachates were relatively stable throughout an 18-month period. The low Cu concentrations observed in the present research and other studies may be attributed to the high affinity of Cu for organic matter (Schnitzer and Skinner, 1966). The EPA has established a Cu limit of 1.0 mg·L^{-1} for domestic water supplies (U.S. EPA, 1976). Based on the current study, the Cu levels resulting from fertilization should not be of concern.

Molybdenum concentrations. Molybdenum concentrations were variable during the first 15 weeks of the study, with significantly greater concentrations measured in the Nutricote treatment compared to the other fertilizer types. After week 15, Mo concentrations were near 0.0 mg·L^{-1} for all treatments. There are currently no federal guidelines established for Mo in surface waters.

Conclusions. Concentrations of Ca, Mg, Fe, Mn, Zn, Cu and Mo in leachates were relatively high during the first 10 to 16 weeks of the 11-month production cycle under cultural conditions typically used for low-nutrient requiring crops such as azalea and camellia. In most cases, leachate concentrations of all nutrients appeared to be at levels that would be considered sufficient for healthy plant growth. From an environmental perspective, only Fe and Mn were at concentrations that exceeded U.S. EPA guidelines, and these elevated concentrations only occurred during the first two months of the experiment. Based on these results, the use of Ca, Mg, Zn, Cu and Mo in the fertilizer program tested should have little or no impact on water quality of nursery runoff. However, the use of Fe and Mn should be carefully considered, as concentrations of these nutrients may exceed federal guidelines, especially during the early phase of a typical production cycle.

Literature Cited

Argo, W.R. and J.A. Biernbaum. 1997. The effect of root media on root-zone pH, calcium, and magnesium management in containers with impatiens. J. Amer. Soc. Hort. Sci. 122:275-284.

Broschat, T.K. 1996. Release rates of soluble and controlled-release potassium fertilizers. HortTechnology 6:128-131.

Broschat, T.K. 2005. Rates of ammonium-nitrogen, nitrate-nitrogen, phosphorus, and potassium from two controlled-release fertilizers under different substrate environments. HortTechnology 15:332-335.

Broschat, T.K. and H.M. Donselman. 1985. Extractable Mg, Fe, Mn, Zn, and Cu from a peat-based container medium amended with various fertilizers. J. Amer. Soc. Hort. Sci. 110:196-200.

Brown, E.F. and F.A. Pokorny. 1977. Potassium distribution and retention in pine bark and sand media. HortScience 12:343-344.

Cabrera R.I. 1997. Comparative evaluation of nitrogen release patterns from controlled-release fertilizers by nitrogen leaching analysis. HortScience 32:669-673.

Carroll, M.D. and J.F. Loneragan. 1969. Response of plant species to concentrations of zinc in solution II. Rates of zinc absorption and their relation to growth. Austral. J. Agric. Res. 20: 457-463.

Chen, J., R.C. Beeson, Jr., T.H. Yeager, R.H. Stamps and L.A. Felter. 2003. Evaluation of captured rainwater and irrigation runoff for greenhouse foliage and bedding plant production. HortScience 38:228-233.

Dancer, W.S., L.A. Peterson and G. Chesters. 1973. Ammonification and nitrification of N as influenced by soil pH and previous N treatments. Soil. Sci. Soc. Amer. Proc. 37:67-69.

Diamond, D. 1995. Phosphorus in soil extracts. QuikChem method 10-115-01-1-A. Lachat Instruments, Milwaukee, Wis.

Dunham, C.W., and D.V. Tatnall. 1961. Mineral composition of leaves of three holly species grown in nutrient sand cultures. Proc. Amer. Soc. Hort. Sci. 78:564-571.

Edwards, D.G., and B.D. Horton. 1981. Influence of magnesium concentrations in nutrient solution on growth, tissue concentration, and nutrient uptake of peach seedlings. J. Amer. Soc. Hort. Sci. 106:401-405.

Engelsjord, M.E., O. Fostad, and B.R. Singh. 1997. Effects of temperature on nutrient release from slow-release fertilisers. 1. Commercial and experimental products. Nutrient Cycling in Agroecosystems 46:179-187.

Flint, H.L. 1962. Effects of different soil levels and methods of application of phosphorus on growth of selected woody ornamental species in containers. Proc. Amer. Soc. Hort. Sci. 81:552-555.

Foster, W.J., R.D. Wright, M.M. Alley, and T.H. Yeager. 1983. Ammonium adsorption on a pine-bark growing medium. J. Amer. Soc. Hort. Sci. 108:548-551.

Franson, M.A. 1985. Method 303A, p. 157-160. In: M.A. Farnson (ed.). Standard methods for the examination of water and wastewater, 16th edition. Amer. Public Health Assn. – Amer. Water Works Assn. - Water Pollution Control Federation, Washington, D.C.

Frost, M.D., J.C. Cole and J.M. Dole. 2003. Fertilizer source affects iron, manganese, and zinc leaching, nutrient distribution, and geranium growth. J. Plant Nutr. 26:315-329.

Gandeza, A.T., S. Shoji and I. Yamada. 1991. Simulation of crop response to polyolefin-coated urea: I. Field dissolution. Soil Sci. Soc. Amer. J. 55:1462-1467.

Gartner, J.B., M.M. Meyer, Jr., and D.C. Saupe. 1971. Hardwood bark as a growing media for container-grown ornamentals. Forest Products J. 21:25-29.

Goertz, H.M. 1993. Controlled release technology. p. 251-274. In: Kirk-Othmer (ed.). Encyclopedia of chemical technology. Vol. 7, 4th ed. Wiley & Sons, New York, NY.

Handreck, K.A. 1989. Assessment of iron availability in soilless potting media. Commun. Soil Sci. Plant Anal. 20:1297-1320.

Handreck, K.A. 1996. Phosphorus immobilization in wood waste-based potting media. Commun. Soil Sci. Plant Anal. 27:2295-2314.

Handreck, K. 1997. Controlled release fertilizers. Measuring nutrient release rates. Austral. Hort. 95(10):51-53.

Handreck, K. and K. Bunker. 1996. Fertilisers and hot weather. Austral. Hort. 94(8):83-85.

Havis, J.R. and J.H. Baker. 1985a. Phosphorus availability in peat-sand media fertilized with several phosphorus sources. J. Environ. Hort. 3:153-155.

Havis, J.R. and J.H. Baker. 1985b. Phosphorus requirement of *Rhododendron* 'Victor' and *Cotoneaster adpressa praecox* grown in a perlite-peat medium. J. Environ. Hort. 3:63-64.

Holcomb, E.J. 1981. Potassium release from selected slow-release fertilizers. Commun. Soil Sci. Plant Anal. 12:1303-1310.

Huett, D.O. 1997a. Fertiliser use efficiency by containerized nursery plants. 1. Plant growth and nutrient uptake. Austral. J. Agr. Res. 48:251-258.

Huett, D.O. 1997b. Fertilizer use efficiency by containerized nursery plants. 2. Nutrient leaching. Austral. J. Agr. Res. 48:259-265.

Huett, D.O. and S.C. Morris. 1999. Fertiliser use efficiency by containerized nursery plants. 3. Effect of heavy leaching and damaged fertilizer prills on plant growth, nutrient uptake, and nutrient loss. Austral. J. Agric. Res. 50:217-222.

Huett, D.O. and B.J. Gogel. 2000. Longevities and nitrogen, phosphorus, and potassium release patterns of polymer-coated controlled-release fertilizers at 30°C and 40°C. Commun. Soil Sci. Plant Anal. 31:959-973.

Husby, C.E., A.X. Niemiera, J.R. Harris, and R.D. Wright. 2003. Influence of diurnal temperature on nutrient release patterns of three polymer-coated fertilizers. HortScience 38:387-389.

Ingram, D.L. 1981. Characterization of temperature fluctuations and woody plant growth in white poly bags and conventional black containers. HortScience 16:762-763.

Ivy, R.L., T.E. Bilderback and S.L. Warren. 2002. Date of potting and fertilization affects plant growth, mineral nutrient content, and substrate electrical conductivity. J. Environ. Hort. 20:104-109.

Johnson, C.M. and A. Ulrich. 1959. Analytical methods for use in plant analysis. Univ. Calif. Agr. Expt. Sta. Res. Bul. 766.

Kochba, M., S. Gambash, and Y. Avnimelech. 1990. Studies on slow release fertilizers. 1. Effect of temperature, soil moisture and water vapor pressure. Soil Sci. 149:339-343.

Lamont, G.P., R.J. Worrall and M.A. O'Connell. 1987. The effects of temperature and time on the solubility of resin-coated controlled-release fertilizer under laboratory and field conditions. Scientia Hort. 32:265-273.

Lunt, O.R. and J.J. Oertli. 1962. Controlled release of fertilizer minerals by incapsulating membranes: II. Efficiency of recovery, influence of soil moisture, mode of application, and other considerations related to use. Soil Sci. Soc. Amer. Proc. 26:584-587.

Mankin, K.R. and R.P. Fynn. 1996. Nutrient uptake response of New Guinea impatiens to light, temperature, and nutrient solution concentration. J. Amer. Soc. Hort. Sci. 121:826-830.

Niemiera, A.X. and R.D. Wright. 1986. The influence of nitrification on the medium solution and growth of holly, azalea, and juniper in a pine bark medium. J. Amer. Soc. Hort. Sci. 11:708-712.

Oertli, J.J. and O.R. Lunt. 1962. Controlled release of fertilizer minerals by incapsulating membranes: I. Factors influencing the rate of release. Soil Sci. Soc. Amer. Proc. 26:579-583.

Patel, A.J. and G.C. Sharma. 1977. Nitrogen release characteristics of controlled-release fertilizers during a four month soil incubation. J. Amer. Soc. Hort. Sci. 102:364-367.

Prasad, M. and M.J. Woods. 1971. Release characteristics of nitrogen fertilizer in peat and sand. J. Agr. Food Chem. 19:96-98.

Rathier, T.M. and C.R. Frink. 1989. Nitrate in runoff water from container grown juniper and Alberta spruce under different irrigation and N fertilization regimes. J. Environ. Hort. 7:32-35.

Sweeney, R.A. 1989. Generic combustion method for determination of crude protein in feeds: Collaborative study. J. Assn. Offic. Anal. Chem. 72:770-774.

Thomas, S. and F.B. Perry, Jr. 1980. Ammonium nitrogen accumulation and leaching from an all pine bark medium. HortScience 15:824-825.

Schnitzer, M. and S.I.M. Skinner. 1966. Organo-metallic interactions in soils: 5. Stability constants of Cu^{++}, Fe^{++}, and Zn^{++}-fulvic acid complexes. Soil Sci. 102:361-365.

Starr, K.D. and R.D. Wright. 1984. Calcium and magnesium requirements of *Ilex crenata* 'Helleri'. J. Amer. Soc. Hort. Sci. 109:857-860.

Thurston, R.V., R.C. Russo, and K. Emerson. 1974. Aqueous ammonia equilibrium calculations. Fisheries Bioassay Lab. Tech. Rpt. No. 74-1, Mont. State Univ., Bozeman, Mont.

Tinus, R.W. and S.E. McDonald. 1979. How to grow tree seedlings in containers in greenhouses. USDA For. Serv. Gen. Tech. Rep. RM-60.

U.S. Environmental Protection Agency. 1976. Quality Criteria for Water. EPA Document No. 440/9-76-023. United States Environmental Protection Agency, Washington D.C.

U.S. Environmental Protection Agency. 1994. Water quality standards handbook. 2nd ed. United States Environmental Protection Agency, Washington, D.C.

Walden, R.F. and R.D. Wright. 1995. Interactions of high temperature and exposure time influence nitrification in a pine bark medium. HortScience 30:1026-1028.

Wright, R.D. 1984. The pour-through method: a quick and easy way to determine a medium's nutrient availability. Amer. Nurseryman 160(3):109-111.

Yeager, T.H. and R.D. Wright. 1982. Phosphorus requirement of *Ilex crenata* Thumb. cv. Helleri grown in pine bark medium. J. Amer. Soc. Hort. Sci. 107:558-562.