

**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 Location

UC Davis and UC Riverside

Project Duration

2.6 years

Project Number

00-0509

Project Leaders

Donald J. Merhaut
Extension Specialist
Dept. of Botany and Plant Sciences
University of California
Riverside, CA 92521

Richard Y. Evans
Extension Specialist
Dept. of Environmental Sciences
University of California
Davis, CA 95616

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 (NO₃) 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 (NO₃⁻) and ammonium (NH₄⁺) leaching from containers on a weekly basis and extractable NH₄⁺, NO₃⁻ 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*, *Hydrangea 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 MgSO₄, 1 mM K₂SO₄, 1 mM KH₂PO₄, 2 mM NH₄NO₃, CaSO₄ 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 NO₃-N and NH₄-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 NO₃-N uptake (Fig. 2). With the exception of *Hydrangea*, all of the species under study took up more NH₄-N than NO₃-N (Fig. 3). Lowering the solution pH did not significantly affect plant preference for NH₄-N or NO₃-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.

	<u>mg N</u>	<u>mL water</u>	<u>mg N/L</u>
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

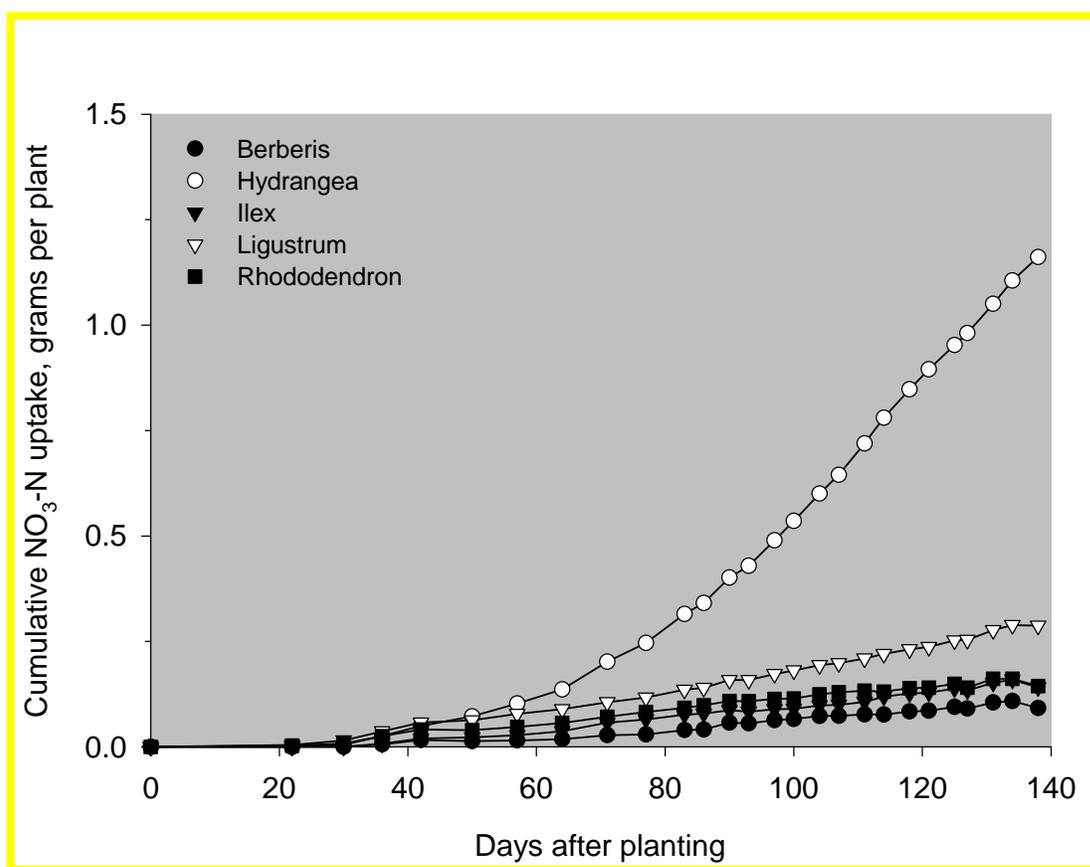


Figure 1. Cumulative nitrogen (N) uptake for *Berberis*, *Hydrangea*, *Ilex*, *Ligustrum*, and *Rhododendron*.

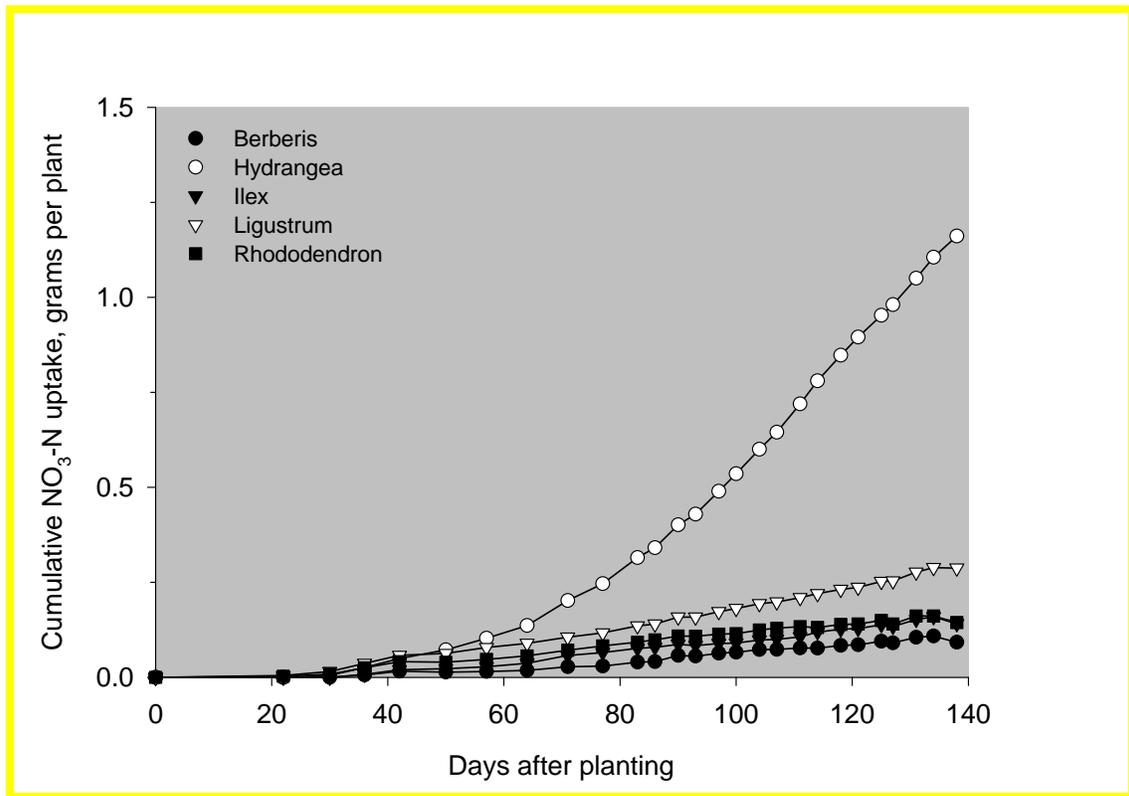


Figure 2. Cumulative $\text{NO}_3\text{-N}$ uptake of *Berberis*, *Hydrangea*, *Ilex*, *Ligustrum*, and *Rhododendron*.

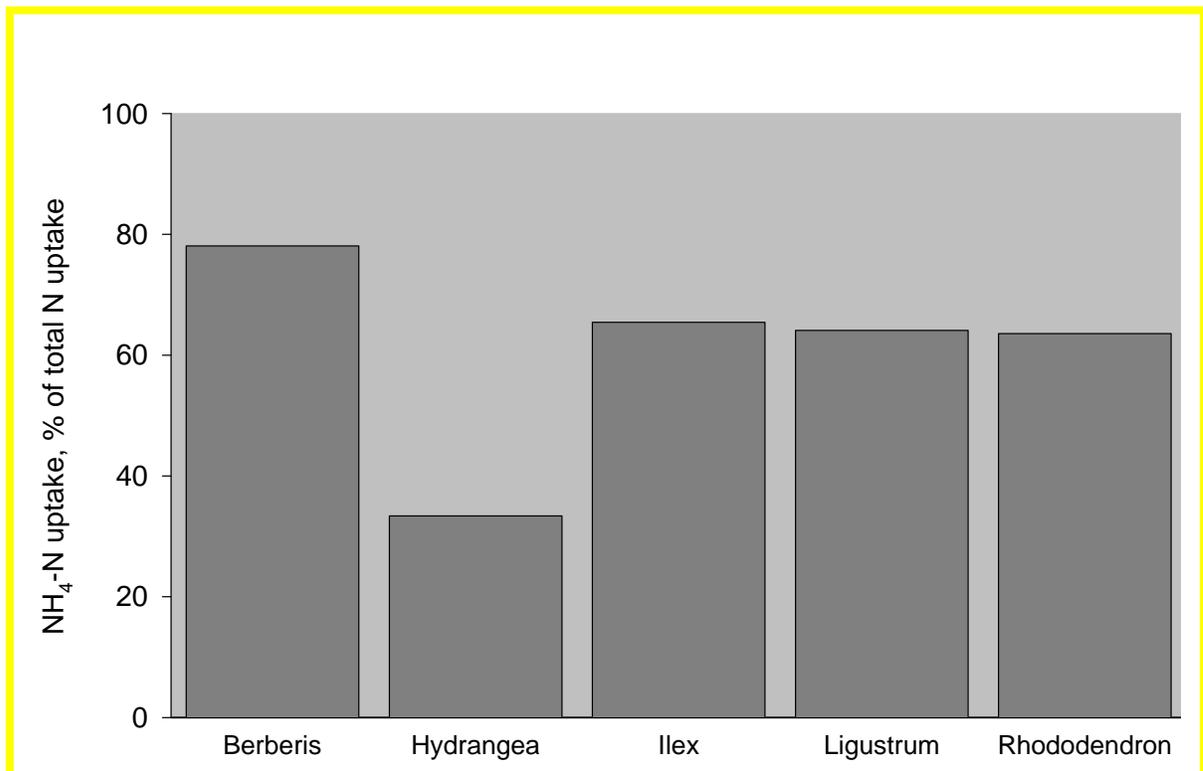


Figure 3. Ammonium ($\text{NH}_4^+\text{-N}$) uptake as a percentage of total N uptake in *Berberis*, *Hydrangea*, *Ilex*, *Ligustrum* and *Rhododendron*.

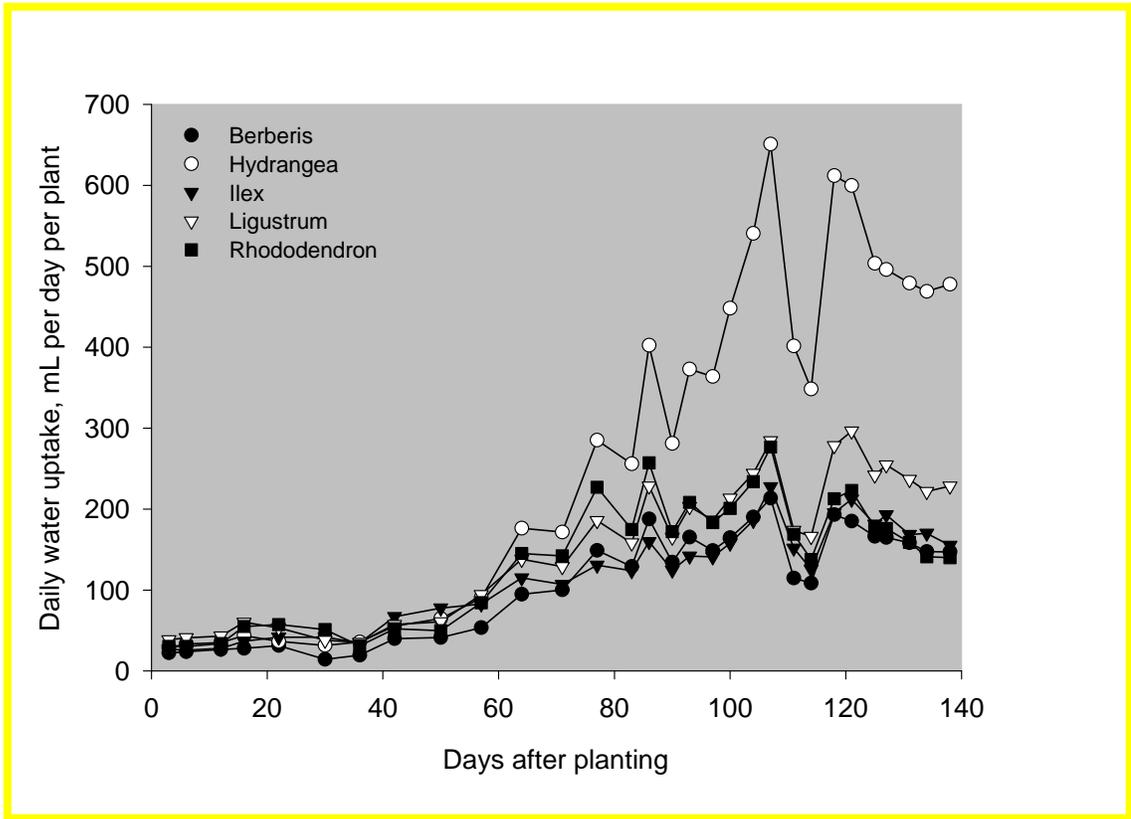


Figure 4. Daily water uptake rates in *Berberis*, *Hydrangea*, *Ilex*, *Ligustrum* and *Rhododendron*

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 ($\text{NH}_4^+\text{NO}_3^-$). 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.

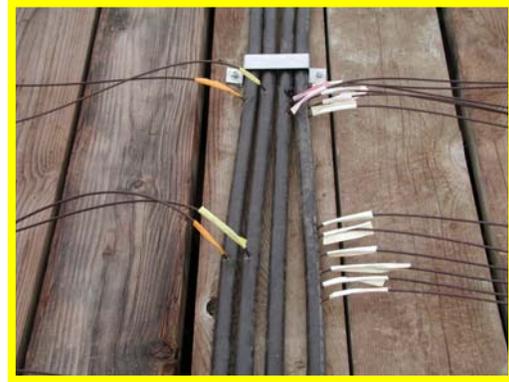


Figure 8. Four irrigation lines used to irrigate crops. Drippers extended out from each line to the pot to be irrigated. White-taped lines were water for the controlled-release fertilizer treatments and the orange, pink and yellow-taped lines represented the three liquid fertilizer treatments.



Figure 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 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.

1 List of fertilizer treatments for Task 2.

<u>Treatment</u>	<u>Fertilizer</u>
1	100 ppm N as 75% NH ₄ ⁺ and 25% NO ₃ ⁻ Liquid fertilizer
2	100 ppm N as NH ₄ NO 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

16 **Subtask 2.4:** Baseline measurements of media (without N fertilizer) and plants were
17 taken. Five replications each of the acid and neutral pH media were measured for total
18 KCL-extractable NH₄⁺ and NO₃⁻, total N, electrical conductivity (EC) pH and total nutrient
19 content. Concentrations of NH₄⁺ and NO₃⁻ were determined with a Technicon
20 Continuous Flow Analyzer. Five each of the Azalea Southern Indica 'Phoenicia' and the
21 *Ligustrum texanum* were harvested, separated into roots and shoots, dried and ground.
22 Dry weights and N concentration of roots and shoots were measured. This data has
23 been collected. This subtask for the controlled release fertilizers was completed by the
24 end of 7/2001. The Liquid Fertilizer portion was completed by the end of 4/2002.

26 **Subtask 2.5 and 2.6:** Weekly tasks of leachate collection and analyses (EC, NO₃⁻N
27 content and NH₄⁺-N content) were performed as planned.

30 **TASK 2 – CURRENT RESULTS AND DISCUSSION**

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

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

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

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

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

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

51
52 5. Nutrient leaching and uptake characteristics from three nitrogen **liquid fertilization**
53 formulations for **Greenhouse-Grown Azaleas** during an eleven month period.

54
55 6. Nutrient leaching and uptake characteristics from three nitrogen **liquid fertilization**
56 formulations for **Outdoor-Grown Ligustrum** during an eleven month period.

57

58

59

60

61

62

63

64

65

66

67

68

69

70

71

72

73

74

75

76

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

81

82 **Introduction**

83

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

97

98 Of the chemicals listed in these guidelines, N has the greatest risk for contaminating
99 runoff, since N usage by the container nursery industry is relatively high (536 lb·A⁻¹ each
100 year) compared to other chemicals used on horticultural crops (Rathier and Frink, 1989)

101 and various cultural practices of the industry are highly conducive to nitrate (NO_3^-)
102 leaching. In order for the nursery industry to act in accordance with these regulations, it
103 is imperative that more efficient fertilization and irrigation guidelines be developed and
104 more effective fertilizers be designed so that nutrient use efficiency (NUE) is optimized
105 and nutrient leaching is minimized.

106

107 Controlled-release fertilizers (CRFs) are used extensively for the production of
108 containerized woody ornamental plants, with the nursery and greenhouse industry
109 accounting for almost 20% of all CRFs used in the United States (Goertz, 1993). Most of
110 the research related to nutrient release characteristics from CRFs have been undertaken
111 using atypical substrates such as 100% sand, under controlled laboratory conditions
112 (Broschat, 1996; 2005; Handreck, 1997; Havis and Baker, 1985a; Holcomb, 1981; Huett
113 and Gogel, 2000; Husby et al., 2003; Lamont et al., 1987; Lunt and Oertli, 1962; Oertli
114 and Lunt, 1962; Patel and Sharma, 1977), or by means of field studies (Gandeza et al.,
115 1991), none of which reflect conditions experienced in container production facilities. In
116 addition, the duration of many experiments has been limited to six months or less, which
117 is insufficient for measuring nutrient release from 12-month-release fertilizer
118 formulations, as alluded to by Havis and Baker (1985a). In the following study, nutrient
119 release patterns of four types of CRFs, when blended into an acid substrate, were
120 measured during an 11-month period in an unheated greenhouse environment to
121 determine characteristics of nutrient release under a typical production scenario.

122

123 **Materials and Methods**

124

125 *Fertilizer treatments.* Treatments consisted of four different CRFs: Osmocote 24-4-9
126 (Scott-Sierra Horticultural Products Co., Marysville, Ohio), Nutricote 18-6-8 Total
127 (Chisso-Asahi Fertilizer Co., Tokyo), Multicote 17-5-11 + minors (Haifa Chemicals,
128 Ltd., Haifa Bay, Israel), and Polyon 17-5-11 + micros (Pursell Technologies, Inc.,
129 Sylacauga, Ala.). All four fertilizers release nutrients based on water diffusion into prills,
130 the rate of which is regulated by temperature. Osmocote did not contain micronutrients;
131 therefore, micronutrients were provided by incorporation of Micromax (Scott-Sierra
132 Horticultural Products Co., Marysville, Ohio), an uncoated, granular fertilizer at a rate of
133 $0.53 \text{ kg}\cdot\text{m}^3$. All CRFs were 365-day release formulations. However, release rates of
134 these CRFs are based on different temperature regimes: 27°C for Osmocote and Polyon,
135 21°C for Multicote, and $21\text{-}27^\circ\text{C}$ for Nutricote. Element concentrations and compounds
136 used in each fertilizer were different (Table 1). Since the percentage of nutrients
137 contained in the different fertilizers varied, the amount of fertilizer added was calculated
138 so that all treatments contained 3.11 g N per container, which is equivalent to 1.17 kg
139 $\text{N}\cdot\text{m}^{-3}$, a rate most fertilizer companies recommended for slow-growing woody
140 ornamentals. While N content for all CRF treatments was the same, the content of other
141 nutrients varied. CRF prills were incorporated throughout the substrate using a portable
142 cement mixer. Substrate with CRF was placed in #1 black polyethylene containers (2.4
143 L; 157 mm top diameter, 127 mm bottom diameter, 178 mm tall; Farrand Enterprises,
144 Chino, Calif.) with side and bottom drainage holes. Each container represented one

145 replication. There were five replications of each treatment for each of 11 months of
146 leachate monitoring. Containers were placed in a randomized complete block design.
147
148 *Leachate collection.* Leachate was collected from each container by placing a plastic
149 sleeve (140 mm bottom diameter and 165 mm top diameter) over each container, each
150 container and sleeve were placed into a plastic 2.45 L (152 mm top diameter, 127 mm
151 bottom diameter, and 152 mm high) bucket. The larger dimensions of the container
152 compared to the collection bucket allowed the containers to be elevated above the level of
153 the leachate. Leachate was collected from buckets twice per week, and volumes from
154 each bucket were combined so that there was one leachate sample per container per
155 week. Leachate electrical conductivity (EC) and pH were measured once per week after
156 the first irrigation of the week. EC was measured with a Horiba conductivity meter
157 model B-173 (Horiba Ltd., Minami-ku Kyoto, Japan) and pH was measured with a
158 Horiba compact pH meter model B-213 (Horiba Ltd., Minami-ku Kyoto, Japan).
159 Immediately following EC and pH measurements, 2 ml of 2 N sulfuric acid were added to
160 each bucket to chemically stabilize the leachate. An additional 2 ml of 2 N sulfuric acid
161 was then added to the emptied bucket, so that subsequent leachate collected from the
162 container during the final part of the week was immediately stabilized. Leachate from
163 the first collection of the week was stored at 4°C until the end of the week, at which time
164 leachate from the remainder of the week was added to the weekly sample. At the end of
165 each week, collection buckets were washed with 10% bleach to prevent algal growth.
166
167

168 **Results and Discussion**

169

170 *Air temperature.* Weekly average greenhouse air temperature ranged between 24 and
171 30°C during the first ten weeks (Aug. through Sept. 2001) and last ten weeks (May 2002
172 through June 2002) of the study (Figure 1). Maximum air temperatures during this time
173 period ranged from 28 to 46°C, which are temperatures observed in other warm-
174 temperate and subtropical growing regions (Ingram, 1981; Lamont et al., 1987). These
175 temperatures were consistently above 21°C, the labeled substrate temperature rating for
176 1-year longevity for Multicote. However, only weekly maximum temperatures were
177 typically above the average labeled temperature ratings of 24°C for Nutricote and 27°C
178 for Osmocote and Polyon. Since nutrient release from many CRFs, including those in the
179 present study, is temperature dependent, any elevated temperatures that may occur can
180 greatly impact nutrient release characteristics of CRFs. In studies related to
181 environmental conditions and CRFs, nutrient release rates increased by up to 200% for
182 every 10°C increase above optimum release temperature (Husby et al., 2003; Kochba et
183 al., 1990; Lamont et al., 1987; Oertli and Lunt, 1962); however, other experiments (Huett
184 and Gogel, 2000) showed only a 15% increase in release rates at higher temperatures. At
185 suboptimum temperatures, nutrient release characteristics have been shown to be
186 inconsistent (Engelsjord et al., 1997); however, others (Kochba et al., 1990) have shown
187 that the nutrient release rates are lower, but uniform.

188

189 *Electrical conductivity.* Leachate electrical conductivity (EC) was elevated during the
190 first five months of the study, relative to the later time frame, regardless of fertilizer type,

191 with significant differences observed among treatments (Figure 2). Similar trends in EC
192 fluctuations have also been observed in other studies (Lamont et al., 1987). During the
193 entire study, the leachate EC of the Osmocote treatment was often significantly lower
194 than the EC from the other treatments, especially Multicote. Both Polyon and Nutricote
195 treatments also had leachate EC levels that were significantly lower than levels recorded
196 for Multicote. Near the end of the study, (weeks 45 and 46), the leachate EC for
197 Osmocote was significantly greater than the EC for Multicote. In diurnal studies (20
198 hours) that compared Osmocote, Nutricote, and Polyon, Osmocote resulted in leachates
199 with lower soluble salts than Nutricote or Polyon at temperatures between 20 and 25°C;
200 however, Osmocote had higher release rates at temperatures above 35°C (Husby et al.,
201 2003). In longer-term studies (Lamont et al., 1987), Osmocote exhibited higher release
202 rates than Nutricote at all temperature regimes studied (5, 10, 15, 20, 25, 30, 35, 40, and
203 45°C). Based on the present study and research by Husby et al. (2003) and Lamont et al.
204 (1987), there are daily as well as weekly trends in nutrient release from CRFs which, in
205 the case of diurnal fluctuations, closely reflect changes in temperature. However, over
206 extended periods of time, the pool of nutrients remaining in the prills diminishes, which
207 results in decreased quantities of nutrient release and thus decreased EC levels, even with
208 increased temperatures during later parts of a production period.

209

210 From an environmental perspective, federal guidelines dictate that soluble salts should
211 not exceed $250 \text{ mg}\cdot\text{L}^{-1}$, based on chloride and sulfate concentrations only. Therefore,
212 monitoring and control of EC, from a nursery production point-of-view, would be
213 irrelevant, since EC takes into account all dissolved salts.

214

215 *pH*. During the first 20 weeks, leachate pH was variable, but consistently acidic (Figure
216 3), even though irrigation water pH was 7.5, indicating that substrate and/or fertilizers
217 used in the study influenced leachate pH more so than did the neutral irrigation water.
218 Other studies (Chen et al., 2003) have demonstrated that a similar substrate containing
219 pine bark, sand, and peat buffered irrigation water of pH 9.7 (with low alkalinity) to a
220 measured substrate pH of approximately 6.5. In addition, a study by Ivy et al. (2002)
221 showed that fertilizer type (Osmocote and Polyon) used does not influence pH.

222

223 Among fertilizer types, few significant differences were detected. Leachate pH from
224 substrate containing Osmocote was higher compared to the leachate pH of Multicote and
225 Nutricote treatments (two and four times, respectively) during the 47-week period. The
226 pH readings in weeks 42 and 43 for Multicote and week 42 for Nutricote were
227 significantly higher than the leachate pH for Osmocote. However, another study (Ivy et
228 al., 2002) showed that fertilizer type (Osmocote and Polyon) did not influence pH but, in
229 a different study (Argo and Biernbaum, 1997), it was determined that leachate pH is
230 influenced by compounds used in fertilizers, especially in respect to the ratios of NH_4^+ to
231 NO_3^- , with pH decreasing when the amount of NH_4^+ relative to NO_3^- increases. In the
232 present study, the amount of N as NH_4^+ ranged between 43% and 53%, except for the
233 Osmocote formulation that contained 76% of the N in the ammoniacal form (NH_4^+ and
234 urea). These differences in N form may not have been different enough to cause
235 significant changes in leachate pH among different fertilizer treatments. None of the
236 changes in pH measured in the present study fell outside the critical ranges established by

237 the U.S. EPA (pH of 5.0-9.0 for domestic water supplies, 6.5 - 8.5 for freshwater aquatic
238 life, and 6.5 – 9.0 for marine aquatic life) (U.S. EPA, 1976).

239

240 *Ammoniacal-nitrogen concentration.* During the first four weeks of the study, $\text{NH}_4^+\text{-N}$
241 concentrations in leachates in all treatments were below $10 \text{ mg}\cdot\text{L}^{-1}$ (Figure 4). From
242 week 5 to week 9, concentrations increased to above $150 \text{ mg}\cdot\text{L}^{-1}$, followed by a decline
243 from week 10 to week 30. During the last 17 weeks, leachate $\text{NH}_4^+\text{-N}$ concentrations
244 were less than $1 \text{ mg}\cdot\text{L}^{-1}$, except for the Osmocote treatment, which averaged $\sim 3.0 \text{ mg}$
245 during the last three weeks of the study, which was significantly greater than with the
246 other fertilizer treatments. When making comparisons among treatments, leachate $\text{NH}_4^+\text{-N}$
247 N from the Multicote treatment was significantly greater than with the other treatments
248 several times during the first 17 weeks of the study. Similar release patterns were
249 observed in other experiments (Broschat, 2005) using 8- to 9-month-release formulations
250 of Osmocote and Nutricote. Broschat (2005) found that 30% to 50% of the $\text{NH}_4^+\text{-N}$ was
251 released from prills of these fertilizers by the end of the second month, and by the
252 seventh month, less than 20% of the $\text{NH}_4^+\text{-N}$ remained in the prills. While patterns of
253 $\text{NH}_4^+\text{-N}$ leaching were similar to release rates measured by Broschat (2005), the
254 percentage of $\text{NH}_4^+\text{-N}$ from the CRF recovered in the leachates in the present study were
255 lower, which is probably associated with the binding of $\text{NH}_4^+\text{-N}$ to organic matter of the
256 container substrate, as described by others (Foster et al., 1983; Thomas and Perry, 1980).
257 The decrease in $\text{NH}_4^+\text{-N}$ concentrations of leachates during the later stages of the present
258 study may be partly accounted for by lower quantities of $\text{NH}_4^+\text{-N}$ that remained in the
259 prills, as was determined by Broschat (2005). In addition, there was probably

260 nitrification of NH_4^+ to NO_3^- in the present study. In studies associated with nitrification
261 of NH_4^+ , it was determined that the majority of the NH_4^+ is converted to NO_3^- , with a
262 slower rate of nitrification when soil pH was lower (Dancer et al., 1973; Niemiera and
263 Wright, 1986) or when substrate temperatures exceed 46°C (Walden and Wright, 1995).
264 In a diurnal study (Husby et al., 2003), NH_4^+ -N release was closely associated with
265 temperature, with greater release of NH_4^+ from Osmocote compared to Nutricote or
266 Polyon at high temperatures ($>35^\circ\text{C}$), but lower release rates at low temperatures
267 ($<35^\circ\text{C}$). In the present study, air temperatures were seldom above 35°C , which may
268 explain the fairly level NH_4^+ -N release rates.

269

270 Federal guidelines do not mention NH_4^+ -N concentration, but do state that concentrations
271 of un-ionized ammonia (NH_3), expressed as NH_3 , should not exceed $0.02 \text{ mg}\cdot\text{L}^{-1}$ for
272 freshwater aquatic life (U.S. EPA, 1976). Based on other research (Thurston et al.,
273 1974), this would mean that total ammonia ($\text{NH}_4^+ + \text{NH}_3$) concentration, which was
274 measured in the present study, would have to be in the range of 16 to $160 \text{ mg}\cdot\text{L}^{-1}$ for a
275 solution pH range of 7.0 to 6.0, but is also dependent on solution temperature. Given
276 these criteria, it is likely that NH_3 concentrations could have exceeded federal limits
277 several times throughout the course of the experiment.

278

279 *Nitrate-nitrogen concentration.* In all fertilizer treatments, NO_3^- -N concentrations were
280 below $10 \text{ mg}\cdot\text{L}^{-1}$ during the first four weeks of the study, with the exception of week 2,
281 when leachate from the Osmocote treatment averaged $32 \text{ mg}\cdot\text{L}^{-1}$ (Figure 5). From week
282 4 to week 9, NO_3^- -N concentrations increased to over $100 \text{ mg}\cdot\text{L}^{-1}$ for all treatments except

283 Osmocote. From week 10 to the end of the study, NO_3^- -N concentration decreased and
284 leveled off to approximately $30 \text{ mg}\cdot\text{L}^{-1}$ for leachates from treatments containing
285 Nutricote, Polyon, or Multicote. However, for Osmocote, leachate NO_3^- -N
286 concentrations gradually increased to approximately $50 \text{ mg}\cdot\text{L}^{-1}$ and then decreased to
287 about $30 \text{ mg}\cdot\text{L}^{-1}$ during the remaining 20-week period. Of the fertilizers tested,
288 Osmocote appeared to produce the most stable release rate of NO_3^- -N. During one-third
289 of the weeks of the study, NO_3^- -N concentrations were lower for Osmocote compared
290 with the leachate collected from the other fertilizer types. Similarly, the NO_3^- -N
291 concentration in leachates collected from the Polyon treatment was significantly lower
292 than for Multicote six weeks out of ten during weeks 25 through 35. The release pattern
293 of NO_3^- in leachates from Osmocote and Nutricote treatments are similar to the release
294 characteristics determined by others (Broschat, 2005; Prasad and Woods, 1971), except
295 that, on a weekly basis, the data from the present study indicated that Osmocote may
296 have a lower, but more stable, NO_3^- release pattern from the prills compared to Nutricote.
297 In general, the elevated concentrations of NO_3^- relative to NH_4^+ , especially during the
298 later half of the study, are probably associated with the nitrification of NH_4^+ in addition to
299 the release of NO_3^- from the fertilizer prills. Other studies have demonstrated significant
300 nitrification of NH_4^+ in soils and substrates of acidic to neutral pH (Dancer et al., 1973;
301 Niemiera and Wright, 1986).

302

303 Based on federal guidelines of a maximum of $10 \text{ mg}\cdot\text{L}^{-1}$ of NO_3^- -N for domestic water
304 use (U.S.EPA, 1976), NO_3^- -N concentrations exceeded permissible levels during most of
305 the experiment. However, if plants had been included in the present study, the likelihood

306 of NO_3^- leaching in excess of $10 \text{ mg}\cdot\text{L}^{-1}$ would probably only exist during the first 12
307 weeks of the study when total concentrations of NO_3^- -N were above $100 \text{ mg}\cdot\text{L}^{-1}$. The
308 only fertilizer product in exception to this was Osmocote, which had relatively low NO_3^- -
309 N concentrations during the entire period of the study.

310

311 **Total inorganic-N concentrations.** Release characteristics as indicated by total
312 inorganic-N concentrations (ammonium + nitrate) showed significant release of N during
313 the first nine weeks of the study, then a decrease and leveling off period during the
314 remaining 36 weeks for Polyon, Nutricote, and Multicote. The exception to this pattern
315 was Osmocote, which had more consistent leachate inorganic N concentrations between
316 30 and $50 \text{ mg}\cdot\text{L}^{-1}$ throughout the entire experimental period. The pattern of high then low
317 N release rates during the beginning and end of the experiment, respectively, are similar
318 to other studies (Huett, 1997b; Huett and Gogel, 2000; Prasad and Woods, 1971; Patel
319 and Sharma, 1977). The initial lag in N appearance in leachate in the present study may
320 be also accounted for by the chemical and biological immobilization of N in the organic
321 substrate, which has been documented by others (Foster et al., 1983; Gartner et al., 1971;
322 Handreck and Bunker, 1996; Thomas and Perry, 1980). In addition, concentrations of
323 NH_4^+ relative to NO_3^- were similar during the first half of the study, but NO_3^- was the
324 predominant inorganic N form during the later half of the study, regardless of fertilizer
325 type. This phenomenon is probably associated with the nitrification of NH_4^+ , as
326 demonstrated in other studies (Dancer et al., 1973) and possibly the faster release rate of
327 NH_4^+ -N from the prills, relative to NO_3^- , as measured by Broschat (2005). In shorter-term
328 studies (6 months), NO_3^- was the predominant N form during the entire experimental

329 period (Cabrera, 1997). Regardless of fertilizer type, the present study did not detect any
330 significant correlation of inorganic N release rate with air temperatures. These results
331 differ from studies conducted by Cabrera (1997) and Handreck (1997), where N release
332 characteristics of Osmocote, Nutricote, and Polyon were closely associated with
333 temperature. However, the experiments conducted by Cabrera lasted 9 months, during
334 which time temperatures slowly increased then decreased, and the studies conducted by
335 Handreck were in a temperature-controlled (21°C) laboratory. In the present study,
336 temperatures fluctuated, with relatively high temperatures during the first 2 months, then
337 decreasing during the winter, and then increasing again during the following spring.

338

339 *Total phosphorus concentrations.* Since fertilizer additions were normalized for N
340 content, total P content added differed among fertilizer treatments, with an average P
341 content of 0.40 g/container for Polyon, Nutricote, and Multicote, but 50% less for
342 Osmocote (0.22 g/container). P concentrations in leachates of all treatments fluctuated
343 throughout the study, but were higher (15 to > 60 mg·L⁻¹) during the first 10 weeks
344 compared to the last 27 weeks of the study, when concentrations averaged below 10
345 mg·L⁻¹ (Figure 7). The pattern of high then low P release rates in the present study is
346 similar to other studies with Osmocote, Nutricote, and Polyon (Huett, 1997b; Huett and
347 Gogel, 2000). When comparing treatments, Multicote tended to produce the highest P
348 concentrations in leachates compared to the other fertilizers types, primarily during the
349 first 37 weeks. For the most part, total P concentrations of other treatments were
350 somewhat similar to each other throughout the study. In another experiment (Broschat,
351 2005), release of P from Osmocote prills during the first five months was significantly

352 greater than that measured from Nutricote; however, by the seventh month, differences in
353 release were not significant. In shorter-term studies (10 weeks), there were no
354 differences in P release rates between Osmocote and Nutricote (Huett, 1997b).
355 According to field and container experiments (Flint, 1962; Handreck, 1996; Havis and
356 Baker, 1985a; 1985b; Wright, 1984; Yeager and Wright, 1982), solution P concentrations
357 of approximately $10 \text{ mg}\cdot\text{L}^{-1}$ are required for optimal growth of woody ornamentals. A
358 fraction of this P is tied in organic substrates, as demonstrated by Handreck (1996).
359 Based on the present study and the experiments of others, it appears that a high release of
360 P from CRFs may elevate the risk of P leaching during the early parts of the production
361 cycle, but a lower release of P may limit plant growth during the later part of a production
362 cycle.

363

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

369

370 *Total potassium concentrations.* Total K concentrations of leachates from all treatments
371 ranged between 10 and $170 \text{ mg}\cdot\text{L}^{-1}$, with higher concentrations during the first 20 weeks
372 of the study compare to the last 27 weeks (Figure 8). When comparing CRF types, K
373 concentrations in leachates from Osmocote and Nutricote treatments were similar, but
374 both were significantly lower than K concentrations of leachates collected from

375 containers containing Polyon or Multicote. These differences may be attributed to the
376 amount of K added, since fertilizer additions were normalized for N. Osmocote and
377 Nutricote contained approximately 36% less K than the Polyon and Multicote treatments.
378 While not measured, a portion of the K released from the prills was probably tied up by
379 the organic fraction, which has been shown to occur with organic substrate (Brown and
380 Pokorny, 1977; Foster et al., 1983). Elevated K release from CRFs during the early part
381 of the production cycle observed in the present study is similar to other studies (Broschat,
382 1996, 2005; Huett, 1997b) that compared K release from Osmocote, Nutricote, and
383 Multicote; however, Broschat (1996, 2005) did not detect differences among fertilizer
384 types. In other research (Holcomb, 1981) with Osmocote, K release rates were linear
385 throughout the 63-day study period. Even though K concentrations were elevated in
386 leachates during the first portion of the experiment, there is no concern of K
387 concentrations exceeding federal recommended guidelines, since no guidelines have been
388 established for K as of yet.

389

390 **Conclusions**

391

392 Under greenhouse conditions, where high temperatures were moderated with evaporative
393 cooling pads and fans, the release characteristics of NH_4^+ , NO_3^- , K, and P from all CRFs
394 tested were elevated during the first half of the study, followed by lower release rates
395 during the later half of the 11-month period, even when temperatures increased during the
396 spring. Differences were noted among fertilizer types. Patterns of leachate EC reflect
397 somewhat the leachate concentrations of N, P, and K. These correlations have also been

398 measured by others (Cabrera, 1997; Huett and Morris, 1999; Husby et al., 2003).
399 Leachate EC is probably associated with both nutrient release from CRF and soluble salts
400 leached out of the substrate during first few weeks of the study. Based on the results of
401 this study and data from other long term studies, it appears that nutrient release from
402 CRFs may be in excess of plant requirements during the first half of the production
403 period (Huett, 1997b; Huett and Gogel, 2000), but may be insufficient during later stages
404 of production (Huett, 1997a), depending on the nutrient demands of the crop being grown
405 and the temperature profiles during production.

406

407 From an environmental perspective, risk of water impairment, when using the CRFs
408 currently studied, would be greatest during the first 20 weeks of crop production, since
409 EC, $\text{NH}_4\text{-N}$, $\text{NO}_3\text{-N}$, total P, and total K were elevated during this time period. Based on
410 guidelines established by the U.S. EPA (1976), the chemical parameters of pH, EC,
411 $\text{NH}_4^+\text{-N}$, $\text{NO}_3^-\text{-N}$, and P, as observed in the present study, were not within acceptable
412 limits during various time frames throughout the 11-month period. However,
413 concentrations of nutrients in leachates would probably be reduced if plants were present
414 in the containers. For this reason, additional research regarding leaching characteristics
415 of CRFs is required, particularly for a typical plant production scenario using woody
416 ornamentals commonly grown in the nursery industry.

417

418

419

420

421

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

426

427 **Introduction**

428

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

440

441 Controlled-release fertilizers (CRFs) are commonly used in the nursery industry. When
442 used properly, these types of fertilizers can reduce the amount of nutrients in runoff
443 compared to water-soluble fertilizers. However, little information is available regarding
444 leaching of plant essential nutrients other than N and P. In the following study, the
445 nutrient release patterns of four types of CRFs, when blended into a substrate, were

446 measured during an 11-month period in an unheated greenhouse environment to
447 determine characteristics of nutrient release under a typical production scenario.

448

449 **Materials and Methods**

450

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

454

455 *Substrate.* Substrate consisted of 5 sphagnum peatmoss (Premier Horticulture Inc., Red
456 Hill, Penn.) : 4 pine bark (6.4-9.5 mm) : 1 washed builders sand (by volume). Substrate
457 was amended with dolomite 65 (Chemical Lime Co., Scottsdale, Ariz.) at a rate of 0.59
458 $\text{kg}\cdot\text{m}^{-3}$ and ultrafine calcium sulfate (Western Mining and Minerals, Apex, Nev.) at a rate
459 of 0.59 $\text{kg}\cdot\text{m}^{-3}$. Substrate and amendments were blended together using a Model
460 MB20L5 Batch Mixer (Measured Marketing, Kankakee, Ill.). Substrate was analyzed for
461 nutrient concentrations prior to incorporation of CRFs by grinding substrate to pass
462 through a 40-mesh screen. The ground sample was then extracted by adding 100 ml
463 deionized water to 50 ml volume of ground substrate and then filtered. Nutrient
464 concentrations in extracts were quantitatively determined using an inductively coupled
465 plasma (ICP) spectrometer (Thermo Electron Corp., model IRIS 1000 HR, Franklin,
466 Mass.) Substrate nutrient concentrations prior to incorporation of CRFs were as follows
467 ($\text{mg}\cdot\text{L}^{-1}$): 13.06 Ca, 10.19 Mg, 2.62 Fe, 0.59 Mn, 0.75 Zn, 0.11 Cu, 0.01 Mo.

468

469 *Fertilizer treatments.* Treatments consisted of four different types of CRFs: Osmocote
470 24-4-9 (Scott-Sierra Horticultural Products Co., Marysville, Ohio), Nutricote 18-6-8
471 Total (Chisso-Asahi Fertilizer Co., Tokyo), Multicote 17-5-11 + minors (Haifa
472 Chemicals, Ltd., Haifa Bay, Israel), and Polyon 17-5-11 + micros (Pursell Technologies,
473 Inc., Sylacauga, Ala.). All four fertilizers release nutrients based on water diffusion into
474 prills, the rate of which is regulated by temperature. Osmocote did not contain
475 micronutrients; therefore, micronutrients were provided by the incorporation of
476 Micromax (Scott-Sierra Horticultural Products Co., Marysville, Ohio). All CRFs were
477 365-day release formulations. However, release rates of the different products are based
478 on different temperature regimes: 27°C for Osmocote and Polyon, 21°C for Multicote,
479 and 21-27°C for Nutricote. Element concentrations and the compounds used in each
480 fertilizer were different (Table 1). Since the percentage of nutrients contained in the
481 different fertilizers varied, the amount of fertilizer added was calculated so that all
482 treatments contained 3.11 g N per container, which is equal to 1.17 kg N·m⁻³, a rate most
483 fertilizer companies recommend for slow-growing woody ornamentals. While N content
484 for all CRF treatments were the same, the content of other nutrients varied. The CRF
485 prills were incorporated throughout the substrate using a portable cement mixer.
486 Substrate with CRF were placed in #1 black polyethylene containers (2.4 L; 157 mm top
487 diameter, 127 mm bottom diameter, 178 mm tall; Farrand Enterprises, Chino, Calif.) with
488 side and bottom drainage holes. Each container represented one replication. There were
489 five replications of each treatment for each month of leachate monitoring. Containers
490 were placed in a randomized complete block design.
491

492 *Cultural Practices.* Substrate and fertilizer treatments were prepared on 1 Aug. 2001.
493 The experiment was conducted from 1 Aug. 2001 through 27 June 2002. Containers
494 were placed in an unheated, poly-covered greenhouse on the University of California,
495 Riverside campus (lat. 33°53'30"N, long. 117°15'00"W). Containers were irrigated with
496 potable water, which contained ($\text{mg}\cdot\text{L}^{-1}$): 64.30 Ca, 9.48 Mg, 0.01 Fe, 0.00 Mn, 0.00 Cu,
497 0.004 Zn, and 0.003 Mo. Irrigation water was distributed uniformly over the surface of
498 the substrate using DRT4-36 ring drippers (Dramm Corporation, Manitowoc, Wis.).
499 Containers were irrigated approximately every 2 d, providing an average irrigation
500 volume of ~ 1 L/week and an average leachate volume of ~ 750 ml/ week.

501

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

506

507 **Results**

508

509 *Calcium concentration.* During the first 13 weeks of the experiment, Ca concentrations
510 in leachates from all treatments fluctuated, with concentrations reaching as high as 300
511 $\text{mg}\cdot\text{L}^{-1}$ (Figure 1). During the last 30 weeks of the study, Ca concentrations in leachates
512 ranged between 25 and 50 $\text{mg}\cdot\text{L}^{-1}$, with few differences among treatments. During
513 certain weeks, some treatments were significantly different from others; however, there
514 did not appear to be any discernable pattern or trend in these differences. The lack of

515 differences among treatments is expected since most of the Ca in all treatments was
516 derived from calcium sulfate and dolomite that were blended into the substrate in
517 addition to Ca present in the potable water. Ca concentrations observed in the present
518 study are similar to leachate readings observed in simulated production systems (Chen et
519 al., 2003), where Ca concentrations ranged from 12 to 42 mg·L⁻¹. In shorter-term (1-2.5
520 months) studies (Huett, 1997b; Huett and Morris, 1999), the greatest loss of Ca occurred
521 during the first week when testing Osmocote and Nutricote.

522

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

532

533 From an environmental perspective, there are no federal guidelines established for Ca.
534 Significant Ca runoff may indirectly contribute to elevated electrical conductivity and
535 pH. However, EPA criterion for salinity is 250 mg·L⁻¹ and is based only on chloride and
536 sulfates (U.S. EPA, 1976), not Ca or any other element. Present EPA criteria for pH are
537 5.0 to 9.0 (domestic water supply), 6.5 to 9.0 (freshwater aquatic life), and 6.5 to 8.5

538 (marine aquatic life) (U.S. EPA, 1976). The other water quality criterion associated with
539 Ca is alkalinity, which is not to exceed 20 mg·L⁻¹ of calcium carbonate (CaCO₃) for
540 freshwater aquatic life, “except where natural concentrations are less”. (U.S. EPA, 1976).

541

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

554

555 Based on plant requirements for Mg that have been established in other studies (Mankin
556 and Fynn, 1996; Starr and Wright, 1984; Wright, 1984), it appears that Mg availability
557 would be sufficient for plant growth in the production scenario studied. In
558 hydroponically grown herbaceous plants, the maximum Mg uptake rate was achieved at a
559 concentration of 30 mg·L⁻¹ (Mankin and Fynn, 1996). In other studies (Starr and Wright,
560 1984; Wright, 1984), optimum plant growth in containerized plants was achieved when

561 leachate Mg concentrations were maintained between 10 and 15 mg·L⁻¹. If the research
562 by Mankin and Fynn (1996) and Wright (1984) can be applied to general containerized
563 production practices, Mg availability from CRFs should not be limiting during a typical
564 11-month plant production cycle.

565

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

570

571 *Iron concentrations.* Iron concentrations in leachates from all treatments were relatively
572 high and fluctuated during the first 12 weeks of the study (Figure 3). Fe concentrations
573 in leachates were relatively stable during the last 30 weeks of the study, with significantly
574 higher concentrations recovered in the leachates from the Nutricote treatment compared
575 to the other three CRF treatments. This may be due to Fe leaching out of broken prills or,
576 in the case of Micromax, Fe directly solubilizing from the fertilizer since Micromax is a
577 non-coated form of micronutrient fertilizer. In other studies with uncoated granular
578 fertilizers, a notable leaching of Fe occurred (Frost et al., 2003; Handreck, 1989) and, in
579 some cases, the leaching rate from granular fertilizers was greater than that observed
580 from soluble fertilizers (Frost et al., 2003). Overall, Fe concentrations measured in the
581 present study, with the exception of the first 11 weeks, were similar to those observed in
582 containerized production systems (Chen et al., 2003). The significant differences with
583 Nutricote may be associated with the iron formulation, which was iron EDTA, a soluble

584 iron form. Iron chelate was also the form of Fe used with Multicote; however, the
585 Multicote treatment resulted in significantly greater leaching than all other CRFs during
586 the first three weeks of the study, which may have resulted in less Fe available for release
587 during the later part of the study. Broschat and Donselman (1985) noted that the leaching
588 of Fe from organic-based substrate was greater with the use of chelated Fe compared to
589 other mineral forms of Fe. It has also been determined that Fe is immobilized by organic
590 substrate, up to $100 \text{ mg}\cdot\text{L}^{-1}$ for certain types of sawdust and bark products (Handreck,
591 1989).

592

593 Based on the present study and the results of other research (Broschat and Donselman,
594 1985; Chen et al., 2003; Frost et al., 2003, Handreck, 1989), it appears that sufficient Fe
595 was probably available for normal plant growth in the simulated production system
596 studied, with the environmental risk of high Fe concentrations ($>0.3 \text{ mg}\cdot\text{L}^{-1}$) in leachates
597 occurring during the first 20 weeks of the production cycle. The primary concern for Fe
598 leaching would be with formulations using chelated iron, which have been found to be
599 easily leached from organic substrates typically used in many containerized production
600 systems. Current federal guidelines indicate Fe concentrations are not to exceed 0.3
601 $\text{mg}\cdot\text{L}^{-1}$ for water for domestic use and $1.0 \text{ mg}\cdot\text{L}^{-1}$ for freshwater aquatic life.

602

603 *Manganese concentrations.* Manganese concentrations in leachates of all fertilizer
604 treatments were relatively high (between 1.0 and $9.0 \text{ mg}\cdot\text{L}^{-1}$), but variable during the first
605 twelve weeks of the study (Figure 4). During the last 30 weeks of the experiment, Mn
606 concentrations were below $2.0 \text{ mg}\cdot\text{L}^{-1}$ for all treatments. In other studies, Mn leached

607 from granular fertilizers, even more so than with the use of liquid fertilizers (Frost et al.,
608 2003). The only significant differences observed were that the Osmocote treatment
609 resulted in higher Mn concentrations in leachates compared to the other CRFs during the
610 first two weeks of the study, then again from weeks 36 through 39 for Polyon and
611 Multicote. Other differences were observed among fertilizer types throughout the
612 experimental period, but no patterns or trends in these differences evolved. The lack of
613 differences is not unexpected, since all fertilizer types contained manganese sulfate as
614 their form of Mn. In other studies (Broschat and Donselman, 1985), it was shown that
615 Mn might precipitate with other compounds at a substrate pH above 6.2; however, in the
616 present study, the initial substrate pH was 4.5. Therefore, solubilization and possible
617 leaching of Mn probably occurred during the beginning of the study. However, as
618 leachate pH increased, and probably substrate pH as well, the solubilization, and
619 therefore the leaching, of remaining Mn was minimized. Based on other research (Tinus
620 and McDonald, 1979), a Mn concentration of $0.5 \text{ mg}\cdot\text{L}^{-1}$ is sufficient for healthy plant
621 growth. Therefore, the Mn concentrations observed in the present study should be
622 adequate for plant requirements. Environmentally, Mn leaching, and therefore the
623 potential for excess Mn in runoff, was high throughout the entire study since federal
624 guidelines indicate that Mn concentrations are not to exceed $0.050 \text{ mg}\cdot\text{L}^{-1}$ for domestic
625 waters and $0.100 \text{ mg}\cdot\text{L}^{-1}$ "for protection of consumers of marine mollusks" (U.S. EPA,
626 1976), levels which are below concentrations measured in the present study.

627

628 *Zinc concentrations.* Leachate concentrations of Zn were relatively high and variable
629 during the first twelve weeks of the study (Figure 5). After week 13, Zn concentrations

630 were below $0.5 \text{ mg}\cdot\text{L}^{-1}$, regardless of fertilizer type. These readings were higher than
631 leachate measurements conducted in other studies (Chen et al, 2003) where Zn
632 concentrations ranged between 0.01 and $0.04 \text{ mg}\cdot\text{L}^{-1}$. Leaching of Zn with granular
633 micronutrients was also noted in other studies (Frost et al., 2003). Leachate Zn
634 concentrations from the Nutricote treatment were significantly higher than with other
635 fertilizer treatments during most of the study, despite the fact that the amount of Zn was
636 three to four times less in the Nutricote treatment compared to the other CRF treatments.
637 For plant growth, the Zn concentrations observed would probably be sufficient for most
638 crops, as noted in other studies (Carroll and Loneragan, 1969; Tinus and McDonald,
639 1979). From an environmental perspective, Zn concentrations were usually below the
640 critical limit of $5.000 \text{ mg}\cdot\text{L}^{-1}$ for domestic water supplies as established by the EPA.

641

642 *Copper concentrations.* Copper concentrations in leachates were usually below 1.00
643 $\text{mg}\cdot\text{L}^{-1}$, regardless of fertilizer type (Figure 6). During weeks 14 and 15, concentrations
644 of Cu increased for all treatments, then decreased and stabilized. There were some
645 differences among treatments, most notable being the higher Cu concentrations with
646 Nutricote relative to the other CRFs for eight weeks out of the 47-week period. In
647 another study (Broschat and Donselman, 1985), copper concentrations in leachates were
648 relatively stable throughout an 18-month period. The low Cu concentrations observed in
649 the present research and other studies may be attributed to the high affinity of Cu for
650 organic matter (Schnitzer and Skinner, 1966). The EPA has established a Cu limit of 1.0
651 $\text{mg}\cdot\text{L}^{-1}$ for domestic water supplies (U.S. EPA, 1976). Based on the current study, the Cu
652 levels resulting from fertilization should not be of concern.

653

654 *Molybdenum concentrations.* Molybdenum concentrations were variable during the first
655 15 weeks of the study, with significantly greater concentrations measured in the Nutricote
656 treatment compared to the other fertilizer types. After week 15, Mo concentrations were
657 near 0.0 mg·L⁻¹ for all treatments. There are currently no federal guidelines established
658 for Mo in surface waters.

659

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

672

673 **Literature Cited**

674

675 Argo, W.R. and J.A. Biernbaum. 1997. The effect of root media on root-zone pH,
676 calcium, and magnesium management in containers with impatiens. *J. Amer. Soc. Hort.*
677 *Sci.* 122:275-284.
678

679 Broschat, T.K. 1996. Release rates of soluble and controlled-release potassium fertilizers.
680 *HortTechnology* 6:128-131.
681

682 Broschat, T.K. 2005. Rates of ammonium-nitrogen, nitrate-nitrogen, phosphorus, and
683 potassium from two controlled-release fertilizers under different substrate environments.
684 *HortTechnology* 15:332-335.
685

686 Broschat, T.K. and H.M. Donselman. 1985. Extractable Mg, Fe, Mn, Zn, and Cu from a
687 peat-based container medium amended with various fertilizers. *J. Amer. Soc. Hort. Sci.*
688 110:196-200.
689

690 Brown, E.F. and F.A. Pokorny. 1977. Potassium distribution and retention in pine bark
691 and sand media. *HortScience* 12:343-344.
692

693 Cabrera R.I. 1997. Comparative evaluation of nitrogen release patterns from controlled-
694 release fertilizers by nitrogen leaching analysis. *HortScience* 32:669-673.
695

696 Carroll, M.D. and J.F. Loneragan. 1969. Response of plant species to concentrations of
697 zinc in solution II. Rates of zinc absorption and their relation to growth. *Austral. J. Agric.*
698 *Res.* 20: 457-463.
699

700 Chen, J., R.C. Beeson, Jr., T.H. Yeager, R.H. Stamps and L.A. Felter. 2003. Evaluation
701 of captured rainwater and irrigation runoff for greenhouse foliage and bedding plant
702 production. *HortScience* 38:228-233.
703

704 Dancer, W.S., L.A. Peterson and G. Chesters. 1973. Ammonification and nitrification of
705 N as influenced by soil pH and previous N treatments. *Soil. Sci. Soc. Amer. Proc.* 37:67-
706 69.
707

708 Diamond, D. 1995. Phosphorus in soil extracts. QuikChem method 10-115-01-1-A.
709 Lachat Instruments, Milwaukee, Wis.
710

711 Dunham, C.W., and D.V. Tatnall. 1961. Mineral composition of leaves of three holly
712 species grown in nutrient sand cultures. *Proc. Amer. Soc. Hort. Sci.* 78:564-571.
713

714 Edwards, D.G., and B.D. Horton. 1981. Influence of magnesium concentrations in
715 nutrient solution on growth, tissue concentration, and nutrient uptake of peach seedlings.
716 *J. Amer. Soc. Hort. Sci.* 106:401-405.
717

718 Engelsjord, M.E., O. Fostad, and B.R. Singh. 1997. Effects of temperature on nutrient
719 release from slow-release fertilisers. 1. Commercial and experimental products. Nutrient
720 Cycling in Agroecosystems 46:179-187.
721

722 Flint, H.L. 1962. Effects of different soil levels and methods of application of phosphorus
723 on growth of selected woody ornamental species in containers. Proc. Amer. Soc. Hort.
724 Sci. 81:552-555.
725

726 Foster, W.J., R.D. Wright, M.M. Alley, and T.H. Yeager. 1983. Ammonium adsorption
727 on a pine-bark growing medium. J. Amer. Soc. Hort. Sci. 108:548-551.
728

729 Franson, M.A. 1985. Method 303A, p. 157-160. In: M.A. Franson (ed.). Standard
730 methods for the examination of water and wastewater, 16th edition. Amer. Public Health
731 Assn. – Amer. Water Works Assn. - Water Pollution Control Federation, Washington,
732 D.C.
733

734 Frost, M.D., J.C. Cole and J.M. Dole. 2003. Fertilizer source affects iron, manganese, and
735 zinc leaching, nutrient distribution, and geranium growth. J. Plant Nutr. 26:315-329.
736

737 Gandeza, A.T., S. Shoji and I. Yamada. 1991. Simulation of crop response to polyolefin-
738 coated urea: I. Field dissolution. Soil Sci. Soc. Amer. J. 55:1462-1467.
739

740 Gartner, J.B., M.M. Meyer, Jr., and D.C. Saupe. 1971. Hardwood bark as a growing
741 media for container-grown ornamentals. *Forest Products J.* 21:25-29.
742
743 Goertz, H.M. 1993. Controlled release technology. p. 251-274. In: Kirk-Othmer (ed.).
744 *Encyclopedia of chemical technology*. Vol. 7, 4th ed. Wiley & Sons, New York, NY.
745
746 Handreck, K.A. 1989. Assessment of iron availability in soilless potting media. *Commun.*
747 *Soil Sci. Plant Anal.* 20:1297-1320.
748
749 Handreck, K.A. 1996. Phosphorus immobilization in wood waste-based potting media.
750 *Commun. Soil Sci. Plant Anal.* 27:2295-2314.
751
752 Handreck, K. 1997. Controlled release fertilizers. Measuring nutrient release rates.
753 *Austral. Hort.* 95(10):51-53.
754
755 Handreck, K. and K. Bunker. 1996. Fertilisers and hot weather. *Austral. Hort.* 94(8):83-
756 85.
757
758 Havis, J.R. and J.H. Baker. 1985a. Phosphorus availability in peat-sand media fertilized
759 with several phosphorus sources. *J. Environ. Hort.* 3:153-155.
760
761 Havis, J.R. and J.H. Baker. 1985b. Phosphorus requirement of *Rhododendron* 'Victor' and
762 *Cotoneaster adpressa praecox* grown in a perlite-peat medium. *J. Environ. Hort.* 3:63-64.

763

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

766

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

769

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

772

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

776

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

780

781 Husby, C.E., A.X. Niemiera, J.R. Harris, and R.D. Wright. 2003. Influence of diurnal
782 temperature on nutrient release patterns of three polymer-coated fertilizers. *HortScience*
783 38:387-389.

784

785 Ingram, D.L. 1981. Characterization of temperature fluctuations and woody plant growth
786 in white poly bags and conventional black containers. HortScience 16:762-763.
787

788 Ivy, R.L., T.E. Bilderback and S.L. Warren. 2002. Date of potting and fertilization affects
789 plant growth, mineral nutrient content, and substrate electrical conductivity. J. Environ.
790 Hort. 20:104-109.
791

792 Johnson, C.M. and A. Ulrich. 1959. Analytical methods for use in plant analysis. Univ.
793 Calif. Agr. Expt. Sta. Res. Bul. 766.
794

795 Kochba, M., S. Gambash, and Y. Avnimelech. 1990. Studies on slow release fertilizers.
796 1. Effect of temperature, soil moisture and water vapor pressure. Soil Sci. 149:339-343.
797

798 Lamont, G.P., R.J. Worrall and M.A. O'Connell. 1987. The effects of temperature and
799 time on the solubility of resin-coated controlled-release fertilizer under laboratory and
800 field conditions. Scientia Hort. 32:265-273.
801

802 Lunt, O.R. and J.J. Oertli. 1962. Controlled release of fertilizer minerals by encapsulating
803 membranes: II. Efficiency of recovery, influence of soil moisture, mode of application,
804 and other considerations related to use. Soil Sci. Soc. Amer. Proc. 26:584-587.
805

806 Mankin, K.R. and R.P. Fynn. 1996. Nutrient uptake response of New Guinea impatiens to
807 light, temperature, and nutrient solution concentration. *J. Amer. Soc. Hort. Sci.* 121:826-
808 830.
809

810 Niemiera, A.X. and R.D. Wright. 1986. The influence of nitrification on the medium
811 solution and growth of holly, azalea, and juniper in a pine bark medium. *J. Amer. Soc.*
812 *Hort. Sci.* 11:708-712.
813

814 Oertli, J.J. and O.R. Lunt. 1962. Controlled release of fertilizer minerals by encapsulating
815 membranes: I. Factors influencing the rate of release. *Soil Sci. Soc. Amer. Proc.* 26:579-
816 583.
817

818 Patel, A.J. and G.C. Sharma. 1977. Nitrogen release characteristics of controlled-release
819 fertilizers during a four month soil incubation. *J. Amer. Soc. Hort. Sci.* 102:364-367.
820

821 Prasad, M. and M.J. Woods. 1971. Release characteristics of nitrogen fertilizer in peat
822 and sand. *J. Agr. Food Chem.* 19:96-98.
823

824 Rathier, T.M. and C.R. Frink. 1989. Nitrate in runoff water from container grown juniper
825 and Alberta spruce under different irrigation and N fertilization regimes. *J. Environ. Hort.*
826 7:32-35.
827

828 Sweeney, R.A. 1989. Generic combustion method for determination of crude protein in
829 feeds: Collaborative study. J. Assn. Offic. Anal. Chem. 72:770-774.
830

831 Thomas, S. and F.B. Perry, Jr. 1980. Ammonium nitrogen accumulation and leaching
832 from an all pine bark medium. HortScience 15:824-825.
833

834 Schnitzer, M. and S.I.M. Skinner. 1966. Organo-metallic interactions in soils: 5. Stability
835 constants of Cu^{++} , Fe^{++} , and Zn^{++} -fulvic acid complexes. Soil Sci. 102:361-365.
836

837 Starr, K.D. and R.D. Wright. 1984. Calcium and magnesium requirements of *Ilex crenata*
838 'Helleri'. J. Amer. Soc. Hort. Sci. 109:857-860.
839

840 Thurston, R.V., R.C. Russo, and K. Emerson. 1974. Aqueous ammonia equilibrium
841 calculations. Fisheries Bioassay Lab. Tech. Rpt. No. 74-1, Mont. State Univ., Bozeman,
842 Mont.
843

844 Tinus, R.W. and S.E. McDonald. 1979. How to grow tree seedlings in containers in
845 greenhouses. USDA For. Serv. Gen. Tech. Rep. RM-60.
846

847 U.S. Environmental Protection Agency. 1976. Quality Criteria for Water. EPA Document
848 No. 440/9-76-023. United States Environmental Protection Agency, Washington D.C.
849

850 U.S. Environmental Protection Agency. 1994. Water quality standards handbook. 2nd ed.
851 United States Environmental Protection Agency, Washington, D.C.
852
853 Walden, R.F. and R.D. Wright. 1995. Interactions of high temperature and exposure time
854 influence nitrification in a pine bark medium. HortScience 30:1026-1028.
855
856 Wright, R.D. 1984. The pour-through method: a quick and easy way to determine a
857 medium's nutrient availability. Amer. Nurseryman 160(3):109-111.
858
859 Yeager, T.H. and R.D. Wright. 1982. Phosphorus requirement of *Ilex crenata* Thumb. cv.
860 Helli grown in pine bark medium. J. Amer. Soc. Hort. Sci. 107:558-562.