Influence of Temperature and Time on Nutrient Release Patterns of Osmocote Plus™, Nutricote™, and Polyon™ Controlled-Release Fertilizers

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(**ABSTRACT**)

Polymer-coated controlled-release fertilizers (PCFs) are the most widely used class of fertilizers in the production of container-grown nursery plants. Nutrient release from PCFs is primarily influenced by temperature. The objective of this study was to determine the influences of temperature and time on the nutrient release patterns of three PCFs (each with a rated longevity of 8-9 months), each using a different coating technology: Osmocote Plus™ 15N-3.93P-9.96K, Polyon™ 18N-2.62P-9.96K, and Nutricote™ 18N-2.62P-6.64K. The first three experiments investigated the effects of time on long-term nutrient release. In Expt. 1, each of the three PCFs were placed in flasks of distilled water maintained at $40^{o}C$ for 22 weeks. Fertilizer solutions were poured off at bi-weekly intervals and measured for electrical conductivity (EC) and NO_3-N, NH_4-N, P, K, Fe, Mn, Cu, and Zn concentrations. Overall, nutrient release for the three PCFs was higher and more variable in the first eight weeks than later in the experiment. Polyon's™ macronutrient release was generally more gradual than that of the other products. Micronutrient release patterns varied substantially between fertilizers and nutrients. In Expt. 2, pine bark (PB)-filled containers were amended with the three PCFs and irrigated regularly in a greenhouse. PCFs were removed from containers when Osmocote Plus'™ NO_3-N supply was ~66% expended and analyzed for EC, NO_3-N, NH_4-N, and P concentration. Except for P, the percentage of each nutrient remaining was roughly comparable to those remaining at the corresponding stage of Expt. 1, suggesting that PCF nutrient release behavior in the laboratory method is comparable with nutrient

release behavior in PB in the greenhouse. At the end of Expts. 1 and 2, Osmocote Plus™ had expended a higher percentage of its nutrients than the other fertilizers. In Expt. 3, substrate solutions were collected weekly from PB-filled containers (same treatments as in Expt. 2) and EC was determined. The substrate solution EC of Osmocote Plus™-fertilized PB began to decline sooner than that of the other fertilizers. Overall, these three experiments led to the conclusion that Osmocote Plus™ nutrient release declines more quickly than does Polyon™ or Nutricote™, while Polyon™ has the most gradual nutrient release pattern.

The objective of the second set of experiments was to determine the effects of temperature on short-term nutrient release. In Expt. 4, 14 g of each PCF was maintained at 40°C until ~33% of the NO_3-N content in Osmocote Plus™ was expended. Each fertilizer was then placed in a sand column and leached with distilled water at ~100 mL/h. Columns were then incrementally subjected to a simulated diurnal container temperature change from 20°C to 40°C and back to 20°C over a period of 20 h. Leachate was collected hourly and measured for soluble salts and NO_3-N and NH_4-N concentrations. For all fertilizers, nutrient release increased and decreased with the respective increase and decrease in temperature. Nutrient release patterns of the three fertilizers were significantly different, with Osmocote Plus™ showing the greatest overall change in nutrient release between 20°C and 40°C and Nutricote™ the least. In Expt. 5, PCFs were placed in flasks of distilled water in constant temperature baths. Initially, fertilizers were held at 40°C for three days and then at temperatures of 22, 28, 34, or 40°C for two weeks. Fertilizer solutions were poured off after the first and second weeks. Only solutions from the second week were analyzed for soluble salts and NO_3-N, NH_4-N, P, and K concentrations. For Osmocote Plus™ and Polyon™, there was a 29% to 86% (depending on the nutrient measured) mean increase in nutrient release between 22°C and 40°C, whereas for Nutricote™ there was a 345% to 364% (depending on the nutrient measured) mean increase. The overall mean increases in nutrient release in Expt. 4 were between 1032% and 4023%, whereas the mean increases in Expt. 5 were between 29% and 364%. In summary, the second set of experiments found that PCF nutrient release was highly sensitive to diurnal temperature changes.

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<u>Introduction</u>

Controlled-release fertilizers (CRFs) are now the most widely used fertilizers in the nursery industry for container-grown plants. A fundamental motivation for the development of CRFs has been the goal of delivering nutrients to plants at a rate that closely approximates plant nutrient demand over an extended period (Goertz, 1993; Oertli, 1980). Fertilizers with this ability can provide many benefits to agriculture, such as greater nutrient use efficiency, better plant growth and quality, lower labor costs, and reduced fertilizer runoff pollution (Goertz, 1993; Shaviv & Mikkelsen, 1993; Oertli, 1980).

CRFs can generally be grouped into three broad categories according to nutrient-release mechanism: (1) organic fertilizer materials, (2) materials of inherently low solubility, and (3) soluble fertilizer materials which are coated with a water-insoluble barrier that limits the rate of fertilizer dissolution (Bunt, 1988; Goertz, 1993). The coating mechanism offers improved flexibility with regard to CRF composition because the coating, rather than the inherent solubilities of the fertilizer contents, is the primary controlling factor of nutrient release. The coating method also allows the manufacturer to modify the nutrient release pattern of the CRF (Goertz, 1993).

At present, CRF coating materials are composed of either sulfur or polymeric substances, or a combination of both (Goertz, 1993). The individual coated fertilizer capsules are called prills. Polymer-coated fertilizers (PCFs) are now the most sophisticated and advanced means of controlling nutrient release and fertilizer longevity (Goertz, 1993). However, polymer-coating technology is generally expensive compared to other CRF technologies. As a result, PCFs are now used primarily in the production of high value crops, such as nursery crops (Goertz, 1993).

For PCFs, nutrients are released through a semipermeable membrane (Bunt, 1988; Goertz, 1993). Water vapor diffuses into the prill and condenses (Bunt, 1988; Goertz, 1993). The condensed water then dissolves some of the fertilizer salts inside and the

resulting fertilizer solution in the prill is thought to be released either via diffusion (Bunt, 1988; Goertz, 1993) or via hydrostatic pressure forcing nutrient solution out of the membrane (Oertli, 1980; Kochba et al., 1990).

Use of PCFs has become widespread in the production of container-grown plants. This is largely because PCFs can reduce labor and management requirements, improve fertilizer use efficiency, and reduce nutrient leaching as compared to liquid fertilization (Bunt, 1988). At the same time, PCFs can produce equivalent or even improved plant growth as compared to liquid fertilization (Wright and Niemiera, 1987).

However, concerns persist as to whether nutrient release from PCFs adequately parallels plant needs (Wright and Niemiera, 1987). For example, Cabrera (1997) found that season-long nitrogen leaching patterns of different PCFs could differ significantly over a growing season, despite the fact that the PCFs had similar (8-9 month) longevity ratings.

To better understand the basis for differences in PCF nutrient release profiles, we need to learn more about the relative effects of environmental factors and coating technologies on PCF nutrient release patterns. A better understanding of the factors that affect PCF nutrient release could potentially lead to more efficient use of currently available PCFs and to the eventual development of more efficient PCFs.

I.   Factors Influencing PCF Nutrient Release

A. <u>Temperature</u>

Early research by Oertli and Lunt (1962a; 1962b) established that temperature is the most important environmental factor influencing of PCF nutrient release. Nutrient release rate was found to increase substantially with increases in temperature. For example, release rate nearly doubled when the temperature was increased from 10°C to 20°C. Because this increase was much greater than would have been expected from diffusion alone, Oertli and Lunt (1962a) hypothesized that temperature-induced changes in coating characteristics contributed substantially to the increase in release rate. Oertli (1980) later hypothesized that high hydrostatic pressure inside PCF prills contributes to nutrient release by forcing nutrient-laden solution out of the prill via mass flow.

Tamimi et al. (1983) studied the effects of temperature and time on N, P and K release from PCFs in cinder-filled columns and found that release rate increased with increasing temperature, but the relationship was different for each nutrient. Worrall (1982), who studied the effects of temperature on PCF release rate in flasks of distilled water, found that temperature had a major effect on release rate and that the magnitude of the temperature effect was different for the two types of PCF studied. Harbaugh and Wilfret (1982) also found strong temperature effects on nutrient release in water. Lamont et al. (1987) studied the effects of time, temperature, and fertilizer type on PCF nutrient release in beakers of distilled water held at different constant temperatures. These investigators found that both temperature and time affected nutrient release rate and formulated a model of nutrient release over time. Generally, nutrient release was found to increase with increasing temperature and nutrient release decreased with time after initial high release levels. Different PCF types also had different nutrient release patterns. In a similar study, Hinklenton and Cairns (1992) modeled the strong relationships that they found between temperature, time, and PCF nutrient release. A recent study by Cabrera (1997) investigated the nitrogen leaching patterns of different PCFs in containers under greenhouse conditions during the growing season. The release patterns of some PCF types were found to correlate with the seasonal pattern of ambient temperature change. However, other types of PCF in this study did not follow the ambient temperature pattern. Kochba et al. (1990) investigated PCF release rates in soil and found that the rate of PCF nutrient release was related linearly to water vapor pressure which, in turn, varied with temperature. They concluded that the entry of water vapor into fertilizer prills was the rate-limiting step, as opposed to diffusion or mass flow out of prills. This finding is consistent with the finding of Oertli and Lunt (1962a) that diffusion alone is not sufficient to account for the observed relationship between temperature and release rate.

B. Other Factors

Oertli and Lunt found that release rate was generally independent of soil pH (1962a) and soil moisture content (1962b), as long as moisture content remained above the wilting point. Furthermore, they determined that microbial activity and external salt

concentration do not have a substantial effect on nutrient release (Oertli and Lunt, 1962a). The lack of a salt concentration effect was attributed to the high nutrient concentration gradient between the inside of a prill and the outside, which was probably not significantly affected by the range of salt concentrations used in the study. Kochba et al. (1990) found that substrate vapor pressure was the rate-limiting step in nutrient release. This indicates that substrate moisture content may be of little importance to nutrient release because substrate vapor pressure changes little with substrate moisture level. Worrall (1982) found that short term exposure of PCF to high temperatures did not appreciably alter subsequent nutrient release at lower temperatures. This indicates that PCF are relatively stable at high temperatures. Oertli and Lunt found that coating thickness (1962a) and method of application (top-dressing versus incorporation) (1962b) significantly affected nutrient release. Thicker coatings decreased release rate relative to thinner coatings and top-dressing generally decreased release rate in comparison to incorporation. Cabrera (1997) also found that top-dressing decreased release rate relative to incorporation. For certain PCF technologies, the addition of special "releasing agents" to the coating may significantly affect release (Goertz, 1993).

C. Nutrient Release Patterns under Different Experimental Conditions

The nutrient release patterns of PCFs have been observed under several experimental conditions. Oertli and Lunt (1962a, 1962b) investigated release patterns of PCFs in beakers of water (water elution) as well as in columns of soil or sand. These investigators found that, over the same time period, total nutrient release was twice as great for a PCF in water than for the same PCF in sand or soil columns (1962a). Oertli and Lunt (1962a) concluded that a buildup of salt concentrations in a thin boundary layer of water may inhibit nutrient release in the soil environment. They also speculated that PCF membrane characteristics may be altered in soil conditions.

Lamont et al. (1987) investigated PCF nutrient release patterns under laboratory conditions (using water elution) and in container substrates outdoors. The investigators found that PCF nutrient release in container substrates was similar to that in water elution.

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II.   Release Patterns of Different Nutrients

A. <u>Macronutrients: Nitrogen, Phosphorus, and Potassium</u>

Most PCF nutrient release studies have investigated macronutrient release. NO_3-N and NH_4-N release have been the focus of the majority of these studies. Cabrera (1997) found that N leaching pattern in containers could be strongly affected by PCF type. Broschat (1996) studied K release from PCFs in sand columns at 21°C and showed that K release rates were similar for some PCF types, but varied substantially for other PCF types.

However, some studies have compared the relative release rates of different macronutrients from PCFs. Oertli and Lunt (1962a) found that NO_3-N was released at a higher rate than P under similar conditions. Oertli and Lunt (1962a) also found that N from NH_4NO_3 was released faster than K. Tamimi et al. (1983) found that N, P, and K release rates increased with increasing temperature. Nitrogen had the fastest release rate, whereas K had the second fastest release rate, and P had the slowest release rate (Tamimi et al., 1983). In addition, release of the nutrients, especially N and P, tended to be linear at lower temperatures (21.1^{o}C and 26.7^{o}C) and curvilinear at higher temperatures (32.2^{o}C and 37.8^{o}C).

Some container studies have compared leachate concentrations of different nutrients in PCF- fertilized substrates. Yeager and Cashion (1993) found that leachate NO_3-N and NH_4-N exhibited similar patterns over time for the PCF type they studied. Ruter (1992) found that leachate EC was highly correlated with NO_3-N concentrations from PCF-fertilized plants. Groves et al. (1998) found different patterns in leachate NO_3-N and NH_4-N that were probably due to nitrification in the container substrates. On the other hand, P concentrations appeared more stable during the experiment than either NO_3-N or NH_4-N concentrations.

B. <u>Micronutrients</u>

Recently, some polymer-coated PCF manufacturers have begun to incorporate micronutrients into their products. Rose and Wang (1999) studied the effectiveness of slow-release micronutrient sources, including PCFs, in pine bark substrate. The PCF studied included types that had micronutrients inside the prills and types that had

micronutrients incorporated into the prill coating. For the PCFs studied, increases in extractable micronutrient levels did not follow a consistent pattern for the three testing dates. However, there have as yet been no detailed studies of micronutrient release from PCFs.

III. Temperature Response Comparisons Among Different PCF Technologies

Several studies have compared the effects of temperature on release rate for different PCF technologies. Worrall (1982) found that for nine-month rated PCFs, Type A (manufactured by Chisso Asahi Fertilizer Co. Ltd., Tokyo) was generally less responsive to temperature increase than was type B (manufactured by Sierra Chemical Co., Marysville, Ohio). Cabrera (1997) showed that certain PCF types may have different release responses to changes in temperature.

IV. Container Temperature: Diurnal Fluctuations

PCFs are used extensively in container plant production. Because PCF nutrient release is strongly affected by temperature, the diurnal temperature fluctuations in nursery containers likely have a significant effect on nutrient release. Furthermore, nutrient uptake and plant growth can also be substantially affected by container temperature, although the effects seem to be largely species-specific (Johnson and Ingram, 1984; Harrison et al., 1988).

Ingram (1981) and Ingram et al. (1989) found that temperatures in the center of a rigid black plastic nursery container in Florida increased from 21^oC in the early morning to 40^oC or more after as little as six hours of outdoor exposure to sunlight. Much of this temperature increase was due to incident radiation from the sun (Martin and Ingram, 1988). Because diurnal temperature fluctuations in containers can be extreme, the determination of how these relatively short-term temperature fluctuations affect PCF nutrient release would be valuable. The present study is the first investigation of the effects of diurnal temperature fluctuations on PCF nutrient release.

V. Summary

Polymer coated fertilizers are widely used in the container plant production because they have the potential to reduce labor and management needs, increase nutrient use efficiency, and maintain good plant growth. To provide these benefits in full, a PCF should have a nutrient release pattern that maintains nutrient levels in the range that promotes optimum plant growth.

The main environmental factor that affects PCF nutrient release is temperature. Increasing temperature generally increases nutrient release. However, the magnitude and pattern of temperature response can vary with coating technology, with coating thickness, and with the presence of "releasing agents" that may be added to the coating.

A thorough understanding of the relationships between PCF nutrient release and temperature is important for evaluating PCF effectiveness. Polymer coated fertilizer temperature response will generally play a large role in determining how well PCF nutrient release parallels plant needs. The present study will investigate the effects of temperature and time on nutrient release for three major PCF technologies. Temperature changes in container substrates are generally short-term diurnal fluctuations. However, until now PCF studies have generally investigated effects of long-term exposure to constant temperatures. Therefore, this study will also investigate the effects of simulated short-term diurnal temperature fluctuations on PCF nutrient release.

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CHAPTER TWO

Influence of Time on Nutrient Release Patterns of Three Controlled-Release Fertilizers

Abstract

Polymer-coated controlled-release fertilizers (PCFs) are the most widely used fertilizers in the production of container-grown nursery plants. The duration and magnitude of PCF nutrient release varies with product and this variation can significantly affect plant growth. Three experiments were conducted to determine the long-term nutrient release patterns of three PCFs (each with a rated longevity of 8-9 months), each using a different coating technology: Osmocote Plus™ 15N-3.93P-9.96K, Polyon™ 18N-2.62P-9.96K, and Nutricote™ 18N-2.62P-6.64K. In Expt. 1, each of the three PCFs was placed in flasks of distilled water maintained at 40°C for 22 weeks. Fertilizer solutions were poured off at bi-weekly intervals and measured for electrical conductivity (EC) and NO_3-N, NH_4-N, P, K, Fe, Mn, Cu, and Zn concentrations. Overall, nutrient release for the three PCFs was higher and more variable in the first eight weeks than later in the experiment.   Polyon's™ macronutrient release was generally more gradual than that of the other products. Micronutrient release patterns varied substantially between fertilizers and nutrients. In Expt. 2, PB-filled containers were amended with the three PCFs and irrigated regularly in a greenhouse. PCFs were removed from containers when Osmocote Plus'™ NO_3-N supply was ~66% expended and analyzed for EC and NO_3-N, NH_4-N, P and K concentrations. Except for P, the percentage of each nutrient remaining was roughly comparable to those remaining at the corresponding stage of Expt. 1, suggesting that PCF nutrient release behavior in the laboratory method is comparable with nutrient release behavior in PB in the greenhouse. At the end of Expts. 1 and 2, Osmocote Plus™ had expended a higher percentage of its nutrients than the other fertilizers. In Expt. 3 substrate solutions were collected weekly from PB-filled containers (same treatments as in Expt. 2) and EC was determined. The substrate solution EC of Osmocote Plus™-fertilized PB began to decline sooner than that of the other fertilizers. Overall, these three experiments led to the conclusion that Osmocote Plus™ nutrient

release declines more quickly than does Polyon™ or Nutricote™, while Polyon™ has the most gradual nutrient release pattern.

Introduction

Controlled-release fertilizers (CRFs) are used extensively in container nursery plant production. A fundamental motivation for the development of CRFs has been the goal of delivering nutrients to plants at rates that approximate plant demand over an extended period (Goertz, 1993; Oertli, 1980). Fertilizers with this ability can benefit the nursery industry by providing greater nutrient use efficiency, better plant growth and quality, lower labor and management costs, and reduced fertilizer runoff pollution (Goertz, 1993; Oertli, 1980; Shaviv & Mikkelsen, 1993).

The most widely used CRFs in container plant production are polymer-coated fertilizers (PCFs). PCFs consist of soluble fertilizer encapsulated in a polymer coating. Each fertilizer capsule is called a prill. PCFs release nutrients through a semipermeable membrane formed by the polymer coating (Bunt, 1988; Goertz, 1993). Water vapor diffuses into the prill, condenses, and then dissolves some of the fertilizer salts inside the prill (Bunt, 1988; Goertz, 1993). The resulting fertilizer solution is thought to be released either via diffusion (Bunt, 1988; Goertz, 1993) or via hydrostatic pressure forcing nutrient solution out of the membrane (Kochba et al., 1990; Oertli, 1980).

PCF nutrient release is primarily influenced by temperature and time (Lamont et al., 1987; Oertli and Lunt 1962a; 1962b). An increase in temperature generally causes an increase in nutrient release rate (Tamimi et al., 1983). PCF manufacturers categorize their products by longevity of nutrient release which is commonly based upon the length of time necessary for the fertilizer to release a high percentage (e.g., 80%) of its contents at a given temperature (e.g. 21°C). However, several investigators have questioned the adequacy of longevity ratings for evaluating PCF performance. For example, Meadows and Fuller (1983) found that nitrogen release from 8-9 month and 12-14 month rated PCFs dropped below satisfactory levels after only four months. In addition, Cabrera (1997) found that different PCFs with 8-9 month longevity ratings have different N release patterns as indicated by nutrient leaching from pots during a growing season in greenhouse conditions.

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Because several factors influence the nutrient release patterns of PCFs, the overall performance of different PCFs can only be adequately evaluated when the effects of these factors are understood. The main objective of this study was to investigate the effects of time on the macronutrient and micronutrient release patterns of three PCFs, each using a different coating technology, under constant temperature conditions in the laboratory and under changing temperature conditions in the greenhouse.

Materials and Methods

Each of the three PCFs used in this experiment were produced by a different manufacturer, each of which uses a different coating technology (Goertz, 1993). The PCF types used were Osmocote Plus™ 15N-3.93P-9.96K (Scotts-Sierra Horticultural Products, Marysville, Ohio), Polyon™ 18N-2.62P-9.96K (Pursell Technologies Inc., Sylacauga, Ala.), and Nutricote™ 18N-2.62P-6.64K (Chisso-Asahi Fertilizer Co., Ltd., Tokyo). Osmocote Plus™ 15N-3.93P-9.96K had a longevity rating of 8-9 months while Polyon™ 18N-2.62P-9.96K and Nutricote™ 18N-2.62P-6.64K each had a longevity rating of 9 months. Furthermore, both Osmocote Plus™ 15N-3.93P-9.96K and Nutricote™ 18N-2.62P-6.64K contained micronutrients (B, Cu, Fe, Mn, Mo, and Zn) in addition to N, P, and K. Information on fertilizer formulation, nutrient sources, and manufacturers' longevity claims is in Appendix E.

Electrical conductivity (EC) of nutrient solutions was measured with a CDM83 Conductivity Meter (Radiometer Copenhagen, Copenhagen). EC was converted, approximately, to mg/L soluble salts by multiplying mS/cm by 700 (Bunt, 1988). NO_3-N concentration was measured with a Cardy NO_3- Nitrate Meter (Spectrum Technologies Inc., Plainfield, Ill.). NH_4-N concentration was measured with an ammonia-selective electrode (HNU Systems, Inc., Newton, Mass.) and an Orion Research Microprocessor Ionalyzer/901 (Orion Research, Boston). Phosphorus, K, Fe, Mn, Cu, and Zn concentrations were measured via inductively coupled plasma (ICP) spectrometry which determines elemental concentrations and does not depend upon the molecular species of an element.

Expt. 1: Soluble salts and macronutrient release patterns under laboratory conditions

For each of the three PCFs, fourteen grams of PCF and 100 mL distilled water were put into 125 mL Erlenmeyer flasks. There were four flasks of each of the three fertilizers. Flasks were completely randomized in a 40°C water bath. Bath temperature was maintained by a thermostatically controlled heater and circulator.

The fertilizer solution in each flask was poured off and collected at one-week intervals for the first eight weeks. Solutions were poured-off at two-week intervals for the remaining 16 weeks of the experiment. At each pour-off, prills were rinsed with 100 mL of distilled water and rinsate was collected. The total solution volume (pour-off combined with rinsate) was then measured. Solutions were analyzed for EC and concentrations of NO_3-N, NH_4-N, P, K, Fe, Mn, Cu, and Zn. Only Osmocote Plus™ and Nutricote™ were formulated with micronutrients. EC was converted to mg soluble salts as previously described. The experimental design was completely randomized with repeated measures (using two-week measurement intervals). There were four replications of each of the three fertilizers. Data were analyzed using SAS (version 6.12, SAS Institute Inc., Cary, N.C.) PROC MIXED using AR(1) autocorrelation for the repeated measures.

Expt. 2: Nutrients remaining after 16 weeks in greenhouse conditions

On 31 July 1998, 2.8 L nursery containers, filled with PB, were amended with one of three different types of PCF (Osmocote Plus™ Plus 15-9-12, Polyon™ 18N-2.62P-9.96K, or Nutricote™ 18N-2.62P-6.64K). Fertilizer prills were placed in a layer between folds of cotton paper dish towels to facilitate subsequent fertilizer removal. The fertilizer prill layer was covered with approximately 5 cm of pine bark. Fertilizers were applied at the manufacturers' recommended rates for incorporation (Osmocote Plus™: 16.8 g; Polyon™: 23.6 g; Nutricote™: 21.9 g). Two sets of six replications of each of the three fertilizer types were prepared (for a total of $2*(3*6) = 36$ experimental containers).

Containers were placed on a bench in a greenhouse in a completely randomized configuration. A row of "guard containers" filled with PB (without fertilizer) were placed around the periphery of the treatment containers to prevent experimental containers on the periphery from receiving more solar radiation than containers inside the

arrangement. Containers were irrigated on Mondays, Wednesdays, and Fridays of each week with 260 mL of water. Ambient greenhouse temperatures were monitored on irrigation days beginning on the sixth week of the experiment. Temperatures were generally in the 17-29°C range through the ninth week and were subsequently in the 17-26°C range.

An additional 30 PB-filled containers, on a different greenhouse bench, were amended with Osmocote Plus™ and these containers were treated as described above. Periodically, fertilizer prills from one of these containers were removed, ground-up with a mortar and pestle, and the contents dissolved in one liter of distilled water. The NO_3-N concentration of this solution was then measured and the percentage of NO_3-N expended was calculated (using the manufacturers' stated formulation as the initial nutrient content for calculating this percentage). On 6 November, 1998 (16 weeks after the start of the experiment), when this percentage reached approximately 60-70% expended, one set of six replications of the three fertilizers was removed from the main experimental group. (The removed containers were replaced with pine bark-filled containers to preserve the original experimental configuration.) The fertilizer contents (prills) of each of these containers were removed, ground up, and solubilized in one liter of distilled water. (Removal of the fertilizer contents was more difficult than anticipated because the cotton dishtowels disintegrated during the course of the experiment.) Solutions were then analyzed for EC, and concentrations of NO_3-N, NH_4-N, P, K, Fe, Mn, Cu, and Zn. The experimental design was completely randomized. Analysis was performed using SAS (version 6.12, SAS Institute Inc., Cary, N.C.) PROC GLM.

Expt. 3: Weekly leachate EC during nine months in greenhouse conditions

On Fridays, the substrate solutions of containers from Expt. 2 (the set of 18 out of the 36 containers described in Expt. 2 that were not sacrificed in Expt. 2) were extracted using the Virginia Tech Extraction Method (Wright, 1987)**,** in which 150 mL of water was poured onto the PB surface, and leachate was collected from the experimental containers. Pour-throughs were performed two to five hours after irrigation, and the EC's of the pour-through solutions were then measured. These pour-throughs continued for 39 weeks (31 July, 1998 through 16 April, 1999).

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The experimental design was completely randomized with repeated measures. There were six replications of each of the three fertilizers. Data were analyzed using SAS (version 6.12, SAS Institute Inc., Cary, N.C.) PROC MIXED using AR(1) autocorrelation for the repeated measures.

Results and Discussion

Nutrient release was analyzed both on an absolute basis and on a percentage basis (using the stated formulations (Appendix E) to calculate initial nutrient content). The percentage calculation removes differences in formulation.

Expt. 1: Soluble salts and macronutrient release patterns under laboratory conditions

There were significant product x time interactions (both for absolute and for percent release) for NO_3-N, NH_4-N, P, K, and soluble salts (Tables 1 and 2). Thus, each product exhibited a significantly different nutrient release pattern over time. Time significantly affected the absolute amount of NO_3-N, NH_4-N, P, K, and soluble salts released during the experiment, and there were also significant differences among products (Table 1). Due to the interactions, the magnitudes or directions of product differences vary with time (Fig. 1). The above mentioned effects were also significant when data were analyzed on a percent released basis, except for NO_3-N, in which case significant differences among products were absent (Table 2).

Soluble salts, NO_3-N, and NH_4-N release patterns were similar within products, but were different among products (Fig. 1). The widest fluctuations in soluble salts, NO_3-N, and NH_4-N release occurred during the first 10 weeks of the experiment. By week 10, NO_3-N, and NH_4-N release rates began to decrease steadily for all products. Overall, change in EC was a good indicator of corresponding changes in NO_3-N, and NH_4-N release (Fig. 1), suggesting that EC may be a useful proxy measure for N release. Potassium release was variable before week eight, then exhibited a steadily decreasing trend for the remainder of the experiment (Fig. 1).

Phosphorus release increased during the first four weeks and subsequently decreased for all fertilizers (Fig. 1). However, the rate of decrease (from weeks 8 through 18) was less for Polyon™ than for Osmocote Plus™ or Nutricote™. In this study, NO_3-N, NH_4-N, and K were 70% or more expended by the end of the experiment, whereas P was less

than 40% expended for Osmocote Plus™ and Nutricote™ and about 60% expended for
Polyon™. Tamimi et al. (1983) also found that P was released much more slowly than
the other macronutrients. These findings seem to indicate that the P sources used in these
fertilizers may be less soluble than the other macronutrient sources. Both Osmocote
Plus™ and Nutricote™ derive their P from a combination of ammonium phosphate and
calcium phosphate whereas Polyon™ derives its P from ammonium phosphate alone.
The solubility of ammonium phosphate (25^oC) is 1 g per 1.7 mL of water (Budavari,
1989) whereas calcium phosphate is insoluble in water (Lide, 1999).

The overall nutrient release patterns discussed above for N, P, and K were similar
whether the data were viewed as absolute nutrient release or percentage nutrient release
(based on stated formulation, Appendix E) (Appendix A: Fig. 1). In general, the
percentage macronutrient nutrient release patterns observed in this study are consistent
with those found in previous studies (Lamont, 1987; Tamimi et al., 1983) which showed
that, at constant high temperatures, nutrient release was higher early in the lifespan of the
product and then began to decline. Overall, the amount of nutrients released by Polyon™
did not fluctuate as widely as did the nutrient release of Osmocote Plus™ and
Nutricote™ (Fig. 1).

Micronutrient release patterns under laboratory conditions

There were significant product x time interactions for Fe, Mn, Zn, and Cu on both an
absolute and a percentage basis (Tables 1 and 2). Thus, these products exhibited
significantly different micronutrient nutrient release patterns over time. For Osmocote
Plus™ and Nutricote™ (Polyon™ does not contain micronutrients), time significantly
affected release of Fe, Mn, and Zn on the basis of absolute amount released and on the
basis of percentage released, and there were significant differences in release among
these products (Tables 1 and 2, α=0.05). Due to the interactions, the directions or
magnitudes of product differences vary with time (fig. 2). For Cu, there was a significant
main effect of time (Tables 1 and 2, α=0.05).

Nutricote™ had a higher release of Fe than did Osmocote Plus™ for the entire
duration of the experiment (Fig. 2). During the first six weeks, when the differences in
release were largest, Nutricote™ released more than twice as much Fe as did Osmocote.

After week six, Fe release from both fertilizers slowly declined. Nutricote™ had a higher Fe release rate than Osmocote Plus™ throughout the experiment despite the fact that it is formulated to have less than one half the amount of iron in Osmocote Plus™ (Appendix E). However, Fe may be in a more soluble form in Nutricote™, which utilizes only chelated iron, whereas Osmocote Plus™ utilizes both iron sulfate and chelated iron (Appendix E). Chelates are more soluble than sulfate forms of micronutrients (Reed, 1996). Mn release from both Osmocote Plus™ and Nutricote™ fluctuated during the first 10 weeks of experiment and then gradually declined (Fig. 2). However, Nutricote™ consistently released between 40% and 590% more Mn than Osmocote Plus™ (Fig. 2), even though both are formulated with the same percentage of Mn and both contained Mn in sulfate form (Appendix E).

Osmocote Plus™ had a very high release of Cu during the first two weeks of the experiment and release quickly decreased by two orders of magnitude by week four (Fig. 2). Nutricote™ had an initial release that was less than 1/3 the size of Osmocote Plus'™ initial release, but Nutricote's™ Cu release was higher than Osmocote Plus™ for the remainder of the experiment. Both fertilizers are formulated with the same amount and type of Cu (see Appendix E).

During the first two weeks of the experiment, Nutricote™ had a very high release of Zn and the rate then declined by more than three orders of magnitude by week four (Fig. 2). Osmocote Plus™ had a much lower initial release. However, the release rates of both fertilizers were similar after week four. These results are noteworthy because, according to the manufacturer's stated formulation, Osmocote Plus™ should have three times more zinc than Nutricote™ (Appendix E). The general patterns discussed above were the same on a percent released basis (Table 2, Appendix A: Fig. 2). However, due to possible discrepancies in the labeled formulations (Appendix C), the percentage values are of doubtful accuracy.

Expt. 2: Nutrients remaining after 16 weeks in greenhouse conditions

After 16 weeks in PB-filled containers in a greenhouse environment, ~36% of Osmocote Plus's™ original NO_3-N content remained (Table 4). At this point in time, a higher percentage of NO_3-N (at least 12% more) remained in Polyon™ and Nutricote™

(Table 4). This was also the case for NH_4-N, P, and K (Table 4). Thus, Osmocote Plus™ had released a higher proportion of its macronutrients early-on than had the other fertilizers. In addition, a higher percentage of Nutricote's™ P remained than for Polyon™ or Osmocote Plus™. Differences in P expenditure between Osmocote Plus™ and Nutricote™ were particularly large, with Nutricote™ retaining almost twice as much of its P as Osmocote Plus™. As mentioned above, this may be related to differences in the types and ratios of P compounds used in the different products.

On the basis of absolute amount of nutrients remaining (Table 5), differences between Osmocote Plus™ and the other fertilizers are quite large. The amount of nutrients remaining in the Osmocote Plus™ treatments was often less than half that of the other fertilizer treatments. This is probably attributable to a combination of differences in manufacturer's recommended application rates, differences in nutrient release characteristics (Table 4), and differences in formulation (Appendix E).

Comparison of the percent of nutrients released in Expts. 1 and 2, at the point when Osmocote Plus'™ NO_3-N was ~66% expended, yields insights on the methodologies used to assess nutrient release from PCFs. A statistical comparison at this stage indicates that there were significant interactions between experimental environment (EE) (i.e., greenhouse (Expt. 1) vs. laboratory environment (Expt. 2)) and product for NO_3-N, and P, but not for K (Table 3, $\alpha=0.05$, using SAS proc GLM). There were significant effects of EE and significant differences among products for NH_4-N, P, and K release and significant differences among products for NO_3-N release (Table 3). Due to the interactions, the directions or magnitudes of product differences vary with EE (Fig. 3). Examining the relative magnitudes of the differences in EE on nutrient release (at the ~66% stage of Osmocote Plus'™ NO_3-N release), the percent K released did not appear to differ much (< 8% for any of the three products) between the two experiments (Fig. 3). However, at the ~66% stage of Osmocote Plus'™ NO_3-N release, Nutricote™ and Osmocote Plus™ released more than 20% more NH_4-N in the constant temperature bath (Expt. 1) than in the greenhouse containers (Expt. 2). There were also seemingly large differences in P-release between Expts. 1 and 2 for all fertilizers (Fig. 3). Osmocote Plus™ appeared to release ~170% more P in Expt. 2 than in Expt. 1, while Polyon™ appeared to release ~37% more and Nutricote™ appeared to release ~81% more.

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However, the seemingly higher P release in Expt. 2 for all fertilizers was probably due either to the consistently higher temperature in this Expt. or to the failure of the nutrient recovery method to adequately recover the P remaining in the fertilizer prills in Expt. 1 (Appendix C).

Expt. 3: Weekly Leachate EC during nine months in greenhouse conditions

In this experiment, PB-filled containers on greenhouse benches were amended with the three different PCFs, irrigated three times a week, and ECs of substrate solutions were monitored weekly. There was a significant product x time interaction (p=0.0001) which indicates that the nutrient release patterns for the three fertilizers were significantly different during the nine month experiment. The effect of time on substrate solution EC was significant (p=0.0001) and there was also a difference among products (p=0.0001). Due to the interaction, the direction or magnitude of product differences vary with time (Fig. 4). In general, substrate solution EC values of Nutricote™ and Polyon™ fertilized pots increased for the first 17 weeks and began to decline thereafter (Fig. 4). On the other hand, the EC values of Osmocote Plus™ fertilized containers began to decrease after week 10 (Fig. 4). Overall, the substrate solution EC patterns for Nutricote™ and Polyon™ were similar for most of the experiment, whereas EC of Osmocote Plus™ containers began to decline sooner than containers fertilized with the other two products.

For the constant temperature bath experiment at 40°C (Expt. 1), all three fertilizers exhibited a relatively high initial release of soluble salts (Fig. 1). However, in the greenhouse EC experiment (Expt. 3), initial soluble salt levels were low for the first several weeks and then increased sharply (Fig. 4). Since there was no overall increase in greenhouse air temperature during this period of time in Expt. 3 (data not shown), the sharp increase in soluble salts that occurred early in Expt. 3 may be attributable to other factors. For example, insufficient leaching fraction during irrigation may have led to a buildup of salts in the substrate after the first several weeks. In addition, the low initial EC levels in Expt. 3 may be partly due to adsorption of fertilizer to the PB substrate. Furthermore, cumulative soluble salts were measured in Expt. 1, whereas salts were measured at "single points in time" in Expt. 3. Thus, if high initial salt releases did indeed occur in Expt. 3, this difference in methodology may have caused the initially

high releases to be missed if they occurred between the "single point in time" EC measurements.

Summary and Conclusions

Polymer coated fertilizer nutrient release was strongly influenced by time and differed among products. In these experiments similar differences among products were observed both in the laboratory under uniform temperature conditions (Figs. 1) and in the greenhouse under variable temperature conditions (Fig. 4). Thus, overall nutrient release in the laboratory and in the greenhouse appears to be comparable for evaluating the release characteristics of PCFs. This is important because PCF manufacturers often evaluate their products under constant-temperature laboratory conditions (Appendix E).

Nutrient release was generally high early in the lifespan of the products and then declined. In all three experiments, Osmocote Plus's™ release declined over time more quickly than did the release of Nutricote™ and Polyon™. Furthermore, Polyon™ generally released its NO_3-N, NH_4-N, P, K, and soluble salts more slowly than the others. This allowed Polyon™ to maintain the highest release of these nutrients for at least six weeks after the initially high release levels of Osmocote Plus™ and Nutricote™ had declined (by week 10). These patterns may be related to the longevity ratings of the three fertilizers. Osmocote Plus™ is rated for 8-9 moths at 21.1^oC, whereas Nutricote™ is rated for 9 months at 25^oC and Polyon™ is rated for 9 months at 26.7^oC (Appendix E). Hence, the somewhat lower longevity rating of Osmocote Plus™ may explain why this fertilizer did not sustain release as long as the others. Furthermore, the somewhat higher temperature used for Polyon's™ longevity rating may explain why this fertilizer was able to maintain higher release levels for a longer period of time. Overall, this study found that Osmocote Plus™ tended to supply more macronutrients than the other PCFs early-on (to a small extent) in Expt. 1 (Fig. 1), whereas this tendency was less apparent in Expt. 3 (Fig. 4).

The observed differences in release patterns among the three PCF products were probably attributable to differences in coating characteristics such as thickness or presence of releasing agents (Goertz, 1993). Coating characteristics and thickness as well as releasing agents are proprietary information and are not available. Future research into

PCF nutrient release characteristics will lead to more effective use of PCFs and to the development of improved PCF products.
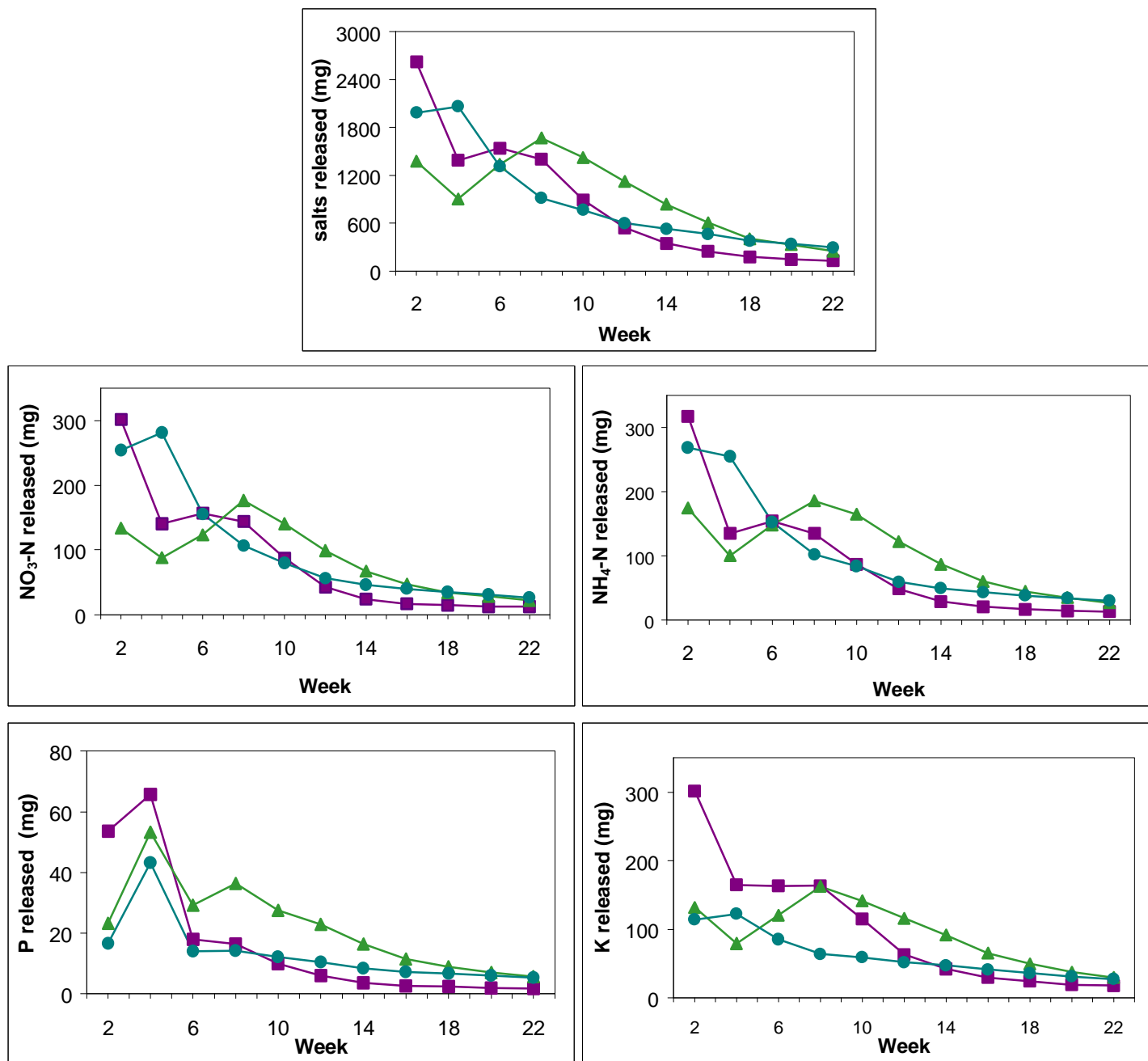
Fig. 1. Soluble salts (EC x 700), NO$_3$-N, NH$_4$-N, P, and K and release patterns of Osmocote Plus™ (■), Polyon™ (▲), and Nutricote™ (●) during a 22 week incubation at 40°C (Expt. 1). Means, n=4.
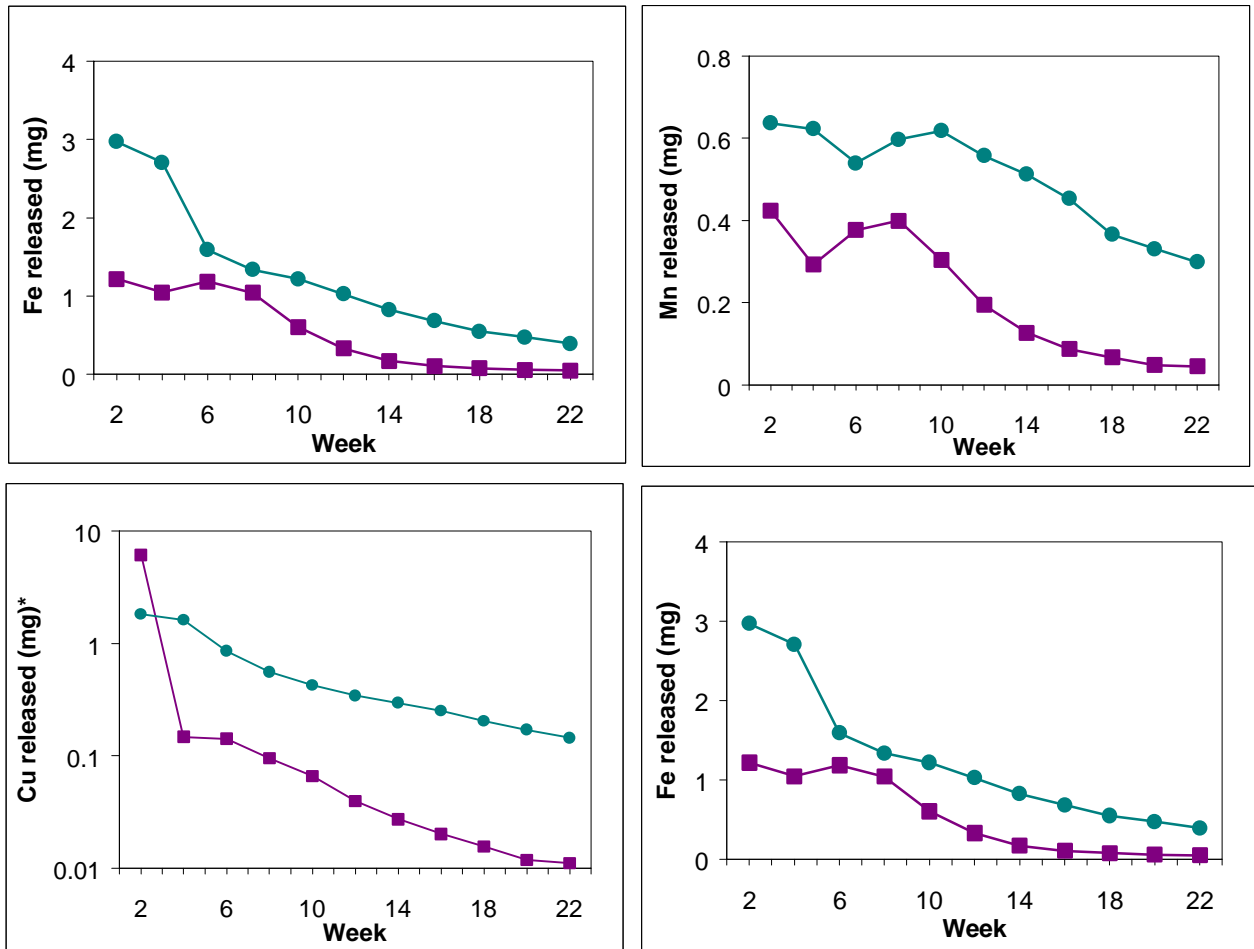
Fig. 2. Fe, Mn, Cu, and Zn release patterns of Osmocote Plus™ (■), Polyon™ (▲), and Nutricote™ (●) during a 22 week incubation at 40°C (Expt. 1). Means, n = 4. *Logarithmic scale

a. Greenhouse container - % released after 16 Weeks

b. 40°C Bath - % expended after 8 weeks
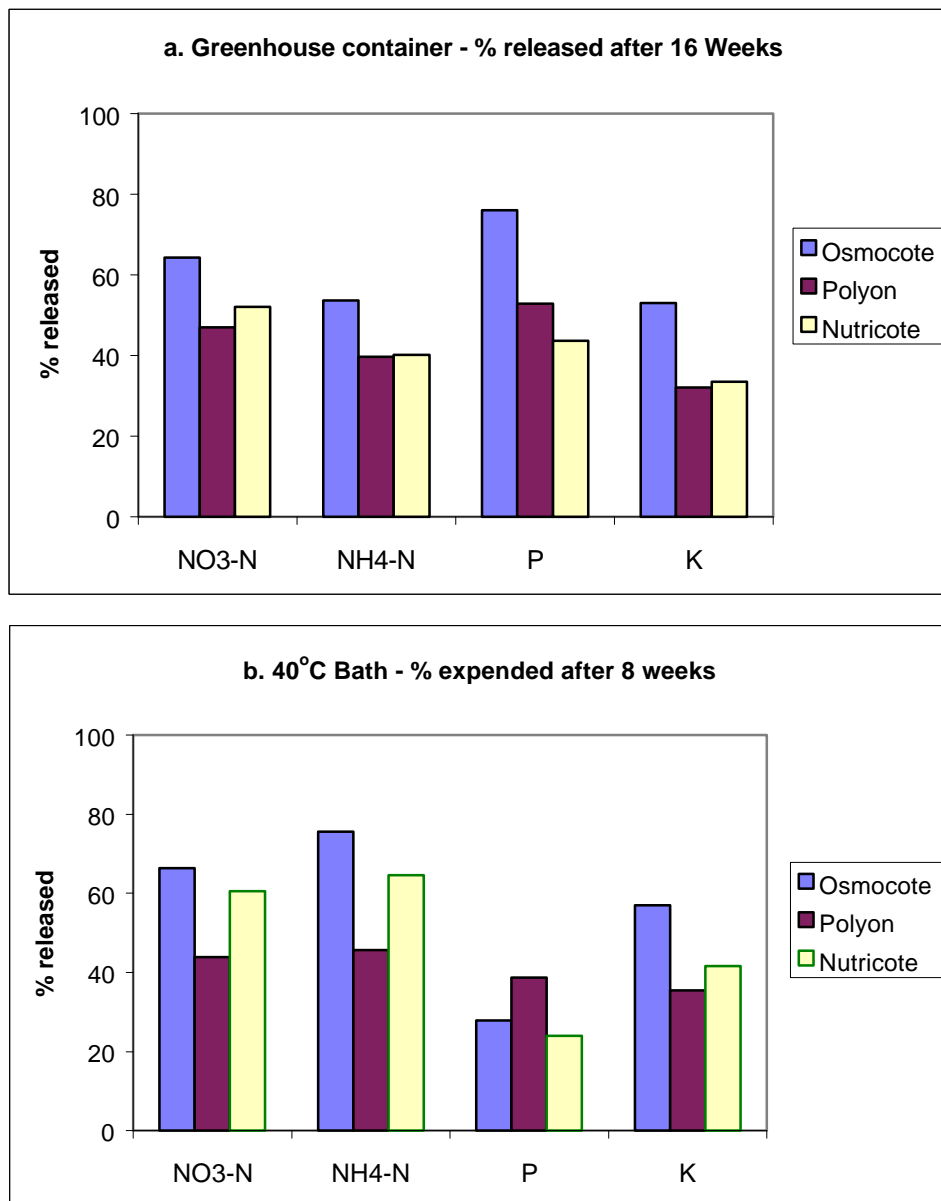
Fig. 3. a. Percent of macronutrients released during 16 weeks in a greenhouse container (Expt. 2). Means, n=6.

Fertilizer prills were placed in greenhouse containers July 31, 1998 and were harvested on November 6, 1998

b. Percent of macronutrients released during 8 weeks in distilled water at 40°C (Expt. 1). Means, n=4.

Osmocote Plus™ had released ~66% of its NO_3-N at this stage in both experiments.

Percentages are based on the stated fertilizer formulation (Appendix E).
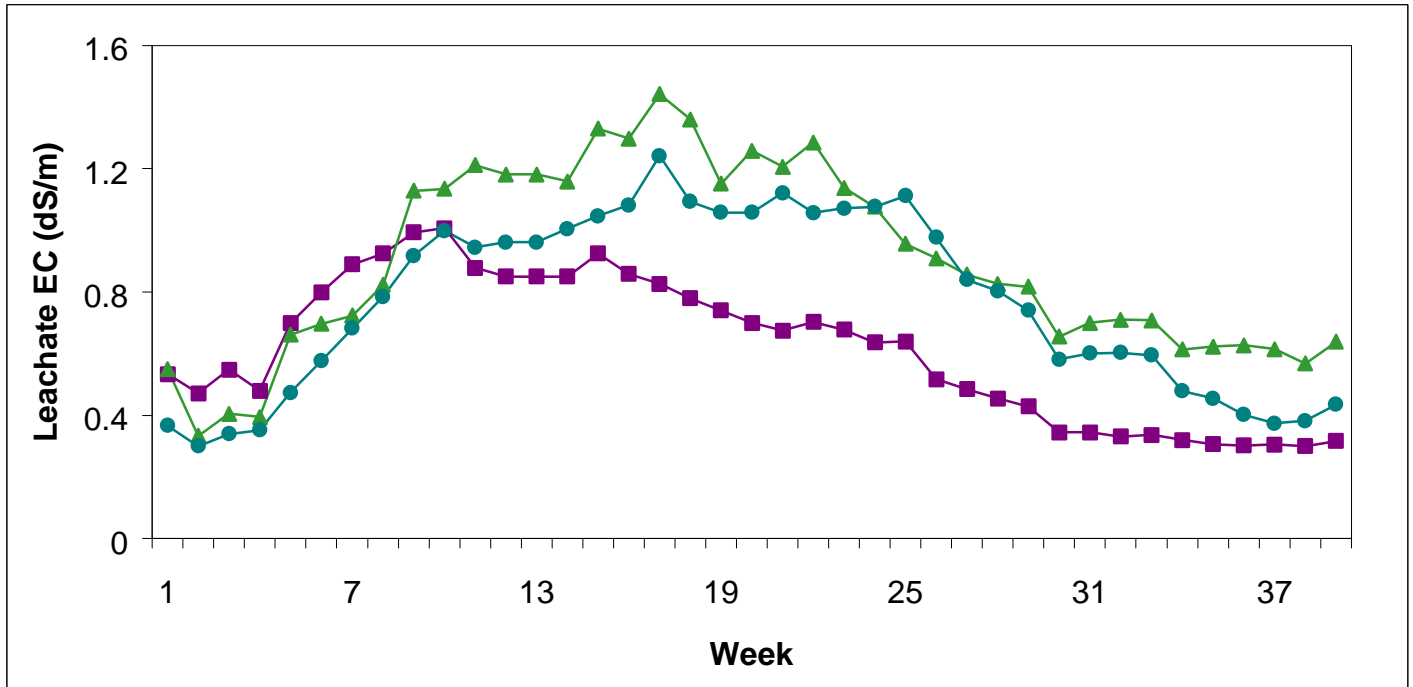
Fig. 4. Leachate EC patterns of Osmocote Plus™ (■), Polyon™ (▲), and

Nutricote™ (●) during a nine month period in greenhouse containers (Expt. 3).

Means, n=6.

The experiment began on July 16, 1998 and ended on April 16, 1999

Table 1. Main effects and interactions for fertilizer products (Osmocote Plus™, Polyon™, and Nutricote™) and time on soluble salts (EC x 700) and nutrient release (on an absolute basis) for a 22 week incubation at 40°C. (not taking formulation into account) (Expt. 1).

	p-values		
Variable	Product	Time	Product x time
Soluble salts	0.0059	0.0001	0.0001
NO_3	0.0003	0.0001	0.0001
NH_4	0.0001	0.0001	0.0001
P	0.0001	0.0001	0.0001
K	0.0001	0.0001	0.0001
Fe	0.0001	0.0001	0.0001
Mn	0.0001	0.0001	0.0001
Cu	0.9347	0.0001	0.0001
Zn	0.0005	0.0001	0.0001

Table 2. Main effects and interactions for fertilizer product (Osmocote Plus™, Polyon™, and Nutricote™) and time on percent nutrient release (based upon formulation) over a 22 week incubation at 40°C (Expt. 1)

	p-values		
Variable	Product	Time	Product x time
NO_3	0.1620	0.0001	0.0001
NH_4	0.0007	0.0001	0.0001
P	0.0001	0.0001	0.0001
K	0.0319	0.0001	0.0001
Fe	0.0001	0.0001	0.0001
Mn	0.0001	0.0001	0.0001
Cu	0.9347	0.0001	0.0001
Zn	0.0210	0.0001	0.0001

Table 3. Main effects and interactions for effects of experimental environment (greenhouse (Expt. 1) vs. laboratory (Expt. 2)) and fertilizer products (Osmocote Plus™, Polyon™, and Nutricote™) on nutrient release (on a percentage expended basis) when Osmocote Plus™ had released ~66% of its NO_3-N in both experiments.

Variable	p-values		
	Experimental Environment (EE)	Product	EE x Product
NO_3	0.0597	0.0001	0.0046
NH_4	0.0001	0.0001	0.0001
P	0.0001	0.0001	0.0001
K	0.0001	0.0001	0.1396

Table 4. Effects of fertilizer products on N, P, and K remaining (%) after 16 weeks in
greenhouse containers (accounts for application rate and formulation
differences), Expt. 2.

	% remaining			
Product	NO_3-N	NH_4-N	P	K
Osmocote Plus™	35.7b[zy]	46.3b	23.9c	47.0b
Polyon™	53.1a	60.4a	47.1b	68.0a
Nutricote™	47.9a	59.9a	56.4a	66.5a

[z]Means, n=6

[y]Means are not significantly different when followed by the same letter (Tukey
HSD, $\alpha = 0.05$)

Table 5. Effects of fertilizer products on nutrients and soluble salts
remaining (mg) after 16 weeks in greenhouse containers (does not account for
application rate or formulation differences) (Expt. 2).

		Nutrients remaining (mg)			
Product	Soluble salts (mg)	NO_3-N	NH_4-N	P	K
Osmocote Plus™	5,279c[zyx]	482b	546c	158c	788c
Polyon™	11,142a	1,062a	1,355a	291b	1,598a
Nutricote™	9,610b	985a	1,128b	323a	967b

[z]Means, n=6

[y]Means are not significantly different when followed by the same letter (Tukey
HSD, $\alpha = 0.05$)

[x]Soluble salts calculated as follows: EC x 700 x (solution volume in L)

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CHAPTER THREE

Influence of Temperature on Nutrient Release Patterns of Three Controlled-Release Fertilizers

Abstract

Two experiments were conducted to determine the effects of temperature on the nutrient release patterns of three polymer coated fertilizers (PCFs), each using a different coating technology: Osmocote Plus™ Plus™ 15N-3.93P-9.96K, Polyon™ 18N-2.62P-9.96K, and Nutricote™ 18N-2.62P-6.64K. In Expt. 1, 14 g of each PCF was maintained at 40°C until ~33% of the NO_3-N content Osmocote Plus™ was expended (based on the manufacturer's formulation). Each fertilizer was then placed in a sand column and leached with distilled water at ~100 mL/h. Columns were then incrementally subjected to a simulated diurnal container temperature change from 20°C to 40°C and back to 20°C over a period of 20 h. Leachate was collected hourly and measured for soluble salts and NO_3-N and NH_4-N concentrations. For all fertilizers, nutrient release increased and decreased with the respective increase and decrease in temperature. Nutrient release patterns of the three fertilizers differed, with Osmocote Plus™ showing the greatest overall change in nutrient release between 20°C and 40°C and Nutricote™ the least. In Expt. 2, PCFs were placed in flasks of distilled water in constant temperature baths. Initially, fertilizers were held at 40°C for three days and then at temperatures of 22, 28, 34, or 40°C for two weeks. Fertilizer solutions were poured off after the first and second weeks. Only solutions from the second week were analyzed for soluble salts, NO_3-N, NH_4-N, P, and K. Temperature significantly affected nutrient release, and nutrient release differed among products. For Osmocote Plus™ and Polyon™, there was a 29% to 86% (depending on the nutrient measured) mean increase in nutrient release when the temperature was raised from 22°C to 40°C, whereas for Nutricote™ there was a 345% to 364% (depending on the nutrient measured) mean increase. The overall mean increases in nutrient release in Expt. 1 were between 1032% and 4023%, whereas the mean increases in Expt. 2 were between 29% and 364%. These data suggest that PCF nutrient release is highly sensitive to diurnal temperature changes, but that this sensitivity may be greater for short term temperature changes than for longer term temperature differences.

Introduction

Controlled-release fertilizers (CRFs) are used extensively in container nursery plant production. A fundamental motivation for the development CRF has been the goal of delivering nutrients to plants at rates that approximate plant demand over an extended period (Goertz, 1993; Oertli, 1980). Fertilizers with this ability can have many benefits to the nursery industry, such as greater nutrient use efficiency, better plant growth and quality, lower labor and management costs, and reduced fertilizer runoff pollution (Goertz, 1993; Oertli, 1980; Shaviv & Mikkelsen, 1993).

The most widely used CRFs in container nursery plant production are polymer-coated fertilizers (PCFs). PCFs consist of soluble fertilizer encapsulated in a polymer coating. Each fertilizer capsule is called a prill. PCFs release nutrients through a semipermeable membrane formed by the polymer coating (Bunt, 1988; Goertz, 1993). Water vapor diffuses into the prill, condenses, and then dissolves some of the fertilizer salts inside the prill (Bunt, 1988; Goertz, 1993). The resulting fertilizer solution is thought to be released either via diffusion (Bunt, 1988; Goertz, 1993) or the forcing of nutrient solution out of membrane by hydrostatic pressure (Kochba et al., 1990; Oertli, 1980).

PCF nutrient release is primarily influenced by temperature and time (Oertli and Lunt 1962a; 1962b; Lamont et al., 1987). An increase in temperature generally causes an increase in nutrient release rate (Tamimi et al., 1983). PCF manufacturers categorize their products by longevity of nutrient release which is based upon the length of time necessary for the fertilizer to release a high percentage (~80%) of its contents at a given temperature (e.g., 21°C). However, several investigators have questioned the adequacy of longevity ratings for evaluating PCF performance. For example, Meadows and Fuller (1983) found that nitrogen release from 8-9 month and 12-14 month rated PCFs dropped below satisfactory levels after only four months. In addition, Cabrera (1997) found that different PCFs with 8-9 month longevity ratings have different N release patterns as indicated by nutrient leaching from pots during a growing season in greenhouse conditions.

Because several factors influence the nutrient release patterns of PCFs, the performance of different PCFs can only be adequately evaluated when the effects of these factors are understood. Previous studies have evaluated temperature effects based upon

incubations at a constant temperature for many weeks (; Lamont, 1987; Tamimi et al., 1983). However, studies have shown that nursery container temperatures often fluctuate widely over the course of a day. Ingram (1981) and Ingram et al. (1989) found that substrate temperatures in the center of a rigid black plastic nursery container in Florida increased from 21°C to 40°C or more in as little as six to nine hours when exposed to the sun. The impact of short-term diurnal temperature fluctuations in containers on PCF nutrient release has not been investigated. The main objective of this study was to investigate the effects of short-term (diurnal) and long-term (week-long) temperature differences (under laboratory conditions) on patterns of nutrient release for three PCFs with different coating technologies.

Materials and Methods

The three PCFs used in this experiment were Osmocote Plus™ 15N-3.93P-9.96K, Polyon™ 18N-2.62P-9.96K, and Nutricote™ 18N-2.62P-6.64K (as described in Chapter 2, p. 13). Electrical conductivity and nutrient concentrations were measured using the equipment and techniques described in Chapter 2, p. 13.

Expt. 1: PCF in sand columns leached with water and subjected to simulated
diurnal temperature changes

Fourteen grams each of the three of PCFs and 100 mL distilled water were put into 125 mL Erlenmeyer flasks. There were two flasks of each of the three fertilizer types. Flasks were placed in a randomized arrangement in a water bath at 40°C. Bath temperature was maintained by a temperature controller and circulator. Flasks were incubated until the average expenditure of NO_3-N (using the manufacturers' stated formulation to compute the initial amount of NO_3-N) approached 33%, which occurred after three weeks of incubation. The purpose of this initial high temperature period was to reduce the contribution of initially very high release rates (characteristic of many PCFs) to subsequent release rate measurements. The fertilizer prills were then removed from the flasks and placed in columns. Sand was then added to cover and fill the spaces between prills. Column length and diameter were ~15.5 cm and 1.5 cm, respectively, and some columns were lengthened to 20 cm to accommodate swelling of prills. Cotton was

placed in the bottom of each column before filling to prevent the escape of sand. A thermocouple was placed in one of the columns.

Three columns, each filled with one of the three PCFs, were then attached to the side of a 7.6 L glass jar that was inside a styrofoam box for insulation. The glass jar was filled with distilled water and the water temperature was controlled by an MTP-5 Microprocessor Temperature Programmer (Neslab Instruments Ltd., Etobicoke, Ont.) and a Digital Exatrol heater and temperature sensor (Neslab Instruments Ltd., Etobicoke, Ont.). A loop of flexible tubing attached to the intake and outflow nozzles of a Lauda RM6 cooling bath (Brinkmann Instruments, Inc., Wesbury, N.Y.) was also placed in the glass jar bath to help control the temperature. Tygon™ flexible plastic tubing (Norton Performance Plastics, Akron, Ohio) was fitted to the bottom of each column and the tubing emerged through a hole in the bottom of the styrofoam box. The end of each tube was positioned over a set of fraction collectors using 18 mm test tubes. Columns were then further insulated by packing polyester fiber between the columns and the styrofoam container wall. After the columns were attached to the bath, distilled water from the bath was pumped (at ~90-100 mL/h) into each column by a peristalic cassette pump (Manostat Corporation, New York) through separate flexible Tygon™ tubes. Leachate from each column was collected separately in test tubes on fraction collectors (~25 mL leachate/tube). The bath temperature was then adjusted so that the column temperature was approximately $20^{\circ}C$. The EC of the leachate was measured intermittently to determine when nutrient release had stabilized for each of the fertilizers. Once nutrient release stabilized at $20^{\circ}C$, columns were subjected to a gradual increase (~$2.4^{\circ}C/h$) to $40^{\circ}C$ and a subsequent decrease to $20^{\circ}C$, which simulated a temperature regime that has been found to occur in outdoor nursery containers (Ingram, 1981). The $20^{\circ}C$ temperature was then maintained for another hour. Leachate from each column was collected for each of the 20 hours of the experiment.

Leachate was analyzed for EC, and NO_3-N and NH_4-N concentrations. The experiment was then repeated for a second replication of three columns containing the three different PCFs. The experiment was again repeated (without replication) when Osmocote Plus™ had reached ~66% NO_3-N expenditure (Fig. 1). The experimental design was completely randomized with repeated measures. There were two replications

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of each of the three fertilizers. Data were analyzed using SAS (version 6.12, SAS Institute Inc., Cary, N.C.) PROC MIXED using AR(1) autocorrelation for the repeated measures.

Expt. 2: PCF in water-filled beakers subjected to constant temperatures for two-week intervals

Fourteen grams of PCF product and 100 mL of distilled water were added to each of 24 flasks (125 mL). There were three PCF products used (as previously described), and fourteen grams of each was added to eight flasks. Flasks were placed in a 40^oC water bath for three days. The purpose of this initial high temperature period was to reduce the contribution of initially very high release rates (characteristic of many PCFs) to subsequent release rate measurements. Bath temperature was maintained by a temperature controller and circulator.

At the end of the three day period at 40^oC, flask solutions were poured-off, rinsed with 100 mL of distilled water, and then re-filled with 100 mL of distilled water. Two water baths, each equipped with a 200 Watt thermostatically-controlled aquarium heater and a 238.5 L/h water pump, were kept at 22^oC (+/- 1^oC). These baths were cooled via loops of Tygon™ tubing connected to recirculating cooling baths. Two other water baths were equipped with thermostatically-controlled heater/circulators and kept at 34^oC . Two flasks of each fertilizer type from the previously mentioned 40^oC bath were randomly arranged in each of the 22^oC and 34^oC baths. After one week, solutions in each of the flasks were poured-off, rinsed with 100 mL of distilled water, re-filled with 100 mL of distilled water, and then replaced in their respective baths.

One week after being replaced in their baths, flask solutions were poured-off and their volumes measured. Solutions were analyzed for NO_3-N, NH_4-N, P and K concentrations, and EC. The water bath temperature treatment procedure was then repeated using bath temperatures of 28^oC and 40^oC. The experiment was a split-plot design. There were two replications of each temperature treatment (whole plot) and two subsample replications of each fertilizer (split plot) within each temperature treatment. Data were analyzed using SAS (version 6.12, SAS Institute Inc., Cary, N.C.) PROC GLM.

Results & Discussion

Expt. 1: PCF column elutions subjected to simulated diurnal temperature changes

For all fertilizers, nutrient release increased and decreased with the respective increase and decrease in temperature (Fig. 1). The increasing and decreasing nutrient release patterns were remarkably symmetrical. For all nutrient release parameters measured (soluble salts, NO_3-N, and NH_4-N), the temperature effect was significant and there was a significant product x temperature interaction (Table 1). (However, only the experiment conducted at 33% Osmocote Plus™ NO_3-N expenditure was replicated and analyzed statistically.) In the product x temperature interaction, the PCFs with the highest and lowest release magnitudes between 20°C and 35°C (Nutricote™ and Osmocote Plus™, respectively), had the lowest and highest magnitudes, respectively, between 35°C and 40°C. This interaction indicates that there were differences in temperature response patterns among the fertilizers. Among products, there were no significant differences in nutrient release (Table 1). This seeming lack of product main effect is likely the result of product differences being cancelled when averaged over temperatures in this interaction. For all fertilizers, increases in nutrient release between 20°C and 40°C were quite large (Fig. 1a, b, c; Appendix B: Table 1). The overall mean increase in nutrient release (between 20°C and 40°C) was largest for Osmocote Plus™ (4023% for NO_3-N) and smallest for Nutricote™ (1032% for NH_4-N) (Fig. 1a, b, c; Appendix B: Table 1).

The experiment was repeated (without replication) when Osmocote Plus™ had reached ~66% NO_3-N expenditure (Fig. 1d). There was a large temperature-mediated nutrient release response for all three fertilizers, similar to that described above. However, this time Polyon™ released ~69% more salts and had a ~57% higher peak salt release than Osmocote Plus™. This may have been because Polyon™ prills contained more fertilizer at this stage than did Osmocote Plus™ despite the fact that prill fertilizer content was not measured at this time. In support of this explanation, data from Expt. 1 in Chapter 2 indicated that, at week three, the NO_3-N contents of Osmocote Plus™, Polyon™, and Nutricote™ were, on average, 33.0%, 15.6%, and 29.3% expended, respectively, whereas at week eight the NO_3-N contents of these PCFs were, on average, 66.3%, 43.9%, and 58.4% expended, respectively.

If these laboratory findings are indicative of PCF performance in nursery conditions, then daily container temperature changes may have rapid effects on container nutrient levels as well as on nutrient release longevity of PCFs. Increases in substrate temperature (to 40°C) have been shown to increase N uptake by some plants (Johnson and Ingram, 1984; Harrison et al., 1988). However, the magnitudes of increase found (a 72% increase from 1.14 g/g leaf dry weight at 27°C to 1.96 g/g leaf dry weight at 40°C in Johnson and Ingram (1984)) are far lower than the increases in PCF nutrient release found in Expt. 1 and for Nutricote™ in Expt. 2, but similar to those found for Osmocote Plus™ and Polyon™ in Expt. 2. Therefore, depending upon plant demand and PCF product, a PCF that releases adequate amounts of nutrients at low temperatures may release excessive amounts of nutrients at higher temperatures. More research is needed to evaluate the significance that PCF nutrient release in response to diurnal temperature changes has for plant growth and nutrient uptake.

Expt. 2: PCFs in water-filled beakers subjected to constant temperatures for two-week intervals

As in Expt. 1, soluble salts and nutrient release increased with increasing temperature (Fig. 2). There were significant temperature x product interactions, significant temperature main effects, and significant differences among products for release of soluble salts, NO_3-N, NH_4-N, P, and K (Table 2). The magnitudes of the temperature effects varied considerably among products (from 29% increase in nutrient release for Osmocote Plus™ NH_4-N to 364% increase in nutrient release for Nutricote™ NO_3-N) (Appendix B: Table 2). The temperature response patterns within fertilizers were similar for soluble salts, NO_3-N, and NH_4-N, but differed among fertilizers (Fig. 2). For these nutrients, Nutricote™ showed a much larger temperature-mediated change in nutrient release than did Osmocote Plus™ or Polyon™ and this accounts for the significant temperature x product interactions for all parameters measured (soluble salts, NO_3-N, NH_4-N, P, and K) (Table 2). The overall level of soluble salts and N release was from 1.5 to 2.4 times higher for Osmocote Plus™ than for Polyon™ at all temperatures (Fig. 2). The P and K release patterns of the three fertilizers were generally similar (Fig. 2).

However, at all temperatures, the amount of P and K released was between 2.1 and 4.0 times higher for Osmocote Plus™ than for Nutricote™ or Polyon™ (Fig. 2).

For all products, the observed temperature responses in Expt. 1 were much greater than those observed in Expt. 2 (Appendix B). For example, in Expt. 1 the NO_3-N release from Osmocote Plus™ increased 4023% as the column temperature increased from 20^oC to 40^oC, whereas in Expt. 2 release was only 45% higher at 40^oC than at 22^oC. There are several factors that may explain this difference. Differences in methodology may account for some of the discrepancy because there is evidence that nutrient release may be higher in the column environment than in the distilled water flask environment, at least for some nutrients (Appendix D). In the distilled water flask environment of Expt. 2, boundary regions of high salt concentration may have formed around fertilizer prills and inhibited nutrient release to some extent (Robert Wright, personal communication). In the columns used in Expt. 1, on the other hand, a relatively high volume of water was continuously washing over the fertilizer prills and this presumably inhibited boundary region formation. However, this hypothesis probably does not fully account for the very large differences observed. Abrasion of the fertilizer prills by sand particles in the columns of Expt. 1 may also have caused an increase in nutrient release. However, the rapid decline in nutrient release with decreasing temperature suggests that permanent damage to the prills was not occurring.

Other possible explanations for the discrepancy between Expts. 1 and 2 involve the rapidity of temperature change and PCF lifespan effects. The nutrient release values of Expt. 2 (Fig. 2) represented nutrient accumulation during one week at constant temperatures. On the other hand, the nutrient release values in Expt. 1 (Fig. 1) represented nutrient accumulation on an hourly basis during a 20 h experiment with rapidly changing temperatures. Hence, PCF temperature response may be greater when temperatures change rapidly than when temperatures remain constant for longer periods. Furthermore, there may be a fertilizer lifespan effect that manifested itself during the longer experimental period in Expt. 2. Findings from Chap. 2, Expt. 1 may lend some insight into this possibility. In Fig. 3 (of this chapter), data from Chap. 2, Expt. 1 are shown for the first eight weeks of nutrient release at 40^oC in distilled water flasks. This figure clearly shows that nutrient release can change substantially over time even when a

constant temperature is maintained. The week-long measurement period in Expt. 2 was between 1.5 and 2.5 weeks into the lifespan of the fertilizers. During this period, nutrient release from Osmocote Plus™ and Polyon™ was declining even at a constant temperature (Fig. 3). On the other hand, nutrient release from Nutricote™ was increasing (Fig. 3). Thus, the possibility exists that the decline in nutrient release for Osmocote Plus™ and Polyon™ interacted with temperature response during the experimental period and partially canceled-out the observed temperature effect. The increasing nutrient release of Nutricote™ may have interacted with temperature response to increase the observed temperature effect. Finally, of importance is the fact that the fertilizer prills used in Expt. 2 were at a somewhat earlier stage in their lifespan than were those used in Expt. 1. Further studies are needed in order to determine the cause(s) of the temperature response differences between Expt. 1 and Expt. 2.

Conclusions

Until now, PCF temperature response has been studied during relatively long periods at constant temperatures. However, temperatures in containers can rapidly undergo large diurnal changes (Ingram, 1981). The present study suggests that PCF nutrient release in response to rapid temperature changes may be different than the temperature response to temperatures that are maintained for longer periods. If future studies confirm these results, the development of new methods for evaluating PCF temperature response that take these differences into account may be desirable. Such methods could give more insight into the actual performance of PCFs in the container environment.
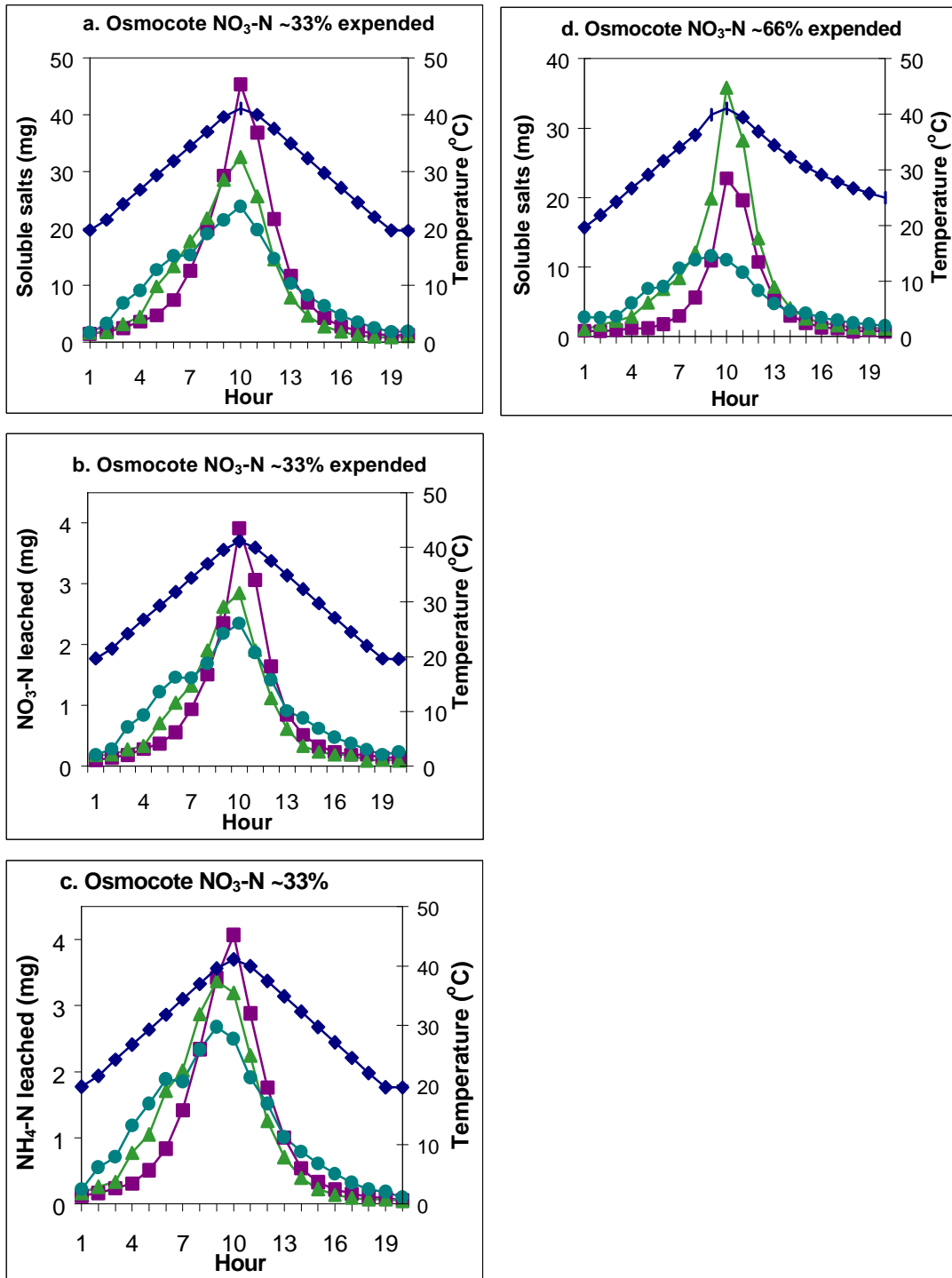
Fig 1. Expt. 1, Soluble salt, NO3-N, and NH4-N release of Osmocote Plus™ (■),
Polyon™ (▲), and Nutricote™ (●) in sand columns subjected to simulated
diurnal temperature changes. Column Temperature (♦)
For a, b, and c (Osmocote Plus™ at 33% NO3-N expended), each point represents
a mean of two observations. For d (Osmocote Plus™ at 66% NO3-N), each point
represents a single observation.

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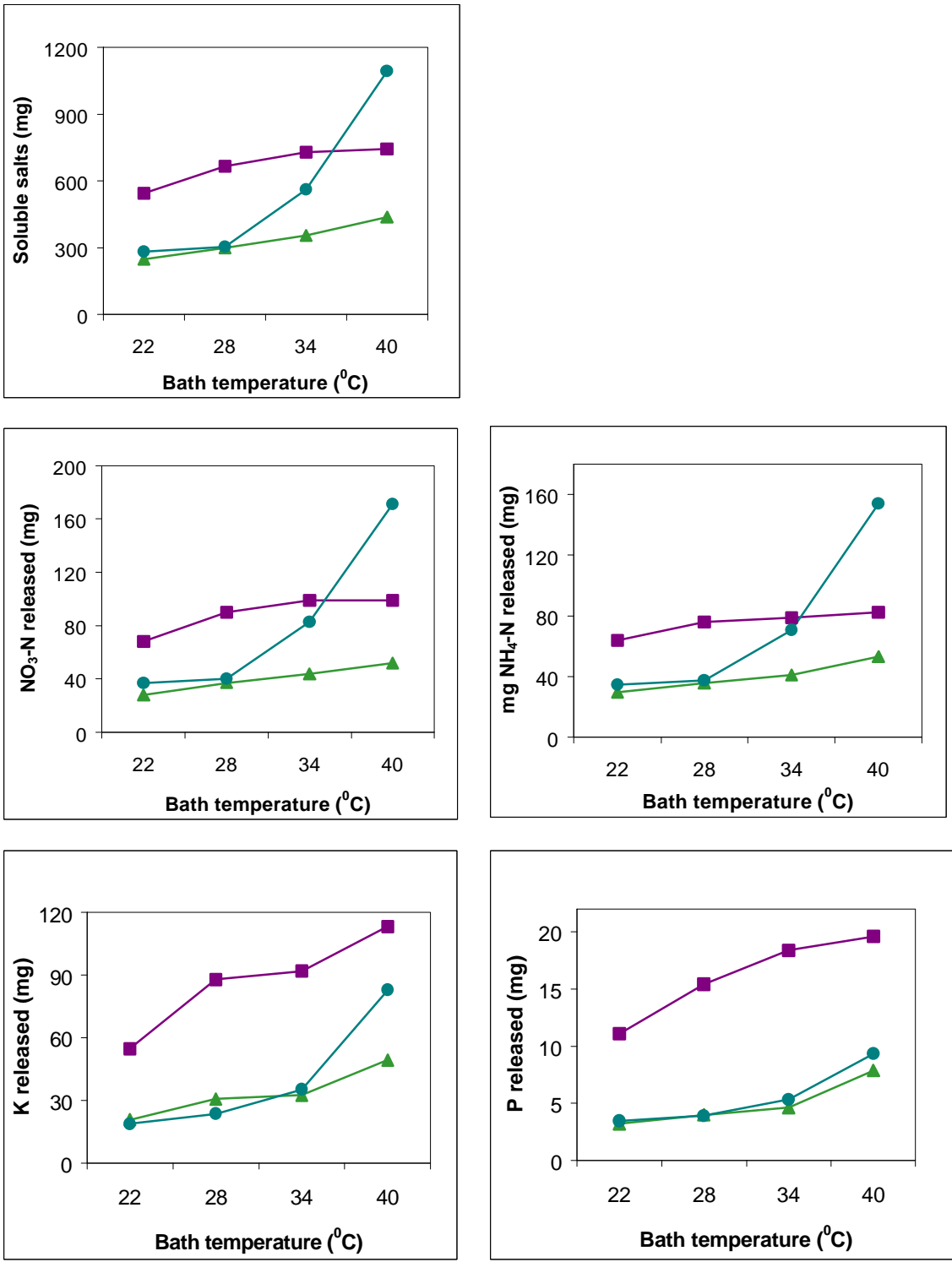
Fig 2. NO$_3$-N, NH$_4$-N, P, K, and soluble salts (converted from EC x 700)
release of Osmocote Plus™ (■), Polyon™ (▲), and Nutricote™ (●) in response
to temperatures maintained for one week (Expt. 2). PCFs were kept in flasks of
distilled water.

Means, n=4.
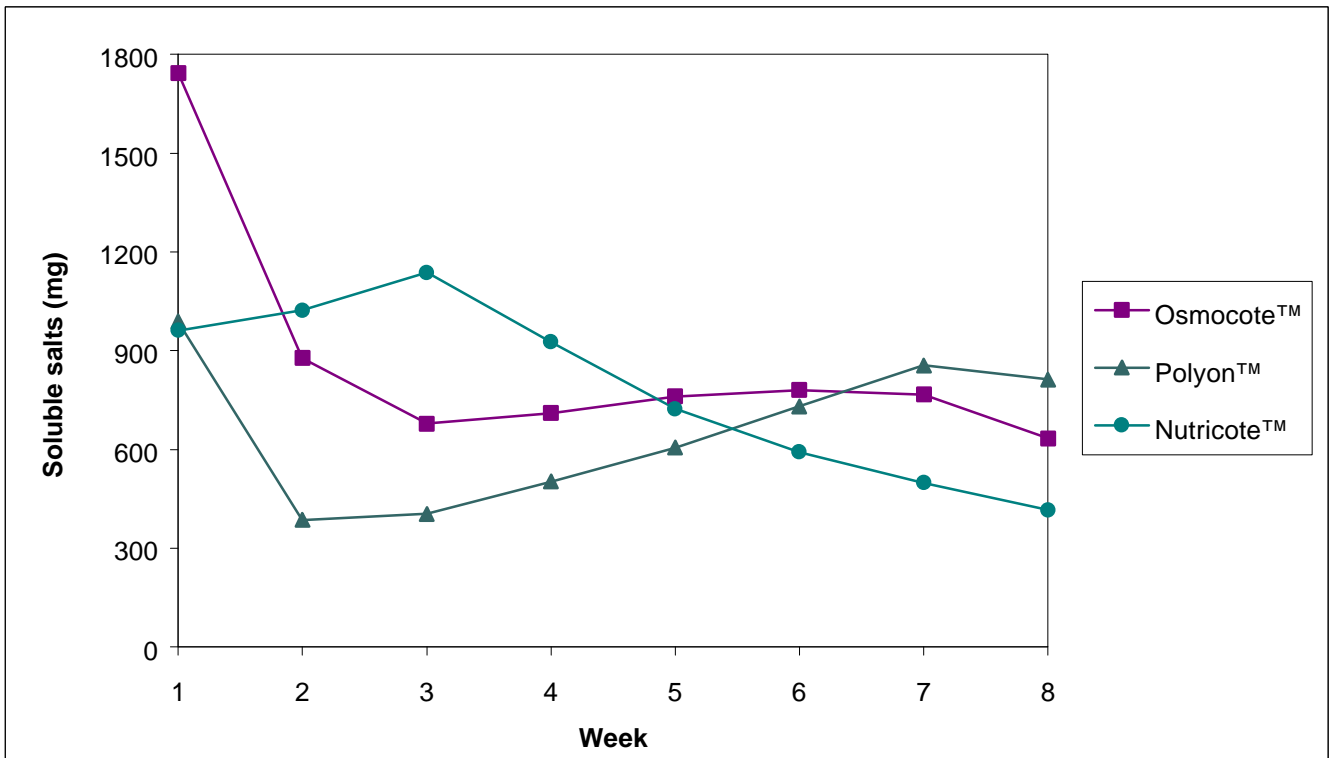
Fig. 3. Soluble salts (derived from EC x 700) release in flasks of distilled water at 40°C
for the first 8 weeks of Expt. 1, Chapter 2.
Fertilizers are Osmocote Plus™ (■), Polyon™ (▲), and Nutricote™ (●)
Means, n=4.

Table 1. Main Effects and Interactions for soluble salts and N release patterns (based upon mg released) for Osmocote Plus™, Polyon™ , and Nutricote™ subjected to simulated diurnal temperature changes (from $20^{o}C$ to $40^{o}C$) in sand columns when ~33% of Osmocote Plus'™ NO_3-N is expended (Expt. 1).

| Variable	p-values		
	Product	Temperature	Product x temperature
Soluble salts	0.8213	0.0001	0.0001
NO_3-N	0.7082	0.0001	0.0003
NH_4-N	0.9018	0.0001	0.0003

Table 2. Main Effects and interactions for nutrient release (based upon mg released) vs. temperature for Osmocote Plus™, Polyon™ , and Nutricote™ held at temperatures of 22 , 28, 34, and $40^{o}C$ for two weeks (Expt. 2)

Variable	p-values		
	Temperature	Product	Temperature x product
Soluble salts	0.0006	0.0001	0.0001
NO_3-N	0.0024	0.0001	0.0001
NH_4-N	0.0003	0.0001	0.0001
P	0.0008	0.0001	0.0002
K	0.0006	0.0001	0.0001

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Percentage Release Figures for Chapter 2, Expt. 1
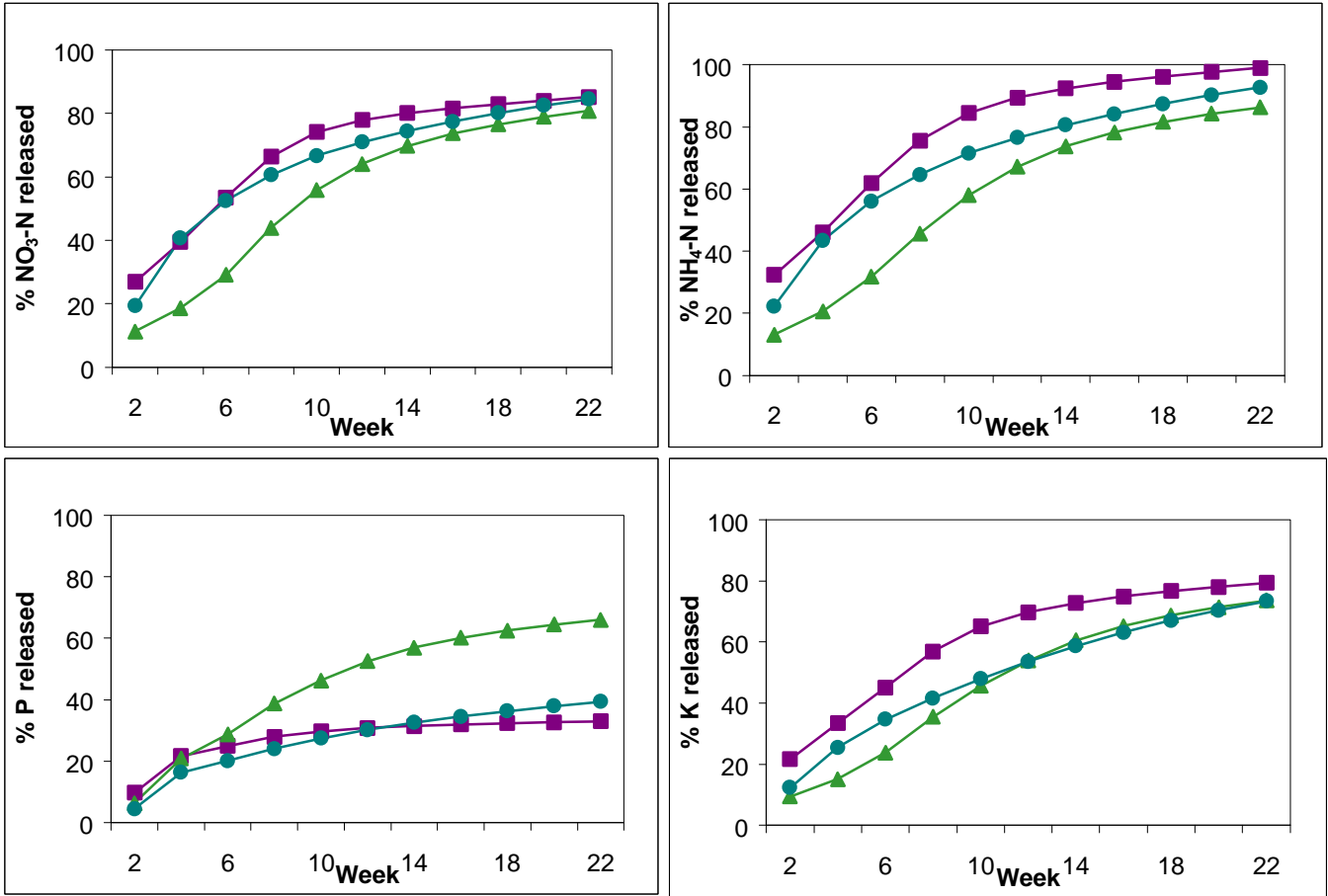
Fig. 1. NO$_3$-N, NH$_4$-N, P, and K release patterns of Osmocote Plus™ (■),

Polyon™ (▲), and Nutricote™ (●) during a 22 week incubation at 40°C

(Expt. 1). Percentages are based on the stated fertilizer formulation

(Appendix E).

Means, n=4.

Fig. 2. Fe, Mn, Cu, and Zn release patterns of Osmocote Plus™ (■), Polyon™ (▲), and

Nutricote™ (●) during a 22 week incubation at 40°C (Expt. 1).

Percentages are based on the stated fertilizer formulation (Appendix E).
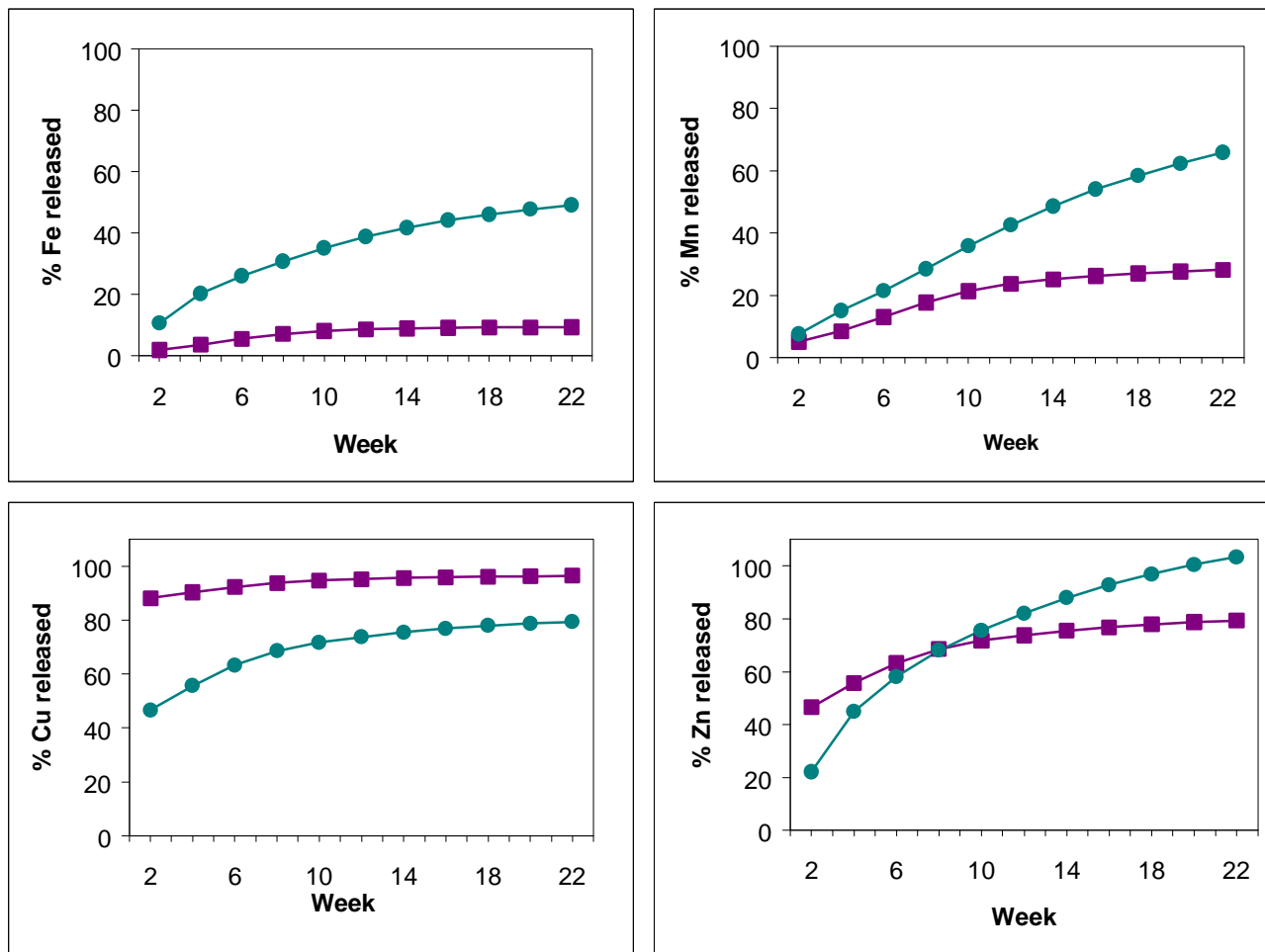
Means, n=4.

Appendix B

Overall Percentage Increases in Nutrient Release for Expts. 1 and 2, Chapter 3

Table 1. Average overall change (%) in nutrient release between highest (40^oC) and lowest (20^oC) temperatures for the column diurnal temperature change experiment (Osmocote Plus™ NO_3-N ~33% expended) (Expt. 1). Means, n=2

Fertilizer	Variable		
	NO_3-N	NH_4-N	Soluble salts
Osmocote Plus™	4023%	3206%	2951%
Polyon™	1492%	1878%	1886%
Nutricote™	1177%	1032%	1367%

Table 2. Average overall change (%) in nutrient release between highest (40^oC) and lowest (20^oC) temperatures for the two-week flask temperature experiment (Expt. 2). Means, n=4

Fertilizer	Variable		
	NO_3-N	NH_4-N	Soluble salts
Osmocote Plus™	45%	29%	36%
Polyon™	86%	80%	76%
Nutricote™	364%	345%	288%

Appendix C

Evaluation of Nutrient Extraction Method for Determining the Fertilizer Contents of PCFs

Objectives

This study was undertaken to evaluate the nutrient extraction method used in Expt. 2, Chapter 2. There was some concern with regard to the ability of this method to adequately dissolve the nutrients remaining inside PCF prills. Because pH is known to affect the solubilities of many plant nutrients, this study investigated the effects of solution pH on solubilization of PCF fertilizer contents. In Expt. 2, distilled H_2O was used as the solvent, whereas in this study both distilled H2O and dilute HCl solvents were compared. This study also aimed to evaluate the correspondence between the PCF manufacturers' stated formulations and actual PCF nutrient contents.

Materials and Methods

The three PCFs studied in this experiment were Osmocote Plus™ 15N-3.93P-9.96K, Polyon™ 18N-2.62P-9.96K, and Nutricote™ 18N-2.62P-6.64K (as described in Chapter 2). EC and nutrient concentrations were measured using the equipment and techniques described in Chapter 2.

Four 14 g samples of Osmocote Plus™ 15N-3.93P-9.96K, Polyon™ 18N-2.62P-9.96K, and Nutricote™ 18N-2.62P-6.64K were measured. Each of these samples was then ground up using a mortar and pestle and thoroughly mixed in either one L of distilled water (pH ~5.1) or one L of HCl solution (pH ~2.8, 200 microliters of 36.5-38% HCl in one L of solution). After mixing, solution volumes were measured and the solutions were analyzed for electrical EC and concentrations of NO_3-N, NH_4-N, P, K, Fe, Mn, Cu, and Zn.

The experiment was a split-plot design. There were two replications of each fertilizer whole-plot treatment and two replications of the two pH sub-plot treatments. Data were analyzed using SAS (version 6.12, SAS Institute Inc., Cary, N.C.) PROC GLM.

Results and Discussion

Based upon percent recovery (compared to stated formulation), there was a significant pH effect for P only (Table 1). However, the magnitude of the pH effect for P was not large (less than a 4% change, Table 2, Fig. 1). For macronutrients other than P, the grinding and solubilization technique recovered nutrient amounts within at most +/- 12% of the stated formulation (Tables 2 and 3). However, recovery percentages for P were all lower than the stated formulation by ~20% (Tables 2 and 3).

For micronutrients, percentage recovery from Osmocote Plus™ was much lower than the stated formulation (Table 3, Fig. 1). The percent recovery for Nutricote™ was much higher than the stated formulation for Mn and Zn (Table 3, Fig. 1). The discrepancies between formulation and actual amount recovered using this nutrient recovery technique may be due either to the relative insolubility of nutrients in water or to discrepancies between stated formulation and actual contents.
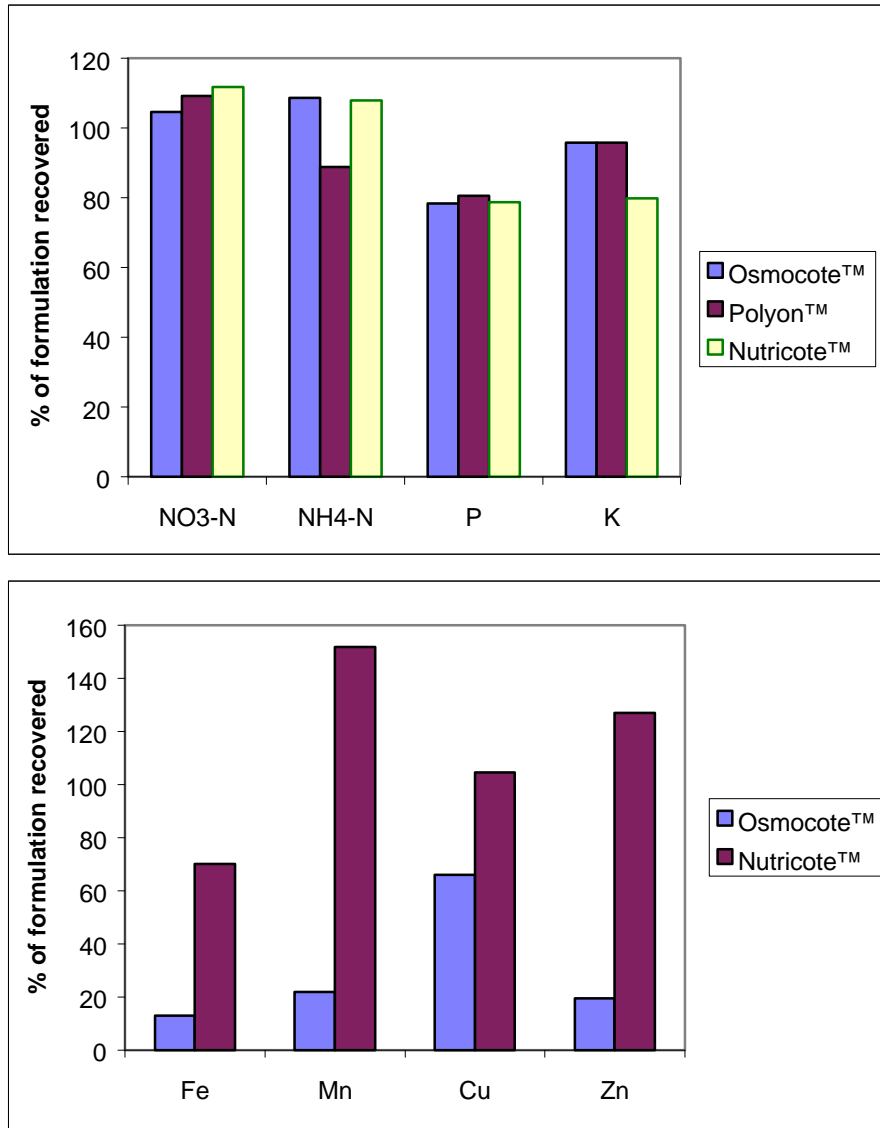
Fig. 1. Mean percent of formulation recovered via the "grinding and solubilization" technique used in Chap. 2, Expt. 2. Means, n=2.

Table 1. ANOVA table for % of formulation recovered using the "grinding and solubilization" technique (Chapter 2, Expt. 2).

Nutrient	p-values		
	Product	pH	Product x pH
NO_3	0.0990	0.2534	0.6464
NH_4	0.0119	0.3964	0.4615
P	0.0523	0.0061	0.0811
K	0.0069	0.3088	0.1541
Fe	0.0196	0.0592	0.0505
Mn	0.0039	0.0965	0.6671
Cu	0.1446	0.7156	0.8832
Zn	0.0052	0.1263	0.3806

Table 2. Effects of pH on % nutrient recovery (across fertilizers) (Chapter 2, Expt. 2).

	Nutrient							
Solvent pH	NO_3	NH_4	P	K	Fe	Mn	Cu	Zn
~5.1 (distilled water)	107a[zy]	102a	76.7b	90.0a	36.1a	85.3a	84.5a	72.2a
~2.8 (distilled water + 200 ppm of 36.5-38% HCl)	110a	102a	81.8a	91.1a	46.9a	88.4a	86.1a	74.3a

[z]Means, n=2

[y]Pairs of means are not significantly different when followed by the same letter (α = 0.05)

Table 3. Mean % recovery (across pH) for three different PCFs using the "grinding and solubilization" technique (Chapter 2, Expt. 2).

	Nutrient							
Fertilizer	NO_3	NH_4	P	K	Fe	Mn	Cu	Zn
Osmocote Plus™	105a[yz]	109a	78.4a	95.9a	13.0a	21.9a	65.9a	19.6a
Polyon™	109a	88.9b	80.6a	95.9a				
Nutricote™	112a	108a	78.7a	79.9b	70.0b	152 b	105b	127b

[z]Means, n=2

[y]Pairs of means are not significantly different when followed by the same letter (Tukey HSD, α = 0.05)

Appendix D

Comparisons between Column Leaching and Flask Elution Methods

Objective

The objective of this study was to determine whether there are significant differences in soluble salt and N release between the column leaching technique used in Chap. 3, Expt. 1 and the bath elution technique used in Chap. 3, Expt. 2.

Materials and Methods

The PCF studied in this experiment was Osmocote Plus™ Plus 15N-3.93P-9.96K (see Appendix E for formulation & longevity rating). EC and nutrient concentrations were measured using the equipment and techniques described in Chapter 2, p. 13.

Four Erlenmeyer flasks (125 mL) were each filled with 14 g of Osmocote Plus™ and 100 mL of distilled water. The flasks were placed in a randomized arrangement in a water bath maintained at $40^{o}C$ by a thermostatic temperature controller and circulator. Flasks were incubated for 4.5 days and were then removed from the bath and the fertilizer solution in each flask was poured-off and measured for EC, NO_3-N, and NH_4-N.

The fertilizer prills from two of the flasks were then placed in sand columns, as described in Chapter 3, Expt. 1. The experimental setup for the columns was also the same as in Expt. 1, Ch. 3. The remaining two prill-filled flasks were re-filled with 100 mL of distilled water and placed in a water bath maintained at $40^{o}C$. The sand columns were also maintained near $40^{o}C$ and leached at ~100 mL/h. After 20 h, the leachate from the columns and the solution from the beakers was collected and analyzed for EC, NO_3-N, and NH_4-N. The experiment was then repeated for a second replication.

The experiment was conducted as a completely randomized design with subsampling. There were two treatment replications and two subsamples. An analysis of covariance was performed using as a covariate the initial measurements of nutrient release after 4.5 days in the $40^{o}C$ bath. This analysis attempted to control for much of the nutrient release variability between samples. Data were analyzed using SAS (version 6.12, SAS Institute Inc., Cary, N.C.) PROC GLM.

In addition, the mean release rates for the column experiment (Chap. 3, Expt. 1) and the two-week temperature bath experiment (Chap. 3, Expt. 2) were calculated for the range of 34 to 40°C and compared. For the aforementioned two experiments and the constant 40° bath experiment (Chap. 3, Expt. 2), mean NO_3-N and NH_4-N release rates at 40°C were calculated and compared.

Results & Discussion

In this experiment, significant differences in nutrient release between the sand column and elution flask techniques were found for soluble salts and NH_4-N (Table 1). However, the observed differences (a ~50% increase at the greatest, for NH_4-N) are not sufficiently large to account for the two to more than 25 fold differences between the nutrient release responses to temperature observed in Expts. 1 and 2 in Chap. 3 (Appendix B, Results and Discussion, Chap. 3). Therefore, it appears that other factors also contributed to the observed discrepancy in the Chap. 3 experiments. In Chap. 3, Expt. 1 (the diurnal temperature/sand column experiment), the prills remained in the columns for longer time periods than in the present experiment. This may have resulted in more swelling of the prills in Expt. 1, Chap. 3 and hence more abrasion which led to higher nutrient release through the abraded membrane. Longer exposure to the air in Expt. 1, Chap. 3 may also have contributed to the differences by affecting prill membrane characteristics and thereby increasing nutrient release. Furthermore, the prills used for the column experiment in Chap. 3 were farther along in their lifespan than those used in the present experiment.

In comparing the previous experiments of Chaps. 2 and 3 (Figs. 1 & 2), it is clear that, at least at temperatures between 34°C and 40°C, PCFs have tended to release N more quickly in leached sand columns than in flasks filled with distilled water. The cause(s) of these differences are not yet clear. More research is needed to determine the cause of the observed nutrient release differences between the sand column and elution flask methodologies.
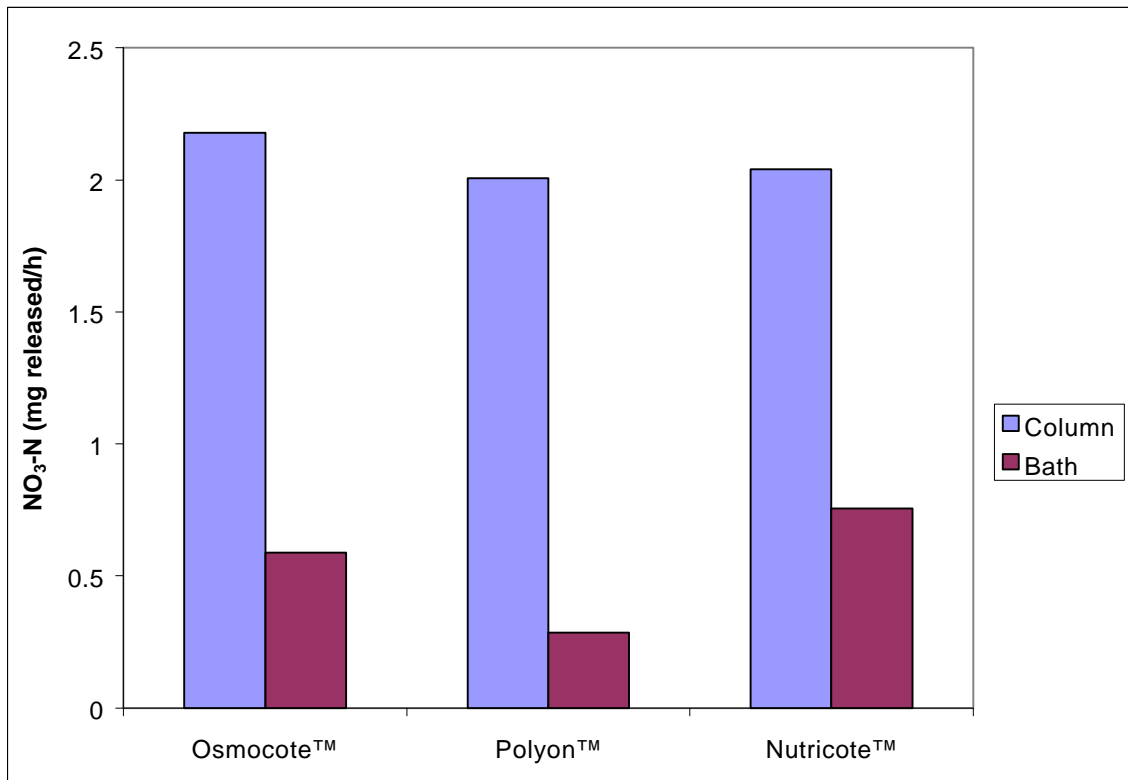
Fig. 1. Comparison of mean NO$_3$-N release rates for the column experiment (Chap. 3, Expt. 1) and the two-week temperature bath experiment (Chap. 3, Expt. 2) over the range of 34 to 40°C.
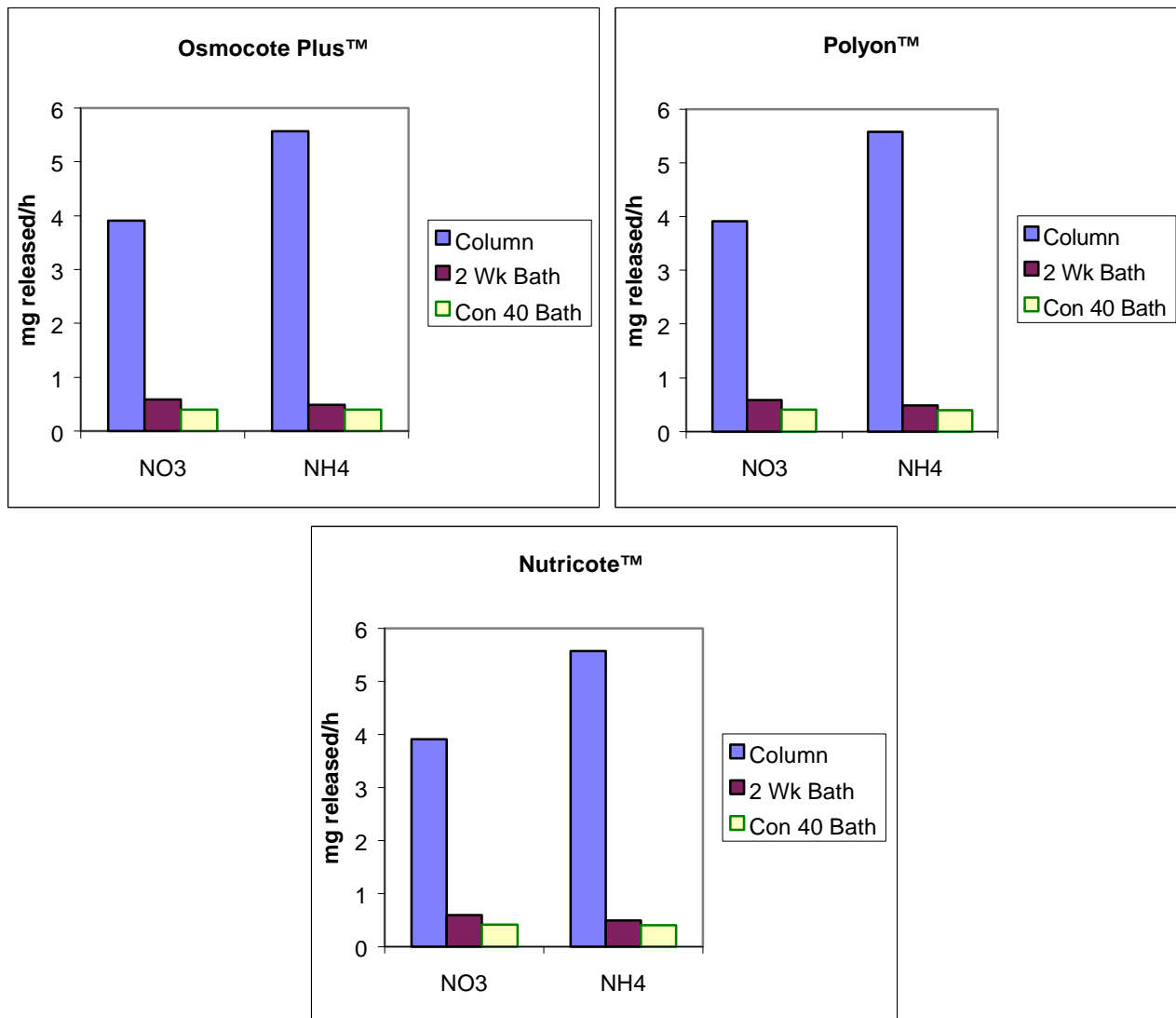
Fig. 2. Comparison of mean NO_3-N and NH_4-N release rates at 40°C for the column experiment (Chap. 3, Expt. 1), the two-week temperature bath experiment (Chap. 3, Expt. 2) and the constant 40°C temperature bath experiment (Chap. 2, Expt. 1).

Table 1. Comparison of column and flask techniques (Analysis of Covariance)

	LS Means		
	Soluble Salts (mg)	NO$_3$-N (mg)	NH$_4$-N (mg)
Column	294.7[z]a[y]	28.8a	30.1a
Flask	199.8b	26.6a	20.0b

[z]Means reported are for n=2 observations

[y]Means are not significantly different when followed by the same letter ($\alpha =$ 0.05)

Appendix E.

PCF Formulations

Lot #: 493510-04	Osmocote Plus™ Plus 15-9-12	
10/97	Longevity: 8-9 months at 70°F	
90326	Source	%
Total N		15
NH_4-N	ammonium nitrate, ammonium phosphate	7
NO_3-N	ammonium nitrate, potassium nitrate	8
P_2O_5	ammonium phosphate, calcium phosphate	9
K_2O	potassium nitrate,	12
Ca	calcium phosphate	
Mg	magnesium sulfate	1
S	magnesium sulfate, copper sulfate, iron sulfate, manganese sulfate, zinc sulfate	2.3
B	boric acid	0.02
Cu	copper sulfate	0.05
Fe	iron sulfate, iron EDTA	0.45
Mn	manganese sulfate	0.06
Mo	sodium molybdate	0.02
Zn	zinc sulfate, zinc oxide	0.05

Product #: 515108	Polyon™ 18N-2.62P-9.96K	
	Longevity: 9 months at 80°F	
	Source	%
Total N		18
NH$_4$-N	ammonium nitrate, ammonium phosphate	9.52
NO$_3$-N	ammonium nitrate	8.48
P$_2$O$_5$	ammonium phosphate	6
K$_2$O	potassium sulfate	12
Ca	calcium?	1.22
S	potassium sulfate	4.4

Lot #: DOT-44P 5H4/Y50/S/91	Nutricote™ 18N-2.62P-6.64K Longevity: 9 months at 77°F	
	Source	%
Total N		18
NH$_4$-N	ammonium nitrate, ammonium phosphates	8.6
NO$_3$-N	ammonium nitrate, Potassium nitrate	9.4
P$_2$O$_5$	ammonium phosphates, calcium phosphate	6
K$_2$O	Potassium nitrate	8
Ca	calcium phosphate	
Mg	magnesium sulfate	1.2
S	magnesium sulfate, copper sulfate, manganese sulfate, zinc sulfate	
B	sodium borate	0.02
Cu	copper sulfate	0.05
Fe	ferrous ethylenediamine tetraacetate	0.2
Mn	manganese sulfate	0.06
Mo	sodium molybdate	0.02
Zn	zinc sulfate	0.015

Chad Eric Husby

Vita

Chad was born in Traverse City, Michigan and grew up in rural Leelanau County, a peninsula in Lake Michigan. He graduated from Suttons Bay High School in June, 1993. He attended Alma College (Alma, Michigan) starting in August 1993 and graduated in April 1997 with a Bachelor of Science degree and a double major in biology and mathematics. Chad performed undergraduate research on jumping spider behavior with Dr. David Clark during the summer of 1994 and presented his work at a meeting of the Michigan Academy of Science, Arts, and Letters. He also worked in the college greenhouse and tutored calculus during his time as an undergraduate. During his senior year, Chad researched into the occurrence of numbers from the Fibonacci Sequence in plant form and development. He presented his work on this subject to the Michigan Chapter of the Mathematical Association of America. He came to Virginia Tech to work on his Master of Science degree in June 1997. He initially worked with Dr. Ronald Morse on weed-crop ecology, but later decided to work with Dr. Alex Niemiera on nursery-related research. While at Virginia Tech, Chad taught four semesters of indoor plants. He completed his Master of Science in June, 2000. He began work on a Master of Applied Statistics (M.A.S.) in June 1999 at The Ohio State University in Columbus, Ohio. He expects to complete this degree in December 2000. During the summer of 2000, Chad will undertake an internship with the Leelanau Conservancy, working on ecological assessment of wetlands in northern Michigan.