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

William R. Argo¹ and John A. Biernbaum²

Department of Horticulture, Michigan State University, East Lansing, MI 48824-1325

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Abstract. Hybrid impatiens (*Impatiens Wallerana* Hook. F.) were planted in a peat-based medium containing two dolomitic liming materials (1.8 kg $\text{Ca}(\text{OH})_2 \cdot \text{Mg}(\text{OH})_2/\text{m}^3$ or 8.4 kg $\text{CaCO}_3 \cdot \text{MgCO}_3/\text{m}^3$) and subirrigated for 17 weeks using four irrigation-water sources (IWSs) with varied bicarbonate alkalinity, Ca^{2+} , Mg^{2+} , and SO_4 -S content and three water-soluble fertilizers (WSFs) that contained (in mg) 200N–20P–200K/liter but a variable $\text{NH}_4^+:\text{NO}_3^-$ 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 8 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 most 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 8, 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, 1996; 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, 1996; 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, 1996; 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, 1996). 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 United States, titratable alkalinity ranged from 2 to 575 mg CaCO_3 /liter (average 147 mg·liter⁻¹); electrical conductivity (EC), from 0 to 6.5 dS·m⁻¹ (average 0.5 dS·m⁻¹); Ca^{2+} , from 0 to 440 mg·liter⁻¹ (average 60 mg·liter⁻¹); Mg^{2+} , from 0 to 300 mg/liter (average 20 mg·liter⁻¹); and Na^+ , from 0 to 1150 mg·liter⁻¹ (average 35 mg·liter⁻¹), 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⁻¹) 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 suffi-

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¹Graduate research assistant.

²Associate professor.

cient acid to reduce the alkalinity to 100 to 120 mg CaCO₃/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 NO₃⁻-N causes the medium pH to increase because of OH⁻ or HCO₃⁻ secretion associated with balancing ion uptake. In comparison, fertilization with NH₄⁺-N causes the medium pH to decrease because of H⁺ secretion during root uptake and nitrification of the NH₄⁺-N to the NO₃⁻-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 WSFs contain a high percentage of NH₄⁺-N and PO₄-P but little Mg²⁺ and no Ca²⁺ [examples: Peter's 21-7-7 Acid Special, 100% NH₄⁺-N, 0.05% Mg²⁺, 0% Ca²⁺; Peter's 20-20-20 General Purpose, 72% NH₄⁺-N, 0.05% Mg²⁺, 0% Ca²⁺; Peter's 20-10-20 Peatlite Special, 40% NH₄⁺-N, 0.05% Mg²⁺, 0% Ca²⁺ (Peter's Fertilizer; Scotts, Marysville, Ohio). Because of the high NH₄⁺-N content, the reaction produced by these WSFs 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 NH₄⁺-N and PO₄-P but high in Ca²⁺ and NO₃⁻-N (examples: Peter's 19-0-16 Western Greenhouse Formula, 24% NH₄⁺-N, 6.5% Ca²⁺, 15 kg acidity/1000 kg; Excel 15-5-15, 28% NH₄⁺-N, 12% Ca²⁺, 68 kg basicity/1000 kg; Peter's 15-0-15 Dark Weather Special, 13% NH₄⁺-N, 14% Ca²⁺, 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 IWSs, and three types of WSFs combined in a 2 × 4 × 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 variance (ANOVA) procedures (SAS Institute, Cary, N.C.) as a 2 × 4 × 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 Ca²⁺, Mg²⁺, and SO₄-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 Ca²⁺ and Mg²⁺ 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 SO₄-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

$$X_{\text{intersection}} = (I_2 - I_1)/(S_1 - S_2) \quad [1]$$

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

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

where the X value is either SO₄-S concentration in mg·liter⁻¹ or root medium pH, Y is tissue S or P in percent of total dry mass, X_{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 S₁, I₁, S₂, and I₂, based on either the applied SO₄-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 (no. 325) screen was incorporated at 1.5 kg·m⁻³. At this incorporation rate, the hydrated lime added 0.5 kg Ca²⁺, 0.3 kg Mg²⁺, and the equivalent of 2.6 kg CaCO₃/m³ to the root medium. A superfine dolomitic carbonate lime (99.5% CaCO₃·MgCO₃, National Lime and Stone) 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 Ca²⁺, 1.1 kg Mg²⁺, and the equivalent of 9.1 kg CaCO₃/m³ 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(NO₃)₂, KNO₃, triple superphosphate (0N-19.8P-0K), and gypsum; 0.3 kg MgSO₄; 0.07 kg fritted trace elements (FTE 555, Scotts, Marysville, Ohio); and 0.2 liters of a wetting agent (Aquagro 2000 L, Aquatrols, Pennsauken, N.J.) per m³ 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⁻¹, and 220 NO₃⁻-N, 14 NH₄⁺-N, 40 PO₄-P, 200 K⁺, 250 Ca²⁺, 185 Mg²⁺, and 110 SO₄-S (mg·liter⁻¹); while the carbonate lime treatments had a pH of 5.5, an EC of 2.6 dS·m⁻¹, and 220 NO₃⁻-N, 13 NH₄⁺-N, 53 PO₄-P, 215 K⁺, 230 Ca²⁺, 160 Mg²⁺, and 95 SO₄-S (mg·liter⁻¹), based on the saturated-medium extract (SME) method (Warncke and Krauskopf, 1983).

IWS. The four IWSs varied in EC, Ca²⁺, Mg²⁺, Na⁺, SO₄-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⁻¹; 105 Ca²⁺, 35 Mg²⁺, 12 Na⁺, 23 SO₄-S (mg·liter⁻¹); and a titratable alkalinity to pH 4.5 (Chau, 1984) of 320 mg CaCO₃/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⁻¹; 20 Ca²⁺, 7 Mg²⁺, 23 Na⁺, 1 SO₄-S (mg·liter⁻¹); and a titratable alkalinity to pH 4.5 of <20 mg CaCO₃/liter. The third type of water (acidified water) was produced by adding H₂SO₄ (93%) to the well water and had a pH of 5.8, an EC of 0.7

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 4-week period.

dS·m⁻¹; concentrations of Ca²⁺, Mg²⁺, and Na⁺ similar to that of the well water; 91 mg SO₄-S/m³; and a titratable alkalinity to pH 4.5 of 120 mg CaCO₃/liter. The fourth 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⁻¹; 56 Ca²⁺, 12 Mg²⁺, 21 Na⁺, and 9 SO₄-S (mg·liter⁻¹); and a titratable alkalinity to pH 4.5 of 130 mg CaCO₃/liter.

WSF. Fertilizer concentrations were maintained at (in mg) 150N–15P–150K/liter for the first 2 weeks and increased to 200N–20P–200K/liter for the remainder of the experiment. The three WSFs varied in NH₄⁺-N, Ca²⁺, Mg²⁺, and SO₄-S concentrations. At

200 mg N/liter, WSF 1 contained 50% NH₄⁺-N with 0 Ca²⁺, 0 Mg²⁺, and 42 SO₄-S (mg·liter⁻¹); WSF 2 contained 25% NH₄⁺-N with 50 Ca²⁺, 25 Mg²⁺, and 35 SO₄-S (mg·liter⁻¹); and WSF 3 contained 3% NH₄⁺-N with 100 Ca²⁺, 50 Mg²⁺, and 3 SO₄-S (mg·liter⁻¹). Micro-nutrients (Fe, Mn, Zn, Cu, B, and Mo) were added to all WSF treatments with a commercially available chelated material [Compound 111 (1.50Fe–0.12Mn–0.08Zn–0.11Cu–0.23B–0.11 Mo), Scotts] at a constant 50 mg·liter⁻¹.

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 Univ., East Lansing, in two well-ventilated glass greenhouse sections with constant air circulation and cement floors. One hybrid impatiens plug ('Super Elfin Violet') from a size 512 plug tray was planted into a 9-cm-tall × 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 twelve 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

Table 1. Cumulative water, Ca²⁺, Mg²⁺, and SO₄-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 Ca²⁺, 0.3 g Mg²⁺, and 0.1 g SO₄-S per pot with the hydrated lime treatments and 1.5 g Ca²⁺, 0.8 g Mg²⁺, and 0.1 g SO₄-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.

IWS	WSF	Hydrated lime				Carbonate lime			
		Applied water (liters)	Ca ²⁺ (g/pot)	Mg ²⁺ (g/pot)	SO ₄ -S (g/pot)	Applied water (liters)	Ca ²⁺ (g/pot)	Mg ²⁺ (g/pot)	SO ₄ -S (g/pot)
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 ²	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

²RO = reverse osmosis.

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 25°C. 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 Univ. 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 4, 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 4 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, Ga.).

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, 1996; 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 4-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 4-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 4-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

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 between weeks 1 and 17. Filled symbols are hydrated lime treatments and hollow symbols are carbonate lime treatments with acidic water-soluble fertilizer (WSF) (● and ○), neutral WSF (■ and □), and basic WSF (▼ and ▽). The dotted lines (...) represent the recommended optimal ranges 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.

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), PO₄-P, Ca²⁺, Mg²⁺, and SO₄-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
<i>pH</i>											
Lime (L)	1	14.7	NS	0.4	NS	162.0	*	972.6	*	32.5	NS
MSEa	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 × 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 × WSF	2	0.1	NS	1.0	NS	6.3	***	3.7	*	9.1	***
IWS × WSF	6	1.4	NS	2.1	NS	4.5	**	4.4	***	11.6	***
L × IWS × WSF	6	2.1	NS	0.2	NS	0.9	NS	0.9	NS	3.1	**
MSEb	70	0.0003		0.0003		0.0004		0.0009		0.0005	
<i>EC</i>											
Lime (L)	1	15.2	NS	0.2	NS	1.6	NS	2.1	NS	9.4	NS
MSEa	1	0.0001		0.0018		0.0027		0.0074		0.0009	
IWS	3	24.2	***	16.4	***	35.9	***	28.1	***	21.6	***
L × 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 × WSF	2	0.7	NS	0.4	NS	1.4	NS	3.0	NS	11.6	***
IWS × WSF	6	2.5	*	2.0	NS	1.7	NS	0.3	NS	2.9	*
L × IWS × WSF	6	0.9	NS	1.8	NS	2.1	NS	0.7	NS	1.8	NS
MSEb	70	0.0011		0.0014		0.0010		0.0018		0.0019	
<i>P</i>											
Lime (L)	1	1633.6	*	97.9	NS	30.6	NS	0.4	NS	0.0	NS
MSEa	1	0.0004		0.0018		0.0008		0.0188		0.0258	
IWS	3	48.1	***	27.2	***	94.8	***	118.7	***	25.2	***
L × 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 × WSF	2	4.5	**	0.0	NS	0.7	NS	1.5	NS	0.5	NS
IWS × WSF	6	8.9	***	9.6	***	33.1	***	56.4	***	12.6	***
L × IWS × WSF	6	1.0	NS	0.6	NS	1.2	NS	1.3	NS	0.2	NS
MSEb	70	0.0013		0.0041		0.0036		0.0042		0.0138	
<i>Ca</i>											
Lime (L)	1	34.6	NS	0.6	NS	1.7	NS	3.4	NS	958.6	*
MSEa	1	0.003		0.0027		0.0022		0.0048		0.0001	
IWS	3	5.2	**	21.9	***	88.1	***	56.9	***	66.7	***
L × 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 × WSF	2	2.2	NS	0.0	NS	2.2	NS	3.5	NS	16.8	***
IWS × WSF	6	0.5	NS	2.7	**	3.9	**	2.0	NS	3.7	**
L × IWS × WSF	6	0.4	NS	2.2	NS	3.1	*	0.3	NS	2.2	NS
MSEb	70	0.0138		0.0071		0.0041		0.0081		0.0052	
<i>Mg</i>											
Lime (L)	1	18.6	NS	1.0	NS	13.4	NS	2362.0	*	12.1	NS
MSEa	1	0.0006		0.0100		0.0037		0.0004		0.0030	
IWS	3	11.7	***	18.5	***	38.1	***	114.2	***	10.9	***
L × 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 × WSF	2	0.4	NS	3.8	NS	0.5	NS	21.8	***	6.4	**
IWS × WSF	6	1.5	NS	1.8	NS	2.8	NS	8.9	***	1.9	NS
L × IWS × WSF	6	1.1	NS	6.1	**	4.2	*	2.9	**	5.9	**
MSEb	70	0.0199		0.0172		0.0249		0.0151		0.0098	
<i>S</i>											
Lime (L)	1	8.2	NS	53.2	NS	0.4	NS	5.1	NS	0.0	NS
MSEa	1	0.0023		0.0001		0.0004		0.0023		0.0006	
IWS	3	133.7	***	404.6	***	366.3	***	177.8	***	332.7	***
L × 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 × WSF	2	3.2	*	0.9	NS	1.0	NS	0.6	NS	3.5	NS
IWS × WSF	6	5.1	***	21.1	***	27.0	***	9.8	***	40.0	***
L × IWS × WSF	6	0.5	NS	0.3	NS	1.2	NS	0.7	NS	2.0	*
MSEb	70	0.0054		0.0029		0.0043		0.0080		0.0040	

²Irrigation-water source.

³Water-soluble fertilizer.

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

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

the various treatments (Fig. 2, Table 2). Over the remaining 9 weeks of the experiment, root-zone pH was unaffected by lime type with Ca^{2+} concentrations in the nutrient solution

the experiment (Table 1). The volume of water applied to theimpatiens 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 WSFs were constant, the amount applied was similar and ranged from 1.5 to 1.8 g N, 0.15 to 0.20 g $\text{PO}_4\text{-P}$, and 1.5 to 1.8 g K^+ per pot (data not shown). In addition, 0.1 g N, 0.1 g $\text{PO}_4\text{-P}$, and 0.2 g K^+ per pot were incorporated initially with the PNC fertilizers. In comparison, the concentrations of Ca^{2+} , Mg^{2+} , and $\text{SO}_4\text{-S}$ in the nutrient solutions varied by a factor of about 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 $\text{SO}_4\text{-S}$ 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 $\text{SO}_4\text{-S}$ per pot, and the carbonate lime treatments received 1.5 g Ca^{2+} , 0.8 g Mg^{2+} , and 0.1 g $\text{SO}_4\text{-S}$ 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 about 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 4, 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 4. Assuming that similar equivalents of lime were required to obtain the same root-medium pH, about 6 kg of the carbonate lime/ m^3 of medium, or 4.5 g/pot, remained unreacted at the week 4 analysis.

After 8 weeks, the root-zone pH ranged from 4.5 to 8.5 within

>150 $\text{mg}\cdot\text{liter}^{-1}$ 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 $\text{mg}\cdot\text{liter}^{-1}$ 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 4, 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, IWSs 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 WSFs 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 $\text{NH}_4\text{-N}$ 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 $\text{dS}\cdot\text{m}^{-1}$) and week 1 (average EC = 0.9 $\text{dS}\cdot\text{m}^{-1}$) (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 $\text{dS}\cdot\text{m}^{-1}$) (data not shown). These data indicate that the initial nutrient concentration represents a highly soluble fraction and is not representative of the

Table 3. Parameters of nonlinear regression analysis from fitting Eqs. [1], [2], and [3] (see text) 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 date was 48 at week 4 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 4 data was not included because of nonsignificance.

Estimated parameters	Week 8	Week 12	Week 17	Units
Intercept (I_1)	1.31 ± 0.10^2	1.25 ± 0.11	1.21 ± 0.14	Dry mass (%)
Slope (S_1)	-0.08 ± 0.02	-0.06 ± 0.2	-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				
$X_{\text{intersection}}$	7.5	7.7	7.4	pH

²Ninety-five percent confidence intervals were calculated as the parameter standard error $\cdot t_{0.025,n}$ distribution.

Fig. 4. The effect of applied Ca^{2+} concentration on the tissue Ca ofimpatiens at 4, 8, 12, and 17 weeks after planting. Individual treatments are acidic water-soluble fertilizer (WSF) (● and ○), neutral WSF (■ and □), and basic WSF (▼ and ▽). The solid line (—) represents the predicted tissue Ca concentration based on linear regression analysis and the dotted line (....) represents the minimum recommended tissue Ca concentration. R^2 values were calculated as $1 - \text{SS}_{\text{residual}} / \text{SS}_{\text{corrected total}}$ and remaining statistical analyses of the individual parameters are presented in Table 4. Data are means of four samples at each date.

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 4 and 48 thereafter. Data are presented in Fig. 4.

	Week 4	Week 8	Week 12	Week 17	Units
<i>Hydrated lime</i>					
Intercept	$1.06 \pm 0.18^*$	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-liter ⁻¹
<i>Carbonate lime</i>					
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-liter ⁻¹

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

long-term nutrient buffering capacity of the root medium, conclusions similar to those of Argo and Biernbaum (1996) 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, 1995, 1996) or a water front moving into the root medium with each irrigation (Yelanich, 1995). After week 4, 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 $\text{dS}\cdot\text{m}^{-1}$ compared to 1 to 2.5 $\text{dS}\cdot\text{m}^{-1}$ 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 $\text{dS}\cdot\text{m}^{-1}$ with the different types of WSFs. The root-zone EC of the RO water treatments averaged 0.5 $\text{dS}\cdot\text{m}^{-1}$ lower than that of the acidified water treatments from week 8 until the end of the experiment. When comparing WSF across IWS, the basic fertilizer/acidified water treatment had a root-zone EC 1.3 $\text{dS}\cdot\text{m}^{-1}$ 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 $\text{PO}_4\text{-P}$ /liter resulted in water-soluble $\text{PO}_4\text{-P}$ medium concentrations ranging from 3 to 25 mg $\text{PO}_4\text{-P}$ /liter by the end of the experiment (Fig. 2). In general, the higher the root-medium pH, the lower the root-medium $\text{PO}_4\text{-P}$ /m³.

In mineral soils fertilized with P, calcium phosphates (dicalcium phosphate and dicalcium phosphate dihydrate) initially control $\text{PO}_4\text{-P}$ solubility at high pH (>7.0) and Al and Fe phosphates control $\text{PO}_4\text{-P}$ 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 $\text{PO}_4\text{-P}$ 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 $\text{PO}_4\text{-P}$ nutrition was 5.5 in media without soil, because above this pH, water-soluble $\text{PO}_4\text{-P}$ 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,

Fig. 5. The effect of applied Mg^{2+} concentration on the tissue Mg of impatiens at 4, 8, 12, and 17 weeks after planting. Individual treatments are acidic water-soluble fertilizer (WSF) (● and ○), neutral WSF (■ and □), and basic WSF (▼ and ▽). The solid line (—) represents the predicted tissue Mg concentration based on linear regression analysis and the dotted line (....) represents the minimum recommended tissue Mg concentration. R^2 values were calculated as $1 - SS_{\text{residual}} / SS_{\text{corrected total}}$, and remaining statistical analyses of the individual parameters are presented in Table 5. Data are means of four samples at each date.

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 24 at week 4 and 48 thereafter. Data are presented in Fig. 5.

	Week 4	Week 8	Week 12	Week 17	Units
<i>Hydrated lime</i>					
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 (%) / $mg \cdot liter^{-1}$
<i>Carbonate lime</i>					
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 (%) / $mg \cdot liter^{-1}$

^zNinety-five percent confidence intervals were calculated as the parameter standard error $\cdot t_{0.025, n}$ distribution.

even though the concentration of water-soluble $PO_4\text{-P}$ 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 $PO_4\text{-P}$ 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 $PO_4\text{-P}$ 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 $PO_4\text{-P}$ in the root medium decreased with increasing pH, the effect on tissue P was minimal until the form of the water-soluble $PO_4\text{-P}$ changed to a less-available form.

Calcium. After week 1, 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 $mg \cdot Ca^{2+} / liter$) 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 4-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 18 to 210 $mg \cdot Ca^{2+} / liter$ 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 8 (0.2% increase in tissue Ca per 40 $mg \cdot liter^{-1}$ increase in applied Ca^{2+} concentration,

Fig. 6. The effect of applied $\text{SO}_4\text{-S}$ concentration on the tissue S ofimpatiens at 4, 8, 12, and 17 weeks after planting. Filled symbols are hydrated lime treatments and hollow symbols are carbonate lime treatments with acidic water-soluble fertilizer (WSF) (● and ○), neutral WSF (■ and □), and basic WSF (▼ and ▽). The solid line (—) represents the predicted tissue S concentration based on Eq. [1] and the dotted line (....) represents the minimum recommended tissue S concentration. R^2 values were calculated as $1 - \text{SS}_{\text{residual}} / \text{SS}_{\text{corrected total}}$, and remaining statistical analyses of the individual parameters are presented in Table 6. Data are means of four samples at each date.

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 $>180 \text{ mg Ca}^{2+}/\text{liter}$ 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 ($70 \text{ mg Ca}^{2+}/\text{liter}$) than the acidic WSF ($18 \text{ mg Ca}^{2+}/\text{liter}$). 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 addi-

tional buffering capacity of the residual carbonate lime.

Magnesium. As with Ca^{2+} , root-medium Mg^{2+} concentrations increased from week 1 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 ($15 \text{ mg Mg}^{2+}/\text{liter}$), 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 $80 \text{ mg Mg}^{2+}/\text{liter}$ 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 8, 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^{-1} increase in applied Mg^{2+} concentration). From Eq. [1], similar tissue Mg concentrations were obtained, independent of the lime type, with the addition of $>60 \text{ mg Mg}^{2+}/\text{liter}$ 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. IWS and WSF were the main factors affecting root-medium $\text{SO}_4\text{-S}$ concentrations (Fig. 2, Table 2). In general, the higher the concentration in the applied nutrient solution, the higher the concentration of $\text{SO}_4\text{-S}$ in the root medium at the end of the experiment. When low concentrations of $\text{SO}_4\text{-S}$ were applied (RO water/basic fertilizer), low concentrations were measured in the

Table 6. Parameters of nonlinear regression analysis from fitting Eqs. [1], [2], and [3] (see text) to percent S in tissue, based on the concentration of $\text{SO}_4\text{-S}$ in the nutrient solution at 4, 8, 12, and 17 weeks after planting. The number of observations per sampling date was 48 at week 4 and 96 thereafter. Data from the lime treatments were used in the same analysis and are presented in Fig. 6.

Estimated parameters	Week 4	Week 8	Week 12	Week 17	Units
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-liter^{-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-liter^{-1}
Calculated parameters					
$X_{\text{intersection}}$	41	32	32	38	mg-liter^{-1}

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

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 $\text{SO}_4\text{-S}$ concentration (3 mg $\text{SO}_4\text{-S}$ /liter), root-zone $\text{SO}_4\text{-S}$ concentrations were maintained at 15 mg $\text{SO}_4\text{-S}$ /liter and may represent the base buffering capacity of the root medium, residual gypsum, or movement of $\text{SO}_4\text{-S}$ 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 $\text{SO}_4\text{-S}$ 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⁻¹ increase in the applied $\text{SO}_4\text{-S}$ concentration. Below this minimum critical concentration, tissue S decreased at 0.2% to 0.5% of dry mass per 30 mg·liter⁻¹ decrease in the applied $\text{SO}_4\text{-S}$ 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 4 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 (1996) 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 $\text{SO}_4\text{-S}$ (Peter's Fertilizers, 1981), additional $\text{SO}_4\text{-S}$ may need to be added as a water-soluble source, as suggested by Reddy and Madore (1995).

Root-medium $\text{SO}_4\text{-S}$ 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 $\text{SO}_4\text{-S}$ 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 WSFs. Nitrogen and K can be managed based on the EC of the nutrient solution. If $\text{PO}_4\text{-P}$ 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 $\text{SO}_4\text{-S}$ 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 $\text{SO}_4\text{-S}$ 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 $\text{SO}_4\text{-S}$ /liter.

There are two main sources of Mg^{2+} for WSFs, MgSO_4 and $\text{Mg}(\text{NO}_3)_2$. If MgSO_4 is used for the Mg^{2+} source, adequate concentrations of $\text{SO}_4\text{-S}$ also will be applied. However, there is only one source of highly soluble Ca^{2+} typically used in WSF, $\text{Ca}(\text{NO}_3)_2$. Therefore, the recommendations for Ca^{2+} supplied by the nutrient solution also will have a direct effect on $\text{NH}_4^+\text{-N}$ 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 $\text{PO}_4\text{-P}$ can be mixed together in high concentrations, such as in a fertilizer stock tank, only if the pH <2.0 (R. Vetanovetz, Scotts, personal communication), while Ca^{2+} and $\text{SO}_4\text{-S}$ 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+} include investigating the use of CaCl_2 or chelated Ca if a high percentage of $\text{NH}_4^+\text{-N}$ 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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