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Root-Zone pH, Calcium, and Magnesium Management
in Peat-Based Container Media

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ROOT-ZONE pH, CALCIUM, AND MAGNESIUM MANAGEMENT IN PEAT-BASED CONTAINER MEDIA

By

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ABSTRACT

Root-Zone pH, Calcium, and Magnesium Management in Peat-Based Container Media

By

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Optimizing the pH, Ca, and Mg management of low- and nonleaching irrigation systems requires an understanding of how a number of sources including lime, preplant nutrient charge (PNC) fertilizers, irrigation-water sources (IWS), water-soluble fertilizers (WSF), root media, and plant species interact during the production of a crop to affect pH, Ca, and Mg management initially and over time. Preplant nutrient charge fertilizers and root media were found to have minimal effect on long-term pH, Ca, and Mg management. By itself, the type of dolomitic liming material, it's particle size and incorporation rate affected the initial pH and final stable pH of an unplanted root medium, but had minimal effect on root-medium Ca and Mg concentrations. With one type of dolomitic carbonate lime ($CaCO_3$ and $MgCO_3$), a large amount of unreacted or residual material remained once the equilibrium pH of the medium was reached. The residual lime affected long-term pH, Ca, and Mg buffering capacity in media given nutrient solutions (NS) containing high NH_4-N, and low Ca and Mg, but not in media given NS containing low NH_4-N, and high Ca and Mg compared to the same medium containing a dolomitic hydrated lime ($Ca(OH)_2$ and $Mg(OH)_2$) with minimal residual material. In addition, the alkalinity concentration in the IWS and the $NH_4 : NO_3$ ratio in the WSF interacted to affect the overall type of reaction (either acidic or basic) produced by the NS in the root medium. A linear relationship was found between the concentration of Ca and Mg in the NS and shoot-tissue Ca and Mg suggesting that other ions contained in the NS (NH_4, K, SO_4) did not interfere with uptake. Instead, the primary factor affecting uptake of Ca and Mg was their concentration in the NS, as affected by the IWS and WSF. Differences in root medium pH and Ca and Mg uptake by nine plant species was also studied.

Dedication

I would like to dedicate this to my wife, Kathy. Thank you for all the love and support.

Acknowledgments

I would like to thank my advisor, John Biernbaum, for giving me the chance to go to graduate school and for his and advise in all my projects. Thanks also goes to the other members of my committee, Drs. Royal Hiens, Robert Schutzki, Boyd Ellis, and Darryl Warncke. I also would like to thank my friends and colleagues Paul Fisher, Jim Faust, Tom and Cara Wallace, Cathy Witman, and Mark Yelanich for their support.

Finally, I would like to acknowledge all the undergraduate students that worked for me through the years. I started to list all the people, but quickly realized that I have forgotten some of their names. For that I am truly sorry, because without their support and dedication, a large part of my research would not have been done.

Guidance Committee:

The paper format was adopted for this dissertation in accordance with departmental and university regulations. As of October 31, 1996, Paper 1 (Geographical characterization of greenhouse irrigation water) has been accepted for publication in HortTechnology. Paper 2 (Availability and persistence of macronutrients from lime and preplant nutrient charge fertilizers in peat-based root media) was submitted and published in the Journal of the American Society for Horticultural Science [121(3):453-460]. Paper 3 (The effect of lime, irrigation-water source, and water-soluble fertilizer on root-zone pH, electrical conductivity, and macronutrient management) was submitted and published in the Journal of the American Society for Horticultural Science [121(3):442-452]. Paper 4 (The effect of container root media on root-zone pH, calcium, and magnesium management with impatiens) has been accepted for publication in the Journal of the American Society for Horticultural Science. Paper 5 (The effect of bedding plant species on pH, electrical conductivity, and macronutrient management) is to submitted for HortScience.

Flowers have spoken to me more than I can tell in written words. They are the hieroglyphics of angels, loved by all people for the beauty of the character, though few can decipher even fragments of their meaning.

Lydia M. Child

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INTRODUCTION

Introduction

Historically, the switch from field soils to soilless root media in ornamental plant production occurred due to the difficulty in obtaining uncontaminated field soil with the proper balance of physical and chemical properties and the improved aeration and drainage provided by coarser soilless root media. Soilless root media can be leached frequently, are difficult to over water, and were designed specifically for automated irrigation system (drip irrigation) which are not uniform in the application of irrigation water and fertilizer salts. It was not uncommon for root-medium pH and nutrient concentrations in both the root medium and plant tissue to be managed using high leaching rates ($> 50\%$) and high fertilizer concentrations (N at 300 to 400 $mg\cdot L^{-1}$) applied with every irrigation.

It is no longer acceptable to manage root-medium pH and macronutrient concentrations in the root medium and plant tissue with high WSF concentrations and high leaching rates because of concerns about water, fertilizer, and chemical runoff into the environment from greenhouses. Irrigation systems that minimize or eliminate water, fertilizer, and chemical runoff into the environment currently exist. With the low- or nonleaching irrigation systems, lower concentrations of fertilizer must be used (N at 150 to 200 $mg\cdot L^{-1}$) in order to prevent salt buildup in the medium (Yelanich and Biernbaum, 1993). It has been suggested that fertilization practices should be based on soil-test nutrient concentrations attained for a given addition of fertilizer, liming material, and irrigation water containing a known nutrient concentration in order to optimize root-medium pH and macronutrient management of these low- and nonleaching irrigation systems (Biernbaum, 1992; Vetanovetz and Knauss, 1988). However, these proposed strategies have not been tested under controlled conditions.

A number of sources interact to affect the nutrient supply in container root media throughout crop production. However, these sources do not affect the nutrient supply simultaneously or with equal intensity. This is especially true for Ca and Mg nutrition, where the sources can include the irrigation-water source, root media, lime, preplant nutrient charge fertilizers, and water-soluble fertilizers. Any discussion of Ca and Mg nutrition in container root media also must include pH management because of the direct or indirect effects that Ca and Mg sources have on pH. Finally, plant growth may directly affect medium pH as well as Ca and Mg uptake. A better understanding of how these sources interact is necessary to improve the recommendations for pH, Ca, and Mg management of container-grown crops over a wide range of conditions using low- or nonleaching irrigation systems. The objective of this study was to determine which sources are important for pH, Ca, and Mg management, and how multiple sources that supply Ca and Mg and affect pH interact during production to affect the overall pH, Ca, and Mg management of a crop.

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SECTION I

GEOGRAPHICAL CHARACTERIZATION OF GREENHOUSE IRRIGATION WATER

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Geographical Characterization of Greenhouse Irrigation Water

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Research Update

Geographical Characterization of Greenhouse Irrigation Water

Additional index words. alkalinity, boron, calcium, chloride, electrical conductivity, magnesium, pH, sodium, sodium-adsorption ratio, sulfate

Summary. Chemical analyses of 4306 randomly selected greenhouse water samples for 1995 from the United States and Canada were obtained from four analytical laboratories and graphically characterized using a distribution analysis. For pH, EC, and nutrient concentrations, a mean and median value and the percentage of samples with concentrations above or below those generally considered acceptable are presented for all samples and the 10 leading states in floricultural production. The median nutrient concentrations were determined to be more representative of the type of water found throughout the United States and Canada than that of the mean values because of the unequal distribution of the data. The overall median water source had a pH of 7.1; an electrical conductivity (EC) at 0.4 $dS \cdot m^{-1}$; an alkalinity of 130 mg $CaCO_3/L$; (in $mg \cdot L^{-1}$) 40 Ca, 11 Mg, 8 SO_4-S, 13 Na, 14 Cl, 0.02 B, and <0.01 F; a Ca : Mg ratio of 3.2 and a sodium adsorption ratio (SAR) of 0.7. The information presented characterizes irrigation water and may assist in the development of more refined fertilizer recommendations for greenhouse crop production.

Several limited studies have been conducted to quantify the nutrient content of different irrigation water sources (IWS) in the United States. Ludwig and Peterson (1984) conducted a study on greenhouse irrigation water, but the data were presented orally, not published in a readily accessible journal. In this study, pH ranged from 3.3 to 10.4 (mean 7.6); electrical conductivity (EC), from 0 to 6.5 $dS{\cdot}m^{-1}$ (mean 0.5 $dS{\cdot}m^{-1}$); alkalinity, from 2 to 575 mg $CaCO_3$/L (mean 147); (in $mg{\cdot}L^{-1}$) Ca, from 0 to 440 (mean 60); Mg, from 0 to 300 (mean 20); Na, from 0 to 1150 (mean 35); and B, from 0 to 2.9 (mean 0.1), based on 662 water samples. However, a large percentage of the samples (30%) came from Ohio, which may have biased the results. Reddy et al. (1996) found that only 11% of the IWS tested contained sufficient concentrations of SO_4-S (30 $mg{\cdot}L^{-1}$) recommended for plant growth in container culture. Reddy (1996) determined that a large number of samples from states along the Atlantic coast (72%), the northeast (88%), and in the Pacific Northwest (83%) of the United States were found to have SO_4-S concentrations < 10 $mg{\cdot}L^{-1}$, while states around the Great Lakes and Midwest tended to have a greater number of samples with SO_4-S concentrations between 10 and 20 $mg{\cdot}L^{-1}$. The concentrations of other nutrients were not reported in the last two studies.

Recommended or acceptable nutrient levels in irrigation water for greenhouse crops have been defined (Table 1). Emphasis needs to be placed on designing a water-soluble fertilizer program for container plant production based on a given medium and IWS (Biernbaum, 1992; Vetanovetz and Knauss, 1988). For example, Argo and Biernbaum (1996) demonstrated that four IWS varying in alkalinity, Ca, Mg, and SO4-S content had a significant effect on root-medium pH and nutrient concentrations as well as shoot-tissue nutrient concentrations with impatiens. Recognizing differences in irrigation water between states or geographical regions is important when making recommendations for the nutritional management of container-grown crops, but little information about regional differences in water quality exists. The objective of this study was to geographically characterize the irrigation water used in the greenhouse industry.

Materials and Methods

Analyses of 4306 randomly selected greenhouse water samples from 1995 were obtained from three commercial laboratories (Fafard Analytical Services, Athens, Ga.; Scotts Analytical Services, Allentown, Pa.; and Sun Gro Analytical Services, Warwick, N.Y.) and one university laboratory (Michigan State University Soil and Plant Nutrient Laboratory, East Lansing, Mich.). All four laboratories measured pH, EC, alkalinity, NO_3-N, PO_4-P, K, Ca, Mg, Na, Cl, and B. Only Fafard and Sun Gro laboratories measured SO_4-S. The possibility of fertilizer solutions being included in the samples was reduced by removing any sample with NO_3-N at >20 $mg \cdot L^{-1}$ and or PO_4-P at >10 $mg \cdot L^{-1}$. We could not account for duplicate analyses from the same source, the possibility that greenhouse operations with a given type of water were more or less likely to submit water samples for analyses, or account for changes in water quality from a single source over time.

Mean and median values were calculated from the overall data set and on a state-by-state basis. Data are presented from the 10 leading states in floriculture production (United States Department of Agriculture Floriculture Crop Summary, 1994, Washington, D.C.). These 10 states accounted for 70% of the wholesale value of floriculture crops in 1994 and for 57% of the total number of samples. Five percent of the samples came from Canada which were included in the overall mean and median values. Only Ontario had enough samples (93) to be included with the state data. The suggested nutrient ranges found in Rose et al. (1995) were used as the comparative values for the presented data, unless otherwise indicated, because it has been our experience that the values from Peterson are the suggested ranges most often reported.

Frequency distributions were calculated from the data using arbitrary ranges that are considered by the authors to have potential cultural significance. The ranges used were 0.4 pH unit; 0.2 $dS \cdot m^{-1}$ for EC; 40 $mg \cdot L^{-1}$ for alkalinity, 20 $mg \cdot L^{-1}$ for Ca, and 10 $mg \cdot L^{-1}$ for Mg, SO_4-S, Na, and Cl. The Ca : Mg ratio was calculated using their concentrations $mg \cdot L^{-1}$. Sodium adsorption ratio (SAR) was calculated as

$$\mathrm{SAR} = \frac{\mathrm{Na}}{[(\mathrm{Ca} + \mathrm{Mg}) / 2]^{1/2}}$$

from Allison et al. (1954), where Na, Ca, and Mg are in $meq \cdot L^{-1}$.

Results and discussion

The mean values calculated in this study were similar to those reported by Ludwig and Peterson (1985). However, for many of the nutrients, the mean value was larger than the median value, indicating an unequal distribution of the data caused by a large proportion of the samples having relatively low concentrations, where as, a small number of samples contained relatively high concentrations.

The pH of the water samples ranged from 2.7 to 11.3. The overall mean pH value of all water samples was 7.0, while the overall median value was 7.1 (Table 2), and the distribution was skewed (Fig. 1). Forty-four percent of the samples were within the suggested range of 5 and 7 (Rose et al., 1995), while 53% of the samples were >7. Water samples from North Carolina had the lowest median pH (6.7) and the Ohio and Illinois samples had the highest median pH (7.4) (Table 2).

The EC of the water samples ranged from <0.01 to 9.8 $dS \cdot m^{-1}$. The overall mean EC of all water samples was 0.6 and the overall median value was 0.4 (Table 2). Ninety-six percent of the samples had an EC within the suggested range of <1.5 $dS \cdot m^{-1}$ (Rose et al., 1995) and 71% had an EC <0.6 $dS \cdot m^{-1}$. Water samples from North Carolina had the lowest median EC (0.2 $dS \cdot m^{-1}$) and the California samples had the highest median EC (0.9 $dS \cdot m^{-1}$) (Table 2).

The alkalinity concentration of the water samples ranged from 0 to 1120 mg $CaCO_3$/L. The overall mean alkalinity of all water samples was 160 mg·$CaCO_3$/L, the overall median value was 130 mg·$CaCO_3$/L (Table 2), and the samples were more uniformly distributed over a wider range than any other factor analyzed (Fig. 1). Twenty-two percent of the water samples contained a alkalinity concentration within the suggested range of 40 to 100 mg·$CaCO_3$/L (Biernbaum, 1994; Rose et al., 1995). Water samples from New Jersey and North Carolina had the lowest median alkalinity concentration (90 mg $CaCO_3$/L) and the Illinois and Michigan samples had the highest median alkalinity concentration (200 mg $CaCO_3$/L) (Table 2). Based on the similar concentration of Na and Cl and low SAR value measured in the samples (Table 2), it is likely that the major source of alkalinity comes from Ca and Mg salts.

The Ca concentration in the water samples ranged from 0 to 560 mg·L^{-1}. The overall mean Ca concentration of the water samples was 52 mg·L^{-1} and the overall median value was 40 mg·L^{-1} (Table 2). Forty-four percent of the samples were within the suggested range of 40 and 120 mg·L^{-1} (Fig. 1) (Rose et al., 1995). Water samples from North Carolina had the lowest median Ca concentration (14 mg·L^{-1}) and the Illinois samples had the highest median Ca concentration (74 mg·L^{-1}) (Table 2).

The Mg concentration in the water samples ranged from 0 to 190 mg·L^{-1}. The overall mean Mg concentration of the water samples was 19 mg·L^{-1} and the overall median value was 11 mg·L^{-1} (Table 2). Seventy percent of the samples were within the suggested range of 6 and 24 mg·L^{-1} (Rose et al., 1995), but 48% of the samples contained Mg at <10 mg·L^{-1} (Fig. 1). Water samples from North Carolina had the lowest median Mg concentration (3 mg·L^{-1}) and the Illinois samples had the highest median Mg concentration (36 mg·L^{-1}) (Table 2).

The Ca : Mg ratio in the water samples ranged from <0.1 to 152. The overall mean Ca : Mg ratio of the water samples was 5.0 and the overall median value was 3.2

(Table 2). Twenty seven percent of the samples had a Ca : Mg ratio of >5 (Fig. 1). Water samples from Illinois had the lowest median Ca : Mg ratio (2.0) and the Texas samples had the highest median Ca : Mg ratio (4.7) (Table 2).

The SO_4-S concentration in the water samples ranged from 0 to 750 $mg \cdot L^{-1}$. The overall mean SO_4-S concentration of the water samples was 27 $mg \cdot L^{-1}$, while the overall median value was 8 $mg \cdot L^{-1}$ (Table 2). Fifteen percent of the samples were within the suggested range of 30 and 80 $mg \cdot L^{-1}$ (Fig. 1) (Reddy et al., 1994; Rose et al., 1995). Water samples from North Carolina had the lowest median SO_4-S concentration (<1 $mg \cdot L^{-1}$) and the Ohio samples had the highest median SO_4-S concentration (23 $mg \cdot L^{-1}$). These data support the conclusion of Reddy (1996) that a majority of the water sources in the United States (77%) are low in SO_4-S (Table 2), but that states around the Great Lakes (IL, MI, OH) tend to have greater SO_4-S concentrations than those states on the East Coast of the United States (FL, NC, NJ, NY, PA).

The Na concentration in the water samples ranged from 0 to 2500 $mg \cdot L^{-1}$. The overall mean Na concentration of the water samples was 33 $mg \cdot L^{-1}$ and the overall median value was 13 $mg \cdot L^{-1}$ (Table 2). Eighty-three percent of the samples were below the suggested maximum concentration of 50 $mg \cdot L^{-1}$ (Rose et al., 1995), with 41% of the samples containing Na at <10 $mg \cdot L^{-1}$ (Fig. 1). Water samples from Florida had the lowest median Na concentration (8 $mg \cdot L^{-1}$) and the California samples had the highest median Na concentration (49 $mg \cdot L^{-1}$) (Table 2).

The SAR concentration in the water samples ranged from 0 to 280. The overall mean SAR of the water samples was 2.6 and the overall median value was 0.7 (Table 2). Ninety-two percent of the samples were below the suggested maximum SAR of 4 (Fig. 1) (Rose et al., 1995) and 62% of the samples had an SAR <1. Water samples from Florida and Michigan had the lowest median SAR (0.4) and the California samples had the highest median SAR (1.6) (Table 2). Based on recommendations from Allison et al.

(1954), most of the water samples had a low potential for SAR hazard, but medium to high potential for salinity hazard (Fig. 2).

The Cl concentration in the water samples ranged from 0 to 1480 $mg \cdot L^{-1}$. The overall mean Cl concentration of the water samples was 33 $mg \cdot L^{-1}$, the overall median value was 14 $mg \cdot L^{-1}$ (Table 2), and the distribution was similar to that of Na (Fig. 1). Ninety-seven percent of the samples were below the suggested maximum concentration of 140 $mg \cdot L^{-1}$ (Rose et al., 1995), with 40% of the samples containing Cl at <10 $mg \cdot L^{-1}$. Water samples from North Carolina had the lowest median Cl concentration (6 $mg \cdot L^{-1}$) and the California samples had the highest median Cl concentration (43 $mg \cdot L^{-1}$) (Table 2).

The B concentration in the water samples ranged from 0 to 11.7 $mg \cdot L^{-1}$. The overall mean B concentration of the water samples was 0.22 $mg \cdot L^{-1}$ and the overall median value was 0.02 $mg \cdot L^{-1}$ (Table 2). Ninety-seven percent of the samples were below the suggested maximum concentration of 1.0 $mg \cdot L^{-1}$ (Rose et al., 1995) and 39% of the samples contained B at <0.01 $mg \cdot L^{-1}$. However, the potential for B toxicity in certain species may be at a much lower concentration. For example, Fafard Analytical Services suggests that B at >0.4 $mg \cdot L^{-1}$ may produce toxicity symptoms (W. McElhannon, Fafard Analytical Services, personal communications). Overall, 8% of the samples contained B at >0.4 $mg \cdot L^{-1}$, and within the individual states, ranged from <1% in the Florida samples to 30% in the California samples (Table 2). Water samples from Pennsylvania had the lowest median B concentration (0.01 $mg \cdot L^{-1}$) and the California samples had the highest median B concentration (0.2 $mg \cdot L^{-1}$) (Table 2).

The F concentration in the water samples ranged from 0 to 8.3 $mg \cdot L^{-1}$. The overall mean F concentration of the water samples was 0.15 $mg \cdot L^{-1}$ and the overall median value was <0.01 $mg \cdot L^{-1}$ (Table 2). Ninety percent of the samples were below the suggested maximum concentration of 1.0 $mg \cdot L^{-1}$ (Rose et al., 1995) and 89% of the samples contained F at <0.01 $mg \cdot L^{-1}$. As with B, the potential for F toxicity in certain species may be at a much lower concentration, but the data indicates that F is either present at concentrations above the suggested maximum concentration (>1.0 $mg \cdot L^{-1}$) or is absent from the water. All states contained some samples with F above the maximum suggested concentration, but the median value for each state was <0.01 $mg \cdot L^{-1}$.

Conclusion

The suggest range for IWS pH and alkalinity is 5 to 7 and 40 to 100 mg $CaCO_3$/L, respectively. In our opinion, IWS outside these ranges are not detrimental to plant growth as long as the pH of the medium is maintained within an acceptable range. Argo and Biernbaum (1996) demonstrated that IWS alkalinity, not pH, is the primary factor influencing medium pH management. Calcium, Mg, and SO_4-S concentrations also are important factors for characterizing irrigation water. However, these nutrients can be supplemented or the proper balance obtained with the addition of water-soluble fertilizers containing Ca, Mg, or SO_4-S. Sodium, Cl, B, or F in irrigation water can create nutritional problems for greenhouse crops, but a relatively small number of samples contained these ions at potentially toxic levels.

Using these data, greenhouse operators can characterize a given water source and how it compares to other water sources being used by the greenhouse industry. These data also may be helpful in determining research priorities in the area of water quality for greenhouse crop production. As the greenhouse industry changes to low- and nonleaching irrigation systems, understanding differences in IWS is one key in the development of more refined state and regional fertilizer recommendations for greenhouse crop production.

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Table 1. Suggested minimum (Min) and maximum (Max) acceptable pH, electrical conductivity (EC), alkalinity, nutrient concentration and sodium adsorption ratio (SAR) for irrigation water used for greenhouse plant production. Units of measure are EC, dS·m^{-1}; alkalinity, mg $CaCO_3$/L; Ca, Mg, SO_4-S, Na, Cl, B, and F, mg·L^{-1}.

	Biernbaum (1994)[z]		Fafard (1996)[y]		Gabriels (1978)		Nelson (1991)[x]		Rose et al. (1995)		Scotts (1996)[w]		Sungro (1996)[v]	
	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max
pH	5.5	7.0	5.0	7.0	NA	NA	NA	NA	5.0	7.0	NA	NA	5.0	7.5
EC	0.2	0.8	0	1.0	0	0.85	0	0.75	0	1.5	0.2	1.3	0	1.0
Alkalinity	40	160[u]	0	100	NA	200	0	40	0	100	40	150[t]	75	150[s]
Ca	25	75	40	120	0	120	NA	NA	40	120	25	100	40	80
Mg	10	30	6	24	0	25	NA	NA	6	24	15	50	20	40
SO_4-S	0	40	NA	NA	NA	NA	NA	NA	0	80	NA	NA	30	60
Na	0	20	0	50	NA	NA	0	70	8	50	0	50	0	80
Cl	0	20	0	20	0	70	0	100	0	140	0	70	0	80
B	0	0.1	0	0.5[r]	0	0.75	0	1.0[r]	0.2	0.8	0	0.5[r]	0	0.5
F	0	0.1	0	0.75[r]	0	1.0	0	0.5[r]	0	1.0	0	1.0[r]	0	1.0
SAR	NA	NA	0	4	NA	NA	NA	NA	0	4	NA	NA	NA	NA

[NA] Not available

[z] Suggested target values from water analysis. A broader range of acceptable values was also presented.

[y] Fafard Analytical Services, Athens, Ga.

[x] Suggested concentrations at which no nutritional problem should occur.

[w] Scotts Analytical Services, Allentown, Pa.

[v] Sun Gro Analytical Services, Warwick, N.Y.

[u] Average suggested alkalinity concentration. The actual acceptable suggested alkalinity concentrations are dependent on the container size. With plugs (in mg $CaCO_3$/L), 40 to 80; while with 15-cm pots, 120 to 180.

[t] Average suggested alkalinity concentration. The actual acceptable suggested alkalinity concentrations are dependent on the container size. With plugs (in mg $CaCO_3$/L), 40 to 120; bedding flats, 40 to 140; 10- to 12-cm pots and large bedding flats, 40 to 160; and 15-cm pots or larger, 60 to 200.

[s] If plugs are grown, alkalinity values on the lower end of the range are suggested.

[r] The concentration that can cause toxicity in certain crops may be much lower.

Table 2. Geographical characterization of the average and median pH, electrical conductivity (EC) alkalinity, water-soluble nutrient concentrations, Ca : Mg ratio, and sodium adsorption ratio (SAR) measured in greenhouse irrigation water from the United States and Canada. Water Ca : Mg ratio was calculated using the concentrations of those nutrients in $mg \cdot L^{-1}$ and SAR was calculated from Eq. [1] using nutrient concentrations in $meq \cdot L^{-1}$. The number of samples in which SO_4-S was measured is less than the total sample number because only two laboratories did SO_4-S analysis.

	Total	CA	FL	TX	MI	OH	NY	PA	NJ	NC	IL	ON
Sample No.[z]	4306	329	280	289	342	118	211	247	92	375	192	101
(SO_4-S No.)	(2276)	(123)	(181)	(181)	(201)	(50)	(111)	(111)	(39)	(206)	(55)	(93)
pH												
Average	7.0	7.1	7.0	7.1	7.1	7.3	7.1	7.0	6.8	6.6	7.1	6.9
Median	7.1	7.1	7.2	7.2	7.3	7.4	7.2	7.0	7.0	6.7	7.4	7.0
< 5.0[y]	3%	2%	5%	2%	1%	1%	1%	1%	8%	5%	6%	<1%
> 7.0	55%	63%	63%	60%	68%	72%	65%	51%	50%	36%	63%	41%
Electrical conductivity ($dS \cdot m^{-1}$)												
Average	0.6	1.0	0.4	0.8	0.6	0.6	0.5	0.6	0.4	0.3	0.7	0.7
Median	0.4	0.9	0.4	0.6	0.6	0.6	0.4	0.4	0.3	0.2	0.7	0.5
> 1.5	4%	20%	1%	8%	3%	4%	2%	6%	3%	1%	2%	10%
Alkalinity (mg $CaCO_3$/L)												
Average	160	170	140	180	200	190	160	140	100	120	220	170
Median	130	150	140	170	200	160	140	120	90	90	200	170
< 40[x]	18%	20%	12%	10%	8%	9%	11%	20%	27%	28%	13%	8%
> 100	61%	63%	70%	71%	77%	66%	73%	59%	47%	49%	72%	66%
Calcium ($mg \cdot L^{-1}$)												
Average	52	78	58	64	69	73	58	54	34	25	66	78
Median	40	61	46	61	69	71	45	42	23	14	74	66
< 40	50%	38%	41%	40%	26%	30%	41%	49%	69%	77%	28%	33%
> 120	6%	22%	7%	10%	8%	9%	3%	8%	3%	<1%	5%	14%
Magnesium ($mg \cdot L^{-1}$)												
Average	19	34	13	15	22	24	15	15	10	6	32	21
Median	11	31	10	8	22	15	11	11	7	3	36	19
< 6	33%	9%	29%	34%	8%	10%	19%	28%	49%	73%	10%	13%
> 24	26%	63%	13%	20%	43%	37%	16%	21%	9%	4%	63%	30%

Table 2. (Cont.)

Sulfate (mg·L^{-1})												
Average	27	33	16	42	30	74	27	40	14	4	74	35
Median	8	17	3	21	20	23	8	21	10	0	20	10
< 30[w]	76%	69%	90%	59%	63%	54%	83%	60%	85%	98%	60%	83%
> 80	8%	14%	5%	16%	5%	20%	6%	13%	<1%	<1%	29%	10%
Sodium (mg·L^{-1})												
Average	33	63	16	64	27	33	24	40	20	30	31	28
Median	13	49	8	30	9	17	14	11	11	9	15	11
> 50	17%	48%	8%	32%	12%	18%	12%	13%	10%	15%	17%	8%
Chloride (mg·L^{-1})												
Average	33	62	26	58	27	32	34	63	20	18	28	44
Median	14	43	12	35	16	17	19	14	15	6	17	14
> 140	3%	8%	3%	9%	2%	3%	4%	3%	<1%	1%	3%	7%
Boron (mg·L^{-1})												
Average	0.22	0.67	0.03	0.17	0.79	0.09	0.06	0.08	0.19	0.18	0.16	0.10
Median	0.02	0.18	0.02	0.06	0.04	0.03	0.01	0.02	0.02	0.01	0.06	0.02
> 1.0	3%	15%	<1%	2%	1%	2%	<1%	1%	3%	4%	1%	4%
> 0.4[v]	8%	30%	<1%	10%	9%	3%	2%	4%	7%	12%	14%	8%
Fluoride (mg·L^{-1})												
Average	0.15	0.04	0.15	0.25	0.13	0.55	0.10	0.04	0.07	0.23	0.13	0.13
Median	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
> 1.0	10%	2%	12%	17%	11%	35%	8%	4%	6%	10%	10%	13%
Ca:Mg ratio												
Average	5.0	2.9	8.5	7.2	3.7	4.4	4.5	4.5	5.5	6.8	2.6	4.2
Median	3.2	2.3	3.9	4.7	3.2	3.5	3.9	3.5	3.4	3.3	2.0	3.3
Sodium-adsorption ratio (SAR)												
Average	2.6	2.5	0.7	5.7	1.7	1.4	1.4	3.7	3.3	3.4	2.8	1.8
Median	0.7	1.6	0.4	1.2	0.4	0.7	0.7	0.6	0.6	0.8	0.6	0.5
> 4	9%	11%	<1%	21%	7%	7%	6%	9%	11%	14%	6%	4%

CA, California; FL, Florida; TX, Texas; MI, Michigan; OH, Ohio; NY, New York; PA, Pennsylvania; NJ, New Jersey; NC, North Carolina; IL, Illinois; and ON, Ontario, Canada.

[z] Sample number. Values inside parentheses are the SO_4-S sample number.

[y] Acceptable pH, EC, nutrient ranges, and SAR for irrigation water were obtained from Rose et al. (1995) unless otherwise noted.

[x] Minimum alkalinity concentrations obtained from Biernbaum (1994).

[w] Minimum SO_4-S concentrations obtained from Reddy et al. (1995).

[v] Maximum B concentrations obtained from W. McElhannon, Fafard Analytical Services, personal communications

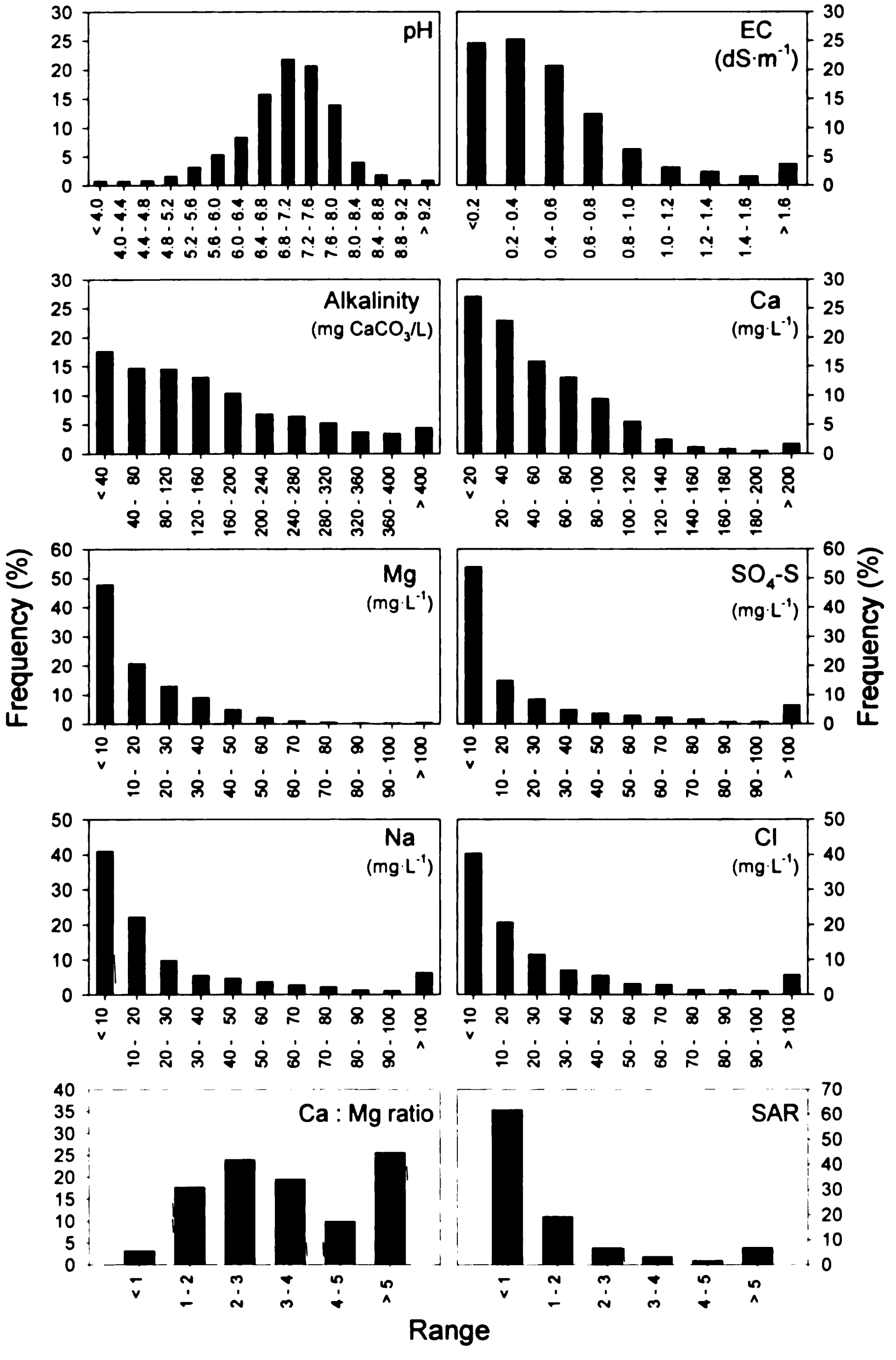

Fig. 1. Frequency distribution based on water pH; electrical conductivity (EC); alkalinity, Ca, Mg, SO_4-S, Na, and Cl concentrations; and the Ca : Mg ratio and sodium adsorption (SAR) ratio. The Ca : Mg ratio was calculated independently for each sample with Ca and Mg concentrations in mg·L^{-1}. The SAR was calculated independently for each sample with Eq. [1] using Ca, Mg, and Na concentrations in meq·L^{-1}. The number of samples in which SO_4-S was measured (2276) is less than the total sample number (4306) because only two laboratories did SO_4-S analysis. Average and median values for the data used to make the graphs are found in Table 2.

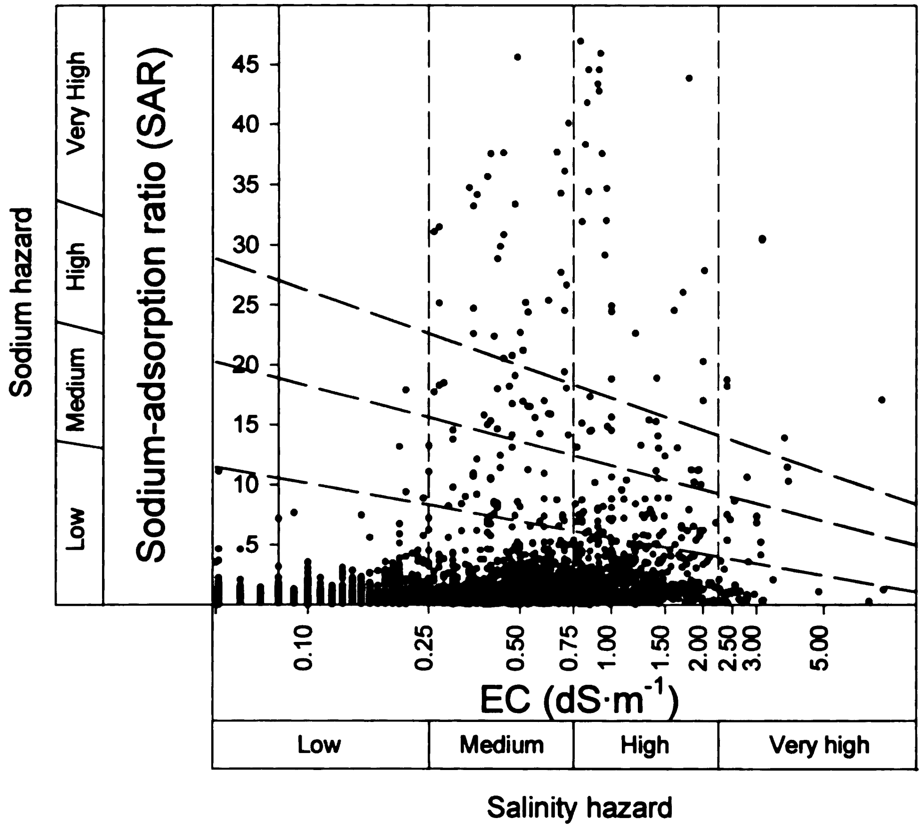

Fig. 2. Classification of the water samples using salinity and sodium hazard based on recommendations found in Allison et al., 1954.

SECTION II

AVAILABILITY AND PERSISTENCE OF MACRONUTRIENTS FROM LIME AND PREPLANT NUTRIENT CHARGE FERTILIZERS IN PEAT-BASED MEDIA

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Availability and Persistence of Macronutrients from Lime and Preplant Nutrient Charge Fertilizers in Peat-Based Root Media

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Abbreviations: EB, evaporation barrier; GC I, Greencare fertilizer I; GC II, Greencare fertilizer II; GC III, Greencare fertilizer III; PNC, preplant nutrient charge; RO, reverse osmosis; SME, saturated media extract; UM, Uni-mix Plus II.

Soils-Plant-Water relationships

Availability and Persistence of Macronutrients from Lime and Preplant Nutrient Charge Fertilizers in Peat-Based Root Media

Additional index words. calcium, evaporation barrier, fertilizer salt stratification, magnesium, nitrogen, phosphorous, potassium, soilless media, subirrigation

Abstract. Using incubation and container culture with subirrigation for up to 28 days, three experiments were conducted with six liming materials of different particle sizes and six blended preplant nutrient charge (PNC) fertilizers. Liming material, particle size, and incorporation rate had an effect on the initial pH (3.5 to 6.1) and the final stable pH (4.8 to 7.8) with one type of Canadian sphagnum peat that did not contain an incorporated PNC. Saturated media extract (SME) Ca and Mg concentrations were <25 and 15 mg/liter, respectively, for both pulverized and superfine dolomitic lime at incorporation rates up to 7.2 kg/m^3. For the blended PNC fertilizers in media containing lime, initial electrical conductivity (EC) and SME nutrient concentrations ranged from (EC) 1.0 to 2.9 dS/m, (mg/liter) 60 to 300 N, 4 to 105 PO_4-P, 85 to 250 K, 120 to 400 Ca, and 60 to 220 Mg. However, within two day, the rapid stratification of fertilizer salts within the pot caused macronutrient concentrations to increase in the top 3 cm of root medium (top layer) by an average of 180% and decrease in the remaining root medium in the pot (root zone) by an average of 57% compared to that measured in the medium at planting. Nutrient concentrations in the top layer continued to increase even when those in the root zone fell below acceptable levels recommended for an SME. The importance of fertilizer salt stratification within a pot lies in the reduced availability of nutrients to the plant and illustrates the limited persistence of the

PNC fertilizers. Testing nutrients in container media several days after planting rather than in freshly mixed media may be more representative of the starting point for a nutritional management program.

Media pH must be managed carefully to control nutrient availability in container root media (Peterson, 1981). Liming materials are added to container root media with acidic peats to increase pH to a level more acceptable for growth (Nelson, 1991; Peterson, 1981; Warncke and Krauskopf, 1983; Williams et al., 1988b). The particle size and incorporation rate of the limestone influence the pH attained at equilibrium (Chapin, 1980; Gibaly and Axley, 1955; Schollenberger and Salter, 1943; Sheldrake, 1980; Williams et al., 1988b). Some information about the differences in lime requirements of certain peats is also available (Argo and Biernbaum, 1994; Lucas et al., 1975; Puustjarvi and Robertson, 1975; Rosenbaum and Sartain, 1982), as is information about the rate of reaction of lime (Williams et al., 1988b) and the effect of water alkalinity in conjunction with lime (Williams et al., 1988a). However, it is not known how the particle size or grind of the materials incorporated influences the resulting water-soluble Ca and Mg concentrations initially or affects the persistence of these nutrient concentrations over time.

In general, unamended acidic peat-based root media do not contain sufficient nutrients for plant growth (Bunt, 1988; Nelson, 1991). Current recommendations for the incorporation of fertilizer materials other than limestone into root media before planting include sources of N, PO_4-P, K, Ca, Mg, SO_4-S, and trace elements (Table 1). These guidelines come from the early soilless container media recommendations, including the Cornell Peat-lite media (Boodley and Sheldrake, 1972), the Pennsylvania State University media (White, 1974), Glasshouse Crops Research Institute media

(Bunt, 1988), and floriculture textbooks (Nelson, 1991). The most commonly recommended macronutrient fertilizers include $Ca(NO_3)_2$, KNO_3, superphosphate or triple superphosphate, and gypsum (Bunt, 1988; Nelson, 1991; Warncke and Krauskopf, 1983). Commercially available preplant nutrient charge (PNC) fertilizers are ground and preblended for particle size uniformity and sometimes mixed with granular wetting agents to provide greenhouse and nursery operators with a complete product (Table 2). In general, the nutrient content of the blended PNC fertilizers is within the range of the original soilless container media recommendations found in Table 1.

The N and K content of the lime and PNC fertilizers is small compared to the total amount applied to a crop. For example, Yelanich (1991) found that a minimum of 1.0 to 1.5 g mineral N/pot was required to produce a poinsettia in a 15-cm-wide by 12-cm-wide (1.3-liter) pot in 16 weeks. An initial incorporation of 0.17 kg mineral N/m^3 would supply 0.22 g mineral N to the 1.3-liter pot, or 15% to 22% of the total N requirement. In comparison, Ca, Mg, PO_4-P, and SO_4-S content of the lime and PNC fertilizers may represent a large percentage, in some cases up to 100%, of the total amount applied to the crop. However, only limited information exists on the initial water-soluble nutrient concentrations that can be expected from the incorporation of the PNC fertilizers (Warncke and Krauskopf, 1983) or their persistence over time. The type of limestone incorporated into the soilless media also may affect nutrient availability and persistence of the PNC, since pH affects the water-soluble nutrient concentration (Peterson, 1981), and the pH of a freshly mixed limed peat-based medium may take up to two weeks to reach equilibrium (Williams et al., 1988b).

It has been suggested that fertilization practices should be based on soil-test nutrient concentrations attained for a given addition of fertilizer, liming material, and irrigation water containing a known nutrient concentration (Biernbaum, 1992;

Vetanovetz and Knauss, 1988). However, these proposed strategies have not been tested under controlled conditions. Since lime and PNC fertilizers contain the initial fertilizer applied to a crop, they represent the starting point in any nutritional program.

The objectives of this research were to determine the concentration of water-soluble nutrients that can be expected from the incorporation of limestone and commercially available PNC fertilizers in peat-based root media initially and over time.

Materials and Methods

Experiments consisted of multiple lime or fertilizer treatments incorporated at one or more rates with two to three replications at several sampling dates. Data were analyzed as a single or multiple factorial at each sampling date using the analysis of variance (ANOVA) procedure of SAS (SAS Institute, 1982). Medium electrical conductivity (EC) and nutrient concentration data were transformed to log(observed + 1) for the ANOVA because of differences in sample variance between treatments. Time was not included in the ANOVA of any experiment because of changing sample variance. Statistical analysis of single-factor experiments is presented in the figures as mean separation with least significant difference (LSD). Statistical analyses of multifactor experiments are presented in tables.

Expt. 1. The liming materials included were ground, pulverized, superfine, and microfine dolomitic carbonate lime (99.5% $CaCO_3$ $MgCO_3$, National Lime and Stone, Carey, Ohio) and analytical-grade $CaCO_3$ (J.T. Baker, Phillipsburg, N.J.). These designations represented the bulk particle size of each material (Schollenberger and Salter, 1943). For example, 60% of ground limestone will pass through a 250- m (#60) screen, 60% of pulverized limestone will pass through a 150- m (#100) screen, 60% of superfine limestone will pass through a 75- m (#200) screen, and 99% of microfine limestone will pass through a 45- m (#325) screen. With the analytical grade $CaCO_3$, 100% passed a 150- m screen but <60% passed a 75- m screen.

The five lime materials were incorporated into 14 liters of a long-fibered Canadian sphagnum moss peat with little dust (Fisons black bale professional grower grade, Sun Gro Horticulture, Bellevue, Wash.) at three incorporation rates: 2.4, 4.8, or 7.2 kg/m^3. Before the lime incorporation, the peat had a pH of 3.8 and contained <4 mg Ca/liter and <2 mg Mg/liter as measured with the saturated media extract (SME). The dolomitic limestone added to the peat 0.5, 1.0, and 1.6 kg Ca and 0.3, 0.6, and 0.9 kg Mg, respectively, per m^3. No other fertilizers were incorporated. The peat was moistened with reverse osmosis (RO) purified water to a level equivalent to 80% to 90% of container capacity in a 15-cm pot, placed into plastic bags, and maintained at a constant 20C in the laboratory. The bags were left open for gas exchange. Subsamples were removed from the plastic bags at mixing and at 3, 7, 13, and 21 days after mixing. The experiment consisted of the five limestone types incorporated at three rates with two replications per treatment for a total of 30 samples at each sampling date.

Experiments 2 and 3 were conducted at Michigan State University, East Lansing, in a well-ventilated glass greenhouse with constant air circulation and cement floors. The root medium used was a 60% (by volume) Canadian sphagnum moss peat (Fisons black bale professional grower grade, Sun Gro Horticulture, Bellevue, Wash.)/20% perlite/20% rockwool (Partek North American, Inc., Brunswick, Ohio) and contained 0.3 kg of a wetting agent (Aquagro "L," Aquatrols, Cherry Hill, N.J.) per m^3 in addition to the indicated PNC and lime treatments. Incorporation rates and nutrient contents for the PNC fertilizers are presented in Table 2. After mixing, media remained in plastic bags with the tops open to the air for gas exchange for two days before the pots were filled. Hybrid impatiens plugs (*Impatiens wallerana* cv. Super Elfin Violet) from a 512 plug tray were planted into 11.5-cm-tall by 11.5-cm-wide (0.7-liter) plastic pots containing media with the lime and PNC treatments, placed onto a flood subirrigation bench, and irrigated daily with RO purified water (pH = 6.0, EC = 0.1 dS/m, alkalinity to pH 4.0 of <20 mg $CaCO_3$/liter, and 20 and 7 mg Ca and Mg/liter, respectively). At a typical irrigation, the benches were filled in 2 min to a 2-cm depth and allowed to drain, which took an additional 5 min.

At each sampling date, the top 3 cm of root medium (top layer) was removed and sampled separately from the remaining root medium within the same pot (root zone). Nutrients were sampled using the SME method with RO purified water as the extractant (Warncke and Krauskopf, 1983). Root-medium pH was measured in the saturated paste before extraction, and EC and macronutrients were measured in the extracted solution. Root-medium pH and NO_3-N were measured with ion-specific electrodes (Orion models 91-02 and 93-07, respectively, Orion Research, Cambridge, Mass.), EC was measured with a platinum electrode at a standard 25C (YSI model 32, Yellow Springs Instruments, Yellow Springs, Ohio), PO_4-P and Mg were determined colorimetrically (Knudsen and Beegle, 1988; Mg-blue method, Technicon Instruments, Tarrytown, N.Y., respectively), and K and Ca were determined by emission spectrometry.

Expt. 2. This experiment consisted of a total of eight treatments, five of which were sampled at 0, 2, 7, 14, 21, and 28 days after planting, and three of which were sampled at 14 and 28 days after planting, with three replications per treatment at each sampling date. Statistical comparisons were made by grouping specific treatments for analysis.

Comparison 1: The three blended PNC fertilizers used were GC I (Greencare I, Greencare Fertilizers, Chicago, Ill.), UM (Uni-mix Plus II, Scotts, Marysville, Ohio), and MSU I (PNC fertilizer blended at MSU) incorporated at 3.9, 2.7, and 3.9 kg/m^3, respectively. In addition to the PNC, a dolomitic hydrated limestone (97% $CaOH_2$ MgO, National Lime and Stone, Carey, Ohio) was incorporated at 1.5 kg/m^3 in the three treatments, which supplied an additional 0.5 kg Ca and 0.3 kg Mg/m^3 of medium. The bulk particle size of the hydrated lime allowed 97% to pass a 45- m (#325) screen. Root media were sampled initially and at 2, 7, 14, 21, and 28 days after planting. The comparison consisted of three PNC fertilizers with three replications at six sampling dates.

Comparison 2: An evaporation barrier was placed on pots containing the GC I, UM, and MSU I media and consisted of an 11.5-cm plastic cover with a 0.5-cm hole melted in the middle for the plant stem and cut from the perimeter to the center so the cover could be inserted after planting. Root media in the covered pots were sampled at 14 and 28 days after planting. The comparison of the uncovered and covered root-zone nutrient concentrations was analyzed as a three-by-two factorial with three replications at the two sampling dates. Top-layer data were analyzed as a single factorial, with replication made across PNC treatments.

Comparison 3: The superfine dolomitic carbonate lime ($CaCO_3$ $MgCO_3$) from Expt. 1 was incorporated at 4.5 or 7.5 kg/m^3 with GC I at 3.9 kg/m^3. The lime treatments added 1.0 and 1.6 kg Ca and 0.6 and 1.0 kg Mg, respectively, per m^3 of root medium in addition to the nutrients supplied by the PNC. These two treatments were compared to the GC I treatment containing the hydrated lime. Root media were sampled initially and at 2, 7, 14, 21, and 28 days after planting, with three replications per treatment at each sampling date.

Expt. 3. The four PNC fertilizers used were GC I, GC II, GC III (Greencare I, II, and III, respectively, Greencare fertilizers, Chicago, Ill.), and MSU II (PNC fertilizer blended at MSU) incorporated at 3.9, 6.2, 0.9, and 2.7 kg/m^3, respectively. In addition to the PNC, the same dolomitic hydrated lime ($CaOH_2$ MgO) from Expt. 2 was incorporated at 1.5 kg/m^3 in all treatments. Root media from the top layer and root zone were sampled initially and at 2, 7, 14, and 21 days after planting. The comparison consisted of four PNC fertilizers with three replications at five sampling dates.

Results and Discussion

Expt. 1. Lime particle size and incorporation rate affected the initial and final stable pH of one type of peat without a PNC (Table 3, Fig. 1), results similar to those obtained by Williams et al. (1988b). With the ground and superfine dolomitic lime treatments at incorporation rates up to 7.2 kg/m^3, the water-soluble Ca and Mg concentrations ranged from 4 to 32 mg/liter and 2 to 15 mg/liter, respectively, and are below the acceptable recommended concentration for the SME (Warncke and Krauskopf, 1983) (Table 3, Fig. 2). Incorporation rate and bulk particle size did not consistently affect the water-soluble Ca or Mg concentration measured in the medium. The continued reaction of the lime (increasing pH over time) did not influence the water-soluble Ca or Mg concentrations in the peat.

Warncke and Krauskopf (1983) reported that 1 kg of dolomitic lime/m^3 incorporated in a root medium increased the water-extractable Ca concentration by 110 mg/liter. At the incorporation rates used in this experiment (2.4, 4.8, and 7.2 kg/m^3), the expected SME Ca concentrations should have been 280, 520, and 800 mg/liter, respectively. Although significant amounts of Ca and Mg probably are associated with the limed peat and may be available to the plant, these ions were not measured with the standard SME procedure (Warncke, 1986).

Experiment 2. In general, initial pH and water-soluble nutrient concentrations of root media containing GC I, UM, and MSU I were at or above those considered optimal for the SME (Warncke and Krauskopf, 1983) (Fig. 3, remaining data not shown). In comparison, Argo (1993) reported that initial pH of five commercial peat-based root media ranged from 6.0 to 6.6; EC, from 1.6 to 3.6 dS/m; and initial nutrient concentrations, from (mg/liter) 65 to 180 N, 3 to 25 PO_4-P, 70 to 328 K, 120 to 580

Ca, and 34 to 130 Mg. Thus, the PNC fertilizers used in this experiment contain amounts of incorporated nutrient similar to those recommended for early soilless media culture (Tables 1 and 2) (Boodley and Sheldrake, 1972; Bunt, 1988; Nelson, 1991; White, 1974), and, except for PO_4-P, the nutrient concentrations in the media with the PNC fertilizers were similar to those measured in fresh commercial root media before planting.

In addition to the lime, there are also recommendations for the water-soluble nutrient concentrations that can be expected from the incorporation of gypsum, superphosphate, $Ca(NO_3)_2$, and KNO_3 (Warncke, 1976; Warncke and Krauskopf, 1983). Using MSU I as an example (Table 2) and not including the lime in the calculation, the predicted water-soluble nutrient concentration would be (mg/liter) 150 N, 25 P, 105 K, and 270 Ca, as measured with the SME. The actual concentration of nutrients measured in media containing MSU I was (mg/liter) 220 N, 105 P, 240 K, and 170 Ca. Warncke (1976) used field soil in five of the six media with the incorporated PNC fertilizers. Perhaps the absence of soil and the greater water-holding capacity of the peat/rockwool/perlite medium used in this experiment affected the partitioning between exchangeable, insoluble, and water-extractable nutrients, which resulted in the difference between the predicted and measured nutrient concentrations.

The concentration of all nutrients tested in the root zone decreased rapidly between planting and 14 days after planting (Fig. 3). Because of the limited amount of plant growth during this period, the nutrients moved from the root zone to the root-medium surface (Table 4, Fig. 4). Once the initial concentration of water-soluble nutrients was reduced because of salt stratification, the residual material from the PNC (if present) did not maintain the root-zone nutrient concentrations at levels acceptable for plant growth.

The movement of fertilizer salts to the top layer with subirrigation is a significant point of fertilizer salt removal from the root zone, similar to that of leaching water from the bottom of the pot (Argo and Biernbaum, 1994; Argo and Biernbaum, 1995a). Fertilizer salt stratification within the pot is thought to be caused by evaporation from the root-medium surface (Argo and Biernbaum, 1994; Argo and Biernbaum, 1995a) or a water front moving into the root medium with each irrigation (Yelanich, 1995). When the surface was covered with an evaporation barrier, the stratification of fertilizer salts within the pot was less at days 14 and 28 compared to that in uncovered pots (Table 4, Fig. 4.).

Another important aspect of fertilizer salt stratification within the pot may be in the reduced availability of nutrients to the plant. In previous work with subirrigated Easter lilies and poinsettias, Argo and Biernbaum (1994, 1995a) found that nutrients that moved to the top layer of the pot were less available to the plant than if the same nutrients remained in the root zone, and the concentration of nutrients in the top layer continued to increase even when root-zone nutrient concentrations were below acceptable levels for an SME. However, in this experiment, the plants were able to extract nutrients from the top layer later in crop development when nutrient concentrations became limiting in the root zone, as illustrated by the decrease in nutrient concentrations in the top layer of uncovered pots after day 14 (Fig. 4). There was a thick mat of roots 0.5 to 1 cm below the root-medium surface by day 14 in the uncovered pots.

The availability of nutrients contained in the top layer may be a result of irrigation frequency. In this experiment, plants in 11.5-cm-tall pots were irrigated daily, resulting in a high moisture content throughout the medium profile for the entire experiment. In comparison, with Easter lilies and poinsettias, Argo and Biernbaum (1994, 1995a) used 15-cm-tall pots irrigated when the root medium reached a moisture content of 25% to 35% of the total water held at container capacity, and nutrients contained in the top layer did not appear to be available to the plant. If the medium is allowed to dry between irrigations, the top layer may not contain sufficient moisture for root growth, rendering the nutrients contained in the top layer unavailable to the plant. George (1989) found that container height influences water absorption with subirrigation, which also may have influenced the availability of nutrients contained in the top layer of the 11.5-cm-tall pots used in this experiment.

Irrigation method also may affect the persistence of the PNC fertilizers in the root zone. Argo and Biernbaum (1995a, 1995b) found that fertilizer salt stratification also occurred with top-watered poinsettias grown with 33% and 25% leaching, respectively. Because of the leaching effects of the water, nutrients contained in the top layer provided a source of nutrients (buffering capacity) for the root zone for up to six weeks once fertilization was stopped (Argo and Biernbaum, 1995b). Thus, the persistence of PNC fertilizers with top-watering methods may be different than that measured in this experiment with subirrigation.

The use of a microfine dolomitic hydrated lime ($CaOH_2$ MgO,1.5 kg/m^3) compared to a superfine dolomitic carbonate lime ($CaCO_3$ $MgCO_3$, 4.5 or 7.5 kg/m^3) did not affect either the initial concentrations of Ca or Mg or the persistence of these ions in the root zone up to 28 days after planting (data not shown), even though more Ca and Mg were added to the root medium containing the carbonate lime treatments (1120 mg Ca and 680 mg Mg per pot at 7.5 kg/m^3) than the same hydrated lime treatments (350 mg Ca and 210 mg Mg per pot at 1.5 kg/m^3). The initial pH of media containing the hydrated lime was 6.0 and remained fairly stable for the entire experiment (Fig. 5). In comparison, the initial pH of the media with the carbonate lime was 4.5 and required 14 days to reach the same pH as the media containing the hydrated lime. As in Expt. 1, the continued reaction of the carbonate lime (increasing pH) did not affect medium Ca and Mg concentrations measured with the SME. Instead, the main effect of the different liming materials on nutrient availability from GC I was due to pH effects on PO_4-P solubility (Fig. 5).

The solubility of PO_4-P can be based on medium pH, EC, and Ca concentrations (Lindsay, 1979). Increasing the initial pH (as with hydrated lime) decreased the initial concentration of water-soluble P (hydrated lime = 65 mg PO_4-P/liter; carbonate lime average = 125 mg PO_4-P/liter) and the amount of P that moved to the top layer (data not shown). The loss of PO_4-P from the root zone into the top layer (or leached from the pot) because of lower initial pH may affect the long-term availability of PO_4-P.

Expt. 3. At the initial soil test, EC, PO_4-P, Ca, and Mg concentrations (Fig. 6), as well as NO3-N and K concentrations (data not shown) were at or above optimum concentrations for an SME in media containing GC I and MSU II. In media containing GC II, initial PO_4-P concentrations were below acceptable levels for an SME because of the limited solubility of the P source (steamed bone meal). Initial nutrient concentrations in media containing GC III were within acceptable levels for an SME but were lower than those of the other PNC fertilizers. The total amount of nutrients incorporated with GC III was lower than that in the other PNC fertilizers (except for Mg) (Table 2). In fact, GC III is similar in N, K, and SO_4-S content to the recommended initial nutrient content of several seedling media (Boodley and Sheldrake, 1972; Bunt, 1988; White, 1974), but with significantly lower PO_4-P and Ca.

As in Expt. 2, the concentration of all nutrients tested in the root zone decreased rapidly and, by day seven, were similar for NO_3-N, K, Ca, and Mg in all treatments (Fig. 6). There was a corresponding increase in the nutrient concentration in the top layer (Fig. 6). As in Expt. 2, the nutrients in the top layer appeared to be available to the plant later in the experiment, as illustrated by the decrease in nutrient concentrations between 7 and 14 days after planting.

Reducing the incorporation rate or limiting the solubility of the nutrient also affected the amount lost to the top layer. For example, decreasing the amount of PO_4-P incorporated into the medium by 50% (GC I vs. MSU II) decreased initial PO_4-P concentrations by 38% (Fig. 6). After 14 days, the concentration of PO4-P in the root zone was above optimal levels for the SME with both PNC fertilizers, and the increase in the concentration of PO_4-P of media containing MSU II was less than that of media containing GC I. In another example, media containing GC I and GC II had similar amounts of incorporated PO_4-P (Table 2). Initial PO_4-P concentrations of media containing GC II were only 5% of the initial concentration of media containing GC I (Fig. 6), and the corresponding increase in the top-layer PO_4-P concentrations with GC II was less than with media containing GC I. Soilless media have a limited ability to retain PO_4-P against leaching (Yeager and Barrett, 1985) and subirrigation or top watering under production conditions (Argo, 1993), which may result in insufficient PO_4-P concentrations later in crop development. Limiting the solubility of the PO_4-P carrier (bone meal) may increase its persistence over time. However, there was some marginal leaf necrosis observed 14 days after planting on the plants grown in media containing GC II, and the odor of the steamed bonemeal during formulation of the PNC was objectionable (L. Metcalf, Greencare Fertilizers, Chicago, Ill. personal communications).

Based on discussions with four commercial peat-based media suppliers, PNC fertilizer incorporation rates from ten years ago were similar to those used in MSU I/GC I. Typical incorporation rates during the past two years for N, P, and K fertilizer have been reduced by as much as half. If a complete water-soluble fertilizer is applied on a constant basis starting at the initial irrigation, it is questionable whether the high initial nutrient concentrations measured in media containing GC I, GC II, UM, MSU I, or MSU II are necessary because of the rapid loss of nutrients from the root zone when subirrigation was used.

In Expts. 2 and 3, the use of dolomitic hydrated lime ($CaOH_2$ MgO) offered a method of rapidly obtaining a root-medium pH of 6.0. At an incorporation rate of 1.5 kg of the hydrated lime per m^3, initial pH was 6.0 and remained relatively stable for up to 28 days in a peat/perlite/rockwool medium. In comparison, the initial pH of the same medium containing up to 7.5 kg of superfine dolomitic carbonate lime ($CaCO_3$ $MgCO_3$) per m^3 was 4.6 and required up to 14 days to equilibrate to 6.0.

Hydrated lime has not been recommended for use as a preincorporated liming material because of the potential for rapid conversion of NH_4 to toxic NH_3 (Bunt, 1988; Nelson, 1991) and damage to new roots (Bunt, 1988). There was no limitation in plant growth caused by interactions with the hydrated dolomitic lime and PNC fertilizers containing high amounts of NH_4-N (UM containing urea formaldehyde and GC II containing bonemeal) probably because the initial medium pH was kept below 7.0, as recommended by Bunt (1988), with organic N fertilizers, and the root medium was allowed to equilibrate for two days before planting.

Because of the highly reactive nature of hydrated lime in addition to the small particle size of the material used, it is probable that most ($>95\%$) had reacted when the equilibrium pH was obtained. Assuming that similar equivalents of lime are required to obtain the same pH, 2.4 kg of the carbonate lime per m^3 is required to obtain the same pH as achieved by 1.5 kg of the hydrated lime per m^3. Under the conditions of the experiment, up to 5 kg of unreacted or residual carbonate lime per m^3 may have remained in the root medium when the equilibrium pH was reached. That unreacted lime was present is further supported by the similarity of the Ca and Mg concentrations in media containing either hydrated or carbonate lime in addition to PNC fertilizers (Expt. 2), even though three times more Ca and Mg was incorporated with the carbonate lime treatments. The effect of the presence or absence of residual lime on the long-term pH, Ca, and Mg buffering capacity of a root medium requires further study.

Recognition of the rapid decrease in nutrient concentrations after planting is important for the proper interpretation of root-medium analysis. When PNC fertilizers have been incorporated, nutrient concentrations in fresh medium taken from a mixing line or a bag will be higher than that of media placed in a container, irrigated, and allowed to dry for several days before sampling. Moistening and incubating the media for several days to two weeks in a closed container likely will give a better estimate of the starting pH, but not EC or macronutrient concentrations. In our opinion, a sample taken two to four days after planting is more representative of the starting point of a nutritional program. Based on these experiments, the EC and nutrient concentrations of media several days after planting likely will fall within the lower acceptable range for nutrient concentrations based on the SME (Warncke and Krauskopf, 1983). However, because of the preliminary nature of these experiments, specific grower recommendations about PNC fertilizers, liming materials, rates, and sampling methods cannot be made.

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Table 1. Recommended preplant nutrient charge fertilizers and rates. The nutrient content of the individual fertilizer salts was estimated from Hawkes et al. (1985).

	Cornell Peat-lite A and B [z]	Cornell foliage media [z]	Pennsylvannia State media [y]	Nelson potting media [x]	GCRI-I potting media [w]	GCRI-2 potting media [w]
	All incorporation rates in kg·m^{-3} of root media					
PNC fertilizers	0.9 KNO_3 0.6 0-8.6-0 [v]	0.9 KNO_3 0.6 0-8.6-0 [v] 1.6 10-4-8[u]	0.6 KNO_3 1.2 0-8.6-0 [v] 0.6 20-8-15[u]	0.6 KNO_3[t] 0.6 $Ca(NO_3)_2$ 0.3 $MgSO_4$[t] 2.7 0-8.6-0 or 1.3 0-19.8-0[s] 0.9 gypsum	0.8 KNO_3 0.4 NH_4NO_3 1.5 0-8.6-0[v]	0.8 KNO_3 0.9 urea-formaldehyde 1.5 0-8.6-0[v]
Lime rate	3.0 ground limestone	4.9 dolomitic limestone	3.0 dolomitic limestone	6.0 dolomitic limestone	2.25 each ground and dolomitic limestone	2.25 each ground and dolomitic limestone
	kg nutrient per m^3 of root medium					
Total N	0.12	0.28	0.2	0.18	0.25	0.45
PO_4-P	0.05	0.12	0.15	0.23	0.13	0.13
K	0.33	0.46	0.31	0.22	0.29	0.29
Ca	0.12	0.12	0.23	0.64	0.29	0.29
Mg	0.00	0.00	0.00	0.03	0.00	0.00
SO_4-S	0.07	0.07	0.14	0.35	0.18	0.18

[z] Boodley and Sheldrake, 1972.

[y] White, 1974.

[x] Nelson, 1991.

[w] Glasshouse Crops Research Institute (Bunt, 1988).

[v] N-P-K content of single superphosphate ($3Ca(H_2PO_4)_2\ H_2O + 7CaSO_4\ 2H_2O + 2HF$).

[u] N-P-K content of blended fertilizer. The exact formulation of this fertilizer is unknown and is not included in the nutrient content calculation for Ca, Mg, or SO_4-S.

[t] The incorporation of these materials is optional (Nelson, 1991) but is included in the nutrient content calculations.

[s] N-P-K content of triple superphosphate ($10Ca(H_2PO_4)_2\ H_2O + 2HF$).

[r] The lime recommendation is not included in the nutrient content calculation.

Table 2. Materials used to produce blended preplant nutrient charge (PNC) fertilizers and estimation of the amount of each macronutrient supplied by the different PNC fertilizer based on the recommended incorporation rate.

	MSU I [z]	MSU II [y]	GC I [x]	GC II [x]	GC III [x]	UM [w]
Fertilizer salts	KNO_3 $Ca(NO_3)_2$ 0-19.8-0 [v] gypsum $MgSO_4$	KNO_3 $Ca(NO_3)_2$ 0-19.8-0 [v] gypsum $MgSO_4$	KNO_3 $Ca(NO_3)_2$ 0-19.8-0 [v] gypsum $MgSO_4$	KNO_3 $Ca(NO_3)_2$ steamed-bone meal gypsum $MgSO_4$	KNO_3 KH_2PO_4 gypsum $MgSO_4$	KNO_3 $(NH_4)H_2PO_4$ urea-formaldehyde K_2SO_4 0-19.8-0 [v] gypsum $MgSO_4$
Rate (kg·m^{-3})	3.9	2.7	3.9	6.2	0.9	2.7
	Elemental analysis (%)					
Total N	4.4	6.3	4.4	3.2	4.0	10.0
PO_4-P	6.2	4.5	6.0	3.9	1.3	4.4
K	5.7	8.3	5.5	3.6	11.6	4.2
Ca	12.9	11.4	8.6	3.7	6.0	4.0
Mg	0.8	1.1	0.7	0.5	3.0	2.5
SO_4-S	5.7	4.9	5.6	3.9	8.8	7.0
	kg nutrient per m^3 of root medium					
Total N	0.17	0.17	0.17	0.19	0.04	0.27
PO_4-P	0.23	0.12	0.23	0.24	0.01	0.12
K	0.22	0.22	0.21	0.22	0.10	0.11
Ca	0.50	0.30	0.33	0.23	0.05	0.11
Mg	0.03	0.03	0.03	0.03	0.03	0.17
SO_4-S	0.22	0.13	0.21	0.24	0.08	0.19

[z] MSU I was 0.6 kg KNO_3 and $Ca(NO_3)_2$, 1.2 kg 0-19.8-0 and gypsum, and 0.3 kg $MgSO_4$ per m^3 of media, respectively.

[y] MSU II was 0.6 kg KNO_3, $Ca(NO_3)_2$, 0-19.8-0, gypsum, and 0.3 kg $MgSO_4$ per m^3 of media, respectively.

[x] Greencare I, II, and III, respectively, Greencare Fertilizers, Chicago, Ill.

[w] Uni-mix Plus II, Peter s Fertilizer, Marysville, Ohio.

[v] N-P-K content of triple superphosphate ($10Ca(H_2PO_4)_2$ $2H_2O + 2HF$).

Table 3. Summary of analysis of variance by sampling date of the effect of lime grind and incorporation rate on the log(observed + 1) transformed pH, Ca, and Mg concentration.

	Sampling day				
<u>pH</u>	0	3	7	13	21
Lime grind (LG)	***	***	***	***	***
Rate (R)	**	***	***	***	***
LG x R	**	***	*	NS	NS
s_ϵ^Z	0.01	0.01	0.01	0.01	0.01
Ca/Mg					
LG	***/***	NS/NS	**/NS	***/***	***/**
R	***/***	**/NS	**/**	***/***	**/*
LG x R	**/***	*/NS	**/**	***/***	**/*
s_ϵ^Z	0.01/0.01	0.02/0.06	0.02/0.02	0.01/0.01	0.02/0.01

NS,*,**,***Nonsignificant or significant at *P* 0.05, 0.01, or 0.001, respectively.

ZSquare root of the mean square error from the ANOVA of the transformed data.

Table 4. Expt. 2. Summary of analysis of variance by sampling date of the effect of an evaporation barrier on the top layer and root zone log(observed + 1) transformed electrical conductivity (EC) and macronutrient concentration.

		EC	NO_3-N	PO_4-P	K	Ca	Mg
Top Layer	Evaporation barrier: Day 14	**	**	**	***	**	**
	Evaporation barrier: Day 28	*	NS	**	*	*	NS
Root zone	Day 14						
	Evaporation barrier (EB)	***	***	*	***	***	***
	PNC fertilizer	***	***	NS	***	***	***
	EB x PNC	NS	NS	NS	**	*	**
	s_ϵ^Z	0.02	0.08	0.16	0.04	0.01	0.04
	Day 28						
	Evaporation barrier (EB)	***	**	***	***	***	***
	PNC fertilizer	*	***	**	*	*	NS
	EB x PNC	NS	**	NS	NS	NS	NS
	s_ϵ^Z	0.03	0.10	0.03	0.06	0.05	0.06

NS,*,**,***Nonsignificant or significant at *P* 0.05, 0.01, or 0.001, respectively.

ZSquare root of the mean square error from the ANOVA of the transformed data.

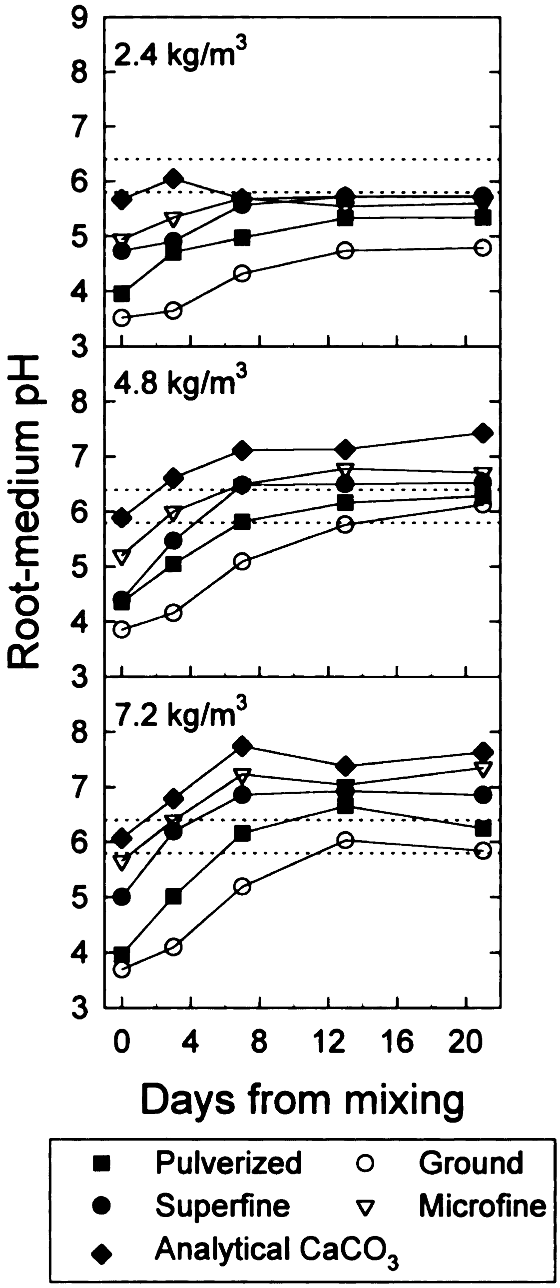

Fig. 1. Expt. 1. The pH of peat amended with ground, pulverized, superfine, or microfine dolomitic carbonate lime ($CaCO_3$ $MgCO_3$), and analytical grade $CaCO_3$ incorporated at either 2.4, 4.8, or 7.2 kg/m^3, respectively, and measured over 21 days. Dotted lines (·····) indicate recommended acceptable ranges for the SME (Warncke and Krauskopf, 1983). Statistical analysis is presented in Table 3.

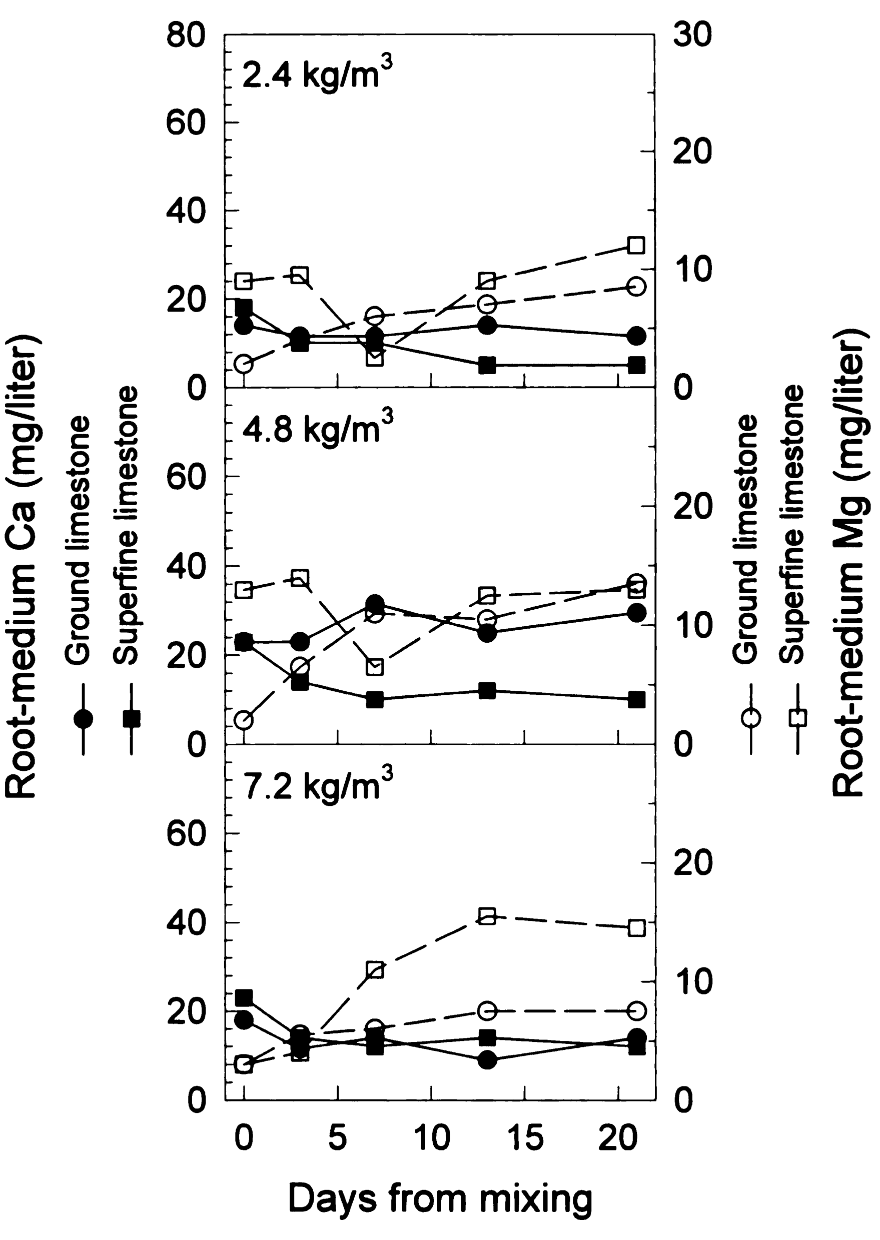

Fig. 2. Expt 1. Calcium and Mg concentrations of peat amended with ground or superfine dolomitic carbonate lime ($CaCO_3$ $MgCO_3$) incorporated at either 2.4, 4.8, or 7.2 kg/m^3, respectively, and measured over 21 days. Minimum acceptable concentrations for Ca is 80 mg/liter and Mg is 30 mg/liter when measured with an SME (Warncke and Krauskopf, 1983). Statistical analysis is presented in Table 3.

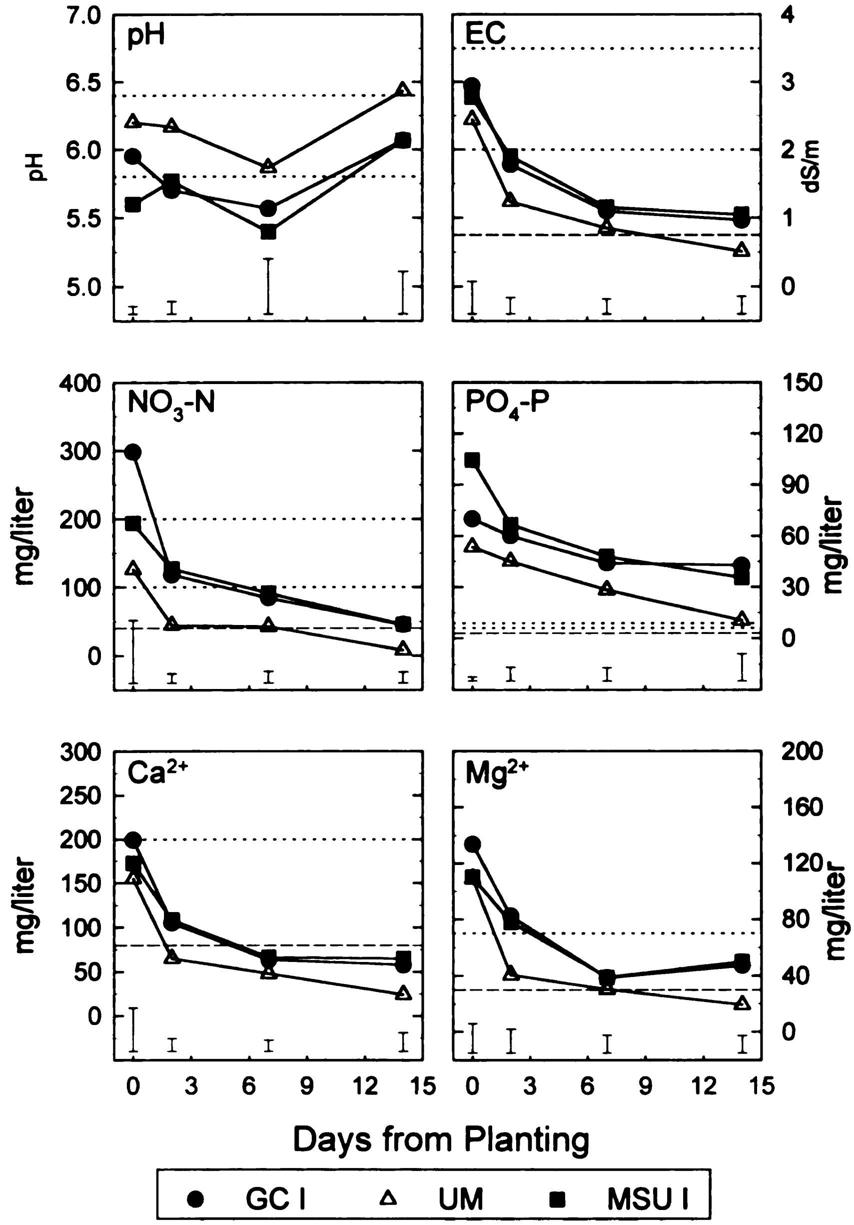

Fig. 3. Expt. 2. Root-zone pH, EC, NO_3-N, PO_4-P, Ca, and Mg concentrations of uncovered subirrigated hybrid impatiens with media containing the blended PNC fertilizers Greencare I, Uni-mix Plus II, and MSU I from planting until day 14. The liming material used was a microfine dolomitic hydrated lime ($CaOH_2$ MgO) incorporated at 1.5 kg/m^3. Dotted lines (·····) indicate recommended optimal concentration(s), the lower dashed line (---) indicates acceptable concentrations for the SME (Warncke and Krauskopf, 1983). Vertical error bars are mean separation using LSD.

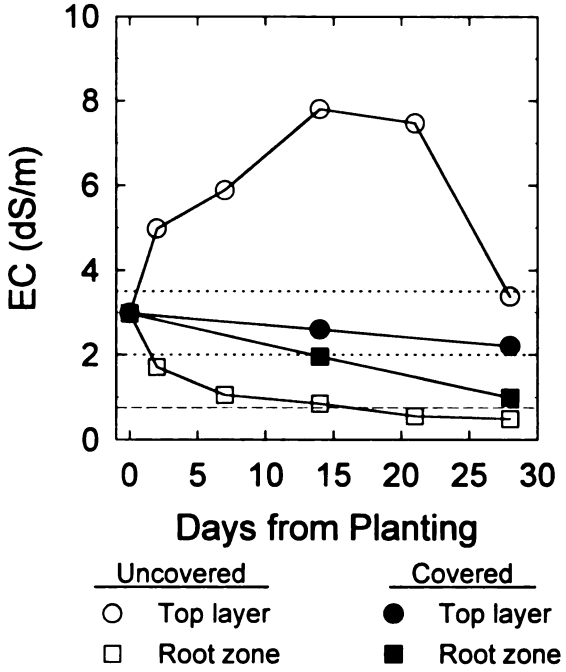

Fig. 4. Expt. 2. Comparison of root-zone and top-layer electrical conductivity (EC) for pots grown without and with an evaporation barrier averaged over media containing three PNC fertilizers from Experiment 2. Dotted lines (·····) indicate recommended optimal concentration(s), and lower dashed lines (---) indicate acceptable concentrations for the SME (Warncke and Krauskopf, 1983). Statistical analysis is presented in Table 4.

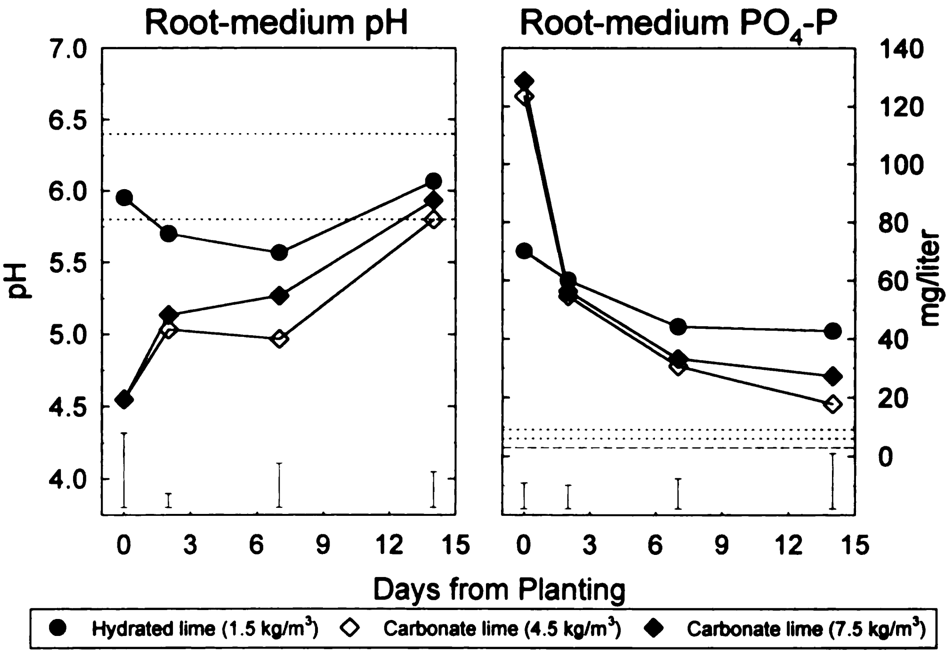

Fig. 5. Expt. 2. Root-zone pH and PO_4-P concentrations in media containing GC I with either a microfine dolomitic hydrated lime ($CaOH_2$ MgO) incorporated at 1.5 kg/m^3 or a superfine dolomitic carbonate lime ($CaCO_3$ $MgCO_3$) incorporated at 4.5 or 7.5 kg/m^3. Dotted lines (·····) indicate recommended optimal concentration(s), the lower dashed line (---) indicates acceptable concentrations for the SME (Warncke and Krauskopf, 1983). Vertical error bars are mean separation using LSD.

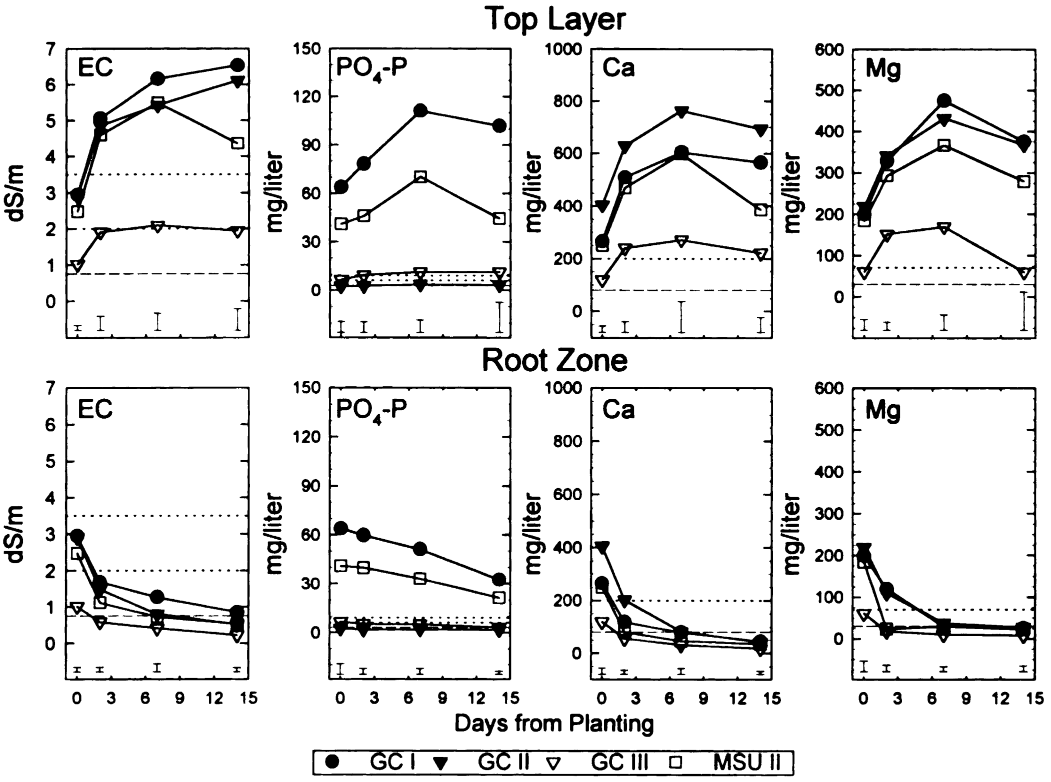

Fig. 6. Experiment 3. Root-zone EC, PO$_4$-P, Ca, and Mg concentrations of subirrigated hybrid impatiens with media containing the blended PNC fertilizers Greencare I, Greencare II, Greencare III, and MSU II from planting until day 14. The liming material used was a microfine dolomitic hydrated lime (CaOH$_2$ MgO) incorporated at 1.5 kg/m^3. Dotted lines (·····) indicate recommended optimal concentration(s), the lower dashed line (---) indicates acceptable concentrations for the SME (Warncke and Krauskopf, 1983). Vertical error bars are mean separation using LSD.

SECTION III

THE EFFECT OF LIME, IRRIGATION-WATER SOURCE, AND WATER-SOLUBLE FERTILIZER ON ROOT-ZONE pH, ELECTRICAL CONDUCTIVITY, AND MACRONUTRIENT MANAGEMENT OF CONTAINER ROOT MEDIA WITH IMPATIENS

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The Effect of Lime, Irrigation-Water Source, and Water-Soluble Fertilizer on Root-Zone pH, EC, and Macronutrient Management of Container Root Media with Impatiens

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Abbreviations: EC, electrical conductivity; IWS, irrigation water source; PNC, preplant nutrient charge; RO, reverse osmosis; SME, saturated media extract; WSF, water-soluble fertilizer.

Soils, Nutrition, and Fertilizers

The Effect of Lime, Irrigation-Water Source, and Water-Soluble Fertilizer on Root-Zone pH, EC, and Macronutrient Management of Container Root Media with Impatiens

Additional index words. calcium, magnesium, peat, phosphorus, tissue analysis, soilless root media, subirrigation, soluble salts, sulfate

Abstract. Hybrid impatiens (*Impatiens Wallerana* Hook. F.) were planted in a peat-based medium containing two dolomitic liming materials (1.8 kg $Ca(OH)_2 \bullet Mg(OH)_2/m^3$ or 8.4 kg $CaCO_3 \bullet MgCO_3/m^3$) and subirrigated for 17 weeks using four irrigation-water sources (IWS) with varied bicarbonate alkalinity, Ca^{2+}, Mg^{2+}, and SO_4-S content and three water-soluble fertilizers (WSF) that contained 200-20-200 mg N-P-K/liter but a variable NH_4:NO_3 ratio, Ca^{2+}, Mg^{2+}, and SO_4-S content. The factorial arrangement of the IWS and WSF resulted in a range of Ca^{2+}, Mg^{2+}, and SO_4-S concentrations varying by a factor of 10. After eight weeks, medium pH ranged from 4.5 to 8.5. The maximum critical medium pH for PO_4-P uptake was 7.4 to 7.7, which probably was due to a change in the majority of the water-soluble P to the less-available HPO_4^{2-} form. Lime type did not affect the long-term increase in medium pH, Ca^{2+}, and Mg^{2+} concentrations with nutrient solutions containing low NH_4-N and high Ca^{2+} and Mg^{2+}. The carbonate lime buffered the medium pH and Ca^{2+} and Mg^{2+} concentrations with nutrient solutions containing high NH_4-N and low Ca^{2+} and Mg^{2+} compared to that measured with the hydrated lime. With both lime types, there was a linear increase in tissue Ca and Mg as the applied concentrations of the various nutrient solutions increased from 18 to 210 mg Ca^{2+}/liter and 7 to 90 mg Mg^{2+}/liter. The relationship was similar for both lime types up to week eight, after which tissue Ca and Mg decreased more rapidly with the hydrated lime and

low solution Ca^{2+} and Mg^{2+} compared to that of the same carbonate lime treatments. The minimum critical SO_4-S concentration in the applied nutrient solution for plant uptake was 30 to 40 mg S/liter. Below this concentration, tissue S decreased rapidly; above, there was little effect on tissue S.

A number of factors, which include lime, the irrigation-water source (IWS), water-soluble fertilizer (WSF), and plant growth, interact to affect the management of pH and nutrient concentrations in container root media throughout crop production. However, not all factors affect medium pH and macronutrient management simultaneously. A better understanding of how these factors interact is necessary to improve the recommendations for pH and nutrient management of container-grown crops over a wide range of conditions.

Lime is added to a soilless root medium to neutralize acidity and increase the pH to an acceptable level for plant growth. Incorporating sufficient lime into a soilless root medium to obtain an initial pH range of 5.5 to 6.4 is recommended (Nelson, 1991; Peterson, 1981; Warncke and Krauskopf, 1983). The amount of liming material required to obtain an equilibrium pH of 6 in the root medium depends on the incorporation rate and particle size (Argo and Biernbaum, 1995b; Chapin, 1980; Gibaly and Axley, 1955; Schollenberger and Salter, 1943; Sheldrake, 1980; Williams et al., 1988b) as well as the surface area of the liming material (Parfitt and Ellis, 1966). There is some information about the time required for the lime to reach a stable pH in soilless medium (Argo and Biernbaum, 1995b; Williams et al., 1988b), the effect of water alkalinity in conjunction with lime in unplanted pots (Williams et al., 1988a), and the water-soluble Ca^{2+} and Mg^{2+} concentrations that can be expected from the incorporation of dolomitic lime into a soilless medium (Argo and Biernbaum, 1995b; Warncke and Krauskopf, 1983).

However, it has been suggested that not all the incorporated liming material may have reacted upon reaching equilibrium (Argo and Biernbaum, 1995b). The significance of residual or unreacted lime on the long-term pH or water-soluble Ca^{2+} and Mg^{2+} buffering capacity in soilless media containing plants has not been quantified.

Several studies have been conducted to quantify the nutrient content of different sources of irrigation water in the United States. Ludwig and Peterson (1984) found that throughout the U.S., titratable alkalinity ranged from 2 to 575 mg $CaCO_3$/liter (average = 147 mg/liter); electrical conductivity (EC), from 0 to 6.5 dS/m (average = 0.5 dS/m); Ca^{2+}, from 0 to 440 mg/liter (average = 60 mg/liter); Mg^{2+}, from 0 to 300 mg/liter (average =20 mg/liter); and Na^+, from 0 to 1150 mg/liter (average = 35 mg/liter), based on 687 water samples from the greenhouse industry. Reddy et al. (1994) found that only 11% of the IWSs tested contained sufficient concentrations of SO_4-S (30 mg/liter) recommended for plant growth in container culture.

Different IWS require different types of management (Bunt, 1988; Nelson, 1991; Vetanovetz and Hulme, 1991). Irrigation water containing large amounts of bicarbonate alkalinity (>250 mg $CaCO_3$/liter) commonly are treated by adding strong mineral acid (HNO_3, H_2SO_4, or H_3PO_4). Researchers recommend adding sufficient acid to reduce the alkalinity to 100 to 120 mg $CaCO_3$/liter or reduce the solution pH to 6.0 to 6.5 (Bunt, 1988; Nelson, 1991; Spurway and Wildon, 1938). Alternative sources such as rainwater or reverse osmosis (RO) purified water are gaining popularity because of their low alkalinity (Biernbaum, 1992). However, rainwater and RO water contain minimal nutrients.

The type of WSF applied to a root medium affects pH and nutrient concentrations two ways: directly, by nutrients applied to the root medium, and indirectly, by acidification of the rhizosphere pH. Fertilization with NO_3^--N causes the medium pH to increase because of OH^- or HCO_3^- secretion associated with balancing ion uptake. In comparison, fertilization with NH_4^+-N causes the medium pH to decrease because of H^+ secretion during root uptake and nitrification of the NH_4^+-N to the NO_3^--N form, which also releases H^+ (Barker and Mills, 1980; Bunt, 1988; Hawkes et al., 1985; Marschner, 1986; Nelson, 1991; Vetanovetz and Hulme, 1991).

Many commercially available WSF contain a high percentage of NH_4^+-N and PO_4-P but little Mg^{2+} and no Ca^{2+} [examples: Peter's 21-7-7 Acid Special, 100% NH_4^+-N, 0.05% Mg^{2+}, 0% Ca^{2+}; Peter's 20-20-20 General Purpose, 72% NH_4^+-N, 0.05% Mg^{2+}, 0% Ca^{2+}; Peter's 20-10-20 Peatlite Special, 40% NH_4^+-N, 0.05% Mg^{2+}, 0% Ca^{2+} (Peter's Fertilizer [Scotts], Marysville, Ohio)]. Because of the high NH_4^+-N content, the reaction produced by these WSF are acidic [21-7-7 = 780 kg acidity/1000 kg, 20-20-20 = 300 kg acidity/1000 kg, 20-10-20 = 210 kg acidity/1000 kg (Peter's Fertilizer)]. In comparison, WSF that produce neutral or basic reactions in the root medium are typically low in NH_4^+-N and PO_4-P but high in Ca^{2+} and NO_3^--N (examples: Peter's 19-0-16 Western Greenhouse Formula, 24% NH_4^+-N, 6.5% Ca^{2+}, 15 kg acidity/1000 kg; Excel 15-5-15, 28% NH_4^+-N, 12% Ca^{2+}, 68 kg basicity/1000 kg; Peter's 15-0-15 Dark Weather Special, 13% NH_4^+-N, 14% Ca^{2+}, 210 kg basicity/1000 kg).

Emphasis needs to be placed on designing a WSF program for container plant production based on a given medium and IWS (Biernbaum, 1992; Vetanovetz and Knauss, 1988). However, these proposed strategies have not been tested under controlled conditions. The objectives of this experiment were to determine how lime, IWS, and WSF interact to affect the management of root-medium pH and medium and shoot-tissue macronutrient concentrations over time.

Materials and Methods

The experiment included 24 treatments composed of two types of lime, four types of IWS, and three types of WSF combined in a 2 x 4 x 3 factorial arrangement. At each sampling date, four pots from each treatment (two pots from each of two greenhouse sections) were sampled. Replication was made between greenhouse sections, while the two pots taken from the same greenhouse section were treated as subsamples for the statistical analysis.

Soil test data were analyzed using SAS's analysis of varience (ANOVA) procedures (SAS Institute, Cary, NC) as a 2 x 4 x 3 split-plot factorial with lime as the main plot and the other factors as subplots at each sampling date. Medium EC and nutrient concentration data were transformed to log(observed + 1) for the ANOVA because of differences in sample variance between treatments. Time was not included in the ANOVA because sample variance changed over time.

Because of the factorial arrangement of the experiment, a range of Ca^{2+}, Mg^{2+}, and SO_4-S concentrations in the nutrient solutions, as well as a range of medium pH values were obtained with the different treatments. Relationships were developed between the concentration of Ca^{2+} and Mg^{2+} in the applied nutrient solutions and tissue Ca and Mg using SAS's linear regression procedure (REG). Relationships also were developed between the concentration of SO_4-S in the nutrient solutions and the tissue S and root-medium pH and tissue P using the intersecting straight line model proposed by Anderson and Nelson (1975) with multiphase functions proposed by Fisher (1995). The functions used were

$$X_{\text{intersection}} = \frac{I_2 - I_1}{S_1 - S_2} \qquad [1]$$

$$\text{If: } X < X_{\text{intersection}}, \text{ then: } Y = S_1X + I_1 \qquad [2]$$

$$\text{If: } X > X_{\text{intersection}}, \text{ then: } Y = S_2X + I_2 \qquad [3]$$

where the X value is either SO_4-S concentration in mg/liter or root medium pH, Y is tissue S or P in percent of total dry mass, $X_{\text{intersection}}$ is the intersection point of the two lines where the Y values are equal and was calculated using Eq. [1], and S and I are the slope and y-intercept of Eqs. [2] and [3], respectively. Initial estimates for the parameters were obtained from a graph of the observed data. Estimates for S_1, I_1, S_2, and I_2, based on either the applied SO_4-S or root-medium pH, were obtained using SAS's nonlinear regression procedure (NLIN).

Lime. The two liming materials varied in reactivity and incorporation rate. A microfine dolomitic hydrated lime (97% $Ca(OH)_2$ MgO, National Lime and Stone, Findlay, Ohio) in which 92% of the material passed through a 45-µm (#325) screen was incorporated at 1.5 kg/m^3. At this incorporation rate, the hydrated lime added 0.5 kg Ca^{2+}, 0.3 kg Mg^{2+}, and the equivalent of 2.6 kg $CaCO_3$/m^3 to the root medium. A superfine dolomitic carbonate lime (99.5% $CaCO_3$ $MgCO_3$, National Lime and Stone, Findlay, Ohio) in which 65% of the material passed through a 75-µm (#200) screen was incorporated at 8.4 kg/m^3. At this incorporation rate, the carbonate lime added 1.8 kg Ca^{2+}, 1.1 kg Mg^{2+}, and the equivalent of 9.1 kg $CaCO_3$/m^3 to the root medium.

The root medium used was (by volume) 70% Canadian sphagnum peat (Fisons professional black bale peat, Sun Gro Horticulture, Bellevue, Wash.) with long fibers and little dust (Von Post scale 1-2; Puustjarvi and Robertson, 1975), and 30% perlite. A preplant nutrient charge (PNC) consisting of 0.6 kg each of $Ca(NO_3)_2$, KNO_3, triple superphosphate (0 N-19.8 P-0 K), and gypsum; 0.3 kg $MgSO_4$; 0.07 kg fritted trace elements (FTE 555, Scotts, Marysville, Ohio); and 0.2 liter of a wetting agent (Aquagro 2000 "L," Aquatrols, Pennsaulken, N.J.) per m^3 of medium, in addition to the lime, were added at mixing. Sufficient RO water was added at mixing to bring the moisture content of the medium to 40% to 50% of container capacity, and the medium was allowed to equilibrate for three days before planting. At planting, the hydrated lime treatments had a pH of 6.1, an EC of 2.3 dS/m, and 220 NO_3^--N, 14 NH_4^+-N, 40 PO_4-P, 200 K^+, 250 Ca^{2+}, 185 Mg^{2+}, and 110 SO_4-S (mg/liter); while the carbonate lime treatments had a pH of 5.5, an EC of 2.6 dS/m, and 220 NO_3^--N, 13 NH_4^+-N, 53 PO_4-P, 215 K^+, 230 Ca^{2+}, 160 Mg^{2+}, and 95 SO_4-S (mg/liter), based on the saturated-medium extract (SME) method (Warncke and Krauskopf, 1983).

Irrigation-water source (IWS). The four IWS varied in EC, Ca^{2+}, Mg^{2+}, Na^+, SO_4-S concentration, and alkalinity content. The high-alkalinity water source (well water) had a pH of 7.8, an EC of 0.6 dS/m; 105 Ca^{2+}, 35 Mg^{2+}, 12 Na^+, 23 SO_4-S (mg/liter); and a titratable alkalinity to pH 4.5 (Chau, 1984) of 320 mg $CaCO_3$/liter. The low-alkalinity water source was RO purified well water, which had a pH of 5.5, an EC of 0.1 dS/m; 20 Ca^{2+}, 7 Mg^{2+}, 23 Na^+, 1 SO_4-S (mg/liter); and a titratable alkalinity to pH 4.5 of <20 mg $CaCO_3$/liter. The third type of water (acidified water) was produced by adding H_2SO_4 (93%) to the well water and had a pH of 5.8, an EC of 0.7 dS/m; concentrations of Ca^{2+}, Mg^{2+}, and Na^+ similar to that of the well water; 91 mg SO_4-S/m^3; and a titratable alkalinity to pH 4.5 of 120 mg $CaCO_3$/liter. The forth irrigation water (well + RO water) was produced by blending well and RO water (1:1.5 by volume) and had a pH of 6.8, an EC of 0.3 dS/m; 56 Ca^{2+}, 12 Mg^{2+}, 21 Na^+, and 9 SO_4-S (mg/liter); and a titratable alkalinity to pH 4.5 of 130 mg $CaCO_3$/liter.

Water-soluble fertilizer (WSF). Fertilizer concentrations were maintained at 150-15-150 mg N-P-K/liter for the first two weeks and increased to 200-20-200 mg N-P-K/liter for the remainder of the experiment. The three WSF varied in NH_4^+-N, Ca^{2+}, Mg^{2+}, and SO_4-S concentrations. At 200 mg N/liter, WSF 1 contained 50% NH_4^+-N with 0 Ca^{2+}, 0 Mg^{2+}, and 42 SO_4-S (mg/liter); WSF 2 contained 25% NH_4^+-N with 50 Ca^{2+}, 25 Mg^{2+}, and 35 SO_4-S (mg/liter); and WSF 3 contained 3% NH_4^+-N with 100 Ca^{2+}, 50 Mg^{2+}, and 3 SO_4-S (mg/liter). Micronutrients (Fe, Mn, Zn, Cu, B, and Mo) were added to all WSF treatments with a commercially available chelated material (Compound 111 [1.50 Fe-0.12 Mn-0.08 Zn-0.11 Cu- 0.23 B-0.11 Mo], Scotts, Marysville, Ohio) at a constant 50 mg/liter.

The type of reaction produced by the WSF was calculated, with values for the reaction produced by the individual salts obtained from Hawkes et al. (1985) and Young and Johnson (1982) multiplied by the percentage that each salt contributed to the total WSF weight. The value obtained for each WSF was used as an estimate of the type (either acidic or basic) and strength (in kg/1000 kg of fertilizer) of reaction produced. Based on these calculations, WSF 1 (acidic WSF) had an acidity of 199 kg/1000 kg, WSF 2 (neutral WSF) had a basicity of 8 kg/1000 kg, and WSF 3 (basic WSF) had a basicity of 175 kg/1000 kg.

Plant culture. The experiment was conducted starting 15 Feb. 1994 at Michigan State University, East Lansing, in two well-ventilated glass greenhouse sections with constant air circulation and cement floors. One hybrid impatiens plug (*Impatiens wallerana* Hook. F. cv. Super Elfin Violet) from a size 512 plug tray was planted into a 9-cm-tall by 12.5-cm-wide (0.75-liter) plastic pot containing medium with one of the two lime types. Twenty-five pots containing medium with each lime type were placed on one of 12 flood subirrigation bench sections in each of the two greenhouses. Both lime types were placed on the same bench section.

Plants on each bench section were irrigated as needed. The time to irrigate was determined gravimetrically when the average mass of six randomly selected pots containing plants and medium (three from each lime treatment) reached a target weight based on a loss of 40% to 50% of the available water. The same six pots were checked daily for the target weight, and when it was reached, nutrient solutions were applied. During an irrigation, benches were filled from a 70-liter reservoir for 2 min to a maximum depth of 2.5 cm and drained in 6 min to the same reservoir. The difference between the mass of the pots before and after the irrigation was the amount of water absorbed by the medium. The amount of nutrients applied per pot was calculated as the sum of the absorbed nutrient solution multiplied by the concentration applied for each irrigation. The nutrient solutions in the 70-liter reservoirs were emptied and prepared fresh weekly.

Root media were sampled initially and collected from four pots (two per treatment from each bench section) at 1, 4, 8, 12, and 17 weeks after planting. All the medium was removed from each pot and separated horizontally into two samples, one containing the top 2.5 cm (top layer), and the other containing the remaining medium from the pot (root zone). Nutrients contained in each media sample were tested using the SME method with RO purified water as the extractant (Warncke, 1986). Only EC was measured in the top layer sample, while pH, EC, NO_3^--N and NH_4^+-N, PO_4-P, K^+, Ca^{2+}, Mg^{2+}, and SO_4-S were measured in the root zone sample. Medium pH was determined by inserting the pH electrode directly into the saturated medium before extraction, and EC and macronutrients were measured in the extracted solution. Medium EC was determined with a platinum electrode at a standard 25C. Nitrate N (Diamond, 1986a), NH_4^+-N (Diamond, 1986b), PO_4-P (Bloxham, 1990), Mg^{2+} (magnesium blue, Technicon Instruments, Tarrytown, N.Y.), and SO_4-S (McKnight, 1991) were determined colorimetrically. Medium K^+ and Ca^{2+} were determined by the Michigan State University soil and nutrient testing laboratory using emission spectroscopy.

Shoot fresh and dry weight and tissue nutrient analysis were determined for four plants per treatment at 4, 8, 12, and 17 weeks after planting. At week four, the entire plant was used in the sample. For the remaining plants, all shoots were pinched back, leaving one internode per stem and four to six stems per plant. At all subsequent sampling dates, only growth after the previous pinch was sampled, and the remaining plants were cut back to the week four pinch level. Shoot N and S were determined by column chromatography, and shoot P, K, Ca, and Mg were determined by plasma emission spectroscopy (Fafard Analytical Laboratory, Athens, Georgia).

Results and Discussion

Plant growth. In general, the experimental treatments affected shoot growth of impatiens minimally (Fig. 1). The average dry mass of the stem below the pinched material was 1.9 g at the end of the experiment (data not shown). Averaged over all treatments, a total of 17.5 g of shoot dry mass was produced over the 17 weeks of the experiment.

In many experiments, plant shoot tissue is sampled sequentially over time or at the end of the experiment (Adams et al.; 1978; Argo and Biernbaum, 1994; Argo and Biernbaum, 1995a, Yelanich, 1995; Yelanich and Biernbaum, 1993). Determining changes in nutrient availability over time is difficult because the nutrient content of the shoot tissue represent the sum of the conditions under which the growth occurred. Cutting the plants back at four week intervals left minimal shoot tissue that could be used as a nutrient reservoir for mobile macronutrients (N, P, K, Mg) while sampling only the new growth tested the ability of the plants to take up mobile and immobile macronutrients (Ca, S) over the four week period. Therefore, there should have been a better correlation between the availability of nutrients in the root medium and tissue nutrient concentrations over the four week period than if the plants were allowed to grow from planting until the sampling date, as typically has been done.

Water and fertilizer applications. The volume of nutrient solutions applied ranged from 7.2 to 8.9 liters/pot over the 17 weeks of the experiment (Table 1). The volume of water applied to the impatiens in this experiment was similar to that required by other species for their normal production schedule (Argo and Biernbaum, 1994; Argo and Biernbaum, 1995b; Yelanich, 1995; Yelanich and Biernbaum, 1993).

Because the N-P-K concentrations in the WSF were constant, the amount applied was similar and ranged from 1.5 to 1.8 g N, 0.15 to 0.20 g PO_4-P, and 1.5 to 1.8 g K^+ per pot (data not shown). In addition, 0.1 g N, 0.1 g PO_4-P, and 0.2 g K^+ per pot were incorporated initially with the PNC fertilizers. In comparison, the concentrations of Ca^{2+}, Mg^{2+}, and SO_4-S in the nutrient solutions varied by a factor of ≈10. The amount applied ranged from 0.2 to 1.6 g Ca^{2+}, 0.1 to 0.7 g Mg^{2+}, and 0.1 to 1.2 g SO_4-S per pot (Table 1). In addition to the nutrient solutions applied, hydrated lime treatments received 0.7 g Ca^{2+}, 0.3 g Mg^{2+}, and 0.1 g SO_4-S per pot, and the carbonate lime treatments received 1.5 g Ca^{2+}, 0.8 g Mg^{2+}, and 0.1 g SO_4-S per pot with the initial incorporation of the lime and PNC fertilizers.

Based on the mass of shoot tissue produced, sufficient nutrients were applied to all treatments to maintain tissue nutrient concentrations at levels recommended by Fortney and Wolf (1981) for floriculture crops. For example, a constant 2% tissue Ca content would have required ≈ 0.35 g Ca^{2+}/pot from the root media. The minimum amount of Ca^{2+} applied to a single treatment throughout the experiment was 0.9 g Ca^{2+}/pot.

Root-zone pH. By week four, root-medium pH was similar for both lime treatments (Fig. 2, Table 2). Because of the highly reactive nature and small particle size of the hydrated lime, most of the material probably had reacted by week four. Assuming that similar equivalents of lime were required to obtain the same root-medium pH, ≈6 kg of the carbonate lime per m^3 of medium, or 4.5 g/pot, remained unreacted at the week four analysis.

After eight weeks, the root-zone pH ranged from 4.5 to 8.5 within the various treatments (Fig. 2, Table 2). Over the remaining nine weeks of the experiment, root-zone pH was unaffected by lime type with Ca^{2+} concentrations in the nutrient solution >150 mg/liter and root-medium pH >6.4 (Fig. 2, Table 2). In comparison, the root-medium pH was higher in the carbonate lime treatments than in the hydrated lime treatments with Ca^{2+} concentrations in the nutrient solution <150 mg/liter and root-medium pH <6.0. The largest difference was measured in the RO water/neutral WSF treatment in which the carbonate lime treatment maintained a root-medium pH of 6.1, 5.9, and 5.8; the hydrated lime treatment, 5.1, 4.6, and 4.6 at weeks 8, 12, and 17, respectively. These values indicate that there were considerable amounts of unreacted carbonate lime in the root medium at week four, which greatly increased the pH buffering capacity of the root medium under acidifying conditions.

The effect of the WSF reaction on root-medium pH also depended on the alkalinity of the IWS. In general, IWS with similar alkalinity levels had a similar root-medium pH throughout the experiment (Fig. 2, Table 2). The root-medium pH range obtained with well water was larger than that with RO water. Thus, if general guidelines for using WSF to manage pH in container media are to be based on the reaction produced, the bicarbonate alkalinity concentration of the IWS and the presence or absence of residual lime must be taken into account. If low quantities of residual lime are present and the alkalinity is at or below the 120 mg $CaCO_3$/liter recommended by Bunt (1988), then the amount of NH_4-N in the WSF must be decreased below 25% to prevent medium pH from falling below recommended acceptable levels.

EC. With all treatments, there was a rapid decrease in root-zone EC as well as the concentration of all macronutrients tested (N, P, K, Ca, Mg, S) between planting (average EC = 2.5 dS/m) and week one (average EC = 0.9 dS/m) (Fig. 2), with a corresponding increase in the nutrient concentration measured in the top 2.5 cm of root medium within the pot (average EC = 4.7 dS/m) (data not shown). These data indicate that the initial nutrient concentration represents a highly soluble fraction and is not representative of the long-term nutrient buffering capacity of the root medium, conclusions similar to those of Argo and Biernbaum (1995b) with blended PNC materials in short-term (14-day) experiments.

The stratification of fertilizer salts may be caused by evaporation from the root-medium surface (Argo and Biernbaum, 1994; Argo and Biernbaum, 1995a, 1995b) or a water front moving into the root medium with each irrigation (Yelanich, 1995). After week four, the root-zone EC increased for the remainder of the experiment (Fig. 2, Table 2). By the end of the experiment, the EC of the top 2.5 cm of root medium ranged from 30 to 40 dS/m compared to 1 to 2.5 dS/m for the remaining root medium within the same pot as measured with the SME.

EC is a measure of the total salt concentration in the root medium (Warncke and Krauskopf, 1983). The effect of the treatments on root-zone EC was based on a combination of the IWS and WSF EC. For example, with the acidified water, root-zone EC ranged from 1.8 to 2.4 dS/m with the different types of WSF. The root-zone EC of the RO water treatments averaged 0.5 dS/m lower than that of the acidified water treatments from week eight until the end of the experiment. When comparing WSF across IWS, the basic fertilizer/acidified water treatment had a root-zone EC 1.3 dS/m higher than the acidic fertilizer/RO water by the end of the experiment. It is important to note that the concentration of N and K in the applied nutrient solutions were similar for all treatments and the range of treatments affected root-medium K minimally, and tissue N and K concentrations were in the acceptable plant-growth range recommended by Fortney and Wolf (1981) (data not shown). In order to fine tune general guidelines for N and K nutrition in container media based on EC, the EC of the nutrient solution must be considered.

Phosphorus. The constant application of 20 mg PO_4-P/liter resulted in water-soluble PO_4-P medium concentrations ranging from 3 to 25 mg PO_4-P/liter by the end of the experiment (Fig. 2). In general, the higher the root-medium pH, the lower the root-medium PO_4-P/m^3.

In mineral soils fertilized with P, calcium phosphates (dicalcium phosphate and dicalcium phosphate dihydrate) initially control PO_4-P solubility at high pH (>7.0) and Al and Fe phosphates control PO_4-P solubility at low pH (Lindsay and Moreno, 1960). In acidic organic soils and soilless root media, which tend to contain naturally low amounts of Al and Fe, P does not precipitate at low pH but does at high pH (Lucas and Davis, 1961; Peterson, 1981; Yeager and Barrett, 1985). Thus, the reduction in the concentration of water-soluble PO_4-P at the higher pH range probably was due, at least initially, to precipitation of P as dicalcium phosphate or dicalcium phosphate dihydrate.

Lucas and Davis (1961) and Peterson (1981) concluded that the optimal pH for PO_4-P nutrition was 5.5 in media without soil, because above this pH, water-soluble PO_4-P concentrations began to decrease. In comparison, Adams et al. (1978) found that the P content of lettuce leaves was unaffected by medium pH up to 6.5, even though the concentration of water-soluble PO_4-P measured in the medium was 38% of that measured at pH 5.5. In this experiment, when root-medium pH was plotted against tissue P concentration, a maximum critical root-medium pH for PO_4-P nutrition was 7.5, 7.7, and 7.4 at weeks 8, 12, and 17, respectively (Fig. 3, Table 3). Below this root-medium pH, tissue P increased at 0.06% to 0.08% of the total dry mass per 1 pH unit decrease, and above the critical pH, tissue P decreased at 0.38% to 0.65% of the total dry mass per 1 pH unit increase (Table 3).

The form of water-soluble PO_4-P is important for uptake into the roots and depends on the root-medium pH. In the root-medium pH range of this experiment (4.5 to 8.5), the two forms present are $H_2PO_4^-$ and HPO_4^{2-} with an equilibrium constant of 7.2. The $H_2PO_4^-$ form of water-soluble P is 10 times more available to the plant than the HPO_4^{2-} form (Bunt, 1988). At a medium pH >7.2, a majority of the water-soluble P is in the less-available HPO_4^{2-} form that resulted in the larger reduction in tissue P than at a medium pH <7.2, at which a majority of the measured P is in the more-available $H_2PO_4^-$ form. Thus, while the concentration of water-soluble PO_4-P in the root medium decreased with increasing pH, the effect on tissue P was minimal until the form of the water-soluble PO_4-P changed to a less-available form.

Calcium. After week one, root-medium Ca^{2+} concentrations increased for the remainder of the experiment, but the increase depended on all three factors tested (Fig. 2, Table 2). In general, the higher the concentration of Ca^{2+} in the nutrient solution, the higher the water-soluble Ca^{2+} concentration in the root medium over the remaining 16 weeks of the experiment. The presence of the carbonate lime also increased water-soluble Ca^{2+} compared to that of the hydrated lime treatments, but the average difference was small (≤ 20 mg Ca^{2+}/liter) and probably was due to the reaction of the acidic or neutral WSF with residual carbonate lime in the medium.

There was a poor relationship between water-soluble Ca^{2+} concentrations in the root medium and tissue Ca (data not shown). The root-medium Ca^{2+} concentrations measured at weeks 4, 8, 12, and 17 are the maximum concentrations from the previous four-week period and therefore do not represent the "average" conditions from which plant growth and Ca uptake occurred. In comparison, the range of Ca^{2+} concentrations in the various nutrient solutions produced from the factorial combinations of IWS and WSF remained constant over time, and there was a relationship between the applied Ca^{2+} concentration in the nutrient solution and tissue Ca.

With both lime types, there was a linear increase in tissue Ca as the applied concentrations increased from 20 to 210 mg Ca^{2+}/liter with the IWS and WSF combinations (Fig. 4, Table 4). The intercept value reflects the Ca^{2+} buffering capacity of the medium if no Ca^{2+} were applied in the fertilizer solution. The relationship was similar for both lime types up to week eight (0.2% increase in tissue Ca per 40 mg/liter increase in applied Ca^{2+} concentration, with a minimum tissue concentration of 1.0% to 1.1%), after which tissue Ca decreased faster with the hydrated lime and low-solution Ca^{2+} compared to that of the carbonate lime treatments. The reduction in the intercept of the hydrated lime treatments by weeks 12 and 17 indicates a reduction in the Ca^{2+} buffering capacity of the medium compared to that of the carbonate lime treatments. Using Eq. [1], similar tissue Ca concentrations could be obtained, independent of the lime type, with the addition of >180 mg Ca^{2+}/liter in the nutrient solution throughout the experiment. In addition, these results indicate that the ionic composition and N form of the WSF had little effect on Ca uptake. Instead, the main factor controlling Ca uptake above the minimum buffering capacity of the medium was bulk nutrient solution Ca^{2+} concentration as influenced by the IWS and WSF.

One possibility for the larger reduction in tissue Ca with the hydrated lime treatments compared to that of the carbonate lime treatments was that Ca^{2+} availability was reduced at low pH, as indicated by Peterson (1981). Plants grown in media containing the hydrated lime and irrigated with RO water containing either acidic or neutral WSF had a similar root-medium pH throughout the experiment (Fig. 2), but the total applied Ca^{2+} concentration was higher with the neutral WSF (70 mg Ca^{2+}/liter) than the acidic WSF (20 mg Ca^{2+}/liter). The tissue Ca concentration was also higher with the RO-neutral WSF treatment at each of the four sampling date (1.6%, 1.7%, 1.7%, and 1.3%, respectively) than with the RO-acidic WSF (1.3%, 1.1%, 0.8%, and 0.5 %, respectively) (Fig. 4). Thus, low pH did not, in itself, reduce Ca^{2+} uptake but did reflect a lack of residual lime in the medium. The difference in tissue Ca concentrations between the hydrated (1.3% Ca) and carbonate (1.7% Ca) lime treatments in plants receiving RO water/neutral fertilizer at the week 17 sampling date reflects the additional buffering capacity of the residual carbonate lime.

Magnesium. As with Ca^{2+}, root-medium Mg^{2+} concentrations increased from week one to the end of the experiment, and the increase depended on all three factors tested (Fig. 2, Table 2). In general, the higher the concentration of Mg^{2+} in the nutrient solution, the higher the water-soluble Mg^{2+} concentration in the root medium over the remaining 16 weeks of the experiment. The presence of the carbonate lime increased water-soluble Mg^{2+} compared to that of the hydrated lime treatments, but the difference was small ($\leq$ 15 mg Mg^{2+}/liter), and probably was due to the reaction of the acidic fertilizer with the carbonate lime.

With both lime types, there was a linear increase in tissue Mg as the applied concentrations increased from 5 to 80 mg Mg^{2+}/liter with the various nutrient solutions (Fig. 5, Table 5). The intercept value reflects the Mg^{2+} buffering capacity of the medium if no Mg^{2+} were applied in the fertilizer solution. The relationship was similar for both lime types up to week eight, after which tissue Mg decreased with the hydrated lime and low-solution Mg^{2+}, while with the carbonate lime treatments, there was little decrease in tissue Mg with decreasing concentrations of applied Mg^{2+} (0.05% increase in tissue Mg per 25 mg/liter increase in applied Mg^{2+} concentration). From Eq. [1], similar tissue Mg concentrations were obtained, independent of the lime type, with the addition of >60 mg Mg^{2+}/liter in the nutrient solution for the duration of the experiment. These results indicate that the ionic composition and N form of the WSF had minimal effect on Mg uptake. The main factor controlling Mg uptake above the minimum buffering capacity of the medium was bulk nutrient solution Mg^{2+} concentration, as influenced by the IWS and WSF.

Sulfate. Irrigation-water source and WSF were the main factors affecting root-medium SO_4-S concentrations (Fig. 2, Table 2). In general, the higher the concentration in the applied nutrient solution, the higher the concentration of SO_4-S in the root medium at the end of the experiment. When low concentrations of SO_4-S were applied (RO water/basic fertilizer), low concentrations were measured in the root medium, indicating that gypsum and $MgSO_4$ initially incorporated with the PNC had minimal persistence in the root zone. However, with the lowest applied SO_4-S concentration (3 mg SO_4-S/liter), root-zone SO_4-S concentrations were maintained at 15 mg SO_4-S/liter and may represent the base buffering capacity of the root medium, residual gypsum, or movement of SO_4-S back into the root zone from high concentration at the root-medium surface.

There was a minimal increase in tissue S with increasing concentration of applied SO_4-S above 30 to 40 mg S/liter (Fig. 6, Table 6). Above this concentration, tissue S increased at 0.0% to 0.05% of dry mass per 30 mg/liter increase in the applied SO_4-S concentration. Below this minimum critical concentration, tissue S decreased at 0.2% to 0.5% of dry mass per 30 mg/liter decrease in the applied SO_4-S concentration. This minimum critical concentration of 30 to 40 mg S/liter corresponds to the 30 mg S/liter recommended by Reddy et al. (1994) for container plant production. In addition, the larger reduction in tissue S at the week four analysis (below 40 mg S/liter in the applied solution) adds further evidence that a large percentage of the gypsum or $MgSO_4$ did not persist in the root zone, as suggested in this experiment and by Argo and Biernbaum (1995b) and root-medium Ca^{2+} and tissue concentrations. Reddy et al. (1994) found that 11% of the IWS tested, based on a survey of water samples, contained >30 mg S/liter. Since many blended WSF do not contain SO_4-S (Peter's Fertilizers, 1981), additional SO_4-S may need to be added as a water-soluble source, as suggested by Reddy and Madore (1995).

Root-medium SO_4-S concentrations up to 150 mg S/liter and applied concentration up to 130 mg S/liter did not cause a significant decrease in tissue Ca concentrations (plant tissue Ca average with acidified water = 1.9%, 2.0%, 2.4%, and 2.1%; and with well water = 1.8%, 1.9%, 2.3%, and 2.0% at weeks 4, 8, 12, and 17, respectively). Although Ca^{2+} and SO_4-S will form soluble ion complexes in solution (Lindsay, 1979), which may reduce plant availability, under the conditions of the experiment, enough of the water-soluble Ca^{2+} remained in the root medium in the free ion form to not inhibit plant uptake.

Root-medium buffering capacity. The pH and nutrient buffering capacity of peat often are associated with the cation exchange capacity (CEC) that is due to the pH-dependent exchange of cations with H^+ ions from organic acid functional groups on the peat particles (Helling et al., 1964). For example, at a pH of 3.7, 4.5, 5.5, and 7.8, acid sphagnum peat is 100%, 50%, 30%, and 0% H^+ saturated, respectively (Lucas et al., 1975; Puustjarvi and Robertson, 1975). Thus, the actual buffering capacity over the pH range in this experiment probably represents a fraction of the total CEC.

This experiment demonstrated that a large difference in pH and nutrient buffering capacity could be obtained with the same root medium by using two liming materials with different reaction rates and amounts of unreacted material remaining in the medium at equilibrium. Perhaps differences in the pH and nutrient buffering capacity observed in commercial media may be attributed to differences in the type and amount of liming material used rather than CEC (C. Bethke, Michigan Peat, Houston, Texas, personal communications).

Macronutrient management. The primary macronutrients (N, P, K) typically are contained in WSF. Nitrogen and K can be managed based on the EC of the nutrient solution. If PO_4-P is present in the WSF, it also can be managed acceptably via EC if the root-medium pH is <7.3 to 7.5.

The secondary macronutrients (Ca, Mg, and S) frequently are ignored because the carriers (lime, gypsum, and $MgSO_4$) are incorporated in relatively large amounts with the PNC fertilizers and may buffer the root media for a long period (Bunt, 1988; Nelson, 1991). Gypsum and $MgSO_4$ do not persist in the root zone of subirrigated pots and probably can be removed by top-watering methods with leaching or mist propagation. Dolomitic carbonate lime buffered the root medium for Ca^{2+} and Mg^{2+}, but long-term reliance on residual lime may be risky, because the amount of material present or its persistence in the medium cannot be determined with the SME analysis.

An alternative method for managing secondary macronutrients may be to ignore the material incorporated with the PNC and lime in the medium and apply nutrient-solution Ca^{2+}, Mg^{2+}, and SO_4-S based on the sum of those ions from both the IWS and

WSF, as suggested by Biernbaum (1992) and Vetanovetz and Knauss (1988). According to the results from this experiment, the concentrations of Ca^{2+}, Mg^{2+}, and SO_4-S that should be applied in the nutrient solution on a constant basis are 160 mg Ca^{2+}/liter, 50 mg Mg^{2+}/liter, and 30 mg SO_4-S/liter.

There are two main sources of Mg^{2+} for WSF, $MgSO_4$ and $Mg(NO_3)_2$. If $MgSO_4$ is used for the Mg^{2+} source, adequate concentrations of SO_4-S also will be applied. However, there is only one source of highly soluble Ca^{2+} typically used in WSF, $Ca(NO_3)_2$. Therefore, the recommendations for Ca^{2+} supplied by the nutrient solution also will have a direct effect on NH_4-N content in the WSF and on root-medium pH management. This type of secondary macronutrient management should result in acceptable Ca^{2+} concentrations for plant uptake, a medium pH maintained at a level much closer to the recommended 5.8 to 6.4 range (Warncke and Krauskopf, 1983), and the conservation of any residual liming material.

Calcium and PO_4-P can be mixed together in high concentrations, such as in a fertilizer stock tank, only if the pH <2.0 (R. Vetanovetz, Scotts, Marysville, Ohio, personal communication), while Ca^{2+} and SO_4-S cannot be combined in a stock tank without subsequent precipitation. Multiple injectors may be required for this type of secondary macronutrient management. Other options for applying Ca^{2+} without N may include investigating the use of $CaCl_2$ if a high percentage of NH_4-N and Ca^{2+} is desired in the WSF.

Conclusion. Impatiens are highly tolerant of a wide range of growth conditions. Because of the similarity in the shoot dry mass accumulation between treatments, the relationships that were developed between the applied nutrient concentration or medium pH and the tissue nutrient concentration were not confounded because of differences in plant growth. These relationships also may be valid for other species used in container-plant production. However, the minimum critical tissue-nutrient concentrations that causes a reduction in growth may be species dependent (Dole and Wilkins, 1988). If other species were grown under the same conditions as those found in this experiment, it is possible that a limitation in growth caused by a nutrient deficiency or toxicity would have occurred.

In the production of container-grown crops, it is no longer acceptable to manage the pH and macronutrient concentrations in the root medium and plant tissue with high WSF concentrations and high leaching rates (Biernbaum, 1992). Irrigation systems that minimize or eliminate water and fertilizer runoff into the environment currently exist. Optimizing the pH and nutrient management of low- or nonleaching irrigation systems requires an understanding of how factors such as lime, IWS, and WSF interact during production. Additional research is needed to determine if recommendations for pH and macronutrient management must be refined further to include differences in root media and or plant species.

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Table 1. Cumulative water, Ca^{2+}, Mg^{2+}, and SO_4-S applied with the various irrigation-water source (IWS) and water-soluble fertilizer (WSF) treatments after 17 weeks. The initial nutrient content of the root medium was not included in the values reported below but was 0.7 g Ca^{2+}, 0.3 g Mg^{2+}, and 0.1 g SO_4-S per pot with the hydrated lime treatments and 1.5 g Ca^{2+}, 0.8 g Mg^{2+}, and 0.1 g SO_4-S per pot with the carbonate lime treatment. Data are the mean of six pots. Statistical analysis indicates a three-way interaction with > 0.01 significance for all four variables measured.

		Hydrated lime				Carbonate lime			
		Applied				Applied			
Well	Acidic	7.8	0.8	0.3	0.6	8.1	0.9	0.3	0.7
Well	Neutral	7.7	1.3	0.5	0.6	7.4	1.2	0.4	0.6
Well	Basic	7.2	1.6	0.6	0.3	7.6	1.6	0.7	0.3
Acidified	Acidic	8.3	0.8	0.3	1.2	8.0	0.8	0.3	1.2
Acidified	Neutral	7.8	1.2	0.5	1.1	7.5	1.1	0.5	1.1
Acidified	Basic	7.4	1.5	0.7	0.8	7.5	1.5	0.7	0.8
Well + RO	Acidic	8.7	0.5	0.1	0.6	8.1	0.5	0.1	0.5
Well + RO	Neutral	8.4	0.9	0.3	0.5	8.1	0.9	0.3	0.5
Well + RO	Basic	8.2	1.4	0.5	0.2	8.2	1.4	0.5	0.2
RO	Acidic	8.9	0.2	0.1	0.5	7.8	0.2	0.1	0.5
RO	Neutral	8.4	0.6	0.3	0.5	8.2	0.6	0.3	0.4
RO	Basic	7.8	1.0	0.5	0.1	7.8	1.0	0.5	0.1

Table 2. Degrees of freedom (df), F-values (A), levels of significance (B), and mean square from error a and b (MSE a or b) from the analysis of variance for the log(observed + 1) transformed root-medium pH, electrical conductivity (EC), PO_4-P, Ca^{2+}, Mg^{2+}, and SO_4-S concentrations at 1, 4, 8, 12, and 17 weeks after planting.

			Week 1		Week 4		Week 8		Week 12		Week 17	
		df	A	B	A	B	A	B	A	B	A	B
pH	Lime (L)	1	14.7	NS	0.4	NS	162.0	*	972.6	*	32.5	NS
	MSE a	1	0.0002		0.0005		0.0001		0.0001		0.0001	
	IWS [z]	3	13.1	***	33.6	***	81.1	***	40.9	***	61.0	***
	L x IWS	3	2.5	NS	0.5	NS	6.8	***	2.7	NS	1.8	NS
	WSF [y]	2	10.5	***	7.9	***	155.7	***	170.6	***	323.0	***
	L x WSF	2	0.1	NS	1.0	NS	6.3	***	3.7	*	9.1	***
	IWS x WSF	6	1.4	NS	2.1	NS	4.5	**	4.4	***	11.6	***
	L x IWS x WSF	6	2.1	NS	0.2	NS	0.9	NS	0.9	NS	3.1	**
	MSE b	70	0.0003		0.0003		0.0004		0.0009		0.0005	
EC	Lime (L)	1	15.2	NS	0.2	NS	1.6	NS	2.1	NS	9.4	NS
	MSE a	1	0.0001		0.0018		0.0027		0.0074		0.0009	
	IWS	3	24.2	***	16.4	***	35.9	***	28.1	***	21.6	***
	L x IWS	3	0.8	NS	0.1	NS	1.4	NS	0.2	NS	2.8	*
	WSF	2	21.2	***	11.3	***	27.9	***	26.4	***	54.8	***
	L x WSF	2	0.7	NS	0.4	NS	1.4	NS	3.0	NS	11.6	***
	IWS x WSF	6	2.5	*	2.0	NS	1.7	NS	0.3	NS	2.9	*
	L x IWS x WSF	6	0.9	NS	1.8	NS	2.1	NS	0.7	NS	1.8	NS
	MSE b	70	0.0011		0.0014		0.0010		0.0018		0.0019	
P	Lime (L)	1	1633.6	*	97.9	NS	30.6	NS	0.4	NS	0.0	NS
	MSE a	1	0.0004		0.0018		0.0008		0.0188		0.0258	
	IWS	3	48.1	***	27.2	***	94.8	***	118.7	***	25.2	***
	L x IWS	3	3.9	**	1.6	NS	0.6	NS	0.3	NS	0.3	NS
	WSF	2	1.0	NS	29.6	***	167.6	***	303.2	***	80.2	***
	L x WSF	2	4.5	**	0.0	NS	0.7	NS	1.5	NS	0.5	NS
	IWS x WSF	6	8.9	***	9.6	***	33.1	***	56.4	***	12.6	***
	L x IWS x WSF	6	1.0	NS	0.6	NS	1.2	NS	1.3	NS	0.2	NS
	MSE b	70	0.0013		0.0041		0.0036		0.0042		0.0138	

Table 2. (Cont.)

Ca	Lime (L)	1	34.6	NS	0.6	NS	1.7	NS	3.4	NS	958.6	*
	MSE a	1	0.0031		0.0027		0.0022		0.0048		0.0001	
	IWS	3	5.2	**	21.9	***	88.1	***	56.9	***	66.7	***
	L x IWS	3	0.5	NS	1.6	NS	3.2	NS	2.9	NS	2.7	NS
	WSF	2	13.7	***	60.3	***	61.3	***	30.9	***	90.6	***
	L x WSF	2	2.2	NS	0.0	NS	2.2	NS	3.5	NS	16.8	***
	IWS x WSF	6	0.5	NS	2.7	**	3.9	**	2.0	NS	3.7	**
	L x IWS x WSF	6	0.4	NS	2.2	NS	3.1	*	0.3	NS	2.2	NS
	MSE b	70	0.0138		0.0071		0.0041		0.0081		0.0052	
Mg	Lime (L)	1	18.6	NS	1.0	NS	13.4	NS	2362.0	*	12.1	NS
	MSE a	1	0.0006		0.0100		0.0037		0.0004		0.0030	
	IWS	3	11.7	***	18.5	***	38.1	***	114.2	***	10.9	***
	L x IWS	3	1.4	NS	5.8	*	5.5	*	17.8	***	3.2	*
	WSF	2	26.0	***	80.5	***	49.2	***	117.9	***	28.5	***
	L x WSF	2	0.4	NS	3.8	NS	0.5	NS	21.8	***	6.4	**
	IWS x WSF	6	1.5	NS	1.8	NS	2.8	NS	8.9	***	1.9	NS
	L x IWS x WSF	6	1.1	NS	6.1	**	4.2	*	2.9	**	5.9	**
	MSE b	70	0.0199		0.0172		0.0249		0.0151		0.0098	
S	Lime (L)	1	8.2	NS	53.2	NS	0.4	NS	5.1	NS	0.0	NS
	MSE a	1	0.0023		0.0001		0.0004		0.0023		0.0006	
	IWS	3	133.7	***	404.6	***	366.3	***	177.8	***	332.7	***
	L x IWS	3	0.4	NS	1.9	NS	0.5	NS	1.3	NS	0.5	NS
	WSF	2	56.5	***	504.0	***	199.8	***	112.1	***	294.1	***
	L x WSF	2	3.2	*	0.9	NS	1.0	NS	0.6	NS	3.5	NS
	IWS x WSF	6	5.1	***	21.1	***	27.0	***	9.8	***	40.0	***
	L x IWS x WSF	6	0.5	NS	0.3	NS	1.2	NS	0.7	NS	2.0	*
	MSE b	70	0.0054		0.0029		0.0043		0.0080		0.0040	

[z] Irrigation-water source.

[y] Water-soluble fertilizer

[NS,*,**,***] Nonsignificant or significant at $P \geq$ 0.05, 0.01, or 0.001, respectively.

Table 3. Parameters of nonlinear regression analysis from fitting Eqs. [1], [2], and [3] to percent P in tissue, based on root-medium pH at 8, 12, and 17 weeks after planting. I and S are the intercept and slope for Eqs. [2] and [3], respectively. The number of observations per sampling data was 48 at week four and 96 thereafter. Data from the lime treatments were used in the same analysis and are presented in Fig. 3. The analysis of the week four data was not included because of nonsignificance.

	Week 8	Week 12	Week 17	units
Estimated parameters				
Intercept (I_1)	1.31 ± 0.10^z	1.25 ± 0.11	1 .21 ± 0.14	% dry mass
Slope (S_1)	-0.08 ± 0.02	-0.06 ± 0.02	-0.07 ± 0.02	% dry mass/1 pH unit
Intercept (I_2)	3.61 ± 0.74	5.13 ± 1.19	4.58 ± 0.88	% dry mass
Slope (S_2)	-0.38 ± 0.09	-0.65 ± 0.14	-0.52 ± 0.11	% dry mass/1 pH unit
Calculated parameters				
$X_{intersection}$	7.5	7.7	7.4	pH

^{z}Ninety-five percent confidence intervals were calculated as the parameter standard error * $t_{0.025,n}$ distribution.

Table 4. Parameters of linear regression analysis for tissue Ca, based on the applied concentration of Ca^{2+} in the nutrient solution. The number of observations per lime treatment was 24 at week four and 48 thereafter. Data are presented in Fig. 4.

	Week 4	Week 8	Week 12	Week 17	units
Hydrated lime					
Intercept	1.06 ± 0.18^z	1.06 ± 0.14	1.01 ± 0.16	0.59 ± 0.15	% dry mass
Slope	0.006 ± 0.001	0.006 ± 0.001	0.008 ± 0.001	0.009 ± 0.001	% dry mass/mg L^{-1}
Carbonate lime					
Intercept	1.08 ± 0.25	1.10 ± 0.20	1.48 ± 0.15	1.47 ± 0.13	% dry mass
Slope	0.005 ± 0.001	0.006 ± 0.001	0.006 ± 0.001	0.004 ± 0.001	% dry mass/mg L^{-1}

^{z}Ninety-five percent confidence intervals were calculated as the parameter standard error * $t_{0.025,n}$ distribution.

Table 5. Parameters of linear regression analysis for tissue Mg, based on the applied concentration of Mg^{2+} in the nutrient solution. The number of observations per lime treatment was 48 at week four and 96 thereafter. Data are presented in Fig. 5.

	Week 4	Week 8	Week 12	Week 17	units
Hydrated lime					
Intercept	0.43 ± 0.05^{z}	0.42 ± 0.05	0.37 ± 0.04	0.30 ± 0.05	% dry mass
Slope	0.005 ± 0.001	0.005 ± 0.001	0.006 ± 0.001	0.007 ± 0.001	% dry mass/mg L^{-1}
Carbonate lime					
Intercept	0.45 ± 0.06	0.51 ± 0.05	0.61 ± 0.06	0.62 ± 0.05	% dry mass
Slope	0.005 ± 0.001	0.004 ± 0.001	0.002 ± 0.001	0.002 ± 0.001	% dry mass/mg L^{-1}

^{z}Ninety-five percent confidence intervals were calculated as the parameter standard error * $t_{0.025,n}$ distribution.

Table 6. Parameters of nonlinear regression analysis from fitting Eqs. [1], [2], and [3] to percent S in tissue, based on the concentration of SO_4-S in the nutrient solution at 4, 8, 12, and 17 weeks after planting. The number of observations per sampling data was 48 at week four and 96 thereafter. Data from the lime treatments were used in the same analysis and are presented in Fig. 6.

	Week 4	Week 8	Week 12	Week 17	units
Estimated parameters					
Intercept (I_1)	0.42 ± 0.11^{z}	0.25 ± 0.06	0.22 ± 0.08	0.28 ± 0.07	% dry mass
Slope (S_1)	0.006 ± 0.002	0.012 ± 0.003	0.015 ± 0.004	0.012 ± 0.003	% dry mass/mg L^{-1}
Intercept (I_2)	0.69 ± 0.04	0.58 ± 0.05	0.66 ± 0.05	0.68 ± 0.06	% dry mass
Slope (S_2)	0.000 ± 0.001	0.002 ± 0.001	0.002 ± 0.001	0.001 ± 0.001	% dry mass/mg L^{-1}
Calculated parameters					
$X_{intersection}$	41	32	32	38	mg $liter^{-1}$

^{z}Ninety-five percent confidence intervals were calculated as the parameter standard error * $t_{0.025,n}$ distribution.

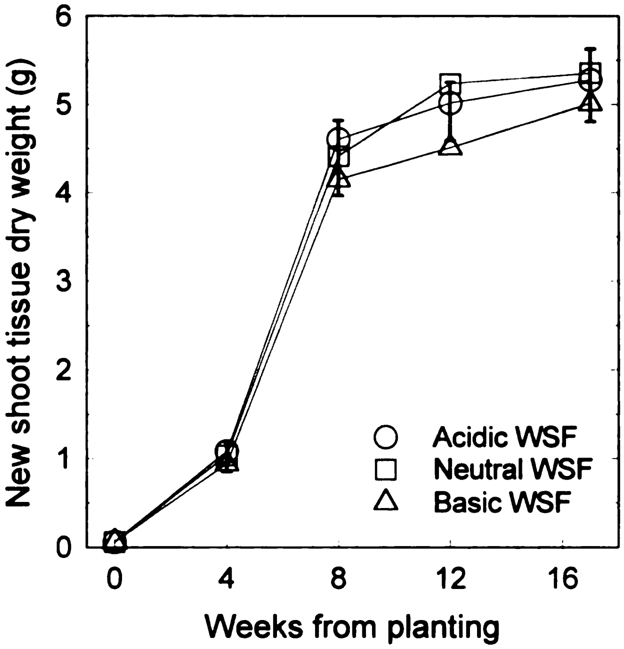

Fig. 1. Average new shoot dry weight of the three water-soluble fertilizer (WSF) treatments from impatiens at 4, 8, 12, and 17 weeks after planting. After each harvest, remaining plants were pruned to the same point. Error bars were calculated as 95% confidence intervals. Data represent only the new shoot growth from the previous four-week period.

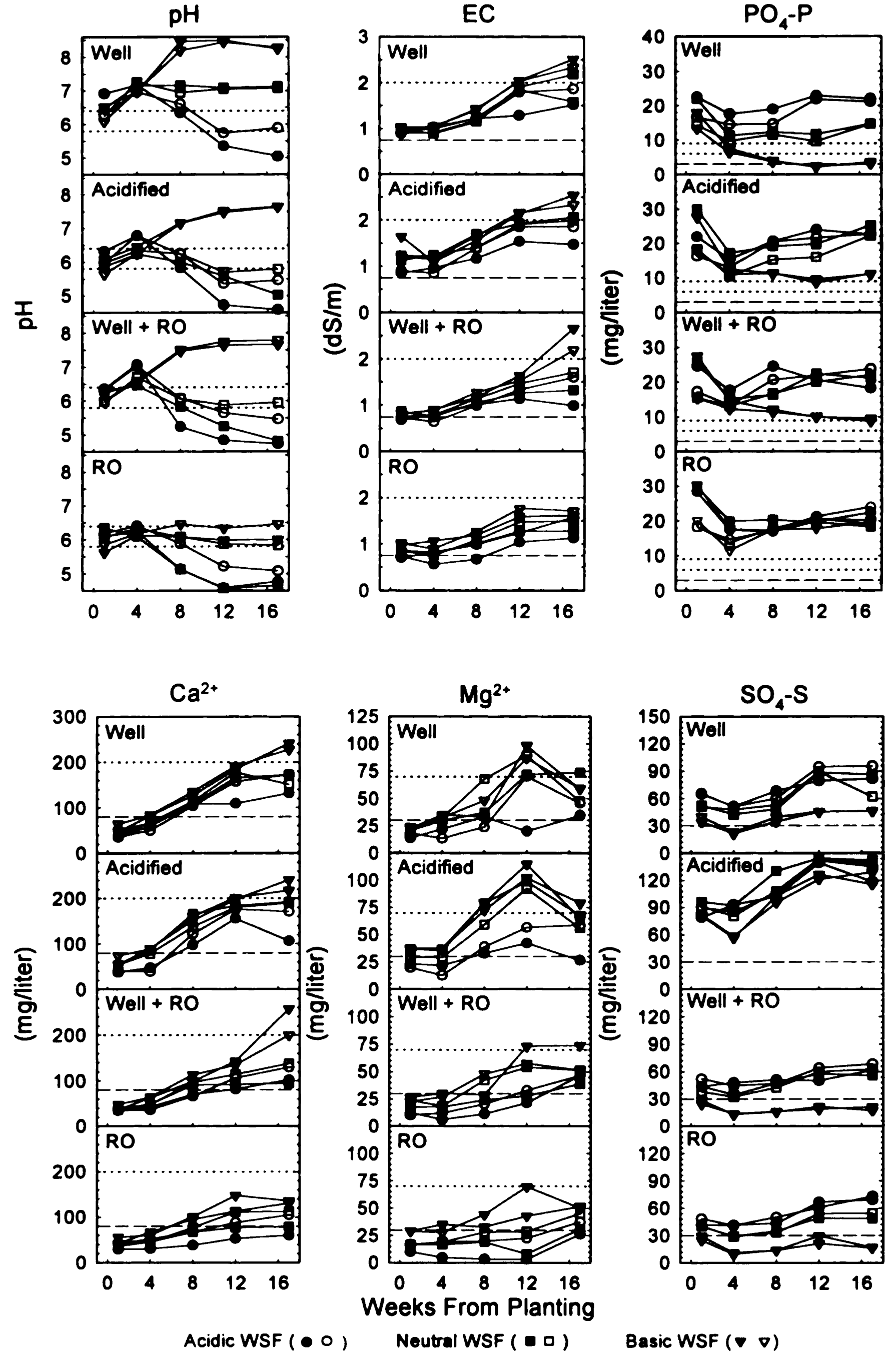

Fig. 2. Root-medium pH, electrical conductivity (EC), PO_4-P, Ca^{2+}, Mg^{2+}, and SO_4-S concentrations in the root zone of plants grown with four irrigation-water sources and three water-soluble fertilizers (WSF) between weeks 1 and 17. Filled symbols are hydrated lime treatments and hollow symbols are carbonate lime treatments. The dotted lines (·······) represent the recommended optimal ranges the and dashed lines (----) represent the lower recommended acceptable range for the saturated media extract (Warncke and Krauskopf, 1983). Statistical analysis is presented in Table 2. Data are means of four samples at each date.

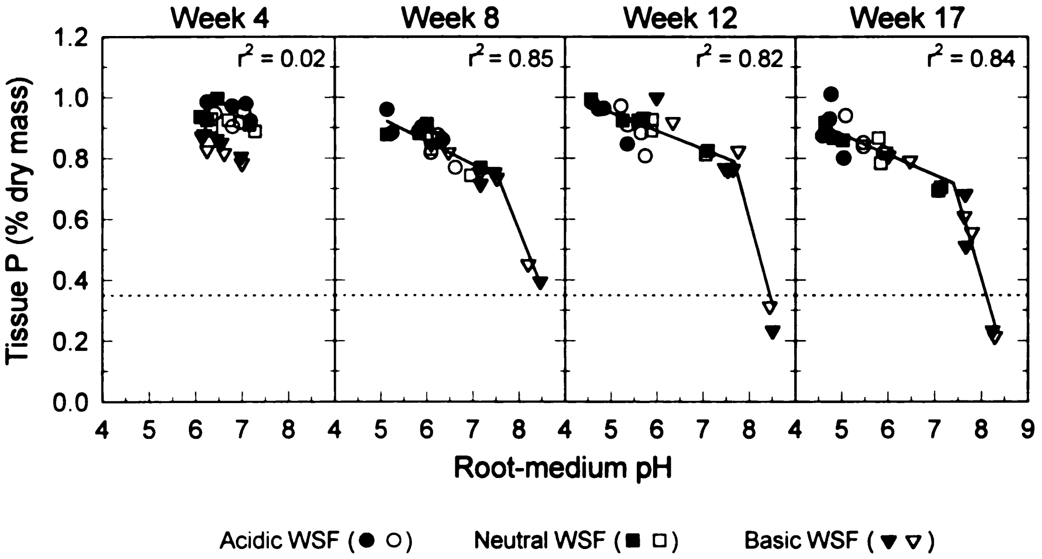

Fig. 3. The effect of root-medium pH on the tissue P of impatiens grown with four irrigation-water sources and three water-soluble fertilizers (WSF) at 4, 8, 12, and 17 weeks after planting. Filled symbols are hydrated lime treatments and hollow symbols are carbonate lime treatments. The solid line (—) represents the predicted tissue P content based on Eq. [1] and the dotted line (·····) represents the minimum recommended tissue P content. R^2 values were calculated as $1\text{-}SS_{residual}/SS_{corrected\ total}$ and remaining statistical analyses of the individual parameters are presented in Table 3. Data are means of four samples at each date.

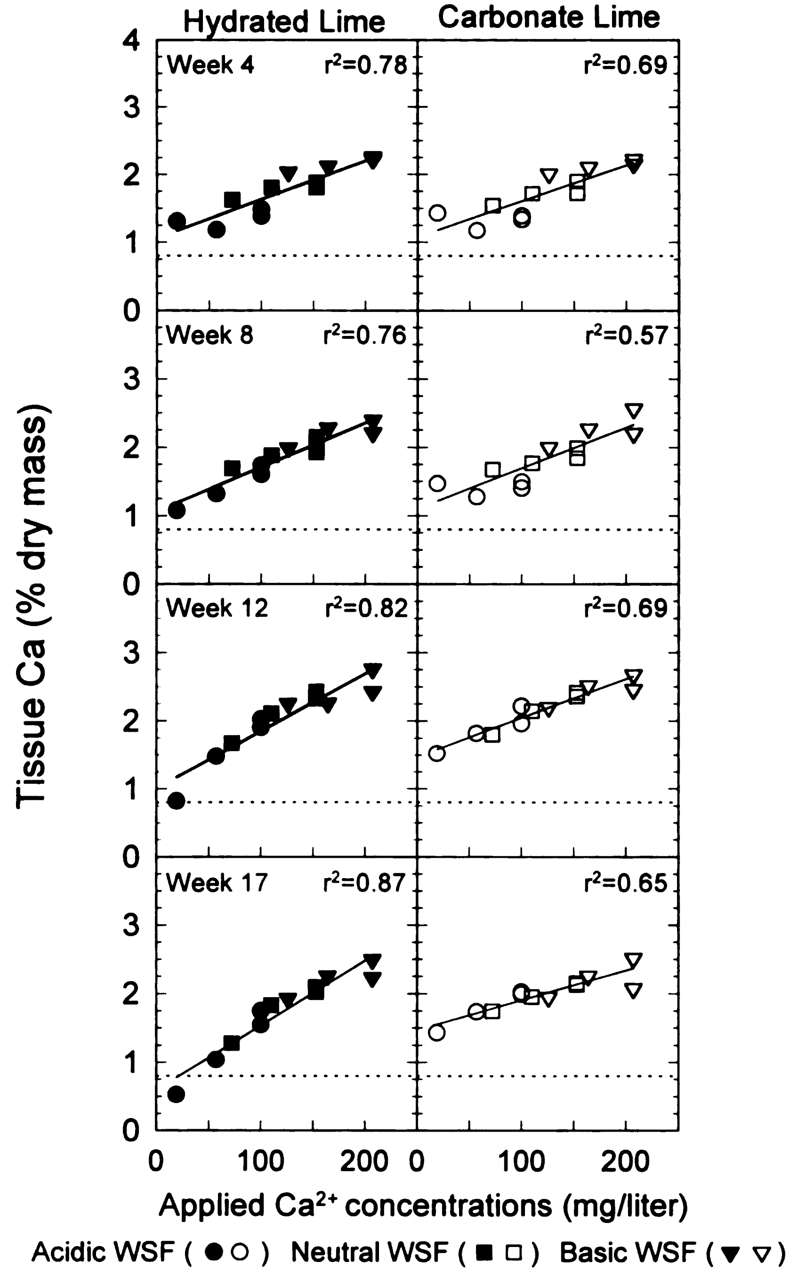

Fig. 4. The effect of applied Ca^{2+} concentration on the tissue Ca of impatiens grown with four irrigation-water sources and three water-soluble fertilizers (WSF) at 4, 8, 12, and 17 weeks after planting. The solid line (—) represents the predicted tissue Ca content based on linear regression analysis and the dotted line (····) represents the minimum recommended tissue Ca content. R^2 values were calculated as $1\text{-}SS_{residual}/SS_{corrected\ total}$, and remaining statistical analyses of the individual parameters are presented in Table 4. Data are means of four samples at each date.

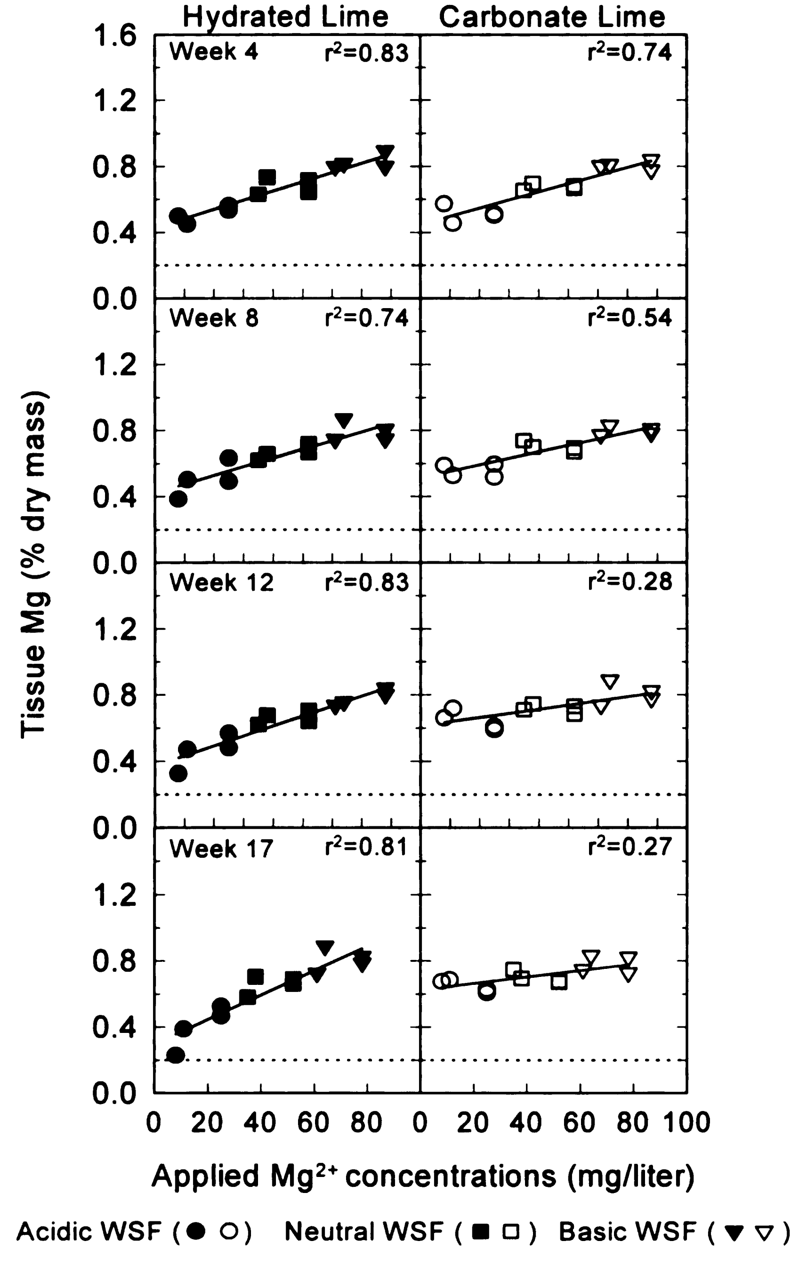

Fig. 5. The effect of applied Mg^{2+} concentration on the tissue Mg of impatiens grown with four irrigation-water sources and three water-soluble fertilizers (WSF) at 4, 8, 12, and 17 weeks after planting. The solid line (—) represents the predicted tissue Mg content based on linear regression analysis and the dotted line (····) represents the minimum recommended tissue Mg content. R^2 values were calculated as 1-$SS_{residual}/SS_{corrected\ total}$, and remaining statistical analyses of the individual parameters are presented in Table 5. Data are means of four samples at each date.

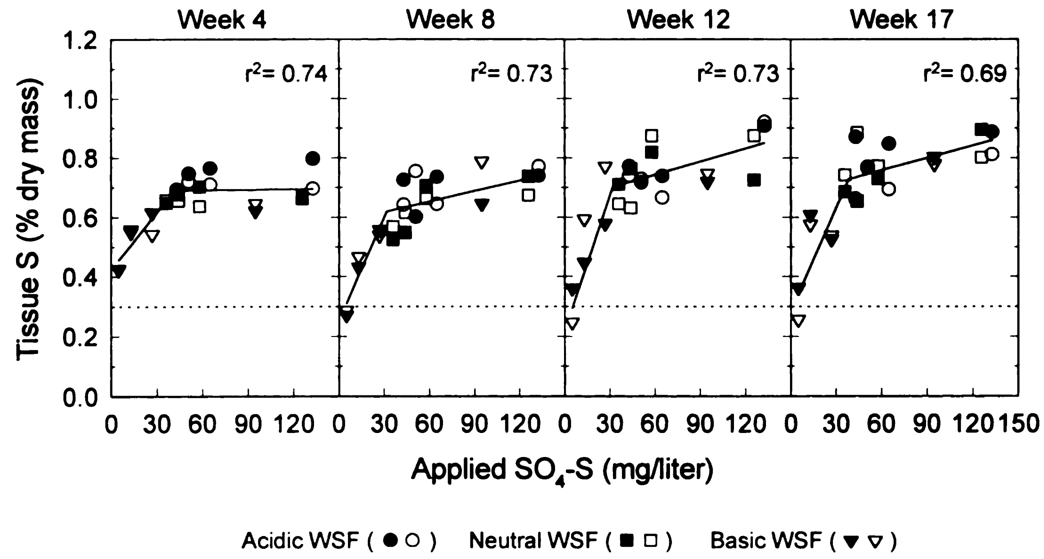

Fig. 6. The effect of applied SO_4-S concentration on the tissue S of impatiens grown with four irrigation-water sources and three water-soluble fertilizers (WSF) at 4, 8, 12, and 17 weeks after planting. Filled symbols are hydrated lime treatments and hollow symbols are carbonate lime treatments. The solid line (—) represents the predicted tissue S content based on Eq. [1] and the dotted line (⋯) represents the minimum recommended tissue S concentration. R^2 values were calculated as $1\text{-}SS_{\text{residual}}/SS_{\text{corrected total}}$, and remaining statistical analyses of the individual parameters are presented in Table 6. Data are means of four samples at each date.

SECTION IV

THE EFFECT OF ROOT MEDIA ON ROOT-ZONE pH, CALCIUM, AND MAGNESIUM MANAGEMENT IN CONTAINER WITH IMPATIENS

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The Effect of Root Media on Root-Zone pH, Calcium, and Magnesium Management in Containers with Impatiens

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Abbreviations: CEC, cation exchange capacity; EC, electrical conductivity; IWS, irrigation-water source; NS, nutrient solution; PNC, preplant nutrient charge; RO, reverse osmosis; SME, saturated media extract; WSF, water-soluble fertilizer

Soils, Nutrition, and Fertilizers

The Effect of Root Media on Root-Zone pH, Calcium, and Magnesium Management in Containers with Impatiens

Additional index words. Cation exchange capacity, coir, irrigation-water source, rockwool, sphagnum peat, soilless media, subirrigation, water-soluble fertilizer

Abstract. Hybrid impatiens (*Impatiens Wallerana* Hook. F.) were planted in six root media containing either 70% (by volume) rockwool, coir, or 4 types of sphagnum peat and 30% perlite. The six media varied in cation exchange capacities (CEC) (from 5 to 76 meq·L^{-1}) and the amount of a dolomitic hydrated lime ($Ca(OH)_2$ and $Mg(OH)_2$ at 0 to 4.5 kg·m^{-3}) required to obtain an initial pH of ≈6.0. Two additional treatments were produced by using a dolomitic carbonate lime ($CaCO_3$ and $MgCO_3$) at 8.4 kg·m^{-3} instead of the hydrated lime in two of the sphagnum peat media. Plants were subirrigated for 17 weeks using three nutrient solutions (NS) that contained N-P-K at 200-20-200 mg·L^{-1} but had a variable NH_4 : NO_3 ratio, Ca^{2+}, and Mg^{2+} content. The NS were designed to produce either acidic, neutral, or basic reactions in the medium. In media containing the hydrated lime, the NS was the primary factor controlling medium pH. However, within each NS treatment, the media did have some effect on buffering the pH over time. There was a linear increase in shoot-tissue Ca and Mg as the applied concentration of Ca^{2+} increased from 18 to 156 mg·L^{-1}; and that of Mg^{2+}, from 5 to 56 mg·L^{-1}. Linear regression analysis of shoot-tissue Ca and Mg based on their concentration in the NS indicated a similar overall decrease in the Ca and Mg supply in all six root media over time. For plants grown in media containing the carbonate lime, shoot dry weight was similar to that of plants grown in the same media with hydrated lime. The presence of the carbonate lime in

the media increased the pH buffering capacity against decreasing pH with the acidic and neutral NS, but not against increasing pH with the basic NS. In the media containing the carbonate lime and given the acidic NS, both root-medium and shoot-tissue Ca and Mg increased by weeks 12 and 17 compared to that of the same medium containing the hydrated lime. There were minimal differences in root-media and shoot-tissue Ca and Mg between lime treatments when given the neutral or basic NS.

A number of sources interact to affect the nutrient supply of container root media throughout crop production (Argo and Biernbaum, 1996a). However, not all sources affect the nutrient supply simultaneously or with equal intensity. This is especially true for Ca^{2+} and Mg^{2+} nutrition, where the sources can include exchange sites associated with the cation exchange capacity (CEC) of the medium, liming materials, and the irrigation-water source (IWS) and water-soluble fertilizer (WSF) that make up the nutrient solution (NS). Any discussion of Ca^{2+} and Mg^{2+} nutrition also must include pH management because of the direct or indirect effects the Ca^{2+} and Mg^{2+} sources have on media pH.

The original Cornell peat-lite mixes contained 50% peat by volume (Boodley and Sheldrake, 1972). The three major types of peat used to produce container media are sphagnum, hypnum, and reed sedge (Bunt, 1988; Nelson, 1991; Puustjarvi and Robertson, 1975) and reflect the parent material of the peat. In general, sphagnum is the most common peat type used in container root media.

The CEC of peat often is associated with the pH and nutrient buffering capacity and are due to the pH-dependent exchange of cations with H^+ from organic acid functional groups on the peat particles. For example, Helling et al. (1964) found that the CEC of a sphagnum peat increased by 140 $meq \cdot L^{-1}$ as the pH increased from 3.5 to 8.0. The ratio of H^+ to cations bound to the peat also changes with increasing pH. At a pH of

3.7, 4.5, 5.5, or 7.8, acid sphagnum peat is 100%, 50%, 30%, or 0% H^+ saturated, respectively (Lucas et al., 1975; Puustjarvi and Robertson, 1975). Bunt (1988) reported that the CEC of peat largely indicates the potential for divalent ions adsorption (Ca^{2+} and Mg^{2+}), with most monovalent cations (NH_4^+-N, K^+, Na^+) remaining water-soluble.

The CEC of peat on a weight basis is much higher than that of mineral soils. For example, Lucas (1982) reported that the CEC of a sphagnum peat was 1000 $meq \cdot kg^{-1}$ while that of a loam mineral soil was 120 $meq \cdot kg^{-1}$. However, because of the low bulk density of the sphagnum peat, the effective CEC measured on a volume basis was 40% less than that of the mineral soil (80 $meq \cdot L^{-1}$ for the peat vs. 140 $meq \cdot L^{-1}$ for the mineral soil). Puustjarvi (1982) reported a linear increase in the CEC of sphagnum peat from 45 $meq \cdot L^{-1}$ to 130 $meq \cdot L^{-1}$ as the degree of decomposition increased from H1 to H5 as measured with the von Post scale (Puustjarvi and Robertson, 1975). The overall increase in CEC was associated with both a higher CEC of the more degraded peat itself (H1 peat was 1000 $meq \cdot kg^{-1}$, H5 peat was 1240 $meq \cdot kg^{-1}$) as well as an increase in the bulk density with greater decomposition (H1 peat was 45 $kg \cdot m^{-3}$, H5 peat was 105 $kg \cdot m^{-3}$).

Other materials such as perlite, polystyrene, or rockwool (RW) have minimal CEC and are included in container media to increase aeration or water-holding capacity (Argo and Biernbaum, 1994; Nelson, 1991). Pine or hardwood bark, coconut mesocarp pith (coir), or expanded vermiculite are added to container media for aeration and water-holding capacity but each also has significant CEC (Bunt, 1988; Nelson, 1991). Researchers suggest that an adequate CEC is desired in a container medium to buffer it from sudden changes in pH and nutrient concentrations (Biernbaum, 1992; Bunt, 1988; Nelson, 1991). However, only limited information exists on how medium CEC affects long-term pH, Ca^{2+}, and Mg^{2+} management under production conditions.

Liming materials ($CaCO_3$, $CaCO_3$ and $MgCO_3$, $Ca(OH)_2$, $Ca(OH)_2$ and $Mg(OH)_2$) are added to a soilless root medium to neutralize acidity, increase pH to a level acceptable for plant growth, and provide a source of Ca^{2+} and Mg^{2+}. Incorporating sufficient lime into a soilless root medium to obtain an initial pH range of 5.5 to 6.4 is recommended (Nelson, 1991; Peterson, 1981; Warncke and Krauskopf, 1983). The amount of liming material (incorporation rate) required to obtain an equilibrium pH of 6 in the root medium depends not only on the components used to produce the medium, but also on the liming material's reactivity and particle size (Argo and Biernbaum, 1996b; Chapin, 1980; Gibaly and Axley, 1955; Schollenberger and Salter, 1943; Sheldrake, 1980; Williams et al., 1988) as well as the surface area (Parfitt and Ellis, 1966). Argo and Biernbaum (1996b) proposed that not all the liming material incorporated into a soilless root medium may have reacted once an equilibrium pH is reached. Residual or unreacted lime that remained in the medium after the equilibrium pH was reached was a significant source of long-term pH, Ca^{2+}, and Mg^{2+} buffering capacity when using an acidic NS containing, low Ca^{2+} and Mg^{2+} in one peat-based medium (Argo and Biernbaum, 1996a).

The NS composed of an IWS and WSF and applied to a root medium interacts to affect the pH and nutrient concentrations two ways: directly (nutrient concentration applied to the root medium) and through fertilizer reaction on root-medium pH. With NO_3^--N fertilization, the medium pH tends to increase because of OH^- or HCO_3^- secretion associated with root ion uptake. In comparison, with NH_4^+-N fertilization, the medium pH tends to decrease because of H^+ secretion during root ion uptake and the bacterial nitrification of the NH_4^+-N to the NO_3^--N form within the medium, which also releases H^+ (Barker and Mills, 1980; Bunt, 1988; Hawkes et al., 1985; Marschner, 1986; Nelson, 1991). Argo and Biernbaum (1996b) found that the degree of change caused by a NS depended not only on the NH_4:NO_3 ratio, but also the alkalinity concentration in the IWS and the presence or absence of residual lime in the medium.

In production of container-grown crops, it is no longer acceptable to manage the pH and macronutrient concentrations in the root medium and plant shoot-tissue with high WSF concentrations and high leaching rates (Biernbaum, 1992). Irrigation systems that minimize or eliminate water and fertilizer runoff into the environment currently exist. Optimizing pH, Ca^{2+}, and Mg^{2+} management of low- or nonleaching irrigation systems requires an understanding of how factors such as media, lime, IWS, and WSF interact during production. The objectives of this research were to investigate how NS composed of three combinations of IWS and WSF interact with root media requiring different lime incorporation rates to affect root-medium pH, Ca^{2+}, and Mg^{2+} management under production conditions.

Materials and Methods

Expt. 1 included 18 treatments composed of six types of media and three types of NS combined in a 6 x 3 factorial arrangement. Expt. 2 included 12 treatments composed of two types of media, two types of lime, and three types of NS combined in a 2 x 2 x 3 factorial arrangement. Six of the 12 treatments from Expt. 2 were the same as those in Expt. 1. At each sampling date, four pots from each treatment (two pots from each of two greenhouse sections) were sampled. Replication was made between greenhouse sections, while the two pots taken from the same greenhouse section were treated as subsamples for statistical analysis.

Soil test data were analyzed using SAS's analysis of variance (ANOVA) procedures (SAS Institute, Cary, N.C.) in Expt. 1 as a 6 x 3 factorial and in Expt. 2 as a 2 x 2 x 6 split-plot factorial, with lime as the main plot and the other factors as subplots at each sampling date. Medium EC and nutrient concentration data were transformed to log(observed + 1) for the ANOVA because of differences in sample variance between treatments. Time was not included in the ANOVA because of lack of homogeneity of variance over time. Relationships were developed between the concentration of Ca^{2+} and

Mg^{2+} in the NS and shoot-tissue Ca and Mg using SAS's linear regression procedure (REG). Significant differences in the slope and intercept between sample weeks was tested using a multiple regression model in SAS's general linear model procedure (GLM).

Expt. 1. The six root media were composed of 30% perlite (by volume) blended with one of the following: medium grind RW (Partek North American, Inc., Brunswick, Ohio); coconut coir pith (Coir) (Scotts, Marysville, Ohio); Fisons black bale professional grower grade Canadian sphagnum moss peat (Peat 1) (Sun Gro Horticulture, Bellevue, Wash.); Fafard Trump Ace professional grower grade Canadian sphagnum moss peat (Peat 2) (Fafard, Anderson, S.C.); Fafard Majestic retail fine Canadian sphagnum moss peat (Peat 3); and Fafard Genuine retail extra fine Canadian sphagnum moss peat (Peat 4). Peats 1 and 2 were long-fibered with little dust (von Post scale 1-2; Puustjarvi and Robertson, 1975) and peats 3 and 4 were more degraded with short fibers and large amounts of dust (von Post scale 3-4). Because of high pH (>8.5), the unamended RW was soaked in 0.5 N HCl for 5 min to remove any residual alkaline material, thoroughly rinsed in reverse osmosis (RO) purified water, and allowed to air dry for three days before blending into media.

Sufficient amounts of a microfine dolomitic hydrated lime ($Ca(OH)_2$ and $Mg(OH)_2$ with 34% Ca and 20% Mg, and a $CaCO_3$ equivalent of 169, National Lime and Stone, Findlay, Ohio) in which 97% of the material passed a 45-μm (#325) screen were added to increase the pH of the medium to 5.8 to 6.4. Because of the different lime requirements of the six media, the amount of hydrated lime added per m^3 was RW (0 kg), coir (0.5 kg), peat 1 (1.5 kg), peat 2 (1.6 kg), peat 3 (2.3 kg), and peat 4 (2.7 kg). These incorporation rates added to the six media, respectively, Ca^{2+} at 0, 0.2, 0.5, 0.5, 0.8, and 0.9 $kg \cdot m^{-3}$; Mg^{2+} at 0, 0.1, 0.3, 0.3, 0.5, and 0.6 $kg \cdot m^{-3}$; and a $CaCO_3$ equivalent of 0, 0.9, 2.6, 2.7, 3.9, and 4.6 $kg \cdot m^{-3}$.

In addition to the lime, a preplant nutrient charge (PNC) consisting of $Ca(NO_3)_2$, KNO_3, triple superphosphate (0N-19.8P-0K), and gypsum at 0.6 $kg{\cdot}m^{-3}$ each; $MgSO_4$ at 0.3 $kg{\cdot}m^{-3}$; fritted trace elements (FTE 555, Scotts, Marysville, Ohio) at 0.07 $kg{\cdot}m^{-3}$; and a wetting agent (Aquagro 2000 L, Aquatrols, Pennsaulken, N.J.) at 0.2 $L{\cdot}m^{-3}$ were incorporated into all media at mixing. Sufficient RO purified well water was added to bring the moisture content of the medium to 40% to 50% of container capacity, and the medium was allowed to equilibrate for three days before planting. At planting, the six media had an average pH of 6.0, an EC of 2.4 $dS{\cdot}m^{-1}$, and 160 NO_3^--N, 45 PO_4-P, 220 K^+, 210 Ca^{2+}, 110 Mg^{2+}, and 145 SO_4-S ($mg{\cdot}L^{-1}$), as measured with the saturated media (SME) analysis with RO water as the extractant (Warncke, 1986).

Nutrient solutions (NS). The NS concentration of N-P-K was maintained at a constant 200-20-200 $mg{\cdot}L^{-1}$ for the duration of the experiment. The three NS varied in NH_4^+-N, Ca^{2+}, Mg^{2+}, Na^+ and SO_4-S concentrations. Nutrient solution 1 (NS 1) was a WSF made from KNO_3, K_2SO_4, $NH_4H_2PO_4$, NH_4NO_3, and urea that contained 50% NH_4^+-N with 0 Ca^{2+}, 0 Mg^{2+}, 0 Na^+, and 42 SO_4-S ($mg{\cdot}L^{-1}$) mixed with RO purified well water that had a pH of 5.5; an EC of 0.1 $dS{\cdot}m^{-1}$; 15 Ca^{2+}, 5 Mg^{2+}, 27 Na^+, 1 SO_4-S ($mg{\cdot}L^{-1}$); and a titratable alkalinity to pH 4.5 (Chau, 1984) of <20 mg $CaCO_3{\cdot}L^{-1}$. Nutrient solution 2 (NS 2) was a WSF made from $Ca(NO_3)_2$, KH_2PO_4, KNO_3, $Mg(NO_3)_2$, and $MgSO_4$ that contained 3% NH_4^+-N with 100 Ca^{2+}, 50 Mg^{2+}, 0 Na^+, and 3 SO_4-S ($mg{\cdot}L^{-1}$) mixed with a blend of well and RO water (1:1.5 by volume) that had a pH of 6.7; an EC of 0.3 $dS{\cdot}m^{-1}$; 52 Ca^{2+}, 16 Mg^{2+}, 24 Na^+, and 10 SO_4-S ($mg{\cdot}L^{-1}$); and a titratable alkalinity to pH 4.5 of 120 mg $CaCO_3{\cdot}L^{-1}$. Nutrient solution 3 (NS 3) was a WSF made from KH_2PO_4, KNO_3, $NaNO_3$, and NH_4NO_3 that contained 25% NH_4^+-N with 0 Ca^{2+}, 0 Mg^{2+}, 62 Na^+, and 0 SO_4-S ($mg{\cdot}L^{-1}$) mixed with the same water as that used for NS 2. Micronutrients (Fe, Mn, Zn, Cu, B, and Mo) were added to all nutrient solutions with a commercially available blended chelated material (Compound 111 [1.50 Fe-0.12 Mn-0.08 Zn-0.11 Cu-0.23 B-0.11 Mo], Scotts, Marysville, Ohio) at a constant 50 $mg{\cdot}L^{-1}$.

The WSF used to make the NS 1, NS 2, and NS 3 were designed to produce either an acidic, basic, or neutral reaction in the media, respectively, and were based on work by Argo and Biernbaum (1996a). The type of reaction produced by the WSF was calculated, with values for the reaction produced by the individual salts obtained from Hawkes et al. (1985) and Young and Johnson (1982) multiplied by the percentage that each salt contributed to the total WSF weight. The value obtained for each WSF was used as an estimate of the type (either acidic or basic) and strength (in kg/1000 kg of fertilizer) of reaction produced. Based on these calculations, NS 1 (acidic NS) had an acidity of 199 kg/1000 kg, NS 2 (basic NS) had a basicity of 175 kg/1000 kg, and NS 3 (neutral NS) had a basicity of 2 kg/1000 kg.

Expt. 2. A dolomitic carbonate lime ($CaCO_3$ and $MgCO_3$, with 22% Ca and 13% Mg, and a $CaCO_3$ equivalent of 108, National Lime and Stone, Findlay, Ohio) in which 60% of the material passed a 75-μm (#200) screen was incorporated at 8.4 $kg{\cdot}m^{-3}$ into media containing peats 1 and 4. At this incorporation rate, the carbonate lime added Ca^{2+} at 1.8 $kg{\cdot}m^{-3}$, Mg^{2+} at 1.1 $kg{\cdot}m^{-3}$, and a $CaCO_3$ equivalent of 9.1 $kg{\cdot}m^{-3}$ to each root media. The lime incorporation rate used in Expt. 2 was not based on the lime requirement of the two media. In addition to the carbonate lime, the same PNC and wetting agent used in Expt. 1 were incorporated at mixing. These two treatments were compared to the same media treatments containing the hydrated lime from Expt. 1. At planting, the two media containing the carbonate lime had an average pH of 4.8, an EC of 2.4 $dS{\cdot}m^{-1}$, and 170 NO_3^--N, 60 PO_4-P, 180 K^+, 170 Ca^{2+}, 140 Mg^{2+}, and 160 SO_4-S ($mg{\cdot}L^{-1}$), as measured with the SME analysis with RO water as the extractant (Warncke, 1986).

Plant culture. The experiment was conducted starting 15 Feb. 1995 at Michigan State University, East Lansing, in two well-ventilated glass greenhouse sections with constant air circulation and cement floors. One hybrid impatiens plug (cv. Super Elfin Violet) from a size 512 plug tray was planted into a 9-cm-tall by 12.5-cm-wide (0.75-L) plastic pot containing medium with one of the two lime types. Twenty-five pots of each medium treatment were placed on three flood subirrigation bench sections in each of the two greenhouses. Where applicable, both lime types were placed on the same bench section.

Plants on each bench section were irrigated independently, with the time to irrigate determined gravimetrically when the average mass of three pots containing plants and medium from each treatment reached a target weight based on a loss of 40% to 50% of the available water. The same three pots were checked daily for the target weight, and when it was reached, NS were applied. During an irrigation, benches were filled with NS from a 70-L reservoir for 2 min to a maximum depth of 2.5 cm and drained in 6 min to the same reservoir. The difference between the mass of the pots before and after the irrigation was the NS absorbed. The amount of nutrients applied per pot was calculated as the sum of the absorbed NS multiplied by the concentration. The NS in the 70-L reservoirs were prepared fresh weekly.

Media physical and chemical characteristics. Medium moisture holding characteristics were determined in the 9-cm-tall by 12.5-cm-wide pots using the method outlined by White and Mastalerz (1966). The blended medium CEC was determined with air-dried, acid-washed media using the method outlined by Rund (1984). Barium from 0.5 N $Ba(OAc)_2$ was used as the replacement ion for the H^+ saturated media. Cation exchange capacity expressed on a volume measurement was calculated by multiplying the bulk density by the CEC measurement based on weight.

Sampling technique. Root media were sampled initially and collected from four pots (two per treatment from each bench section) at 1, 4, 8, 12, and 17 weeks after planting. All the medium was removed from each pot and separated horizontally into two samples, one containing the top 2.5 cm (top layer), and the other containing the remaining medium from the pot (root zone). Nutrients contained in each medium sample were tested using the SME method with RO purified water as the extractant (Warncke, 1986). Only EC was measured in the top-layer sample, while pH, EC, NO_3^--N, NH_4^+-N, PO_4-P, K^+, Ca^{2+}, Mg^{2+}, and SO_4-S were measured in the root-zone sample. Medium pH was determined by inserting the ion-specific electrode directly into the saturated medium before extraction, and EC and macronutrients were measured in the extracted solution. Medium EC was determined with a platinum electrode at a standard 25 °C; Mg was determined colorimetrically (magnesium blue, Technicon Instruments, Tarrytown, N.Y.); and Ca^{2+} was determined using emission spectroscopy by the Michigan State University Soil and Nutrient Testing Laboratory. Medium CEC also was measured in the top layer and root zone at the week 17 sampling date using the method outlined previously.

Shoot dry weight and shoot-tissue nutrient analysis were determined for four plants per treatment at 4, 8, 12, and 17 weeks after planting. At week four, the entire plant was used in the sample. For the remaining plants, all shoots were pinched back, leaving one internode per stem and four to six stems per plant. At all subsequent sampling dates, only growth after the previous pinch was sampled, and the remaining plants were cut back to the week-four pinch level. Shoot-tissue macronutrients and micronutrients (Fe, Mn, Cu, Zn, B, and Mo) were determined by plasma emission spectroscopy (Fafard Analytical Laboratory, Athens, Georgia).

Results and Discussion

Media physical and chemical characteristics. The six root media used in this experiment had air space ranging from 18% to 28% and a total water-holding capacity from 49% to 63% of the 0.75-L pot at container capacity (Table 1). These values were within established guidelines for container media (Bunt, 1988).

Cation exchange capacity of the media used in this experiment ranged from 34 to 639 meq·kg^{-1} (Table 1). However, because of the low bulk density of the medium, the CEC on a volume basis ranged from 5 to 76 meq·L^{-1}. The effective cation exchange sites of the media in the pot was lower still because the pot size was 0.75 L and the top 2 to 3 cm that contains 35% of the medium were without roots. Nutrients contained in the top layer of subirrigated pots are generally unavailable to the plant (Argo and Biernbaum, 1996a; Yelanich, 1995). Any cation exchange sites associated with the medium contained in the top layer probably will not affect the remaining medium within the pot with subirrigation. In fact, when the CEC of media contained in the top-layer sample was tested after 17 weeks, there was a 5% to 20% decrease (by weight) compared to the same media at planting (data not shown). In comparison, the CEC of the root zone did not change between planting and week 17.

Plant growth. In Expt. 1, new shoot growth was affected by media and NS (Fig. 1). However, except for plants grown in the RW media, the differences in shoot dry weight were not consistent across NS or between the sampling dates. There were minimal differences in the shoot dry weight of plants grown with the basic NS than either the acidic or neutral NS. In Expt. 2, the growth of plants in media containing the carbonate dolomitic lime was similar to that of plants grown in the same media with hydrated lime, but there were media differences similar to those measured in Expt. 1 (data not shown). In comparison, Argo and Biernbaum (1996a) measured only small differences between impatiens grown under similar conditions using 24 combinations of lime, IWS, and WSF but with a single root medium.

Plants grown in the RW medium were much smaller than those grown in the other root media (Fig. 1) with all three NS. The reason for the limited growth is unclear but may have been due to poor rooting of the plugs into the RW medium. Several species including African violet, chrysanthemums, Easter lily, gerbera, gloxinia, kalanchoe, and poinsettia were grown in 100% acid-washed RW with subirrigation and were of equal size and quality to those grown in commercially available Peatlite media (Biernbaum, unpublished data; Yelanich, 1995). However, in those experiments, a PNC and wetting agent were not incorporated into the RW medium before planting. The initial nutrient concentrations from the PNC were slightly higher in the RW media (2.8 $dS \cdot m^{-1}$) than in the other media (remaining media average of 2.3 $dS \cdot m^{-1}$), but were within normally acceptable limits (Warncke and Krauskopf, 1983). Wetting agents can be phytotoxic to impatiens (Bhat et al.,1989) which may have caused the limited growth of the RW treatments plants in this experiment.

Water and fertilizer applications. Excluding the RW treatments, the volume of water applied ranged from 6.1 to 7.3 L per pot over the 17 weeks of the experiment (Table 2). Because the N-P-K concentrations in the NS were constant, the amount applied was similar and ranged from 1.4 to 1.8 g N and K^+, and 0.23 to 0.26 g PO_4-P per pot, including the PNC fertilizers (data not shown). In comparison, the concentrations of Ca^{2+} and Mg^{2+} in the NS varied by a factor of almost 10, and the amount of Ca^{2+} and Mg^{2+} incorporated with the lime also varied because of the different lime requirements of the six media. The total amount applied ranged from 0.5 to 1.9 g Ca^{2+} and 0.14 to 0.87 g Mg^{2+} per pot in Expt. 1 (Table 2). In Expt. 2, the incorporation of the dolomitic carbonate lime increased the total amount of Ca and Mg applied per pot to 1.7 to 2.5 g Ca^{2+} and 0.9 to 1.2 g Mg^{2+} per pot and was similar for the peat 1 and peat 4 media with each NS.

Argo and Biernbaum (1996a) found that impatiens grown with shoot-tissue Ca and Mg concentrations as low as 0.4% and 0.2%, respectively, produced a similar amount of dry mass compared to impatiens grown with shoot-tissue Ca and Mg concentrations at 2.5% and 1.0%, respectively. Based on the amount of shoot tissue produced, sufficient

Ca and Mg were applied to the crop to maintain the highest shoot-tissue Ca and Mg concentrations (2.5% and 1%, respectively) for the duration of the experiment in all treatments (excluding the RW treatments). For example, in Expt. 1, the amount of Ca required as a percentage of the total Ca applied would have averaged 36% (33% to 46%) with the acidic NS, 25% (23% to 33%) with the neutral NS, and 16% (14% to 20%) with the basic NS. For Mg, the amount required as a percentage of the total Mg applied would have averaged 38% (25% to 65%) with the acidic NS, 27% (20% to 41%) with the neutral NS, and 16% (12% to 19%) with the basic NS. With the RW treatments, the amount of Ca as a percentage of the total Ca applied required to maintain 2.5% shoot-tissue Ca would have been 40%, 26%, and 10% for the acidic, neutral, and basic NS, respectively. However, with Mg, the acidic NS did not supply enough for the 1% shoot-tissue Mg, but the other two treatments supplied excess Mg so that the percentage of the total amount applied would have been 57% and 11% with the neutral and basic NS, respectively.

Root-zone pH. In Expt. 1, the initial pH of the media ranged from 5.7 in the peat 1 medium to 6.4 in the peat 3 medium. By week 1, the pH of all media had increased and ranged from 6.3 in the peat 4 medium to 6.8 in the RW medium, as averaged over the NS (Fig. 2, Table 3). In general, the primary factor controlling medium pH in Expt. 1 was the NS (Fig 2, Table 3), which was affected by the percentage of NH_4^+-N in the WSF and the alkalinity concentration in the IWS (Argo and Biernbaum, 1996a). Within each NS treatment, the media did have some effect on buffering pH. For example, the pH of the coir medium given acidic NS decreased most between weeks 1 and 4, but was similar to that of the other root media thereafter. With the neutral NS, the highest pH was maintained in media containing the more-degraded peat (peat 3 and 4), while the coir media maintained the lowest pH. With the basic NS, only media containing peat 4 temporarily slowed the increase in root-medium pH, but by week 17, the pH was similar to that of the coir and RW media.

In Expt. 2, media containing the dolomitic carbonate lime at 8.4 $kg \cdot m^{-3}$ had an average pH of 4.8 at planting, which increased to an average of 6.0 by week 1, similar to the average of 6.3 in the same media containing the hydrated lime (Fig. 3). After week 1, the effect that the type of lime incorporated into the medium had on the long-term pH buffering capacity depended on the type of NS applied (Fig. 3, Table 4). With the acidic NS, peat type had minimal effect on pH buffering. Instead, the residual lime was the primary factor buffering medium pH through week 12. With the neutral NS, peat type had some effect on pH buffering capacity, but the peat effect could be negated with residual lime contained in the medium. With the basic NS, lime type had minimal effect on pH buffering. Instead, the primary factor buffering the medium was the peat type (Fig. 3, Table 4).

Argo and Biernbaum (1996a) suggest that reliance on residual lime for pH buffering is risky because it cannot be measured with the standard SME analysis. The pH buffering loss in the peat 4 medium given the acidic NS after the week 12 sampling date indicates that the residual lime contained in the medium may have been depleted. Since the peat 4 medium had a higher initial lime requirement than that of the peat 1 medium to obtain the same pH, there would have been less residual lime for long-term buffering. An alternative to reliance on residual lime for pH buffering may be to use a WSF with <40% to 50% NH_4^+-N, especially for long-term crops grown with an IWS containing an alkalinity at <120 mg $CaCO_3 \cdot L^{-1}$.

Calcium. In Expt. 1, initial root-medium Ca^{2+} concentrations ranged from 127 $mg \cdot L^{-1}$ in peat 1 media to 384 $mg \cdot L^{-1}$ in the coir media at planting (data not shown). However, by week 1, root-medium Ca^{2+} concentrations had decreased to an average of 44% of the initial concentration (Fig. 2, Table 3). After the week 1 sampling date, the

Ca^{2+} concentration remained below the suggested acceptable level (80 mg·L^{-1}) with the acidic WSF, but was at or above the recommended level with the neutral and basic WSF for the remainder of the experiment, as measured with the SME (Fig. 2) (Warncke and Krauskopf, 1983). The Ca^{2+} concentration in the RW medium was higher than that of the other root media from week 8 until the end of the experiment with the three NS.

With the six media from Expt. 1, there was an overall linear increase in shoot-tissue Ca as the applied Ca^{2+} concentrations in the NS increased from 18 to 156 mg·L^{-1} (Fig. 4, Table 5). The intercept value reflects the Ca supplied by the root medium if no additional Ca^{2+} were applied in the NS. The decrease in the intercept value and increase in the slope between the weeks 4 and 17 sampling date indicates an overall decrease in the amount of Ca supplied by the medium over time (Table 5). The improvement in the r^2 between the week 4 and week 17 analyses indicates a decrease in the influence of the media treatments on Ca uptake over time.

A linear trend with only three treatment levels does not necessarily indicate a linear relationship. However, a similar linear relationship between the concentration of Ca^{2+} in the NS and shoot-tissue Ca was reported by Argo and Biernbaum (1996a) with impatiens grown with 12 NS. The results from this experiment add further support to the conclusion of Argo and Biernbaum (1996a) that: 1) the main factor affecting the uptake of Ca into the plant was the concentration of Ca^{2+} in the NS, as affected by both the WSF and IWS; and 2) other ions in the NS (NH_4^+-N, K^+, Mg^{2+}, or SO_4-S) did not interfere with uptake.

If the amount of shoot tissue produced during the entire experiment was taken into account, then the shoot tissue of plants grown in the peat 4 media accumulated the most Ca per pot (0.17 g) while those grown in the RW media accumulated the least Ca per pot (0.05 g), as averaged over the NS treatments. However, it cannot be determined from this experiment if Ca was more available in the peat 4 media resulting in higher average shoot growth, or if the higher average growth of plants in the peat 4 media resulted in more Ca uptake compared to that of plants grown in the RW medium.

In Expt. 2, the presence of dolomitic carbonate lime in the peat 1 and 4 media did not increase their initial Ca^{2+} concentration (carbonate lime treatment Ca was 165 $mg \cdot L^{-1}$; hydrated lime treatment average was 155 $mg \cdot L^{-1}$) or effect Ca^{2+} concentrations through week 4 compared to the same media with hydrated lime (Fig 3,Table 4). However, after week 8, Ca^{2+} concentrations in media containing the dolomitic carbonate lime increased with the acidic NS compared to that of the same media with hydrated lime (Fig. 3, Table 4). In comparison, there were no consistent differences in media Ca concentration between lime types in the media receiving neutral or basic NS. There was a corresponding increase in shoot-tissue Ca for plants grown in media containing the carbonate lime and receiving the acidic NS at the weeks 12 and 17 sampling dates compared to plants grown in the same media containing the hydrated lime (Fig. 5). Shoot-tissue Ca was similar for both lime treatments for plants grown with neutral or basic NS.

We interpret the results to indicate that the large amount of residual lime contained in the medium after the equilibrium pH was reached did not, in itself, buffer the root-medium Ca concentrations or influence Ca uptake. Instead, the increase in root-medium and shoot-tissue Ca resulted from the reaction of the acidic NS (50% NH_4^+-N WSF with RO water) with the lime. Decreasing the percentage of NH_4^+-N in the WSF and increasing the alkalinity content of the IWS decreased the overall acidity of the NS and almost completely negated the residual lime as a Ca source. Similar results were found by Niemiera and Wright (1986) when nitrification within the medium was inhibited. Thus, if a less acidic WSF is used in conjunction with a low alkalinity (<120 mg $CaCO_3 \cdot L^{-1}$) and low Ca^{2+} IWS in order to better manage root-medium pH, then the WSF also should contain Ca^{2+}. Argo and Biernbaum (1996a) reported that NS Ca^{2+}

concentrations at 100 to 160 mg·L^{-1} were sufficient to maintain impatiens shoot-tissue Ca concentrations at >2% and were independent of the effect of residual lime in the medium.

The linear relationship between the NS Ca^{2+} concentration and shoot-tissue Ca presented in this and other experiments indicates the Ca status of all the shoot tissue sampled from the plant. Because Ca is immobile in the plant, Ca deficiencies often are localized events (bract edge burn in poinsettias, black heart in celery, blossom end rot in tomatoes and peppers, leaf edge burn in lettuce) that may occur even when the overall Ca status of the plant is high (Marschner, 1986). Increasing overall shoot-tissue Ca has many benefits, including increased stem strength (McDaniel et al., 1986) and resistance to pathogens (Marschner, 1986), but may not necessarily affect the localized Ca deficiencies found in many crops (Jacques et al., 1991; Marschner, 1986; Woltz and Harbaugh, 1985).

Magnesium. In Expt.1, initial root-medium Mg^{2+} concentrations ranged from 64 mg·L^{-1} in the coir medium to 163 mg·L^{-1} in the peat 4 medium at planting (data not shown). However, by week 1, root-medium Mg^{2+} concentrations had decreased to an average of 33% of the initial concentration (Fig. 2, Table 3). After the week 1 sampling date, the Mg^{2+} concentration remained below the suggested acceptable level (30 mg·L^{-1}) with the acidic and neutral NS, but was at or above the recommended level with the basic WSF for the remainder of the experiment as measured with the SME (Fig. 2) (Warncke and Krauskopf, 1983).

As with Ca, there was an overall linear increase in shoot-tissue Mg as the applied Mg^{2+} concentration in the NS increased from 5 to 72 mg·L^{-1} (Fig. 4, Table 5). The intercept value reflects the Mg supplied by the root medium if no additional Mg were applied in the NS. The decrease in the intercept value and increase in the slope between the weeks 4 and 17 sampling dates indicates a decrease in the amount of Mg supplied by the medium over time (Table 5). The improvement in the r^2 between the week 4 and week 17 analyses indicates a decrease in the influence of the media treatments on Mg uptake over time. We interpret the results from this experiment add further support to the conclusion of Argo and Biernbaum (1996a) that: 1) the main factor affecting the uptake of Mg into the plant was the concentration of Mg^{2+} in the NS, as affected by both the WSF and IWS; and 2) other ions in the NS (NH_4^+-N, K^+, Ca^{2+}, or SO_4-S) did not interfere with uptake.

In Expt. 2, the presence of the dolomitic carbonate lime in the peats 1 and 4 media increased the medium Mg^{2+} concentrations with acidic NS compared to that of the same media with hydrated lime (Fig. 3, Table 4). In comparison, there were no consistent differences in the medium Mg^{2+} concentration between lime types in the media receiving the neutral or basic NS. There was a corresponding increase in shoot-tissue Mg concentration for plants grown in media containing the carbonate lime and receiving the acidic NS at the weeks 12 and 17 sampling dates compared to plants grown in the same media containing the hydrated lime (Fig. 5). Shoot-tissue Mg was similar for both lime treatments for plants grown with the neutral or basic NS. If a less acidic WSF is used in conjunction with a low alkalinity (<120 mg $CaCO_3 \cdot L^{-1}$) and low Mg^{2+} IWS in order to better manage root-medium pH, it should also contain Mg^{2+}. Argo and Biernbaum (1996a) found that NS Mg^{2+} concentrations at 30 to 50 $mg \cdot L^{-1}$ were sufficient to maintain impatiens shoot-tissue Mg concentrations of >1% and were independent of the effect of residual lime in the medium.

Conclusion. The finer, more degraded sphagnum peats containing large percentages of fine particles and dust (peat 4) are often not used in commercially available blend soilless media because of their adverse effects on physical properties (Bunt, 1988; Puustjarvi and Robertson, 1975). In medium containing peat 4, there was a decrease in the overall porosity (Table 1), but the percent air space at container capacity was similar to the other media. The shoot dry mass of plants grown in the peat 4 medium was similar to or greater than those grown in media containing grower grade sphagnum peats (peat 1 and 2). Neither the soil test data (which included all macronutrients) nor the shoot-tissue analysis data (which included macronutrients and micronutrients) were sufficiently different to expect the variation in shoot growth observed in this experiment. Argo and Biernbaum (1995) proposed that the plant growth measured in many experiments depends on the irrigation management of the medium. If the irrigation management used in this experiment were different (irrigated on a fixed schedule), then the amount of dry mass produced by plants grown in the different media probably also would have been different.

Cation exchange capacity has been the primary focus of pH and nutrient buffering capacity in soilless container root media (Bunt, 1988; Nelson, 1991). For the six media tested in this experiment, CEC influenced pH, Ca, and Mg buffering capacity. However, other sources of buffering capacity existed including the residual lime, which had a much greater effect on the buffering capacity of the media than did CEC under acidic (pH, Ca, and Mg buffering) or neutral (pH buffering) conditions. Another source of buffering capacity not addressed in this study is the fertilizer salts that are concentrated at the root-medium surface because of salt stratification within the pot. With top watering, these salts buffered the macronutrient concentration in the root zone for six weeks after fertilization was stopped with poinsettias (Argo and Biernbaum, 1995).

The pH of some components can be slightly acidic (coir pH is 5.4 to 6.4) to highly basic (RW pH is 8.5 to 9.5 before acidification). In media containing a large percentage of these materials, less lime will be needed to increase the starting pH to the suggested 5.5 to 6.4 compared to media using large percentages of an acidic peat. Reducing the lime incorporation rate also may reduce the amount of residual lime in the medium, which is a significant source of long-term pH, Ca, and Mg (if dolomitic lime) buffering capacity. Alternative sources of Ca or Mg, such as gypsum or $MgSO_4$, were not persistent in the medium for more than a few weeks after planting if some leaching occurred or subirrigation was used (Argo and Biernbaum, 1995, 1996a, 1996b). If components that reduces lime incorporation rates are used in media, a WSF containing a lower percentage of NH_4^+-N in addition to Ca^{2+} and Mg^{2+} should be used to prevent the medium's pH from falling below the suggested 5.8 to 6.4 (Warncke and Krauskopf, 1983) compared to the same crop grown in media containing residual lime. The exact percentage of NH_4^+-N in the WSF to maintain a stable pH depends on the alkalinity concentration in the IWS and the WSF concentration.

Further study is needed to determine the effects that other components, such as vermiculite or bark, have on the pH and nutrient buffering capacity of a soilless root medium. Quantification of the effects that different plant species have on pH and nutrient management also is needed. Finally, it is not known if the uptake of Ca^{2+} and Mg^{2+} in species besides impatiens is affected only by the concentration of those ions in the NS. Future experiments should be performed with consideration for the interactive effects WSF has with irrigation-water alkalinity, lime, and root-medium components on maintaining a stable root-medium pH and supplying Ca^{2+} and Mg^{2+} (Argo and Biernbaum, 1996a; Niemiera and Wright, 1986).

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Table 1. Average air space (AS), water space at container capacity (CC) in a 9-cm-tall pot, bulk density (BD), and cation exchange capacity (CEC) of six root media composed of 70% (by volume) of the material listed below with 30% perlite. Reported values are the mean of five samples.

	AS	CC	BD	CEC[z]	
Root media	Percentage by volume		$kg{\cdot}m^{-3}$	$meq{\cdot}kg^{-1}$	$meq{\cdot}L^{-1}$
Rockwool	28 a[y]	49 e	114 a	34 e	5 e
Coir	19 c	63 a	84 c	408 d	34 d
Peat 1	24 b	56 c	87 c	580 bc	50 b
Peat 2	23 b	61 b	76 d	543 c	41 c
Peat 3	19 c	62 ab	87 e	615 ab	53 b
Peat 4	18 c	52 d	119 b	639 a	76 a

[z] 0.1 N BaOAc was used to determine the CEC of acid-washed root media.

[y] Mean separation by Duncans's multiple range test, $P \leq 0.05$.

Table 2. Cumulative water, Ca^{2+}, and Mg^{2+} applied to plants grown in various media and nutrient solution (NS) treatments after 17 weeks. The initial nutrient content of the root medium was included in the values reported below. Data are the mean of three pots from each treatment.

	Acidic NS			Neutral NS			Basic NS		
	Applied water (liter)	Ca (g/pot)	Mg (g/pot)	Applied water (liter)	Ca (g/pot)	Mg (g/pot)	Applied water (liter)	Ca (g/pot)	Mg (g/pot)
				Dolomitic hydrated lime (Expt. 1)					
Rockwool	4.7	0.3	0.04	4.5	0.5	0.09	5.0	1.0	0.36
Coir	6.5	0.5	0.14	7.0	0.7	0.22	6.1	1.3	0.51
Peat 1	6.3	0.7	0.29	6.5	1.0	0.36	6.3	1.6	0.67
Peat 2	6.7	0.7	0.30	6.6	1.0	0.37	6.3	1.6	0.68
Peat 3	6.9	0.9	0.42	7.0	1.2	0.50	6.9	1.9	0.84
Peat 4	7.3	1.0	0.48	7.3	1.3	0.56	6.4	1.9	0.87
				Dolomitic carbonate lime (Expt. 2)					
Peat 1	6.3	1.7	0.88	6.1	1.9	0.95	6.1	2.5	1.25
Peat 4	6.2	1.8	0.88	6.8	1.9	0.96	6.2	2.5	1.26

Table 3. Degrees of freedom (df), F-values (A), levels of significance (B), and mean square error (MSE) from the analysis of variance for the log(observed + 1) transformed root-zone pH, Ca^{2+}, and Mg^{2+} concentrations at 1, 4, 8, 12, and 17 weeks after planting in Expt. 1.

		Week 1		Week 4		Week 8		Week 12		Week 17	
	df	A	B	A	B	A	B	A	B	A	B
						Root-zone pH					
Media (M)	5	10.9	***	10.8	***	10.9	***	10.9	***	7.6	***
NS [z]	2	3.6	*	13.0	***	459.0	***	867.1	***	1092.1	***
M x NS	10	1.7	NS	4.7	***	5.8	***	10.3	***	10.8	***
MSE	53	0.0426		0.1476		0.0579		0.0469		0.0580	
						Root-zone Ca^{2+}					
Media (M)	5	98.6	***	14.4	***	4.8	**	25.8	***	26.0	***
NS	2	137.7	***	164.1	***	141.0	***	213.1	***	290.4	***
M x NS	10	3.7	**	1.8	NS	2.0	NS	3.3	**	2.9	*
MSE	53	0.0034		0.0043		0.0075		0.0052		0.0043	
						Root-zone Mg^{2+}					
Media (M)	5	5.8	***	7.3	***	4.6	**	9.7	***	14.6	***
NS	2	96.5	***	51.6	***	70.0	***	70.6	***	133.3	***
M x NS	10	0.5	NS	3.8	**	4.9	**	5.1	***	5.0	***
MSE	53	0.0108		0.0389		0.0417		0.0414		0.0423	

[z] Nutrient solution.

NS, *, **, *** Nonsignificant or significant at $P < 0.05$, 0.01, or 0.001, respectively.

Table 4. Degrees of freedom (df), F-values (A), levels of significance (B), and mean square of error a and error b from the analysis of variance for the log(observed + 1) transformed root-zone pH, Ca^{2+}, and Mg^{2+} concentrations at 1, 4, 8, 12, and 17 weeks after planting in Expt. 2.

		Week 1		Week 4		Week 8		Week 12		Week 17	
	df	A	B	A	B	A	B	A	B	A	B
						Root-zone pH					
Lime (L)	1	41.5	NS	71.7	NS	62.1	NS	20.5	NS	104.5	NS
Error a	1	0.0196		0.0130		0.0876		0.3798		0.1716	
Media (M)	1	3.7	NS	1.0	NS	5.9	*	18.6	***	35.5	***
NS[z]	2	14.4	***	4.4	*	148.5	***	332.8	***	669.1	***
M x L	1	0.2	NS	0.2	NS	1.0	NS	5.8	*	22.4	***
NS x L	2	3.4	NS	4.7	*	16.2	***	67.3	***	38.2	***
M x NS	2	1.0	NS	2.3	NS	20.7	***	41.9	***	18.9	***
M x NS x L	2	1.3	NS	2.0	NS	4.7	*	3.9	*	5.6	**
Error b	34	0.0385		0.0769		0.0654		0.0369		0.0476	
						Root-zone Ca^{2+}					
Lime (L)	1	16.0	NS	0.0	NS	228.0	*	21.8	NS	37.2	NS
Error a	1	0.0007		0.0003		0.0001		0.0032		0.0029	
Media (M)	1	0.5	NS	3.0	NS	3.0	NS	4.0	NS	14.2	***
NS	2	260.3	***	61.1	***	69.6	***	155.5	***	138.3	***
M x L	1	2.1	NS	0.1	NS	0.7	NS	16.3	***	4.3	*
NS x L	2	2.1	NS	0.5	NS	7.9	**	18.4	***	14.7	***
M x NS	2	2.4	NS	0.6	NS	0.6	NS	2.3	NS	2.1	NS
M x NS x L	2	0.8	NS	1.5	NS	5.5	**	6.0	**	3.4	NS
Error b	34	0.0018		0.0052		0.0055		0.0041		0.0059	
						Root-zone Mg^{2+}					
Lime (L)	1	19.1	NS	0.1	NS	999.6	***	23.9	NS	29.5	NS
Error a	1	0.0013		0.0096		0.0001		0.0432		0.0653	
Media (M)	1	2.6	NS	6.8	*	0.2	NS	0.8	NS	3.4	NS
NS	2	86.9	***	21.6	***	25.4	***	32.9	***	33.8	***
M x L	1	5.3	*	2.6	NS	1.3	NS	9.1	**	2.4	NS
NS x L	2	2.8	NS	1.2	NS	15.0	***	18.0	***	19.4	***
M x NS	2	2.9	NS	5.8	**	5.3	**	10.5	***	6.4	**
M x NS x L	2	1.0	NS	4.8	*	9.0	***	4.0	*	2.6	NS
Error b	34	0.0143		0.0489		0.0369		0.0315		0.0368	

[z] Nutrient solution.

NS, *, **, *** Nonsignificant or significant at $P < 0.05$, 0.01, or 0.001, respectively.

Table 5. Parameters of linear regression analysis for shoot-tissue Ca and Mg based on the concentration of Ca^{2+} and Mg^{2+} applied in the nutrient solution of plants grown in six root media containing various amounts of hydrated dolomitic lime ($Ca(OH)_2$ and $Mg(OH)_2$). Plants grown in media containing Peat 1 and 4 with the dolomitic carbonate lime ($CaCO_3$ and $MgCO_3$) were not included in the regression analysis. The number of observations used in the analysis was 36 at week 4 and 72 thereafter. Data are presented in Fig. 4.

	Week 4	Week 8	Week 12	Week 17	Units
Shoot-tissue Ca					
Intercept	1.17 ± 0.14[z] a[x]	1.03 ± 0.07 a	0.72 ± 0.09 b	0.41 ± 0.07 c	Dry mass (%)
Slope	0.004 ± 0.001 a	0.007 ±0.001 b	0.009 ± 0.001 c	0.010 ± 0.001 c	Dry mass (%)/mg·liter^{-1}
Shoot-tissue Mg					
Intercept	0.62 ± 0.07 a	0.49 ± 0.03 b	0.38 ± 0.03 c	0.28 ± 0.03 d	Dry mass (%)
Slope	0.003 ± 0.002 a	0.005 ± 0.001 ab	0.005 ± 0.001 ab	0.006 ± 0.001 b	Dry mass (%)/mg·liter^{-1}

[z] Ninety-five percent confidence intervals were calculated as the parameter standard error * t0.025,n distribution.

[x] Mean separation of the of the individual parameters at each sampling date using a multiple linear regression model in SAS's general linear model procedure (GLM) (SAS Institute, Cary, N.C.).

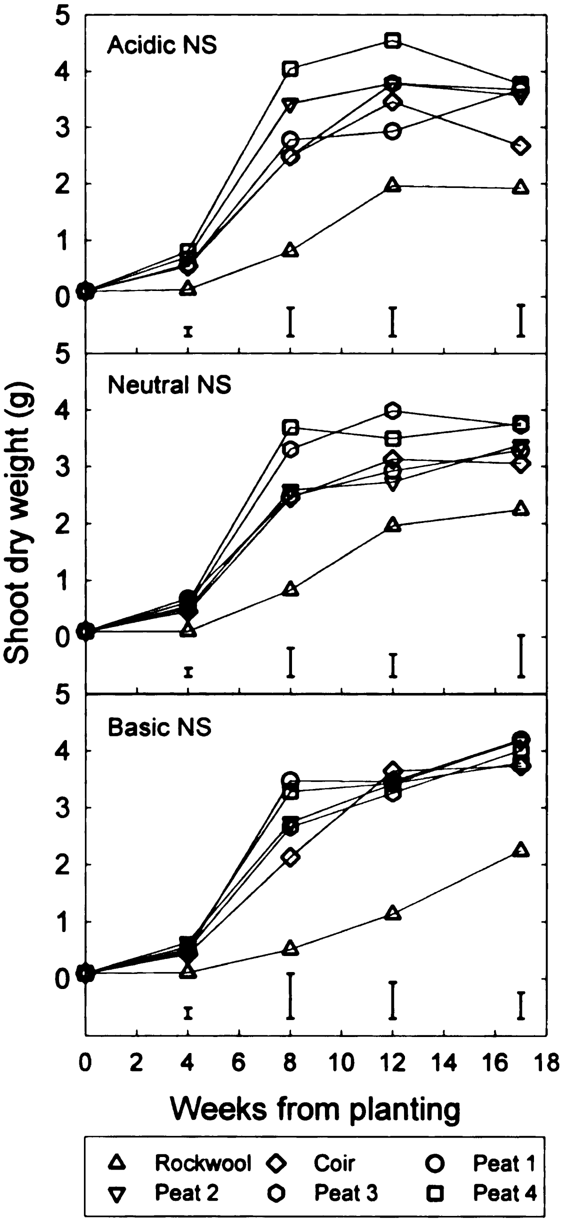

Fig. 1. New shoot dry weight of impatiens grown in six root media containing various rates of hydrated dolomitic lime ($Ca(OH)_2$ and $Mg(OH)_2$) with three nutrient solution treatments at 4, 8, 12, and 17 weeks after planting in Expt. 1. After each harvest, remaining plants were pruned to the same point. Data represent only the new shoot growth from the previous four-week period. Error bars were calculated as 95% confidence intervals for each nutrient solution. Data are means of four samples at each date.

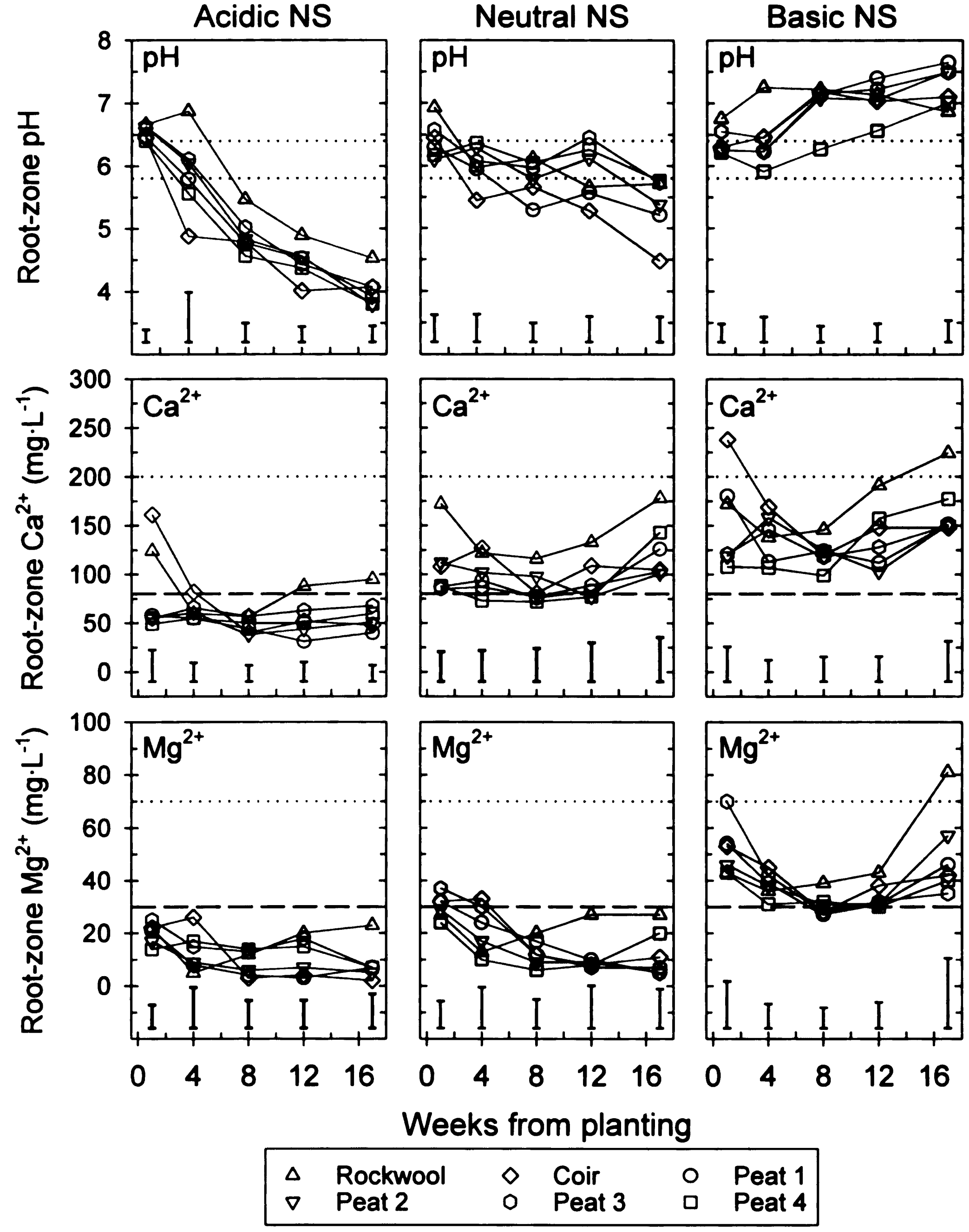

Fig. 2. Root-zone pH, Ca^{2+}, and Mg^{2+} concentrations in plants grown in six root media containing various rates of hydrated dolomitic lime ($Ca(OH)_2$ and $Mg(OH)_2$) with three nutrient solutions between weeks 1 and 17 in Expt. 1. The dotted lines (·····) represent the recommended optimal ranges and dashed lines (----) (if present) represent the lower recommended acceptable range for the saturated media extract (Warncke and Krauskopf, 1983). Error bars were calculated as 95% confidence intervals for each nutrient solution. Overall statistical analysis is presented in Table 3. Data are means of four samples at each date.

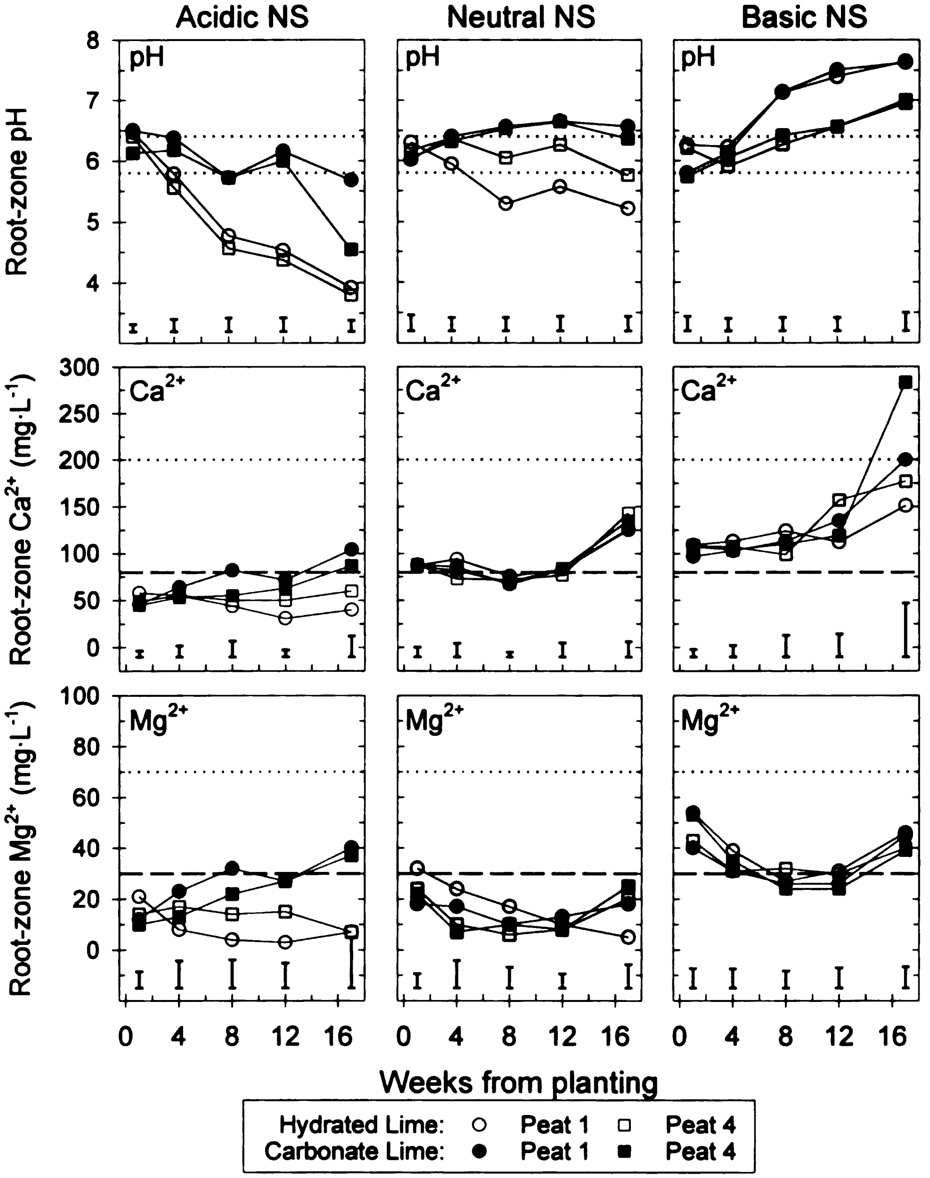

Fig. 3. Root-zone pH, Ca^{2+}, and Mg^{2+} concentrations in plants grown in two media containing either hydrated dolomitic lime ($Ca(OH)_2$ and $Mg(OH)_2$) or carbonate dolomitic lime ($CaCO_3$ and $MgCO_3$) with three nutrient solutions between weeks 1 and 17 in Expt. 2. The dotted lines (·····) represent the recommended optimal ranges and dashed lines (----) (if present) represent the lower recommended acceptable range for the saturated media extract (Warncke and Krauskopf, 1983). Error bars were calculated as 95% confidence intervals for each nutrient solution. Overall statistical analysis is presented in Table 4. Data are means of four samples at each date.

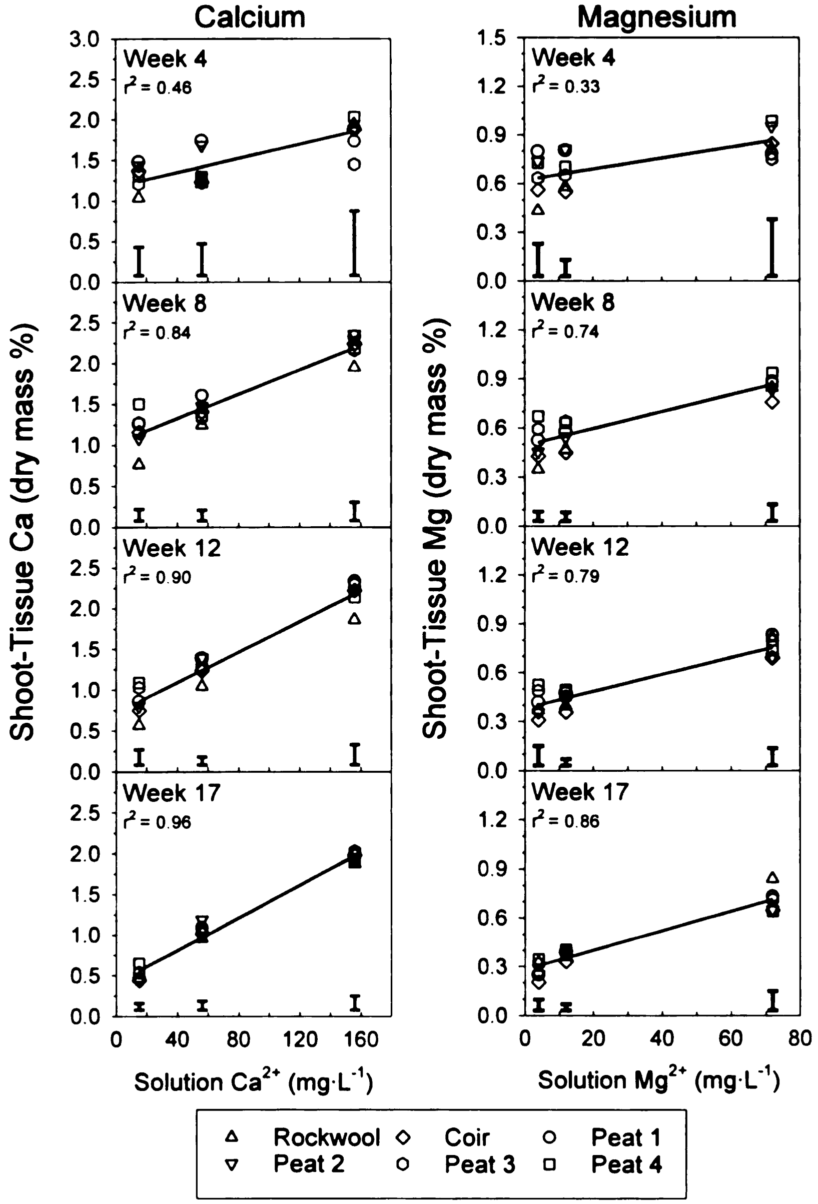

Fig. 4. The effect of applied Ca^{2+} and Mg^{2+} concentration on the shoot-tissue Ca and Mg of impatiens grown in six root media at 4, 8, 12, and 17 weeks after planting in Expt. 1. The solid line (—) represents the predicted shoot-tissue Ca concentration based on linear regression analysis. The r^2 values were calculated as $1\text{-}SS_{residual}/SS_{corrected\ total}$, and remaining statistical analyses of the individual parameters are presented in Table 5. Data are means of four samples at each date.

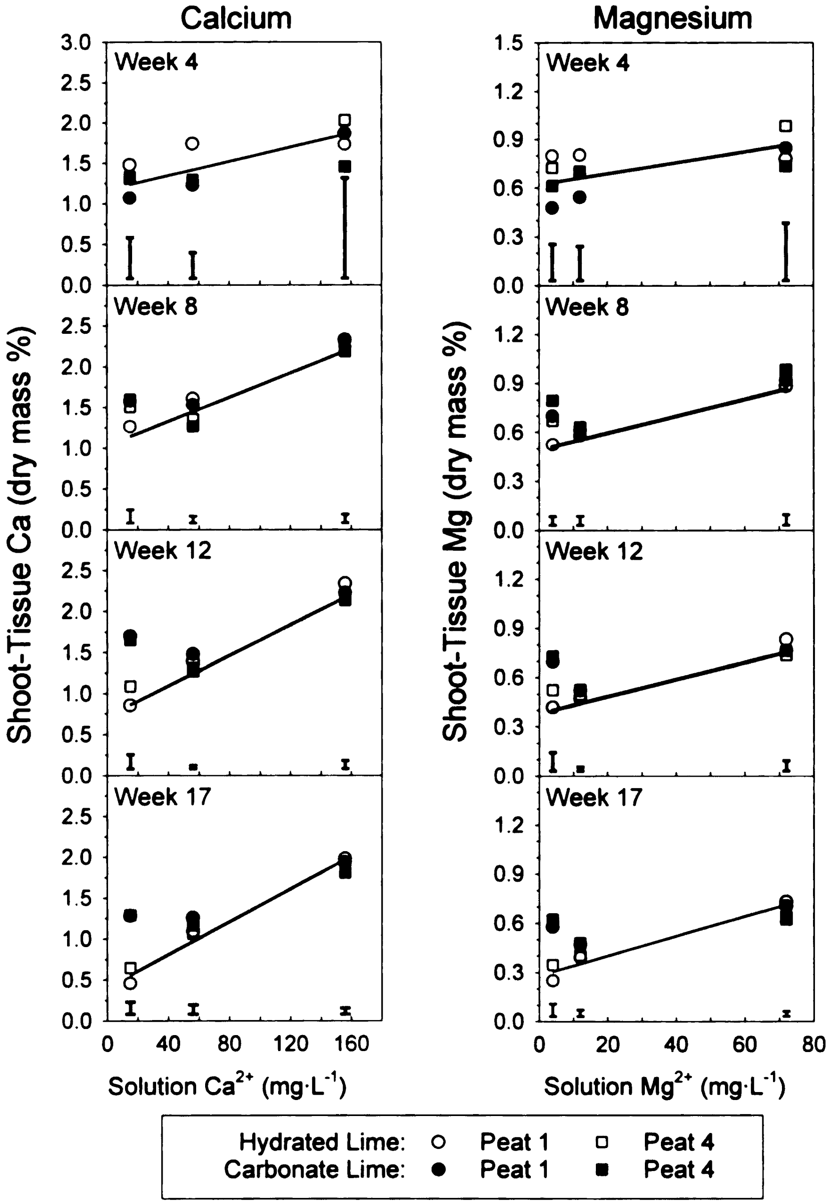

Fig. 5. The effect of applied Ca^{2+} and Mg^{2+} concentration on the shoot-tissue Ca and Mg of impatiens grown in two root media containing either hydrated dolomitic lime ($Ca(OH)_2$ and $Mg(OH)_2$) or carbonate dolomitic lime ($CaCO_3$ and $MgCO_3$) at 4, 8, 12, and 17 weeks after planting in Expt. 2. The solid line (—) represents the predicted shoot-tissue Ca concentration based on linear regression analysis from Fig. 4 and Table 5. Data are means of four samples at each date.

SECTION V

THE EFFECT OF BEDDING PLANT SPECIES ON ROOT-ZONE pH, CALCIUM, AND MAGNESIUM MANAGEMENT

Effect of Bedding Plant Species on pH, Calcium, and Magnesium Management in Peat-Based Root Media

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Effect of Bedding Plant Species on pH, Calcium, and Magnesium Management in Peat-Based Root Media

Additional index words. peat, soilless media, water-soluble fertilizer

Abstract. Nine bedding plant species were grown for 28 days in a peat-based root media and fertilized with one of three nutrient solutions (NS) composed of three commercially available water-soluble fertilizers that varied in NH_4 : NO_3 ratio, Ca, and Mg content mixed with a single irrigation water source. A NS was applied with every irrigation. In general, the NS affected the shoot-dry weight of the nine species minimally. Increasing the NH_4 content of the NS decreased medium pH. Plant species also affected medium pH. In general, medium containing geraniums had the lowest pH while medium containing petunias had the highest pH given the same NS and averaged over the last 14 days of the experiment. There was a linear increase in shoot-tissue Ca and Mg as the concentration of Ca in the NS increased from 50 to 96 $mg \cdot L^{-1}$; and that of Mg, from 15 to 38 $mg \cdot L^{-1}$. Linear regression analysis of shoot-tissue Ca and Mg based on their concentration in the NS indicated differences in uptake between species.

Media pH must be managed carefully to control nutrient availability in container root media (Peterson, 1981). A number of sources that include root medium, lime, the irrigation-water source (IWS), and water-soluble fertilizer (WSF) interact to affect the nutrient supply in container root media throughout crop production (Argo and Biernbaum, 1996; 1997). However, not all sources affect medium pH and macronutrient management simultaneously or with equal intensity under all conditions. For example, Argo and Biernbaum (1996) demonstrated that residual or unreacted lime contained in a root medium after the initial equilibrium pH was reached greatly increased the pH, Ca, and Mg buffering capacity given an acidic NS with low concentrations of Ca and Mg. Residual lime contained in the root medium had no effect on pH, Ca, or Mg management when irrigated with nutrient solutions (NS) containing basic WSF and high concentrations of Ca and Mg.

The plant may also affect pH management. With agronomic crops, some species are less susceptible to lime-induced iron chlorosis because of the plants ability to lower the rhizosphere pH through root exodation of H^+ and organic acid (citrate, malate) when grown in calcareous soils ($pH > 7.8$). In comparison, species that do not lower the rhizosphere pH are much more susceptible to lime-induced iron chlorosis (Marschner, 1986). Among cultivars of the same species, there may be considerable differences in the susceptibility of lime-induced iron chlorosis because of differences in the cultivars ability to lower the rhizosphere pH (Froehilich and Fehr, 1981; Saxena and Sheldrake, 1980)

In Floriculture crops, much less is known of species or cultivar effects on medium pH and the resulting differences in nutrient uptake. In laboratory experiments on germinating seedlings, Bailey et al. (1996) found that substrate pH varied from 4.5 with tomatoes to 7.5 with zinnia under the same conditions. In greenhouse experiments, Argo et al. (1997) found that the average root-medium pH of ten potted plant species given the same WSF (20N-4.3P-16.6K Peatlite Special [Scotts, Marysville, Ohio]) ranged from 5.1

with African violets to 6.5 with gerbera. In addition, WSF concentration also influenced root medium pH. For example, the root-medium pH of gerbera decreased from 7.1 to 5.8 as the N concentration of the WSF increased from 50 to 200 mg·L^{-1}, while with African violets, the root-medium pH also decreased, but from 5.2 to 4.8, given the same WSF concentrations.

Different plant species are thought to have different rates of nutrient uptake (Bunt, 1988; Dole and Wilkens, 1988). Argo and Biernbaum (1996, 1997) found that the uptake of Ca and Mg into the shoot tissue of impatiens increased linearly as the concentration of those ions in the NS increased. However, it is not known if the uptake of Ca and Mg into the shoot tissue of other species is affected only by the NS Ca and Mg concentration. The objective of this study was to determine differences in pH management and Ca and Mg uptake in nine bedding plant species.

Materials and Methods

The experiment included 27 treatments composed of three nutrient solutions and nine species with three replications per treatment. Soil test data were analyzed using SAS's analysis of variance (ANOVA) procedures (SAS Institute, Cary, N.C.) as a 9 x 3 factorial at each sampling date. Time was not included in the ANOVA because sample variance changed over time. Relationships were developed between the concentration of Ca and Mg in the applied nutrient solutions and shoot-tissue Ca and Mg using SAS's linear regression procedure (REG). Slopes and intercepts were compared using SAS's general linear model procedure (GLM) for multiple linear regression.

The root medium used was (by volume) 70% Canadian sphagnum peat (Fisons professional black bale peat, Sun Gro Horticulture, Bellevue, Wash.) with long fibers and little dust (Von Post scale 1-2; Puustjarvi and Robertson, 1975), and 30% perlite. A dolomitic hydrated lime ($Ca(OH)_2$ and $Mg(OH)_2$) was added at 1.5 kg·m^{-3}. In addition, 0.4 kg each of KNO_3 and gypsum, 0.1 kg triple superphosphate (0 N-19.8 P-0 K), and

0.07 kg fritted trace elements (FTE 555, Scotts, Marysville, Ohio) per m^3 of medium were added at mixing. Sufficient reverse osmosis (RO) purified water was added at mixing to bring the moisture content of the medium to 40% to 50% of container capacity, and the medium was allowed to equilibrate for three days before planting. At planting, the medium had a pH of 5.9; and electrical conductivity (EC) of 1.3 $dS \cdot m^{-1}$; and (in $mg \cdot L^{-1}$) 75 NO_3-N, 20 P, 110 K, 105 Ca, 55 Mg, and 60 SO_4-S, based on the saturated media extract (Warncke, 1986).

The three nutrient solutions varied in the $NH_4 : NO_3$ ratio, P, Ca, and Mg concentrations, but were applied at a constant N concentration of 100 $mg \cdot L^{-1}$. The three commercially available WSF were 1) acidic WSF with (in % of total mass) 20 N, 4.3 P, 16.6 K, 0 Ca, 0 Mg Peatlite Special, which had an $NH_4 : NO_3$ ratio of 0.67 and a potential acidity of 200 kg/1000 kg of fertilizer; 2) neutral WSF with 17 N, 2.2 P, 14.1 K, 3 Ca, 1 Mg, which had an $NH_4 : NO_3$ ratio of 0.25 and a potential acidity of 0 kg/1000 kg of fertilizer; and 3) basic WSF with 13 N, 0.9 P, 10.8 K, 6 Ca, 3 Mg PlugCare Plus, which had an $NH_4 : NO_3$ ratio of 0.03 and a potential basicity of 150 kg/1000 kg of fertilizer (Greencare Fertilizers, Chicago, Ill.). The WSF were mixed with a blend of well and RO water (1:1.5 by volume) that had a pH of 6.7; an EC of 0.3 $dS \cdot m^{-1}$; 50 Ca^{2+}, 15 Mg^{2+}, 25 Na^+, and 10 SO_4-S ($mg \cdot L^{-1}$); and a titratable alkalinity to pH 4.5 of 130 mg $CaCO_3 \cdot L^{-1}$. The total nutrient concentration of the three NS applied at every irrigation is found in Table 1.

The experiment was conducted starting 6 March 1996 at Michigan State University, East Lansing, in a well-ventilated glass greenhouse sections with constant air circulation and cement floors. The bedding plant species tested were 'Orbit Hot Pink' geraniums (*Pelargonium* x hortorum), 'Super Elfin Violet' impatiens (*Impatiens Wallerna* Hook F.), 'Bonanza Yellow' marigold (*Tagetes patula*), 'Pink' Nonstop begonia (*Begonia* x tuberhybrida), 'Orange Crown' pansy (*Viola* x wittrockiana), 'Flash

Rose' petunia (*Petunia* x hybrida), 'Sizzler Lavender' salvia (*Salvia splendens*), 'Little Bright Eyes' vinca (*Vinca rosea*), and 'Vodka' wax begonia (*Begonia x semperflorens-cultorum*). Plugs from a 512 tray (288 tray for geraniums) were planted into 1204 (0.07 L per cell) bedding plant flats containing the peat/perlite medium. Plants in each flat were irrigated as needed with 0.5 L from one of the three NS using a small sprinkling can for uniform distribution. The volume of solution applied produced minimal leaching.

Root media were sampled initially and collected from one cell per flat (three per treatment) at 3, 7, 14, 21, and 28 days after planting. Medium pH and EC were tested using the 1:2 sampling method (Biernbaum et al., 1993). Medium pH and EC were determined by inserting the electrodes directly into the slurry.

Shoot dry weight and tissue nutrient analysis were determined at 35 days after planting. Eight plants per replication (three replications per treatment) were combined for shoot-tissue nutrient analysis. Shoot-tissue N was determined colorimetrically, and shoot P, K, Ca, and Mg were determined by plasma emission spectroscopy (Michigan State University Plant and Soil Testing Laboratory, East Lansing).

Results and Discussion

Plant growth. The average per plant shoot dry mass ranged from 1.2 g with geraniums to 0.4 g with Nonstop begonias after five weeks of growth. In general, NS treatments did not affect either visual appearance (data not shown) or the shoot dry weight (Table 2) of the nine species. These results are similar to those of Argo and Biernbaum (1996; 1997) in which the ratio of $NH_4 : NO_3$ contained in the NS affected the shoot dry weight of impatiens minimally.

Root-medium pH. Between planting and day 7, root-medium pH was similar for all treatments (Fig. 1). Argo and Biernbaum (1996, 1997) found that the NS had minimal effect on root-medium pH up to four weeks after planting in larger-size containers (0.75 L), which suggests that for a time after planting, the plant and the applied NS have minimal effect on root medium pH. Nutritional problems associated with either low or high medium pH that occur during this short time period are probably due to an incorrect lime incorporation rate. The duration of the period when the root medium and lime are the primary factors affecting medium pH probably is influenced by the ratio of container size to the plant size and the irrigation frequency.

After day 7, both the nutrient solution and plant species affected root-medium pH (Fig. 1). Plants grown in media given the acidic NS had the lowest root-medium pH, while those given the basic NS had the highest medium pH. In general, the media of geraniums had the lowest pH and geraniums tended to lower the pH independently of the NS that was applied. In comparison, the other species maintained their medium pH up to 1.4 pH units higher than that of the geraniums given the same NS. For the remaining species averaged over the NS treatments, the media from the wax begonias had the lowest pH, while the petunias had the highest pH over the last three weeks of the experiment.

Bailey et al. (1996) suggest that the same WSF should not be used on all species because of the effect that the reaction produced by the WSF has on medium pH. However, it may be difficult to use different WSF on bedding plant species being grown in the same greenhouse. An alternative method for optimizing pH management using the same WSF may be to use two or more media with different starting pH values. For example, species that tend to decrease medium pH (geraniums) can be planted into a medium with a starting pH >6.0. In comparison, species that tend to increase pH (petunias) can be planted into a medium with a starting pH < 5.8. While plant species will still affect the medium pH, the amount of change required to produce either toxicity problems because of low pH (Fe and Mn toxicity in geraniums) or deficiency problems because of high pH (Fe deficiency in petunias) will be increased.

Shoot-tissue Ca. The higher the Ca concentration in the applied NS, the higher the tissue Ca (Fig. 2). With each of the nine species, there was an overall linear increase in shoot-tissue Ca as the applied Ca concentrations in the NS increased from 50 to 96 mg·L^{-1} (Fig. 2, Table 3). The intercept value reflects the Ca supplied by the root medium if no additional Ca were applied in the NS. The slope and intercept values of the nine species indicate that impatiens were the most efficient at taking up Ca, while Nonstop begonia, pansies, vinca, and wax begonias were the least efficient given the same NS.

A linear trend with only three treatment levels does not necessarily indicate a linear relationship. However, a similar linear relationship between the concentration of Ca in the NS and shoot-tissue Ca of impatiens was reported by Argo and Biernbaum (1996) using 12 different NS that varied by a factor of 10 in the Ca concentration. We interpret the results of this experiment to add further support to Argo and Biernbaum's (1996) conclusion that other ions in the NS (NH_4, K) did not interfere with Ca uptake. Instead the main factor affecting uptake in the nine species tested is NS Ca concentration, as affected by both the WSF and IWS.

Shoot-tissue Mg. As with Ca, the higher the Mg concentration in the applied NS, the higher the tissue Mg (Fig. 3). With each of the nine species, there was an overall linear increase in shoot-tissue Mg as the applied Mg concentrations in the NS increased from 15 to 38 mg·L^{-1} (Fig. 3, Table 3). The intercept value reflects the Mg supplied by the root medium if no additional Mg were applied in the NS. The slope and intercept values of the nine species indicate that impatiens were the most efficient at taking up Mg while geraniums, pansies, and vinca, were the least efficient given the same NS.

Conclusion. In the production of container-grown crops, it is no longer acceptable to manage the pH and macronutrient concentrations in the root medium and plant tissue with high WSF concentrations and high leaching rates (Biernbaum, 1992). Irrigation systems that minimize or eliminate water and fertilizer runoff into the environment currently exist. Optimizing the pH, Ca, and Mg management of low- or nonleaching irrigation systems requires an understanding of how a variety of factors, including the plant species and the NS, interact during production. Further study is needed to determine the effect that varieties within a given plant species have on pH and nutrient management. Quantification of the effects that different-size containers have on pH and nutrient management is also needed. Finally, it is not known how changing the WSF N concentration affects root-medium pH, Ca, and Mg management. Future experiments should be performed with consideration of the interactive effects WSF, irrigation-water alkalinity, lime, root-medium components, and plant species have on maintaining a stable root-medium pH and supplying Ca and Mg.

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Table 1. Total concentrations of the nutrient solution (NS) used in the experiment.

	NH_4-N	NO_3-N	PO_4-P	K ($mg{\cdot}L^{-1}$)	Ca	Mg	Na
Acidic NS [z]	40	60	23	83	50	15	22
Neutral NS [y]	20	80	13	83	68	21	22
Basic NS [x]	3	97	7	83	96	38	22

[z] 20 N-4.3 P-16.6 K-0 Ca-0 Mg Peatlite Special (Greencare fertilizers, Chicago, Ill.) mixed with a blend of reverse osmosis and well water.

[y] 17 N-2.2 P-14.1 K-3 Ca-1 Mg (Greencare fertilizers, Chicago, Ill.) mixed with a blend of reverse osmosis and well water.

[x] 13 N-0.9 P-10.8 K-6 Ca-3 Mg PlugCare Plus (Greencare Fertilizers, Chicago, Ill.) mixed with a blend of reverse osmosis and well water.

Table 2. Shoot dry weight of nine species grown using three nutrient solutions (NS) containing different $NH_4 : NO_3$ ratios, Ca and Mg concentrations. Mean separation across rows using LSD at $P > 0.05$. Data are mean of three samples.

		Dry weight (g)	
	Acidic NS	Neutral NS	Basic NS
Geranium	0.99 a	1.27 a	1.25 a
Impatiens	0.87 a	0.86 a	0.80 a
Marigold	0.81 a	0.81 a	0.95 a
Nonstop begonia	0.45 a	0.42 a	0.46 a
Pansy	0.85 a	0.97 a	0.85 a
Petunia	1.06 a	1.11 a	1.06 a
Salvia	1.19 a	0.95 a	1.05 a
Vinca	0.67 a	0.49 ab	0.42 b
Wax begonia	0.53 a	0.74 a	0.65 a

Table 3. Parameters of linear regression analysis for tissue Ca and Mg, based on the applied concentration of Ca and Mg in the nutrient solution. Mean separation across columns of the individual parameters used a multiple linear regression model in SAS's general linear model procedure (GLM) (SAS Institute, Cary, N.C.).

	Intercept (dry mass [%])	Slope (dry mass [%]/mg·L^{-1})	r^2
	Shoot-tissue Ca		
Geraniums	0.89 ± 0.16 ab	0.006 ± 0.002 c	0.88
Impatiens	1.03 ± 0.18 a	0.016 ± 0.002 a	0.97
Marigold	0.87 ± 0.21 ab	0.007 ± 0.003 bc	0.83
Nonstop begonia	0.49 ± 0.25 c	0.008 ± 0.003 bc	0.83
Pansy	0.40 ± 0.23 c	0.008 ± 0.003 bc	0.84
Petunia	0.72 ± 0.29 bc	0.010 ± 0.004 b	0.83
Salvia	0.90 ± 0.20 ab	0.008 ± 0.003 bc	0.86
Vinca	0.45 ± 0.39 c	0.007 ± 0.005 bc	0.61
Wax begonia	0.52 ± 0.17 c	0.008 ± 0.002 bc	0.91
	Shoot-tissue Mg		
Geraniums	0.41 ± 0.10 cd	0.006 ± 0.004 c	0.63
Impatiens	0.73 ± 0.07 a	0.011 ± 0.003 bc	0.93
Marigold	0.61 ± 0.12 bc	0.006 ± 0.004 c	0.57
Nonstop begonia	0.64 ± 0.10 b	0.006 ± 0.004 c	0.69
Pansy	0.44 ± 0.07 cd	0.006 ± 0.003 c	0.80
Petunia	0.43 ± 0.15 cd	0.017 ± 0.005 a	0.89
Salvia	0.45 ± 0.11 c	0.009 ± 0.004 bc	0.82
Vinca	0.33 ± 0.13 d	0.008 ± 0.005 bc	0.65
Wax begonia	0.31 ± 0.11 d	0.018 ± 0.004 a	0.94

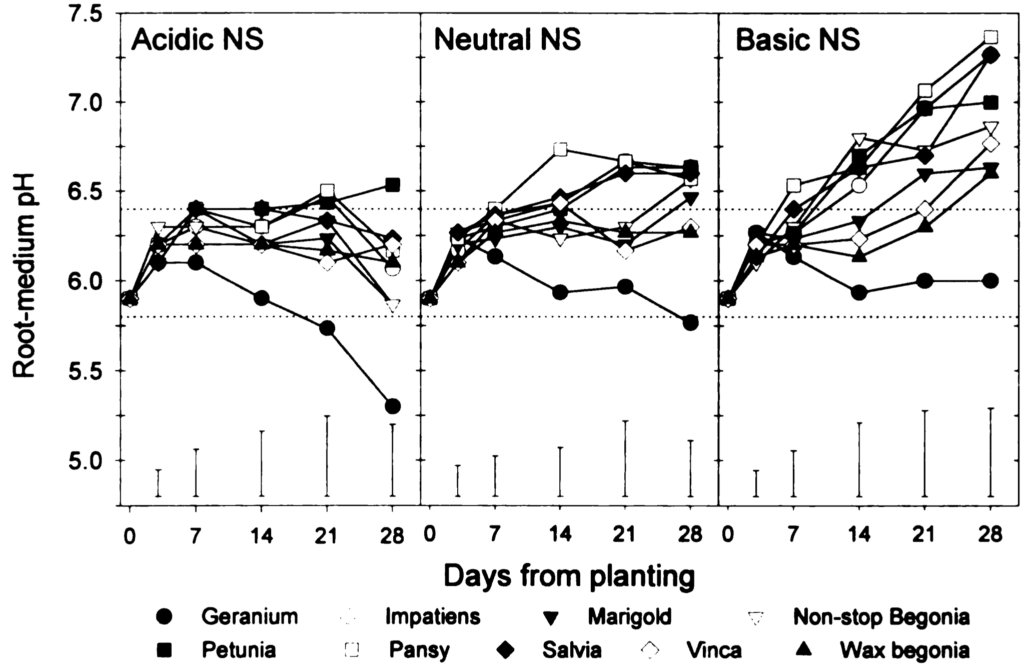


Fig. 1. Root-medium pH of nine species grown with three nutrient solutions (NS) (Table 1). The dotted lines represent the recommended optimal ranges for the 1:2 testing method (Warncke and Krauskopf, 1986). Vertical error bars are mean separation using LSD. Data are mean of three samples.

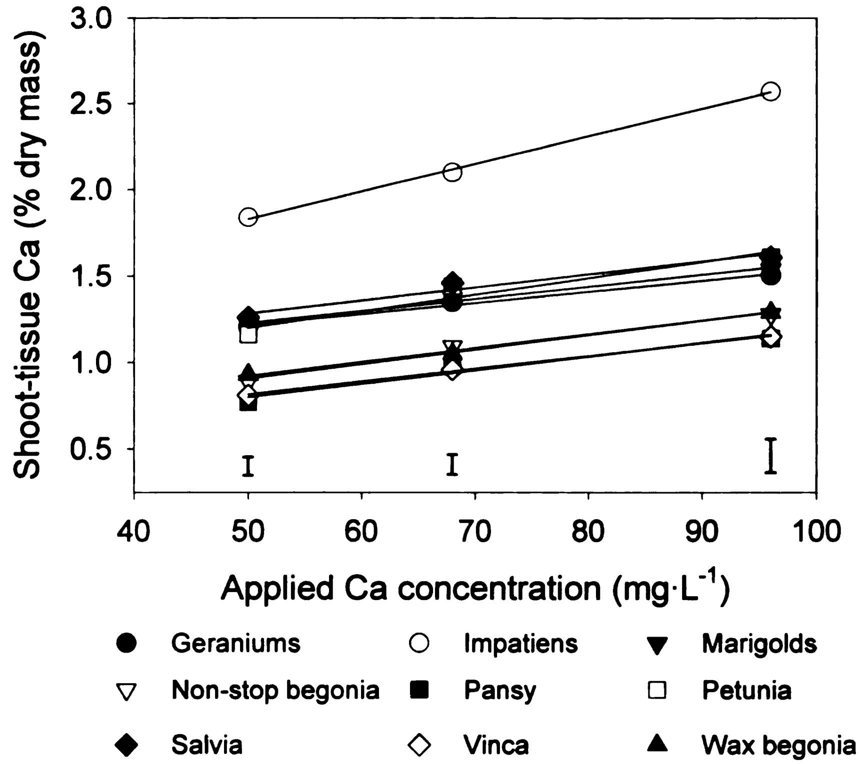


Fig. 2. The effect of applied Ca concentration on the shoot-tissue Ca of nine species at 35 days after planting. The solid line represents the predicted shoot-tissue Ca concentration based on linear regression analysis. The statistical analysis of the individual parameters are presented in Table 3. Data are mean of three samples.

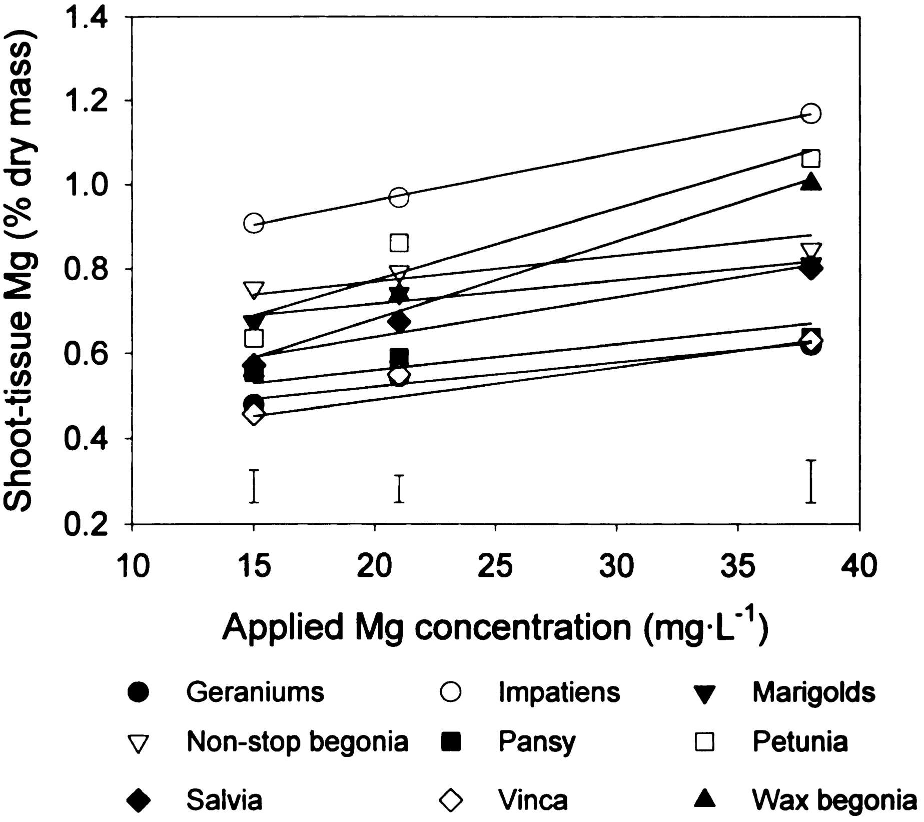


Fig. 3. The effect of applied Mg concentration on the shoot-tissue Mg of nine species at 35 days after planting. The solid line represents the predicted shoot-tissue Mg concentration based on linear regression analysis. The statistical analysis of the individual parameters are presented in Table 3. Data are mean of three samples.

Summary

Summary

A number of sources interact to affect the nutrient supply in container root media throughout crop production. However, these sources do not affect the nutrient supply simultaneously or with equal intensity. This is especially true for Ca and Mg nutrition, where the sources can include the irrigation-water source (IWS), root media, lime, preplant nutrient charge (PNC) fertilizers, and water-soluble fertilizers (WSF). Any discussion of Ca and Mg nutrition in container root media also must include pH management because of the direct or indirect effects that Ca and Mg sources have on pH. Finally, plant growth may directly affect medium pH as well as Ca and Mg uptake. A better understanding of how these sources interact is necessary to improve the recommendations for pH, Ca, and Mg management of container-grown crops over a wide range of conditions using low- or nonleaching irrigation systems. The objective of this study was to determine which sources are important for pH, Ca, and Mg management, and how multiple sources that supply Ca and Mg and affect pH interact during production to affect the overall pH, Ca, and Mg management of a crop.

Root-zone pH management.

Relative importance: Nutrient solution (IWS and WSF) > plant species > residual lime > root media

The NS, which is composed of the alkalinity concentration in the IWS combined with the reaction produced by the WSF, was the most important factor influencing pH management in container grown crops. For example, a similar medium pH was maintained with a NS combining an acidic WSF (potential acidity of 199 kg/1000 kg) with 320 $mg \cdot L^{-1}$ alkalinity in the IWS or a basic WSF (potential basicity of 175 kg/1000 kg) with 20 mg·L^{-1} alkalinity in the IWS. Decreasing the concentration of the WSF lessened effect that the WSF had on the overall reaction produced by the NS.

Plant species also affected medium pH with differences up to 1.4 units given the same NS. However, the plant effect could be modified by the NS. For example, the pH of medium containing geraniums was 5.3 with an acidic NS, 5.8 with a neutral NS, and 6.0 with a basic NS, while with petunias, it was 6.1 with an acidic NS, 6.6 with a neutral NS, and 7.4 with a basic NS after 28 days in production.

Lime that is incorporated into a medium at planting can be divided into two categories, the first is the lime that reacts with the medium to increase pH to some equilibrium level and the second is the unreacted or residual lime that remains in the medium once the equilibrium pH is reached. The equilibrium pH was affected by lime incorporation, particle size, and the reactivity of the liming material. The presence of residual lime increased long-term pH buffering in media given an acidic NS containing low Ca and Mg. For example, media containing residual lime given an acidic NS had a pH of 5.8, while media containing little residual lime and given the same NS had a pH of 4.5 after seventeen weeks. Reducing the acidity of the NS by reducing the NH_4-N content and increasing the alkalinity concentration in the IWS negated the residual lime as a source of pH buffering.

Root media had the least influence on pH management. Media containing more degraded peats slowed the increase in root-medium pH when given neutral or basic NS compared to media containing less degraded sphagnum peats, coir, or rockwool. However, there was minimal differences between media type in the decrease of root-medium pH when given acidic NS. Root medium also influenced lime incorporation rate which may affect the amount of residual lime remaining in a medium once the equilibrium pH was reached.

Calcium and Mg management.

Relative importance: Nutrient solution (IWS and WSF) > plant species >
residual lime > PNC fertilizers > root media

The Ca and Mg concentration in the NS, which was affected by the Ca and Mg concentration in both the IWS and WSF, was the most important factor influencing Ca and Mg management in container grown crops. With impatiens, it was demonstrated that there was a linear increase in the shoot tissue Ca and Mg concentrations as the concentration of Ca in the NS increased from 20 to 210 $mg \cdot L^{-1}$, and that of Mg, from 7 to 90 $mg \cdot L^{-1}$. Other ions contained in the NS (NH_4, NO_3, K, SO_4) did not appear to affect Ca or Mg uptake.

The linear increase in shoot-tissue Ca and Mg was found in eight other bedding plant species in addition to impatiens. However, there were differences in the shoot-tissue Ca and Mg concentrations of the nine species. Given the same NS, impatiens were found to contain the highest shoot-tissue Ca and Mg, while Nonstop begonia, pansies, vinca, and wax begonias contained the lowest shoot-tissue Ca while geraniums, pansies, and vinca had the lowest shoot-tissue Mg.

The lime that reacted initially to increase the medium's pH was found to have a minimal effect on root-medium Ca or Mg (if dolomitic lime) concentrations. However, the residual lime did influence long-term Ca and Mg management. Both root-medium and shoot tissue Ca and Mg concentrations were increased when given an acidic NS containing low Ca and Mg. Reducing the acidity of the NS by reducing the NH_4-N content and increasing the alkalinity concentration in the IWS negated the residual lime as a Ca or Mg source.

Preplant nutrient charge fertilizer other than lime (gypsum, triple superphosphate, $Ca(NO_3)_2$, $MgSO_4$) did increase the initial Ca and Mg concentration in the medium.

However, the nutrients supplied with the PNC fertilizers were found to be very soluble and easily removed from the root zone because of leaching or salt stratification within the pot. With subirrigation, the PNC fertilizers had no effect on root-zone nutrient concentrations for longer than one week.

Historically, root media has been the primary focus of nutrient management and buffering in container grown crops. In these experiments, root media had minimal influence on both short term and long term Ca and Mg management. For example, the Ca and Mg concentrations in the root medium and shoot tissue of plants grown in a 70% rockwool/30% perlite medium were similar to those of plants grown in a 70% highly degraded peat/30% perlite medium. However, root medium did influence lime incorporation rate which may affect the amount of residual lime remaining in a medium once the equilibrium pH was reached.

APPENDIX A

GEOGRAPHICAL CHARACTERIZATION OF GREENHOUSE IRRIGATION WATER FROM THE TEN LEADING STATES IN FLORICULTURE PRODUCTION

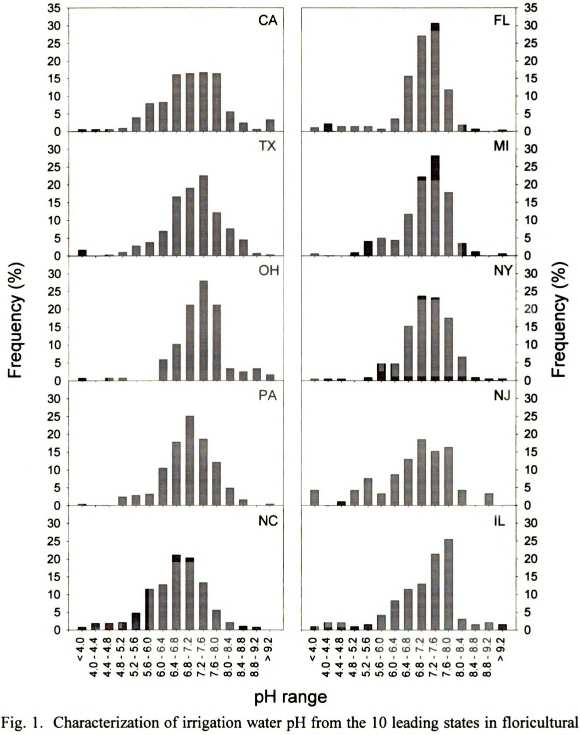


Fig. 1. Characterization of irrigation water pH from the 10 leading states in floricultural production (United States Department of Agriculture Floriculture Crops 1994 Summary, Washington D.C.).

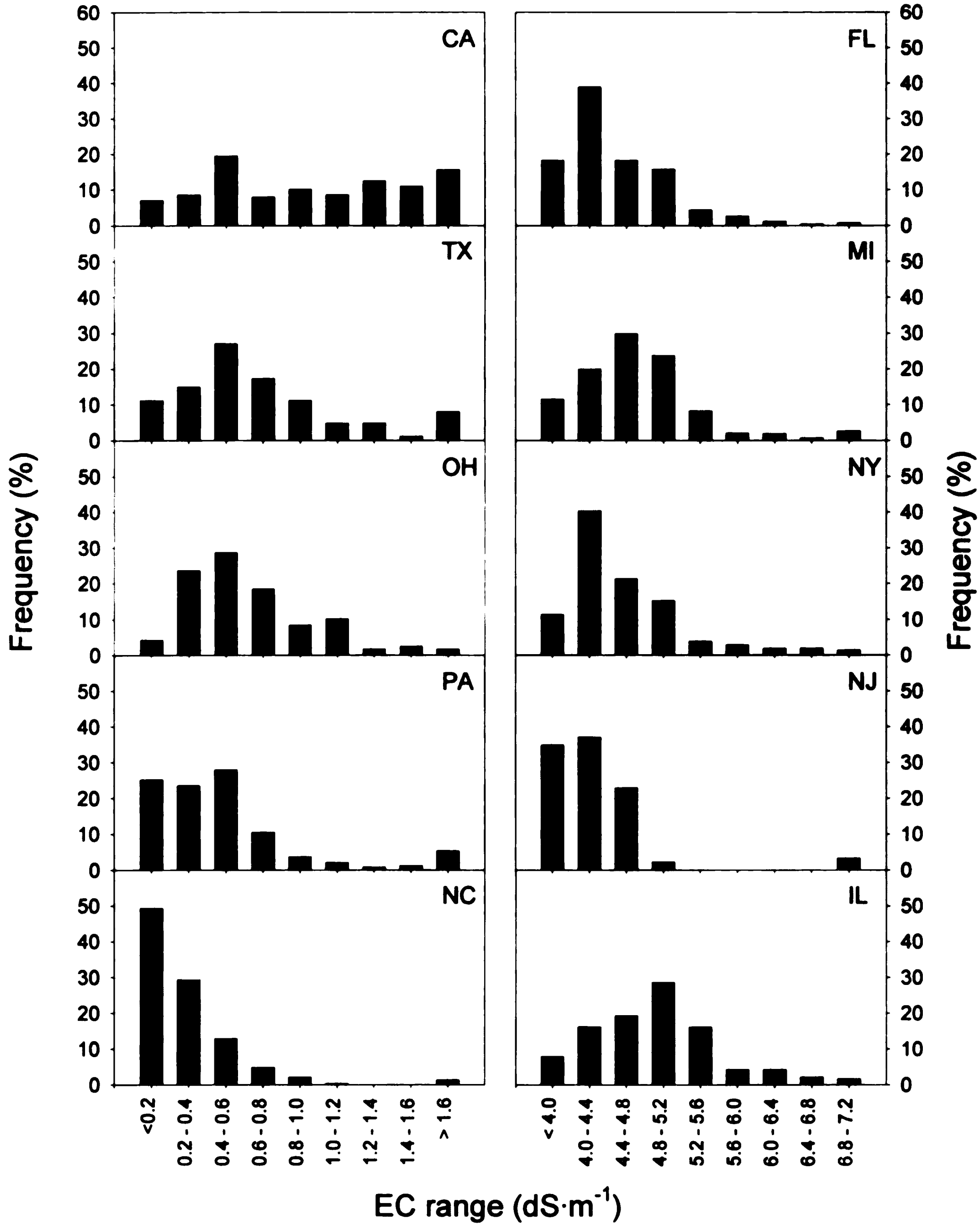


Fig. 2. Characterization of irrigation water electrical conductivity (EC) (in dS·m^{-1}) from the 10 leading states in floricultural production (United States Department of Agriculture Floriculture Crops 1994 Summary, Washington D.C.).

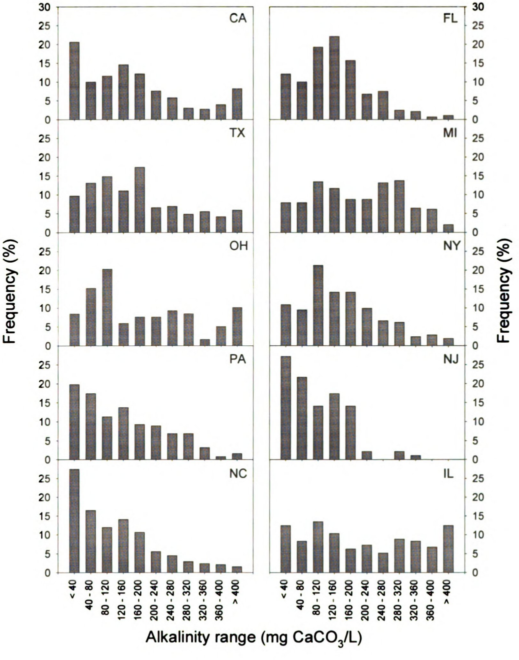


Fig. 3. Characterization of irrigation water alkalinity concentrations (in mg $CaCO_3$/L) from the 10 leading states in floricultural production (United States Department of Agriculture Floriculture Crops 1994 Summary, Washington D.C.).

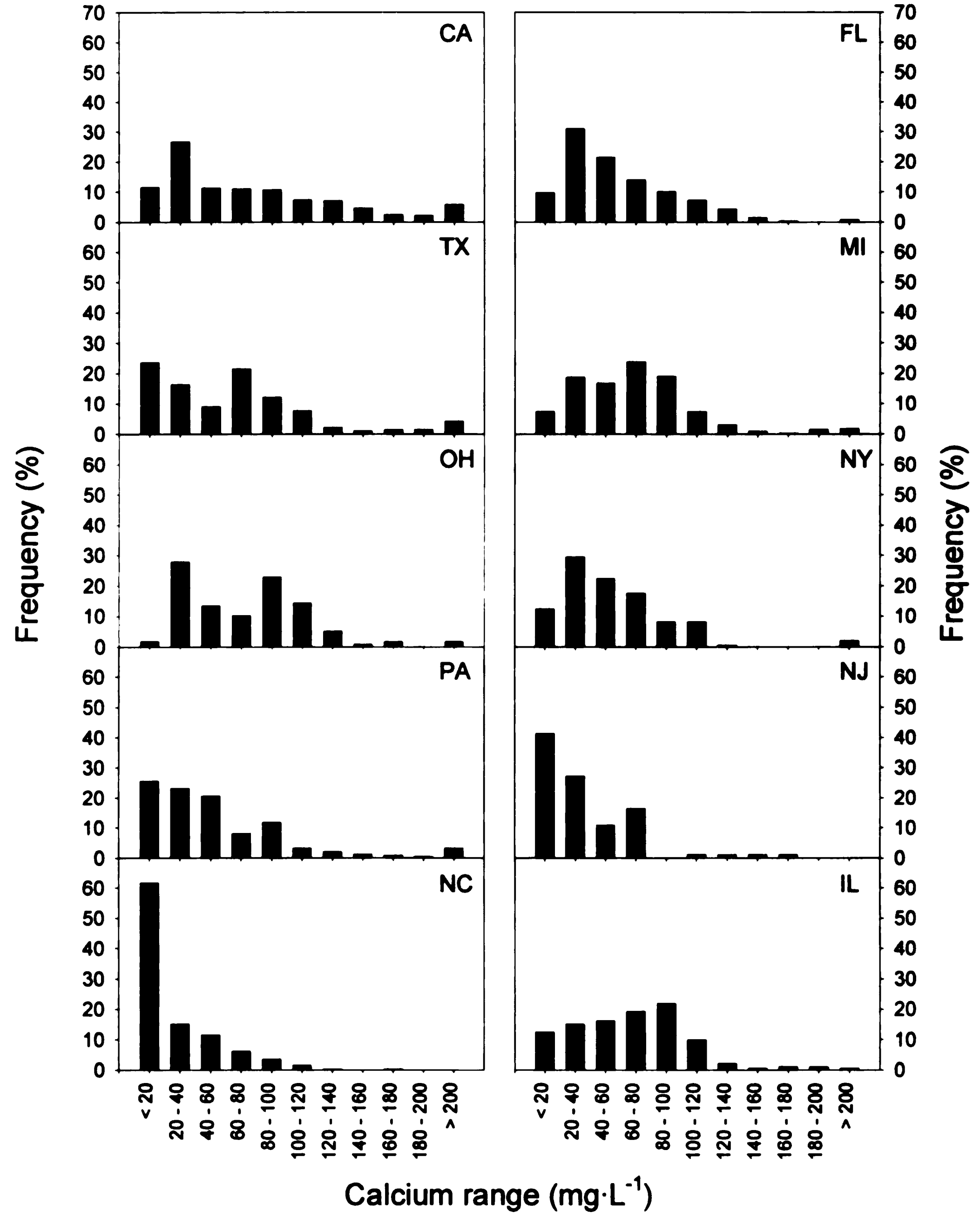


Fig. 4. Characterization of irrigation water calcium concentrations (in mg·L^{-1}) from the 10 leading states in floricultural production (United States Department of Agriculture Floriculture Crops 1994 Summary, Washington D.C.).

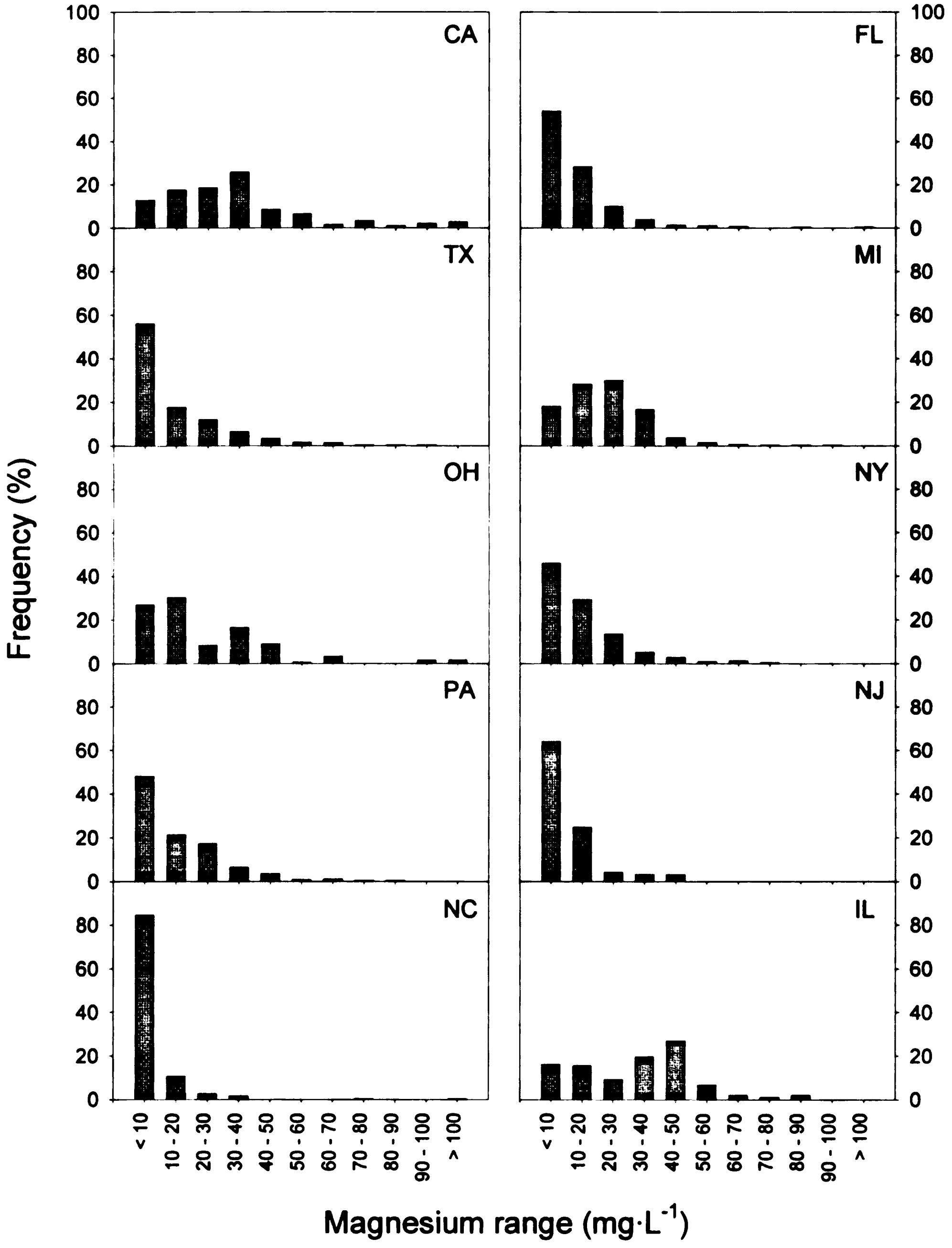


Fig. 5. Characterization of irrigation water magnesium concentrations (in mg·L^{-1}) from the 10 leading states in floricultural production (United States Department of Agriculture Floriculture Crops 1994 Summary, Washington D.C.).

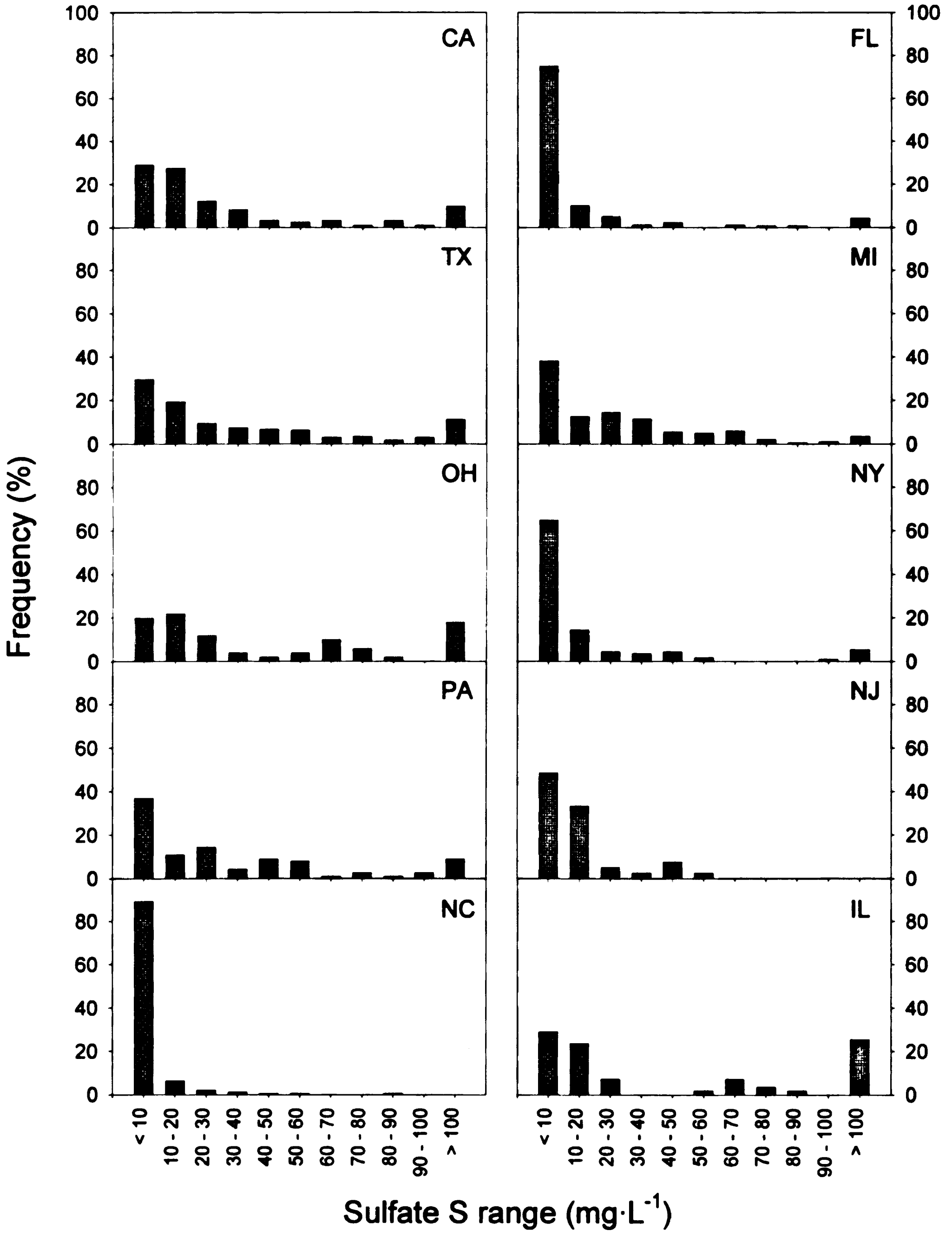


Fig. 6. Characterization of irrigation water sulfate S concentrations (in mg·L^{-1}) from the 10 leading states in floricultural production (United States Department of Agriculture Floriculture Crops 1994 Summary, Washington D.C.).

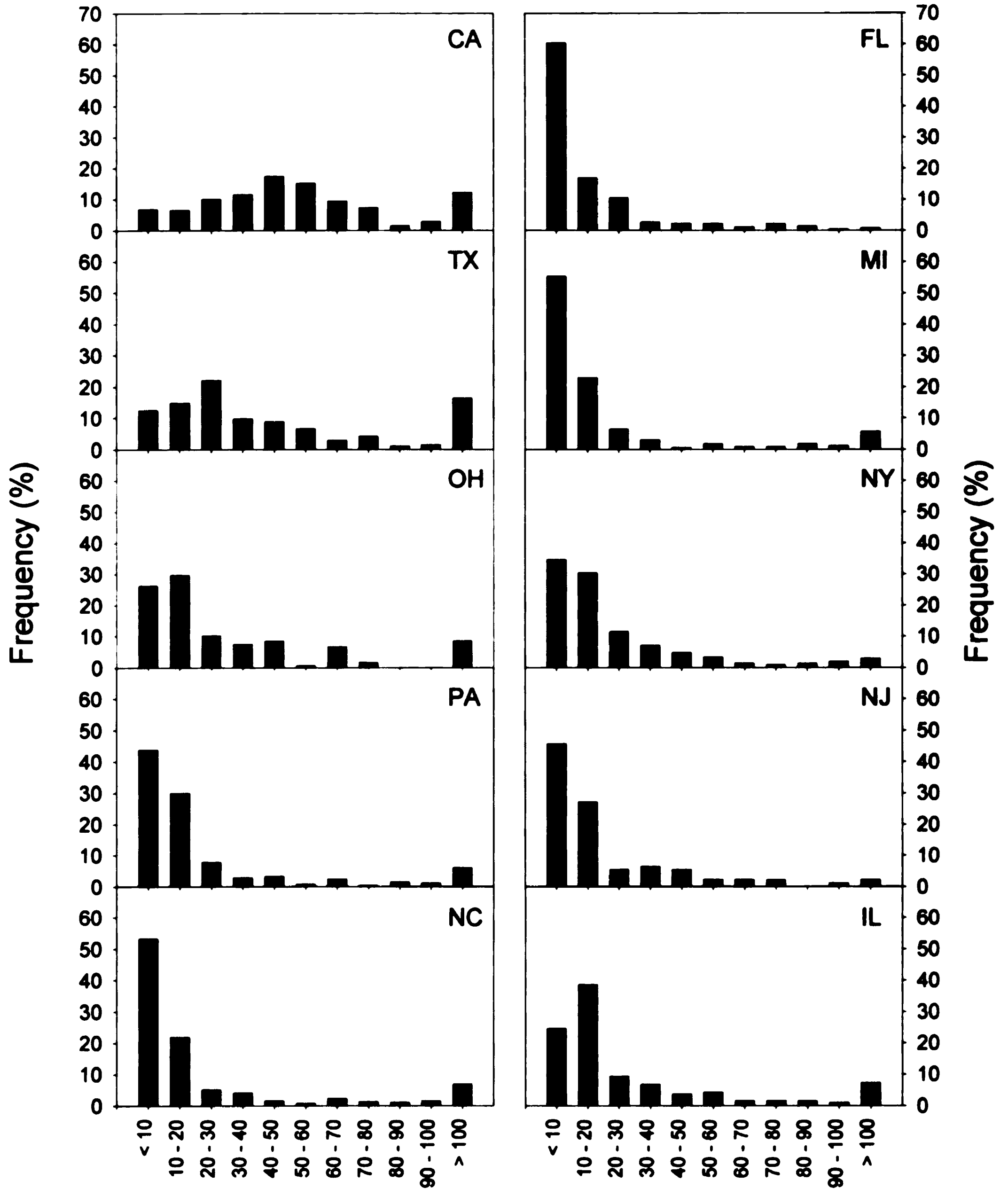
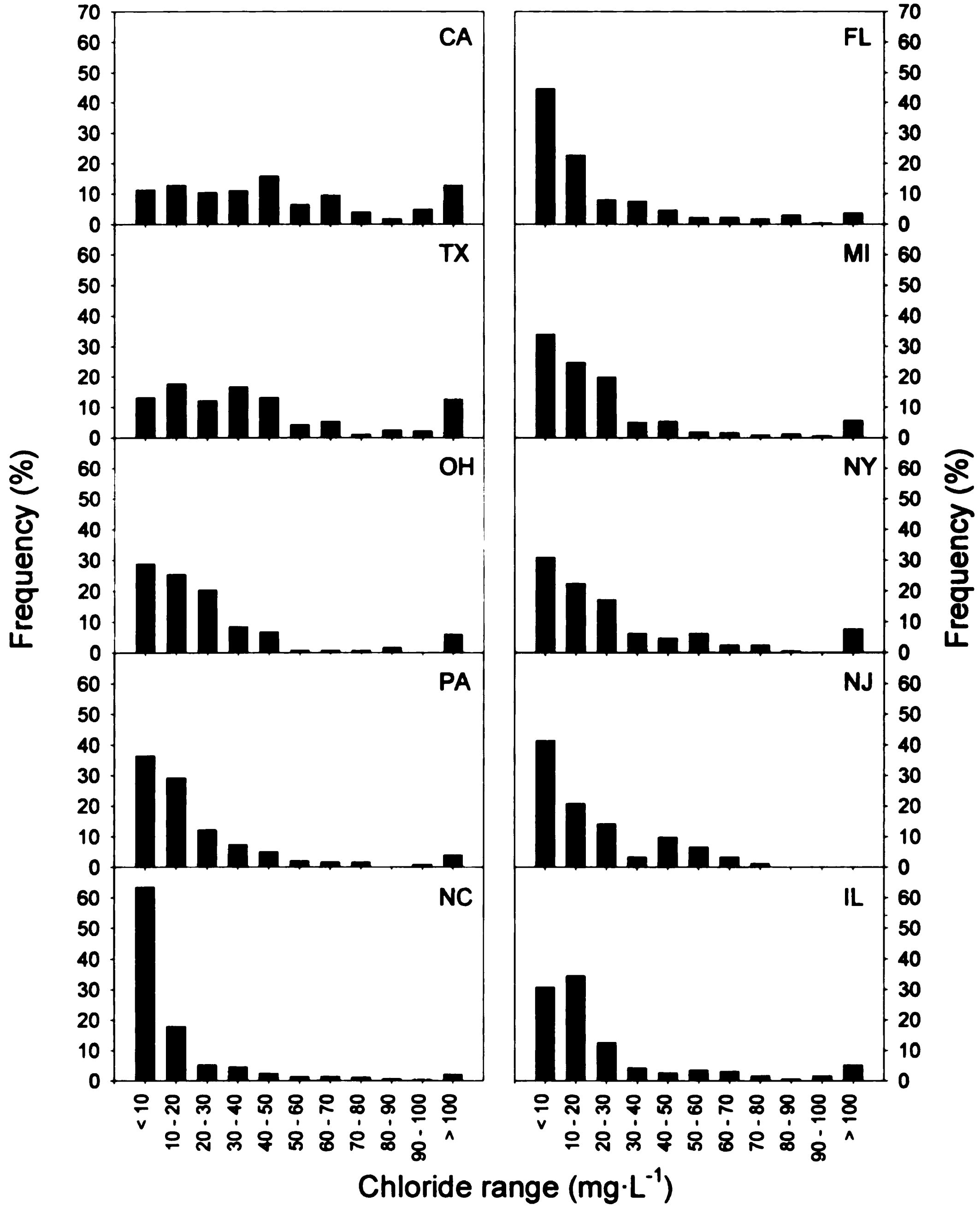


Fig. 7. Characterization of irrigation water sodium concentrations (in mg·L^{-1}) from the 10 leading states in floricultural production (United States Department of Agriculture Floriculture Crops 1994 Summary, Washington D.C.).



Characterization of irrigation water chloride concentrations (in mg·L^{-1}) from the 10 leading states in floricultural production (United States Department of Agriculture Floriculture Crops 1994 Summary, Washington D.C.).

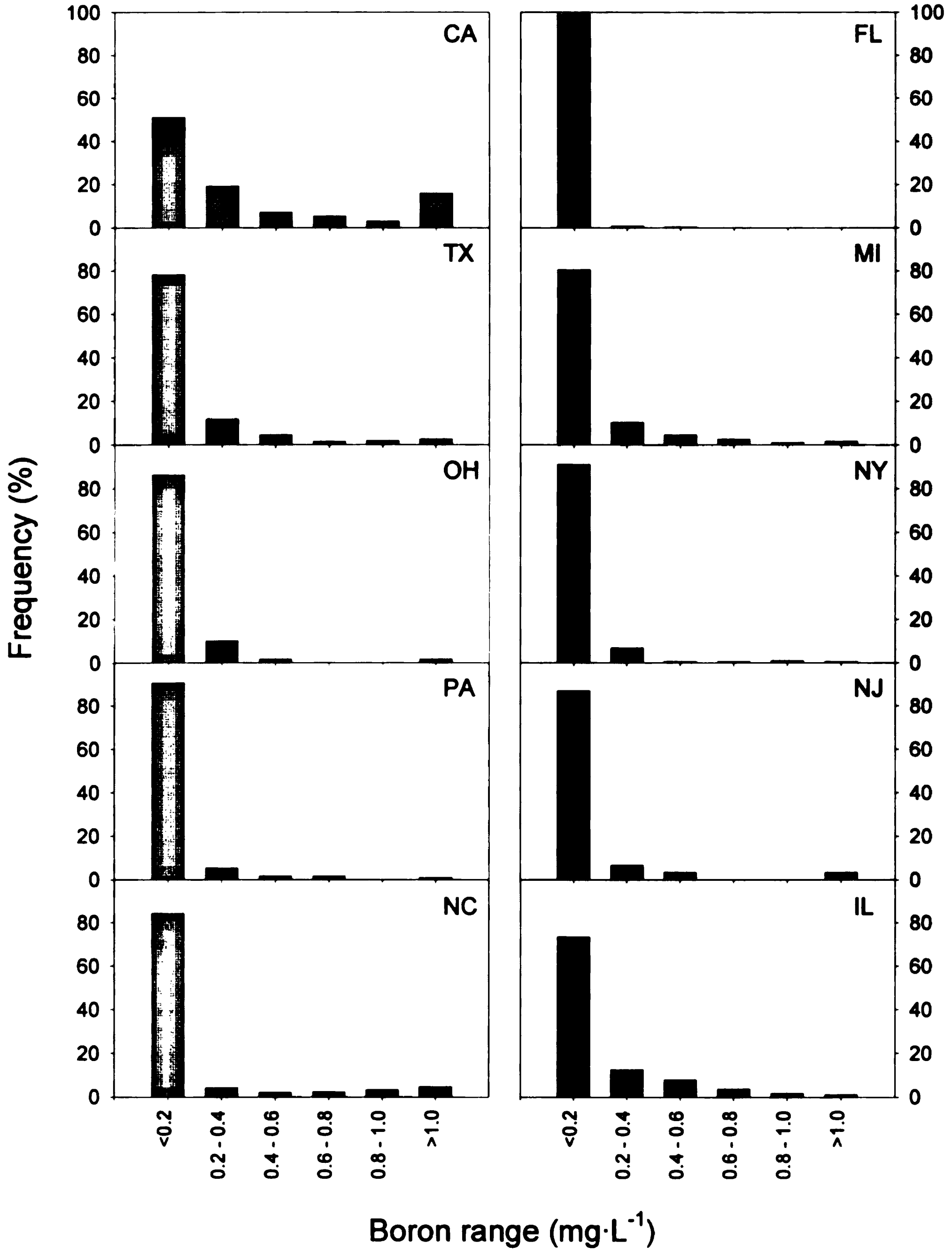


Fig. 8. Characterization of irrigation water boron concentrations (in mg·L^{-1}) from the 10 leading states in floricultural production (United States Department of Agriculture Floriculture Crops 1994 Summary, Washington D.C.).

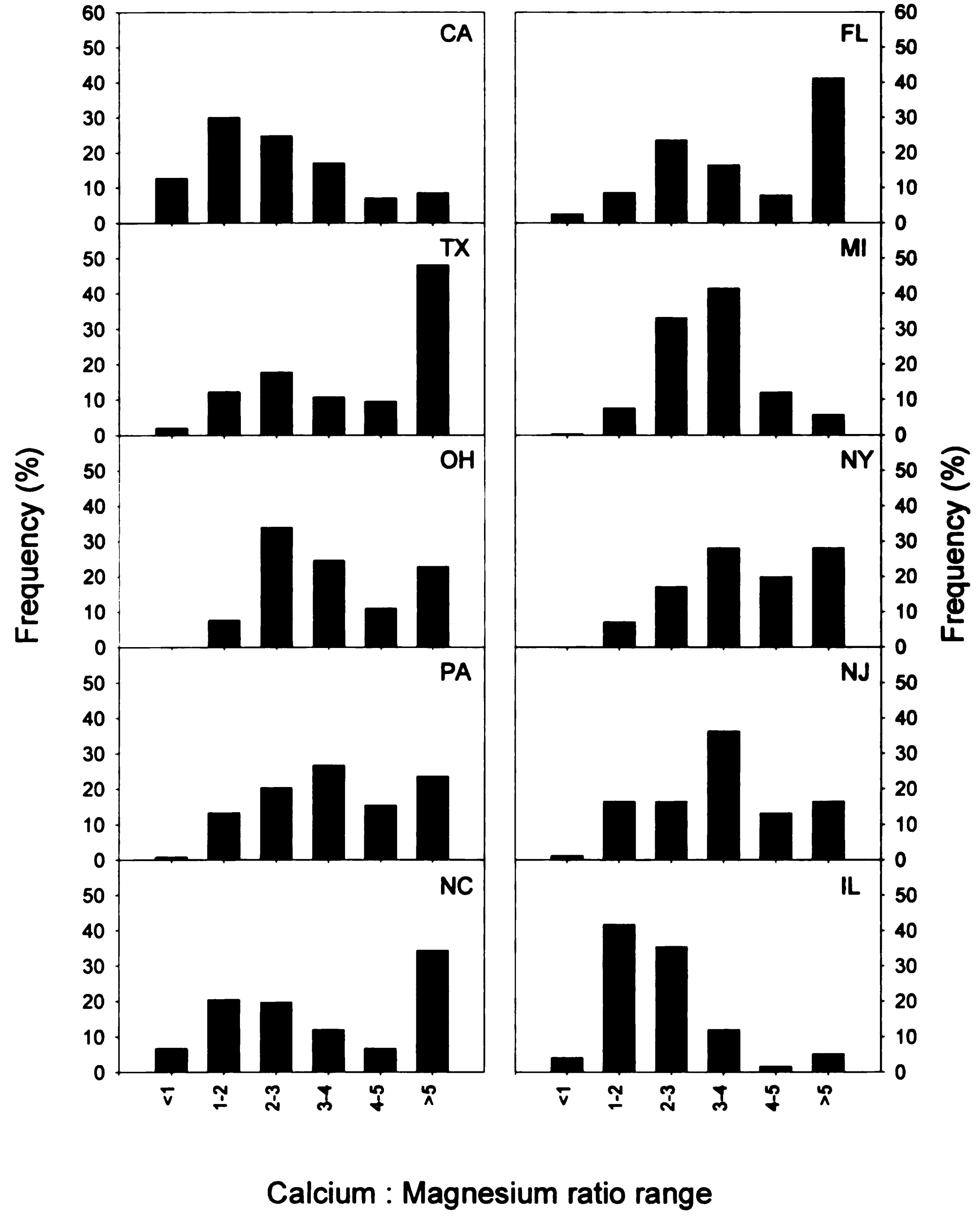


Fig. 9. Characterization of irrigation water Ca : Mg ratio from the 10 leading states in floricultural production (United States Department of Agriculture Floriculture Crops 1994 Summary, Washington D.C.). Values were calculated independently for each sample.

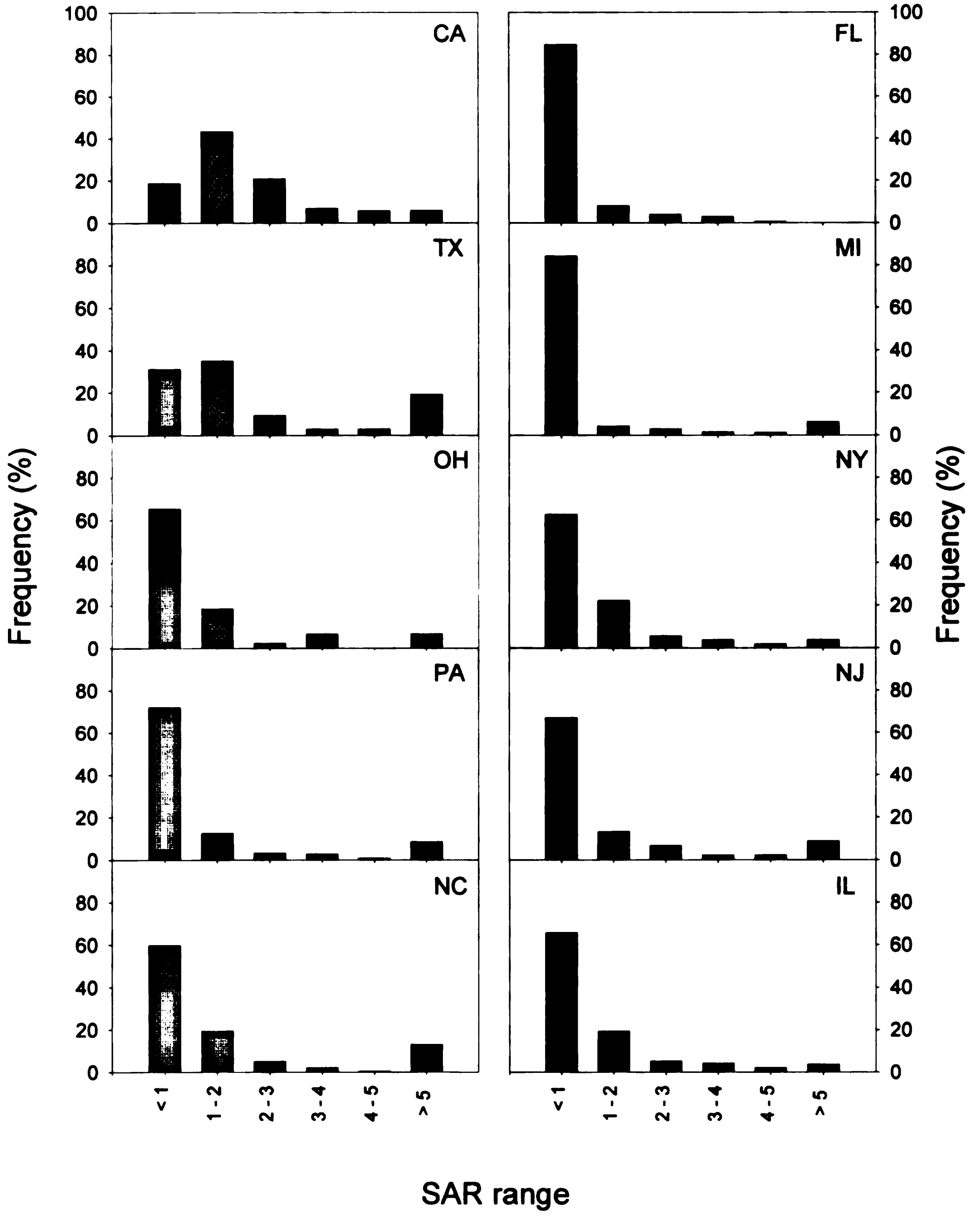


Fig. 10. Characterization of irrigation water sodium adsorption ratio (SAR) from the 10 leading states in floricultural production (United States Department of Agriculture Floriculture Crops 1994 Summary, Washington D.C.). Values were calculated independently for each sample.

APPENDIX B

NUTRIENT COMPOSITION OF COMMERCIALLY AVAILABLE BLENDED WATER-SOLUBLE FERTILIZERS USED IN THE GREENHOUSE INDUSTRY

Champion water-soluble fertilizer (Chilean Nitrate Corp., Norfolk, Virginia)

Table 1. Macronutrient information for Champion water-soluble fertilizers.

	Elemental Analysis (%)								EC	Reaction [x]		
Formula[z]	NH_4-N	NO_3-N	Urea	P	K	Ca	Mg	S	Slope[y]	Type	Strength	Macronutrient salts
9-30-25	4.0	5.0	-	13.1	20.7	-	0.8	1.6	100	A	135	KNO_3, KH_2PO_4, $Mg(NO_3)_2$, $NH_4H_2PO_4$, $(NH4)_2SO_4$
9-45-15	6.5	2.5	-	19.7	10.9	-	0.5	1.0	85	A	290	KNO_3, KH_2PO_4, $Mg(NO_3)_2$, $MgSO_4$, $NH_4H_2PO_4$
15-0-15	1.5	13.5	-	-	10.9	6.4	2.0	-	116	B	142	$Ca(NO_3)_2$, KNO_3, $Mg(NO_3)_2$, NH_4NO_3
15-20-25	4.0	7.4	3.6	8.7	20.7	-	0.5	0.7	135	A	125	KNO_3, $MgSO_4$, $NH_4H_2PO_4$, $(NH4)_2SO_4$, urea
17-4-28	5.2	11.8	-	1.7	23.1	-	1.0	2.2	135	A	53	KNO_3, $MgSO_4$, $NH_4H_2PO_4$, NH_4NO_3, $(NH4)_2SO_4$
17-17-17	7.9	9.1	-	7.4	14.0	-	1.0	1.8	156	A	14	KNO_3, $Mg(NO_3)_2$, $NH_4H_2PO_4$, NH_4NO_3, $(NH4)_2SO_4$
20-8-20	7.9	12.1	-	3.5	14.5	-	0.9	1.2	156	A	190	KNO_3, $MgSO_4$, $NH_4H_2PO_4$, NH_4NO_3
20-20-20	3.8	5.8	10.4	8.7	16.5	-	0.1	0.1	200	A	263	KNO_3, $MgSO_4$, $NH_4H_2PO_4$, NH_4NO_3, $(NH4)_2SO_4$, urea
21-7-7	11.3	1.9	7.8	3.1	5.8	-	1.0	12.9	172	A	724	KNO_3, $MgSO_4$, KH_2PO_4, $(NH4)_2SO_4$, urea
23-10-21	-	4.3	18.7	4.4	17.3	-	1.3	1.7	385	A	265	KNO_3, $MgSO_4$, KH_2PO_4, urea
24-8-16	6.1	7.5	10.4	3.5	13.2	-	0.5	1.5	200	A	378	KNO_3, $MgSO_4$, $NH_4H_2PO_4$, $(NH4)_2SO_4$, urea
24-9-9	12	12	-	3.9	7.4	-	1.0	2.2	179	A	411	KNO_3, $MgSO_4$, $NH_4H_2PO_4$, NH_4NO_3, $(NH4)_2SO_4$

[z] N-P_2O_5-K_2O formula.

[y] Units for EC slope are mg·L^{-1} N per 1 dS·m^{-1}.

[x] The potential reaction of the water-soluble fertilizer. The type of reaction is either acidic (A) or basic (B) and the strength of the reaction is given in kg of acidity or basicity per 1000 kg of fertilizer.

Table 2. Total nutrient concentration supplied by Champion water-soluble fertilizer at an N concentration of 200 mg·L^{-1}.

	NH_4-N	NO_3-N	Urea-N	P	K	Ca	Mg	S	Na	Cl	Fe	Mn	Cu	Zn	B	Mo
Formula[z]								(mg·L^{-1})								
9-30-25	89	111	-	291	459	-	18	36	-	-	1.1	0.2	0.2	0.2	0.2	0.22
9-45-15	144	56	-	437	242	-	11	22	-	-	1.1	0.2	0.2	0.2	0.2	0.22
15-0-15	20	180	-	-	145	85	27	-	-	-	0.7	0.1	0.1	0.1	0.1	0.13
15-20-25	53	99	48	117	275	-	7	9	-	-	0.7	0.1	0.1	0.1	0.1	0.13
17-4-28	61	139	-	21	272	-	12	26	-	-	0.6	0.1	0.1	0.1	0.1	0.12
17-17-17	93	107	-	87	165	-	11	21	-	-	0.6	0.1	0.1	0.1	0.1	0.12
20-8-20	79	121	-	35	145	-	9	12	-	-	0.5	0.1	0.1	0.1	0.1	0.10
20-20-20	38	58	104	87	165	-	1	1	-	-	0.5	0.1	0.1	0.1	0.1	0.05
21-7-7	108	18	74	29	55	-	10	123	-	-	0.5	0.1	0.1	0.1	0.1	0.10
23-10-21	-	37	163	38	151	-	11	15	-	-	0.4	0.1	0.1	0.1	0.1	0.09
24-8-16	51	63	87	29	110	-	4	13	-	-	0.4	0.1	0.1	0.1	0.1	0.08
24-9-9	100	100	-	33	62	-	8	18	-	-	0.4	0.1	0.1	0.1	0.1	0.08

[z] N-P_2O_5-K_2O formula.

Micronutrients supplied by Fe, FeEDDHA; Mn, MnEDTA; Cu, CuEDTA; Zn, ZnEDTA; B, H_3BO_3; Mo, Na_2MoO_4.

Greencare water-soluble fertilizer (Greencare fertilizers, Chicago, Ill.)

Table 3. Macronutrient information for Greencare water-soluble fertilizers.

Formula[z]	Elemental Analysis (%) NH$_4$-N	NO$_3$-N	Urea	P	K	Ca	Mg	S	EC Slope[y]	Reaction[x] Type	Strength	Macronutrient salts
9-45-15	9.0	-	-	19.7	12.4	-	-	-	83	A	472	KCl, $NH_4H_2PO_4$
13-2-13	0.6	12.8	-	0.9	10.7	6.0	3.0	-	147	B	190	$Ca(NO_3)_2$, KNO_3, $Mg(NO_3)_2$, $NH_4H_2PO_4$
13-4-20	0.4	12.6	-	1.7	16.5	4.0	3.0	-	134	B	166	$Ca(NO_3)_2$, KH_2PO_4, KNO_3, $Mg(NO_3)_2$,
15-15-15	3.0	11.0	1.0	6.6	12.4	7.0	-	-	141	A	27	$Ca(NO_3)_2$, KNO_3, $NH_4H_2PO_4$
15-3-16	2.8	13.0	-	1.3	13.2	3.0	2.0	-	143	B	85	$Ca(NO_3)_2$, KH_2PO_4, KNO_3, $Mg(NO_3)_2$, NH_4NO_3
17-5-17	3.4	13.6	-	2.2	14.0	3.0	1.0	-	156	A	0	$Ca(NO_3)_2$, KNO_3, $Mg(NO_3)_2$, $NH_4H_2PO_4$, NH_4NO_3
20-0-20	-	11.0	9.0	-	16.5	6.0	-	-	200	A	0	$Ca(NO_3)_2$, KNO_3, urea
20-10-20	8.0	12.0	-	4.4	16.5	-	-	-	152	A	213	KNO_3, $NH_4H_2PO_4$, NH_4NO_3
20-20-20	3.9	6.2	9.9	8.7	16.5	-	-	-	250	A	292	KNO_3, $NH_4H_2PO_4$, urea
20-5-30	1.0	8.8	10.2	2.2	24.8	-	-	-	227	A	77	KNO_3, $NH_4H_2PO_4$, urea
21-7-7	13.2	-	7.8	3.1	5.8	-	0.5	10.0	179	A	866	KCl, $MgSO_4$, $NH_4H_2PO_4$, $(NH_4)_2SO_4$, urea

[z] $N\text{-}P_2O_5\text{-}K_2O$ formula.

[y] Units for EC slope are mg·L^{-1} N per 1 dS·m^{-1}.

[x] The potential reaction of the water-soluble fertilizer. The type of reaction is either acidic (A) or basic (B) and the strength of the reaction is given in kg of acidity or basicity per 1000 kg of fertilizer.

Table 4. Total nutrient concentration supplied by Greencare water-soluble fertilizer at an N concentration of 200 mg·L^{-1}.

Formula[z]	NH$_4$-N	NO$_3$-N	Urea-N	P	K	Ca	Mg	S (mg·L^{-1})	Na	Cl	Fe	Mn	Cu	Zn	B	Mo
9-45-15	200	-	-	437	275	-	-	-	-	250	1.7	0.8	0.6	1.1	0.3	0.16
13-2-13	9	191	-	13	161	90	45	-	-	-	1.2	0.6	0.4	0.8	0.2	0.12
13-4-20	6	194	-	27	254	62	46	-	-	-	1.2	0.6	0.4	0.8	0.0	0.12
15-15-15	40	147	13	88	165	93	-	-	-	-	1.0	0.5	0.4	0.7	0.2	0.09
15-3-16	36	164	-	17	167	38	25	-	-	-	1.1	0.5	0.4	0.7	0.0	0.10
17-5-17	40	160	-	26	165	35	12	-	-	-	0.9	0.4	0.3	0.6	0.2	0.08
20-0-20	-	110	90	-	165	60	-	-	-	-	0.8	0.4	0.3	0.5	0.2	0.07
20-5-30	10	88	102	22	248	-	-	-	-	-	0.8	0.4	0.3	0.5	0.2	0.07
20-10-20	80	120	-	44	165	-	-	-	-	-	0.8	0.4	0.3	0.5	0.2	0.07
20-20-20	39	62	99	87	165	-	-	-	-	-	0.8	0.4	0.3	0.5	0.2	0.07
21-7-7	125	-	75	29	55	-	5	95	-	-	0.7	0.4	0.3	0.5	0.1	0.07

[z] $N\text{-}P_2O_5\text{-}K_2O$ formula.

Micronutrient concentrations < 0.0 indicate that the nutrients are present in the water-soluble fertilizer but their calculated concentration is below 0.05 mg·L^{-1}.

Micronutrients supplied by Fe, FeEDDHA; Mn, MnEDTA; Cu, CuEDTA; Zn, ZnEDTA; B, H_3BO_3; Mo, Na_2MoO_4.

Masterblend water-soluble fertilizer (Vaughan Seed Co., Chicago, Ill.)

Table 5. Macronutrient information on Masterblend water-soluble fertilizers.

	Elemental Analysis (%)								EC	Reaction [x]		
Formula[z]	NH_4-N	NO_3-N	Urea	P	K	Ca	Mg	S	Slope[y]	Type	Strength	Macronutrient Salts
9-45-15	9.0	-	-	19.7	12.4	-	0.1	0.1	83	A	470	KCl, $NH_4H_2PO_4$
10-30-20	4.4	5.7	-	13.1	16.5	-	0.6	0.8	104	A	213	KH_2PO_4, KNO_3, $MgSO_4$, $NH_4H_2PO_4$
12-0-43	-	12.0	-	-	35.5	-	0.1	0.1	104	B	225	KNO_3
12-36-14	6.8	4.1	1.1	15.7	11.6	-	0.1	0.1	94	A	340	KNO_3, $MgSO_4$, $NH_4H_2PO_4$, urea
13-2-13	0.6	12.8	-	0.9	10.7	6.0	3.0	-	147	B	190	$Ca(NO_3)_2$, KNO_3, $Mg(NO_3)_2$, $NH_4H_2PO_4$
14-0-14	1.2	12.9	-	-	10.2	5.9	2.9	-	116	B	205	$Ca(NO_3)_2$, KNO_3, $Mg(NO_3)_2$
15-0-15	-	13.0	2.0	-	12.4	11.0	-	-	135	B	210	$Ca(NO_3)_2$, KNO_3, urea
15-5-25	4.2	10.8	-	2.2	20.7	-	1.3	1.7	114	A	39	KNO_3, $MgSO_4$, $NH_4H_2PO_4$, urea
15-10-30	2.2	9.1	3.7	4.4	24.8	-	0.1	0.1	143	A	38	KNO_3, $MgSO_4$, $NH_4H_2PO_4$, urea
15-11-29	2.2	8.6	4.3	4.8	24.0	-	0.1	0.2	147	A	45	KNO_3, $MgSO_4$, $NH_4H_2PO_4$, urea
15-15-15	3.0	7.2	4.8	6.6	12.4	-	0.1	0.1	156	A	131	KNO_3, $MgSO_4$, $NaNO_3$, $NH_4H_2PO_4$, urea
15-16-17	4.5	10.5	-	7.0	14.0	-	0.1	0.2	147	A	83	KNO_3, $MgSO_4$, $NaNO_3$, $NH_4H_2PO_4$, NH_4NO_3
15-20-25	4.0	7.0	4.0	8.7	20.7	-	0.1	0.1	147	A	148	KNO_3, $MgSO_4$, $NH_4H_2PO_4$, urea
15-30-15	5.8	4.5	4.8	13.1	12.4	-	0.1	0.1	161	A	335	KNO_3, $MgSO_4$, $NH_4H_2PO_4$, urea
16-4-12	2.1	14.0	-	1.7	9.9	-	0.1	0.1	147	B	38	KNO_3, $MgSO_4$, $NaNO_3$, $NH_4H_2PO_4$, NH_4NO_3
20-0-20	5.0	15.0	-	-	16.5	6.0	-	-	147	A	20	$Ca(NO_3)_2$, KNO_3, NH_4NO_3
20-2-20	7.1	5.9	7.1	0.9	16.5	-	1.0	8.0	161	A	413	KNO_3, $MgSO_4$, $NH_4H_2PO_4$, $(NH_4)_2SO_4$, urea
20-5-30	1.0	8.8	10.2	2.2	24.8	-	0.1	0.1	227	A	77	KNO_3, $MgSO_4$, $NH_4H_2PO_4$, urea
20-10-20	8.0	12.0	-	4.4	16.5	-	0.1	0.1	152	A	213	KNO_3, $MgSO_4$, $NH_4H_2PO_4$, NH_4NO_3
20-15-25	2.8	7.8	9.4	6.6	20.7	-	0.2	0.2	238	A	122	KNO_3, $MgSO_4$, $NH_4H_2PO_4$, urea
20-19-18	3.8	5.2	11.1	8.3	14.9	-	0.2	0.2	250	A	320	KNO_3, $MgSO_4$, $NH_4H_2PO_4$, urea
20-20-20	3.9	6.2	9.9	8.7	16.5	-	0.1	0.1	250	A	292	KNO_3, $MgSO_4$, $NH_4H_2PO_4$, urea
21-7-7	1.6	7.5	11.9	3.1	5.8	-	0.1	0.1	238	A	185	KNO_3, $MgSO_4$, $NaNO_3$, $NH_4H_2PO_4$, urea
21-7-7	9.1	-	12.0	3.1	5.8	-	0.1	10.0	179	A	780	KCl, $MgSO_4$, $NH_4H_2PO_4$, $(NH_4)_2SO_4$, urea
24-8-16	7.2	9.6	7.2	3.5	13.2	-	0.1	0.1	227	A	345	KNO_3, $MgSO_4$, $NH_4H_2PO_4$, NH_4NO_3, $(NH_4)_2SO_4$, urea
25-0-25	-	7.3	17.8	-	20.7	-	0.1	0.1	333	A	203	KNO_3, urea
25-5-20	1.2	6.0	17.9	2.2	16.5	-	0.1	0.1	385	A	293	KNO_3, $MgSO_4$, $NH_4H_2PO_4$, urea
25-10-10	1.8	2.7	20.6	4.4	8.3	-	0.1	0.1	625	A	520	KNO_3, $MgSO_4$, $NH_4H_2PO_4$, urea
27-15-12	3.0	3.8	20.3	6.6	9.9	-	0.1	0.1	455	A	470	KNO_3, $MgSO_4$, $NH_4H_2PO_4$, urea
30-10-10	2.2	3.2	24.7	4.4	8.3	-	0.1	0.1	714	A	518	KNO_3, $MgSO_4$, $NH_4H_2PO_4$, urea

[z] N-P_2O_5-K_2O formula

[y] Units for EC slope are $mg \cdot L^{-1}$ N per 1 $dS \cdot m^{-1}$.

[x] The potential reaction of the water-soluble fertilizer. The type of reaction is either acidic (A) or basic (B) and the strength of the reaction is given in kg of acidity or basicity per 1000 kg of fertilizer.

Masterblend water-soluble fertilizer (Vaughan Seed Co., Chicago, Ill.)

Table 6. Total nutrient concentration supplied by Masterblend water-soluble fertilizer at an N concentration of 200 $mg \cdot L^{-1}$.

Formula[z]	NH_4-N	NO_3-N	Urea-N	P	K	Ca	Mg	S	Na	Cl	Fe	Mn	Cu	Zn	B	Mo
								($mg \cdot L^{-1}$)								
9-45-15	200	-	-	437	275	-	1	1	-	250	1.1	0.1	0.1	0.1	0.2	0.02
10-30-20	87	113	-	262	330	-	12	16	-	-	1.0	0.1	0.1	0.1	0.1	0.02
12-0-43	-	200	-	-	592	-	1	1	-	-	0.8	0.1	0.1	0.0	0.1	0.02
12-36-14	113	68	18	262	193	-	1	1	-	-	0.8	0.1	0.1	0.0	0.1	0.02
13-2-13	9	191	-	13	161	90	45	-	-	-	0.8	0.3	0.3	0.3	0.1	0.01
14-0-14	16	184	-	-	145	84	41	-	-	-	0.8	0.3	0.3	0.3	0.1	0.01
15-0-15	-	173	27	-	165	147	-	-	-	-	0.7	0.0	0.1	0.0	0.1	0.01
15-5-25	56	144	-	29	275	-	18	23	-	-	1.0	0.6	0.1	0.7	0.1	1.00
15-10-30	29	122	49	58	330	-	1	1	-	-	0.7	0.0	0.1	0.0	0.1	0.01
15-11-29	29	114	57	64	319	-	2	2	-	-	1.0	0.6	0.1	0.2	0.3	0.10
15-15-15	39	96	64	87	165	-	1	1	60	-	0.7	0.0	0.1	0.0	0.1	0.01
15-16-17	60	140	-	93	187	-	2	2	90	-	1.0	0.5	0.1	0.2	0.3	0.10
15-20-25	53	93	53	117	275	-	1	1	-	-	0.7	0.0	0.1	0.0	0.1	0.01
15-30-15	77	59	64	175	165	-	1	1	-	-	0.7	0.0	0.1	0.0	0.1	0.01
16-4-12	26	174	-	22	124	-	1	1	185	-	0.7	0.0	0.1	0.0	0.1	0.01
20-0-20	50	150	-	-	165	60	-	-	-	-	1.0	0.6	0.1	0.2	0.2	0.10
20-2-20	71	59	71	9	165	-	10	80	-	-	0.5	0.0	0.0	0.0	0.1	0.01
20-5-30	10	88	102	22	248	-	1	1	-	-	0.5	0.0	0.0	0.0	0.1	0.01
20-10-20	80	120	-	44	165	-	1	1	1	1	1.0	0.6	0.1	0.2	0.2	0.10
20-15-25	28	78	94	66	207	-	2	2	-	-	1.0	0.6	0.1	0.2	0.2	0.10
20-19-18	38	52	111	83	149	-	2	2	-	-	1.0	0.6	0.1	0.2	0.2	0.10
20-20-20	39	62	99	87	165	-	1	1	-	-	0.5	0.0	0.0	0.0	0.1	0.01
21-7-7	16	71	113	29	55	-	1	1	78	-	1.0	0.0	0.0	0.0	0.1	0.01
21-7-7	86	-	114	29	55	-	1	82	-	50	1.4	0.0	0.0	0.0	0.1	0.01
24-8-16	60	80	60	29	110	-	1	1	-	-	0.4	0.2	0.2	0.2	0.0	0.01
25-0-25	-	58	142	-	165	-	1	1	-	-	0.4	0.0	0.0	0.0	0.1	0.01
25-5-20	9	48	143	17	132	-	1	1	-	-	0.4	0.0	0.0	0.0	0.1	0.01
25-10-10	14	21	165	35	66	-	1	1	-	-	0.8	0.0	0.0	0.0	0.1	0.01
27-15-12	22	28	150	49	73	-	1	1	-	-	0.9	0.5	0.5	0.5	0.2	0.00
30-10-10	14	21	165	29	55	-	-	-	-	-	0.3	0.0	0.0	0.0	0.1	0.01

[z] $N-P_2O_5-K_2O$ formula.

Micronutrient concentrations < 0.0 indicate that the nutrients are present in the water-soluble fertilizer but their calculated concentration is below 0.05 $mg \cdot L^{-1}$.

Micronutrients supplied by Fe, FeDTPA; Mn, MnEDTA; Cu, CuEDTA; Zn, ZnEDTA; B, H_3BO_3; Mo, Na_2MoO_4.

Peters water-soluble fertilizer (Scotts, Marysville, Ohio).

Table 7. Macronutrient information on Peters Professional water-soluble fertilizers.

	Elemental Analysis (%)								EC	Reaction [x]		
Formula[z]	NH_4-N	NO_3-N	Urea	P	K	Ca	Mg	S	Slope[y]	Type	Strength	Macronutrient salts
5-11-26	-	5.0	-	4.8	21.5	-	3.1	4.0	51	B	30	KH_2PO_4, KNO_3, $MgSO_4$
5-50-17	5.0	-	-	21.9	14.0	-	0.1	0.1	60	A	400	KCl, KH_2PO_4, $MgSO_4$, $NH_4H_2PO_4$
9-45-15	9.0	-	-	19.7	12.4	-	0.1	0.1	83	A	472	KCl, $MgSO_4$, $NH_4H_2PO_4$
10-30-20	4.4	5.6	-	13.1	16.5	-	0.6	0.8	104	A	213	KNO_3, KH_2PO_4, $MgSO_4$, $NH_4H_2PO_4$
12-0-43	-	12.0	-	-	35.5	-	0.1	0.1	104	B	226	KNO_3, $MgSO_4$
12-36-14	6.8	4.1	1.1	15.7	11.6	-	0.1	0.1	94	A	340	KNO_3, $MgSO_4$, $NH_4H_2PO_4$, urea
15-0-15	2.0	13.0	-	-	12.4	11.0	-	-	135	B	210	$Ca(NO_3)_2$, KNO_3, urea
15-5-25	4.2	10.8	-	2.2	20.7	-	1.3	1.7	128	A	38	KNO_3, $MgSO_4$, $NH_4H_2PO_4$, NH_4NO_3
15-10-30	2.2	9.1	3.7	4.4	24.8	-	0.1	0.1	143	A	38	KNO_3, $MgSO_4$, $NH_4H_2PO_4$, urea
15-11-29	2.1	8.6	4.3	4.8	24.0	-	0.1	0.2	147	A	46	KNO_3, $MgSO_4$, $NH_4H_2PO_4$, urea
15-15-15	3.0	7.2	4.8	6.6	12.4	-	0.1	0.1	156	A	131	KNO_3, $MgSO_4$, $NaNO_3$, $NH_4H_2PO_4$, urea
15-16-17	3.2	8.0	3.8	7.0	14.0	-	0.1	0.2	147	A	108	KNO_3, $MgSO_4$, $NaNO_3$, $NH_4H_2PO_4$, urea
15-17-17	6.6	8.4	-	7.4	14.0	-	0.8	1.1	135	A	232	KNO_3, $MgSO_4$, $NH_4H_2PO_4$, NH_4NO_3
15-20-25	4.0	7.0	4.0	8.7	20.7	-	0.1	0.1	147	A	149	KNO_3, $MgSO_4$, $NH_4H_2PO_4$, NH_4NO_3
15-30-15	5.8	4.4	4.8	13.1	12.4	-	0.1	0.1	161	A	335	KNO_3, $MgSO_4$, $NH_4H_2PO_4$, NH_4NO_3
16-4-12	1.1	10.0	5.0	1.7	9.9	-	0.1	0.1	147	A	37	KNO_3, $MgSO_4$, $NaNO_3$, $NH_4H_2PO_4$, urea
20-0-20	-	11.0	9.0	-	16.5	6.0	-	-	200	A	0	$Ca(NO_3)_2$, KNO_3, urea
20-1-20	5.8	14.2	-	0.4	16.5	-	0.2	0.2	143	A	61	KNO_3, $MgSO_4$, $NaNO_3$, $NH_4H_2PO_4$, NH_4NO_3
20-2-20	7.1	5.9	7.1	0.9	16.5	-	0.1	8.0	161	A	414	KNO_3, $MgSO_4$, $NH_4H_2PO_4$, $(NH_4)_2SO_4$, urea
20-5-30	1.0	8.8	10.2	2.2	21.8	-	0.1	0.1	227	A	77	KNO_3, $MgSO_4$, $NaNO_3$, $NH_4H_2PO_4$, urea
20-10-20	8.0	12.0	-	4.4	16.5	-	0.2	0.2	152	A	211	KNO_3, $MgSO_4$, $NH_4H_2PO_4$, NH_4NO_3
20-19-18	3.8	5.2	11.1	8.3	14.9	-	0.2	0.2	250	A	320	KNO_3, $MgSO_4$, $NH_4H_2PO_4$, urea
20-20-20	4.0	5.6	10.4	8.7	16.5	-	0.1	0.1	250	A	299	KNO_3, $MgSO_4$, $NH_4H_2PO_4$, urea
20-30-10	5.8	3.0	11.3	13.1	8.3	-	0.1	0.1	278	A	475	KNO_3, $MgSO_4$, $NH_4H_2PO_4$, urea
21-7-7	1.4	7.7	12.0	3.1	5.8	-	0.1	0.1	238	A	185	KNO_3, $MgSO_4$, $NaNO_3$, $NH_4H_2PO_4$, urea
21-7-7	9.1	-	12.0	3.1	5.8	-	0.1	10.0	179	A	780	KCl, $MgSO_4$, $NH_4H_2PO_4$, $(NH_4)_2SO_4$, urea
24-8-16	7.2	9.6	7.2	3.5	13.2	-	0.1	1.0	227	A	346	KNO_3, $MgSO_4$, $NH_4H_2PO_4$, NH_4NO_3, $(NH_4)_2SO_4$, urea
25-0-25	-	7.3	17.8	-	20.7	-	0.1	0.1	333	A	203	KNO_3, $MgSO_4$, urea
25-5-15	8.3	11.8	4.9	2.2	12.4	-	0.2	0.2	208	A	320	KNO_3, $MgSO_4$, $NH_4H_2PO_4$, NH_4NO_3, urea
27-15-12	3.0	3.8	20.3	6.6	9.9	-	0.1	0.1	455	A	470	KNO_3, $MgSO_4$, $NH_4H_2PO_4$, urea
30-10-10	2.1	3.2	24.7	4.4	8.3	-	0.1	0.1	714	A	520	KNO_3, $MgSO_4$, $NH_4H_2PO_4$, urea

[z] $N-P_2O_5-K_2O$ formula

[y] Units for EC slope are $mg \cdot L^{-1}$ N per 1 $dS \cdot m^{-1}$.

[x] The potential reaction of the water-soluble fertilizer. The type of reaction is either acidic (A) or basic (B) and the strength of the reaction is given in kg of acidity or basicity per 1000 kg of fertilizer.

Peters Professional water-soluble fertilizer (Scotts, Marysville, Ohio).

Table 8. Total nutrient concentration supplied by Peters Professional water-soluble fertilizer at an N concentration of 200 mg·L^{-1}.

	NH_4-N	NO_3-N	Urea-N	P	K	Ca	Mg	S	Na	Cl	Fe	Mn	Cu	Zn	B	Mo
Formula^z								(mg·L^{-1})								
5-11-26	-	200	-	192	859	-	124	162	-	-	12.0	2.0	0.6	0.6	2.0	0.40
5-50-17	200	-	-	874	562	-	2	3	-	25	2.0	1.0	0.1	0.1	0.3	0.04
9-45-15	200	-	-	437	275	-	2	3	-	250	1.1	0.6	0.1	0.1	0.2	0.02
10-30-20	87	113	-	262	330	-	12	16	-	-	1.0	0.5	0.1	0.1	0.1	0.02
12-0-43	-	200	-	-	592	-	1	1	-	-	0.8	0.4	0.1	0.0	0.1	0.02
12-36-14	114	68	18	262	193	-	1	1	-	-	0.8	0.42	0.1	0.0	0.1	0.02
15-0-15	-	173	27	-	165	147	-	-	-	-	0.7	0.3	0.1	0.0	0.1	0.01
15-5-25	56	144	-	29	275	-	18	23	-	-	1.0	0.6	0.1	0.7	0.1	1.00
15-10-30	29	122	49	58	330	-	1	1	-	-	0.7	0.3	0.1	0.0	0.1	0.01
15-11-29	29	144	57	64	319	-	2	2	-	-	1.0	0.6	0.1	0.2	0.3	0.10
15-15-15	40	96	64	87	165	-	1	1	60	-	0.7	0.3	0.1	0.0	0.1	0.01
15-16-17	42	107	51	93	187	-	2	3	65	-	1.0	0.6	0.1	0.2	0.3	0.10
15-17-17	88	112	-	99	187	-	11	15	-	-	1.0	0.6	0.1	0.2	0.3	0.10
15-20-25	53	93	53	117	275	-	1	1	-	-	0.7	0.3	0.1	0.0	0.1	0.10
15-30-15	77	59	64	175	165	-	1	1	-	-	0.7	0.3	0.1	0.0	0.1	0.01
16-4-12	13	125	62	22	124	-	1	1	140	-	0.6	0.3	0.1	0.1	0.1	0.01
20-0-20	-	110	90	-	165	60	-	-	-	-	1.0	0.6	0.1	0.2	0.2	0.10
20-1-20	58	142	-	4	165	-	2	3	43	-	1.0	0.6	0.1	0.2	0.2	0.10
20-2-20	71	59	71	9	165	-	1	80	-	-	0.5	0.2	0.2	0.2	0.2	0.01
20-5-30	10	88	102	22	248	-	1	1	-	-	0.5	0.3	0.0	0.0	0.1	0.01
20-7-79	70	116	14	31	157	-	3	4	-	-	4.0	0.6	0.6	0.6	0.3	0.05
20-10-20	80	120	-	44	165	-	1	1	-	-	1.0	0.6	0.1	0.2	0.2	0.10
20-19-18	38	52	111	83	149	-	2	3	-	-	1.0	0.6	0.1	0.2	0.2	0.10
20-20-20	40	56	104	87	165	-	1	1	-	-	0.5	0.3	0.0	0.0	0.1	0.01
20-30-10	58	30	113	131	83	-	1	1	-	-	0.5	0.3	0.0	0.0	0.1	0.01
21-7-7	86	-	114	29	55	-	1	1	40	-	1.4	0.2	0.0	0.0	0.1	0.01
21-7-7	13	73	114	29	55	-	1	95	-	50	1.0	0.2	0.0	0.0	0.1	0.01
24-8-16	60	80	60	29	110	-	1	8	-	-	0.4	0.2	0.2	0.2	0.0	0.01
25-0-25	-	58	142	165	-	-	1	1	-	-	0.4	0.2	0.0	0.0	0.1	0.01
25-5-15	66	95	39	17	99	-	1	2	-	-	1.0	0.6	0.1	0.7	0.2	0.10
27-15-12	22	28	150	49	73	-	1	1	-	-	0.9	0.5	0.5	0.5	0.2	0.00
30-10-10	14	21	165	29	55	-	1	2	-	-	0.3	0.2	0.0	0.0	0.1	0.01

[z] N-P_2O_5-K_2O formula.

Micronutrient concentrations < 0.0 indicate that the nutrients are present in the water-soluble fertilizer but their calculated concentration is below 0.05 mg·L^{-1}.

Peters Excel water-soluble fertilizer (Scotts, Marysville, Ohio).

Table 9. Macronutrient information on Peters Excel water-soluble fertilizers

	Elemental Analysis (%)								EC	Reaction [x]		
Formula[z]	NH_4-N	NO_3-N	Urea	P	K	Ca	Mg	S	Slope[y]	Type	Strength	Macronutrient Salts
10-0-0	-	10.0	-	-	-	-	9.0	-	147	B	178	$Mg(NO_3)_2$
14-5-38	-	11.9	2.1	2.2	31.4	-	-	-	102	B	154	KNO_3, urea phosphate
15-0-0	1.0	14.0	-	-	-	18.0	-	-	135	B	197	$Ca(NO_3)_2$
15-2-20	1.5	12.7	0.8	0.9	16.5	3.8	2.0	-	147	B	121	$Ca(NO_3)_2$, KNO_3, $Mg(NO_3)_2$, NH_4NO_3, urea phosphate
15-5-15	1.2	11.8	2.1	2.2	12.4	5.0	2.0	-	128	B	71	$Ca(NO_3)_2$, KNO_3, $Mg(NO_3)_2$, NH_4NO_3, urea phosphate
21-5-20	6.5	12.6	1.9	2.2	16.5	-	-	-	172	A	195	KNO_3, $MgSO_4$, urea phosphate

[z] N-P_2O_5-K_2O formula

[y] Units for EC slope are $mg \cdot L^{-1}$ N per 1 $dS \cdot m^{-1}$.

[x] The potential reaction of the water-soluble fertilizer. The type of reaction is either acidic (A) or basic (B) and the strength of the reaction is given in kg of acidity or basicity per 1000 kg of fertilizer.

Table 10. Total nutrient concentration supplied by Peters Excel water-soluble fertilizer at an N concentration of 200 $mg \cdot L^{-1}$.

	NH_4-N	NO_3-N	Urea-N	P	K	Ca	Mg	S	Na	Cl	Fe	Mn	Cu	Zn	B	Mo
Formula[z]								($mg \cdot L^{-1}$)								
10-0-0	-	200	-	-	-	-	180	-	-	-	1.5	0.7	0.1	0.8	0.3	0.14
14-5-38	-	170	30	31	448	-	-	-	-	-	1.1	0.5	0.1	0.6	0.2	0.10
15-0-0	13	187	-	-	-	240	-	-	-	-	1.0	0.5	0.1	0.5	0.2	0.09
15-2-20	20	169	11	12	220	50	27	-	-	-	1.3	0.7	0.1	0.3	0.1	0.09
15-5-15	16	157	27	29	165	67	27	-	-	-	1.0	0.5	0.1	0.5	0.2	0.09
21-5-20	62	120	18	21	157	-	-	-	-	-	1.0	0.5	0.1	0.7	0.2	0.10

[z] N-P_2O_5-K_2O formula.

Micronutrients supplied by Fe, FeDTPA; Mn, MnEDTA; Cu, CuEDTA; Zn, ZnEDTA; B, H_3BO_3; Mo, Na_2MoO_4.

Plantex water-soluble fertilizer (Plantco, Inc., Brampton, Ontario, Canada).

Table 11. Macronutrient information from Plantex water-soluble fertilizers.

	Elemental Analysis (%)								EC	Reaction [x]		
Formula[z]	NH_4-N	NO_3-N	Urea	P	K	Ca	Mg	S	Slope[y]	Type	Strength	Macronutrient salts
10-52-10	7.8	0.9	1.3	22.7	8.3	-	-	-	111	A	470	KNO_3, KH_2PO_4, $NH_4H_2PO_4$, urea
14-0-14	1.2	12.9	-	-	10.2	5.9	2.9	-	116	B	205	$Ca(NO_3)_2$, KNO_3, $Mg(NO_3)_2$, NH_4NO_3
15-15-18	3.0	8.3	3.7	6.6	14.9	-	0.2	-	143	A	85	KNO_3, MgEDTA, $NH_4H_2PO_4$, urea
15-15-30	3.0	8.8	3.3	6.6	24.8	-	-	-	125	A	40	KNO_3, $NH_4H_2PO_4$, NH_4NO_3, urea
15-30-15	5.9	4.4	4.7	13.1	12.4	-	-	-	167	A	340	KNO_3, KH_2PO_4, $NH_4H_2PO_4$, NH_4NO_3, urea
20-2-20	8.0	12.0	-	0.9	16.5	-	0.1	-	125	A	254	KNO_3, MgEDTA, $NH_4H_2PO_4$, NH_4NO_3
20-5-30	1.0	8.8	10.2	2.2	24.8	-	-	-	200	A	60	KNO_3, $NH_4H_2PO_4$, urea
20-10-20	8.0	12.0	-	4.4	16.5	-	0.1	-	143	A	202	KNO_3, MgEDTA, $NH_4H_2PO_4$, NH_4NO_3,
20-20-20	3.9	5.9	10.3	8.7	16.5	-	-	-	200	A	253	KNO_3, $NH_4H_2PO_4$, Urea
21-7-7	13.8	2.1	5.1	3.1	5.1	-	-	-	125	A	775	KNO_3, $NH_4H_2PO_4$, $(NH4)_2SO_4$, urea
24-8-16	4.5	4.8	14.7	3.5	11.6	-	0.1	-	250	A	427	KNO_3, MgEDTA, $NH_4H_2PO_4$, Urea
28-14-14	2.8	4.1	21.2	6.1	10.2	-	-	-	333	A	450	KNO_3, $NH_4H_2PO_4$, Urea

[z] N-P_2O_5-K_2O formula.

[y] Units for EC slope are $mg{\cdot}L^{-1}$ N per 1 $dS{\cdot}m^{-1}$.

[x] The potential reaction of the water-soluble fertilizer. The type of reaction is either acidic (A) or basic (B) and the strength of the reaction is given in kg of acidity or basicity per 1000 kg of fertilizer.

Table 12. Total nutrient concentration supplied by Plantex water-soluble fertilizers at an N concentration of 200 $mg{\cdot}L^{-1}$.

	NH_4-N	NO_3-N	Urea-N	P	K	Ca	Mg	S	Na	Cl	Fe	Mn	Cu	Zn	B	Mo
Formula[z]								($mg{\cdot}L^{-1}$)								
10-52-10	156	18	26	545	165	-	-	-	-	-	2.0	1.0	1.0	1.0	0.4	0.01
14-0-14	16	184	-	-	145	84	41	-	-	-	1.4	0.7	0.7	0.7	0.3	0.21
15-15-18	40	111	49	87	198	-	2	-	-	-	1.3	0.7	0.7	0.7	0.3	0.20
15-15-30	39	117	43	87	330	-	-	-	-	-	1.3	0.7	0.7	0.7	0.3	0.01
15-30-15	79	59	63	175	165	-	-	-	-	-	1.3	0.7	0.7	0.7	0.3	0.01
20-2-20	80	120	-	9	165	-	1	-	-	-	1.0	0.5	0.5	0.5	0.2	0.15
20-5-30	10	88	102	22	248	-	-	-	-	-	1.0	0.5	0.5	0.5	0.2	0.01
20-10-20	80	120	-	44	165	-	1	-	-	-	1.0	0.5	0.5	0.5	0.2	0.15
20-20-20	39	59	103	87	165	-	-	-	-	-	1.0	0.5	0.5	0.5	0.2	0.01
21-7-7	131	20	49	29	48	-	-	-	-	-	1.0	0.5	0.5	0.5	0.2	0.01
24-8-16	38	40	123	29	97	-	1	-	-	-	0.8	0.4	0.4	0.4	0.2	0.00
28-14-14	20	29	151	44	73	-	-	-	-	-	0.7	0.4	0.4	0.4	0.1	0.00

[z] N-P_2O_5-K_2O formula.

Micronutrient concentrations < 0.005 indicate that the nutrients are present in the water-soluble fertilizer but their calculated concentration is below 0.05 $mg{\cdot}L^{-1}$.

Micronutrients supplied by Fe, FeEDTA; Mn, MnEDTA; Cu, CuEDTA; Zn, ZnEDTA; B, H_3BO_3; Mo, Na_2MoO_4.

Technigro water-soluble fertilizer (Sun Gro Horticulture, Belleville, Wash.).

Table 13. Macronutrient information from Technigro water-soluble fertilizers.

	Elemental Analysis (%)								EC	Reaction[x]		
Formula[z]	NH_4-N	NO_3-N	Urea	P	K	Ca	Mg	S	Slope[y]	Type	Strength	Macronutrient salts
15-0-15	1.3	13.8	-	-	12.4	9.5	1.0	-	135	B	209	$Ca(NO_3)_2$, KNO_3, $Mg(NO_3)_2$, NH_4NO_3
16-17-17	7.1	8.9	-	7.4	14.0	-	0.9	1.3	135	A	220	KNO_3, $MgSO_4$, $NH_4H_2PO_4$, NH_4NO_3
17-5-24	5.3	11.7	-	2.2	19.8	-	2.0	2.6	132	A	63	KNO_3, $MgSO_4$, $NH_4H_2PO_4$, NH_4NO_3
20-9-20	8.5	11.6	-	3.9	16.5	-	-	1.4	147	A	255	KNO_3, $NH_4H_2PO_4$, NH_4NO_3, $(NH4)_2SO_4$
20-18-18	4.8	5.5	9.7	7.9	14.9	-	-	1.4	208	A	355	KNO_3, $NH_4H_2PO_4$, $(NH4)_2SO_4$, urea
20-18-20	1.2	6.1	9.4	7.9	16.5	-	-	1.0	208	A	305	KNO_3, $NH_4H_2PO_4$, $(NH4)_2SO_4$, urea
21-0-20	-	10.9	10.1	-	16.5	6	-	-	200	A	8	$Ca(NO_3)_2$, KNO_3, urea
24-7-15	6.8	10.0	7.2	3.1	12.4	-	1.0	1.3	217	A	306	KNO_3, $MgSO_4$, $NH_4H_2PO_4$, NH_4NO_3, urea

[z] $N-P_2O_5-K_2O$ formula.

[y] Units for EC slope are $mg \cdot L^{-1}$ N per 1 $dS \cdot m^{-1}$.

[x] The potential reaction of the water-soluble fertilizer. The type of reaction is either acidic (A) or basic (B) and the strength of the reaction is given in kg of acidity or basicity per 1000 kg of fertilizer.

Table 14. Total nutrient concentration supplied by Technigro water-soluble fertilizers at an N concentration of 200 $mg \cdot L^{-1}$.

	NH_4-N	NO_3-N	Urea-N	P	K	Ca	Mg	S	Na	Cl	Fe	Mn	Cu	Zn	B	Mo
Formula[z]								($mg \cdot L^{-1}$)								
15-0-15	17	183	-	-	165	126	13	-	-	-	1.0	0.5	0.2	0.3	0.2	0.16
16-17-17	89	111	-	93	176	-	11	16	-	-	1.0	0.5	0.2	0.3	0.2	0.15
17-5-24	62	138	-	26	233	-	24	31	-	-	1.0	1.0	0.2	0.7	0.1	1.00
20-9-20	85	116	-	39	165	-	-	14	-	-	1.0	0.5	0.2	0.3	0.2	0.15
20-18-18	48	55	97	79	149	-	-	14	-	-	1.0	0.5	0.2	0.3	0.2	0.15
20-18-20	14	73	113	94	198	-	-	12	-	-	0.6	0.4	0.1	0.1	0.1	0.02
21-0-20	-	104	96	-	157	57	-	-	-	-	1.0	0.5	0.2	0.3	0.2	0.15
24-7-15	56	83	60	25	103	-	8	11	-	-	1.0	0.5	0.2	0.3	0.0	0.15

[z] $N-P_2O_5-K_2O$ formula.

Micronutrient concentrations < 0.05 indicate that the nutrients are present in the water-soluble fertilizer but their calculated concentration is below 0.05 $mg \cdot L^{-1}$.

Macronutrients supplied by Fe, FeDTPA; Mn, MnEDTA; Cu, CuEDTA; Zn, ZnEDTA; B, H_3BO_3; Mo, Na_2MoO_4.