

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

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ABSTRACT. Hybrid impatiens (*Impatiens Wallerana* Hook. F.) were planted in six root media containing either 70% (by volume) rockwool, coir, or four 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 (CaCO₃ and MgCO₃) 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 at 200N-20P-200K mg·L⁻¹ but had a variable NH₄⁺:NO₃⁻ ratio and Ca²⁺ and Mg²⁺ 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 Ca²⁺ increased from 18 to 156 mg·L⁻¹ and that of Mg²⁺ increased 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 mass 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, 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 concentration 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 Ca²⁺ and Mg²⁺ 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 Ca²⁺ and Mg²⁺ nutrition also must include pH management because of the direct or indirect effects the Ca²⁺ and Mg²⁺ 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.

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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 peat particles. For example, Helling et al. (1964) found that the CEC of a sphagnum peat increased by 140 meq·L⁻¹ as the pH increased from 3.5 to 8.0. The ratio 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 (Ca²⁺ and Mg²⁺), with most monovalent cations (NH₄⁺-N, K⁺, Na⁺) remaining water soluble.

The CEC of peat on a mass basis is much higher than that of mineral soils. For example, Lucas (1982) reported that the CEC of a sphagnum peat was 1000 meq·kg⁻¹, while that of a loam mineral soil was 120 meq·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·L⁻¹ for the peat vs. 140 meq·L⁻¹ for the mineral soil). Puustjarvi (1982) reported a linear increase in the CEC of sphagnum peat from 45 to 130 meq·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 a higher CEC of the more degraded peat itself (H1 peat was 1000 meq·kg⁻¹, H5 peat was 1240 meq·kg⁻¹) as well as an increase in the bulk density with greater decomposition (H1 peat was 45 kg·m⁻³, H5 peat was 105 kg·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

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.

Root media	AS (%)	CC (%)	BD (kg·m ⁻³)	CEC ²	
				meq·kg ⁻¹	meq·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

²One-half molar BaOAc was used to determine the CEC of acid-washed root media.

^yMean separation by Duncan's multiple range test at $P \leq 0.05$.

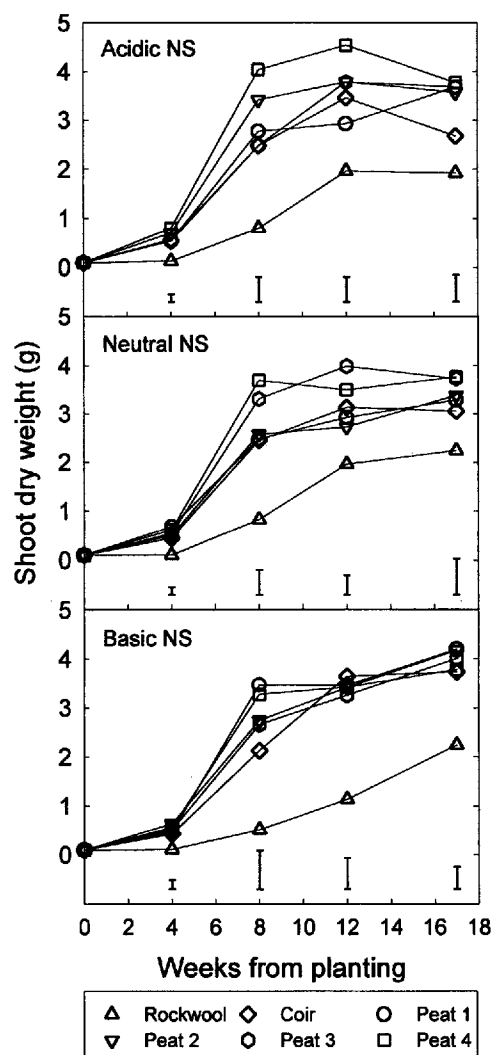


Fig. 1. New shoot dry mass of impatiens grown in six root media containing various rates of hydrated dolomitic lime [$\text{Ca}(\text{OH})_2$ and $\text{Mg}(\text{OH})_2$] with three nutrient solution treatments at 4, 8, 12, and 17 weeks after planting in Expt. 1. After each harvest, remaining plants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

(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 (Birnbaum, 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 , $\text{Ca}(\text{OH})_2$, and $\text{Ca}(\text{OH})_2$ and $\text{Mg}(\text{OH})_2$] 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 Birnbaum, 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 Birnbaum (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 Birnbaum, 1996a).

The NS, composed of an IWS and WSF and applied to a root medium, interacts to affect the pH and nutrient concentrations in 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 Birnbaum (1996b) found that the degree of change caused by a NS depended not only on the $\text{NH}_4^+ : \text{NO}_3^-$ 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 (Birnbaum, 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. Our objectives 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

Experiment 1 included 18 treatments composed of six types of media and three types of NS combined in a 6×3 factorial arrangement. Experiment 2 included 12 treatments composed of two types of media, two types of lime, and three types of NS combined in a 2

$\times 2 \times 3$ 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 analysis of variance (ANOVA) procedures (SAS Inst., Cary, N.C.) in Expt. 1 as a 6×3 factorial and in Expt. 2 as a $2 \times 2 \times 6$ 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 $\log(\text{observed} + 1)$ 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. Significant differences in the slope and intercept between sample weeks was tested using a multiple regression model in SAS's general linear model procedure.

EXPERIMENT 1. The six root media were composed of 30% perlite (by volume) blended with one of the following: medium grind RW (Partek North American, Brunswick, Ohio); coconut coir pith (coir) (Scotts, Marysville, Ohio); Fisons, black bale, professional-grower grade Canadian sphagnum moss (peat 1) (Sun Gro Horticulture, Bellevue, Wash.); Fafard Trump Ace professional-grower grade Canadian sphagnum moss (peat 2) (Fafard, Anderson, S.C.); Fafard Majestic, retail, fine Canadian sphagnum moss (peat 3); and Fafard Genuine, retail, extra-fine Canadian sphagnum moss (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 3 d before blending into media.

Sufficient amounts of a microfine dolomitic hydrated lime [$\text{Ca}(\text{OH})_2$ and $\text{Mg}(\text{OH})_2$ 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 (no. 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 cubed meter was (in kg) 0 RW, 0.5 coir, 1.5 peat 1, 1.6 peat 2, 2.3 peat 3, and 2.7 peat 4. These incorporation rates added to the six media, respectively, Ca^{2+} at 0, 0.2, 0.5, 0.5, 0.8, and 0.9 $\text{kg}\cdot\text{m}^{-3}$; Mg^{2+} at 0, 0.1, 0.3, 0.3, 0.5, and 0.6 $\text{kg}\cdot\text{m}^{-3}$; and a CaCO_3 equivalent of 0, 0.9, 2.6, 2.7, 3.9, and 4.6 $\text{kg}\cdot\text{m}^{-3}$.

In addition to the lime, a preplant nutrient charge (PNC) consisting of $\text{Ca}(\text{NO}_3)_2$, KNO_3 , triple superphosphate (0N–19.8P–0K), and gypsum at 0.6 $\text{kg}\cdot\text{m}^{-3}$ each; MgSO_4 at 0.3 $\text{kg}\cdot\text{m}^{-3}$; fritted trace elements (FTE 555, Scotts, Marysville, Ohio) at 0.07 $\text{kg}\cdot\text{m}^{-3}$; and a wetting agent (Aquagro 2000 L, Aquatrols,

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.

Root media	Acidic NS			Neutral NS			Basic NS		
	Applied water (L)	Ca (g/pot)	Mg (g/pot)	Applied water (L)	Ca (g/pot)	Mg (g/pot)	Applied water (L)	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

Pennsauken, N.J.) at 0.2 $\text{L}\cdot\text{m}^{-3}$ 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 3 d before planting. At planting, the six media had an average pH of 6.0, an EC of 2.4 $\text{dS}\cdot\text{m}^{-1}$, and (in $\text{mg}\cdot\text{L}^{-1}$) 160 NO_3^- -N, 45 PO_4 -P, 220 K^+ , 210 Ca^{2+} , 110 Mg^{2+} , and 145 SO_4 -S, as measured with the saturated media (SME) analysis with RO water as the extractant (Warncke, 1986).

NUTRIENT SOLUTION. The NS concentration of N–P–K was maintained at a constant 200N–20P–200K $\text{mg}\cdot\text{L}^{-1}$ for the duration of the experiment. The three NS varied in NH_4^+ -N, Ca^{2+} , Mg^{2+} , Na^+ and SO_4 -S concentrations. NS 1 was a WSF made from KNO_3 , K_2SO_4 , $\text{NH}_4\text{H}_2\text{PO}_4$, NH_4NO_3 , and urea that contained (in $\text{mg}\cdot\text{L}^{-1}$) 50% NH_4^+ -N with 0 Ca^{2+} , 0 Mg^{2+} , 0 Na^+ , and 42 SO_4 -S mixed with RO purified well water that had a pH of 5.5; an EC of 0.1 $\text{dS}\cdot\text{m}^{-1}$; (in $\text{mg}\cdot\text{L}^{-1}$) 15 Ca^{2+} , 5 Mg^{2+} , 27 Na^+ , 1 SO_4 -S; and a titratable alkalinity to pH 4.5 (Chau, 1984) of CaCO_3 at <20 $\text{mg}\cdot\text{L}^{-1}$. NS 2 was a WSF made from $\text{Ca}(\text{NO}_3)_2$, KH_2PO_4 , KNO_3 , $\text{Mg}(\text{NO}_3)_2$, and MgSO_4 that contained (in $\text{mg}\cdot\text{L}^{-1}$) 3% NH_4^+ -N with 100 Ca^{2+} , 50 Mg^{2+} , 0 Na^+ , and 3 SO_4 -S 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 $\text{dS}\cdot\text{m}^{-1}$; (in $\text{mg}\cdot\text{L}^{-1}$) 52 Ca^{2+} , 16 Mg^{2+} , 24 Na^+ , and 10 SO_4 -S; and a titratable alkalinity to pH 4.5 of CaCO_3 at 120 $\text{mg}\cdot\text{L}^{-1}$. NS 3 was a WSF made from KH_2PO_4 , KNO_3 , NaNO_3 , and NH_4NO_3 that contained (in $\text{mg}\cdot\text{L}^{-1}$) 25% NH_4^+ -N with 0 Ca^{2+} , 0 Mg^{2+} , 62 Na^+ , and 0 SO_4 -S 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 $\text{mg}\cdot\text{L}^{-1}$.

The WSF used to make NS 1–3 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 mass. The value obtained for each WSF was used as an estimate of the type (either acidic or basic) and strength (in kilograms per 1000 kg of fertilizer) of reaction produced. Based on these calculations, NS 1 (acidic NS) had an acidity of 199 $\text{kg}\cdot 1000\text{kg}^{-1}$, NS 2 (basic NS) had

a basicity of 175 kg·1000 kg⁻¹, and NS 3 (neutral NS) had a basicity of 2 kg·1000 kg⁻¹.

EXPERIMENT 2. A dolomitic carbonate lime (CaCO₃ and MgCO₃, with 22% Ca and 13% Mg, and a CaCO₃ equivalent of 108; National Lime and Stone, Findlay, Ohio) in which 60% of the material passed a 75- μ m (no. 200) screen was incorporated at 8.4 kg·m⁻³ into media containing peats 1 and 4. At this incorporation rate, the carbonate lime added Ca²⁺ at 1.8 kg·m⁻³, Mg²⁺ at 1.1 kg·m⁻³, and a CaCO₃ equivalent of 9.1 kg·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·m⁻¹, and (in mg·L⁻¹) 170 NO₃⁻-N, 60 PO₄⁻-P, 180 K⁺, 170 Ca²⁺, 140 Mg²⁺, and 160 SO₄⁻-S, 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 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 \times 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 mass based on a loss of 40% to 50% of the available water. The same three pots were checked daily for the target mass, 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 were 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 \times 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 mass.

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, NO₃⁻-N, NH₄⁺-N, PO₄⁻-P, K⁺, Ca²⁺, Mg²⁺, and SO₄⁻-S were measured in the root-zone

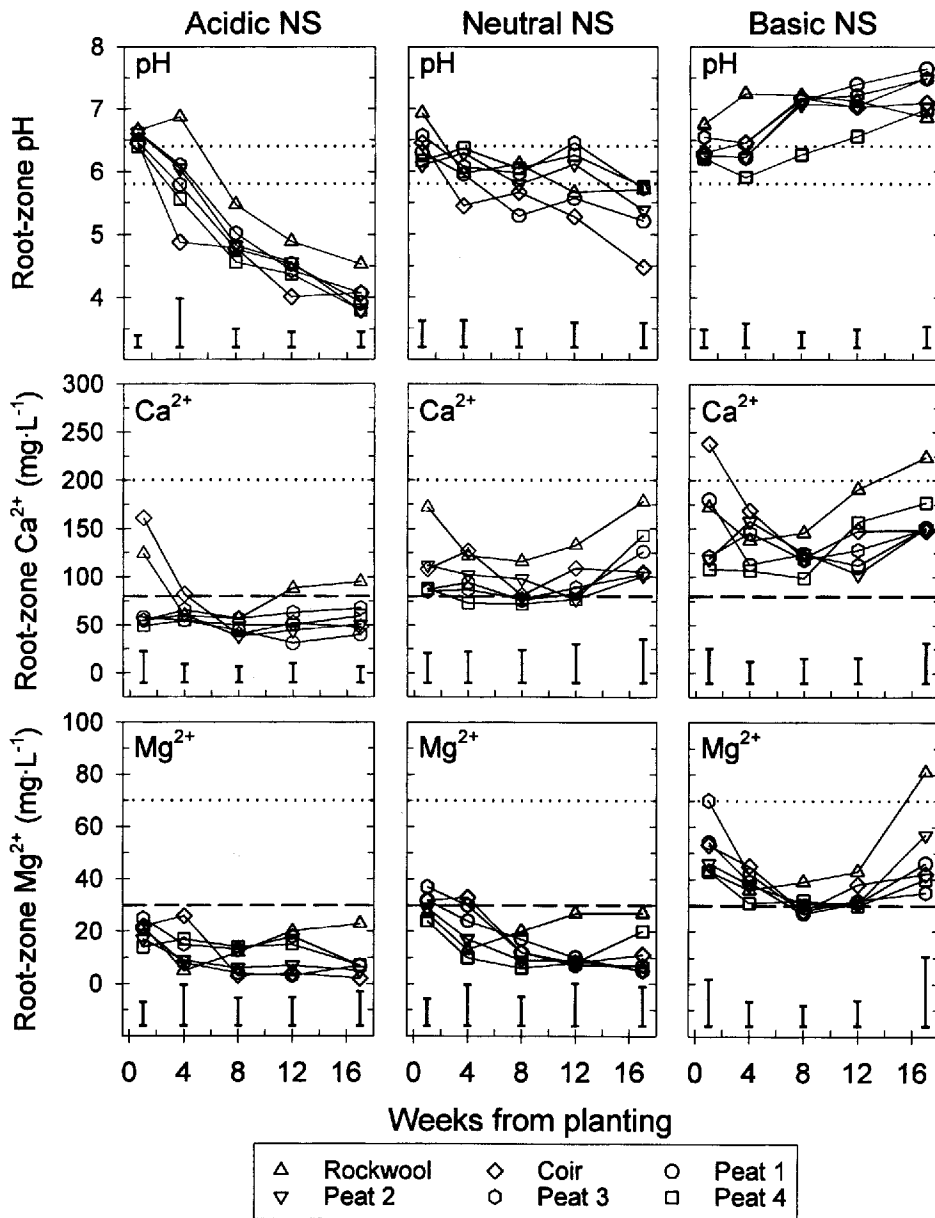


Fig. 2. Medium pH, Ca²⁺, and Mg²⁺ concentrations in the root zone of plants grown in six root media containing various rates of hydrated dolomitic lime [Ca(OH)₂ and Mg(OH)₂] with three nutrient solutions between weeks 1 and 17 in Expt. 1. The dotted lines (.....) represent the recommended optimal ranges 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.

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 Ca²⁺ was determined using emission spectroscopy by the Michigan State Univ. 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 previously outlined.

Shoot dry mass and shoot-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-tissue macronutrients and micronutrients (Fe, Mn, Cu, Zn, B, and Mo) were determined by plasma emission spectroscopy (Fafard Analytical Laboratory, Athens, Ga.).

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 based on volume 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 mass) 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 mass were not consistent across NS or between the sampling dates. There were less differences in the shoot dry mass 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

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, Ca²⁺, and Mg²⁺ concentrations at 1, 4, 8, 12, and 17 weeks after planting in Expt. 1.

	df	Week 1		Week 4		Week 8		Week 12		Week 17	
		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 ²	2	3.6	*	13.0	***	459.0	***	867.1	***	1092.1	***
M × 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 Ca²⁺											
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 × 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 Mg²⁺											
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 × 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	

²Nutrient solution.

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

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·m⁻¹) than in the other media (remaining media average of 2.3 dS·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 PO₄-P per pot, including the PNC fertilizers (data not shown). In comparison, the concentrations of Ca²⁺ and Mg²⁺ in the NS varied by a factor of almost 10, and the amount of Ca²⁺ and Mg²⁺ 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 Ca²⁺ and 0.14 to 0.87 g Mg²⁺ 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 Ca²⁺ and 0.9 to 1.2 g Mg²⁺ per pot and was similar for the peat 1 and 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 $\text{NH}_4^+\text{-N}$ 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 $8.4 \text{ kg}\cdot\text{m}^{-3}$ 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% $\text{NH}_4^+\text{-N}$, especially for long-term crops grown with an IWS containing an alkalinity with CaCO_3 at $<120 \text{ mg}\cdot\text{L}^{-1}$.

CALCIUM. In Expt. 1, initial root-medium Ca^{2+} concentrations ranged from $127 \text{ mg}\cdot\text{L}^{-1}$ in peat 1 media to $384 \text{ mg}\cdot\text{L}^{-1}$ in the coir media at planting (data not shown). However, by week 1,

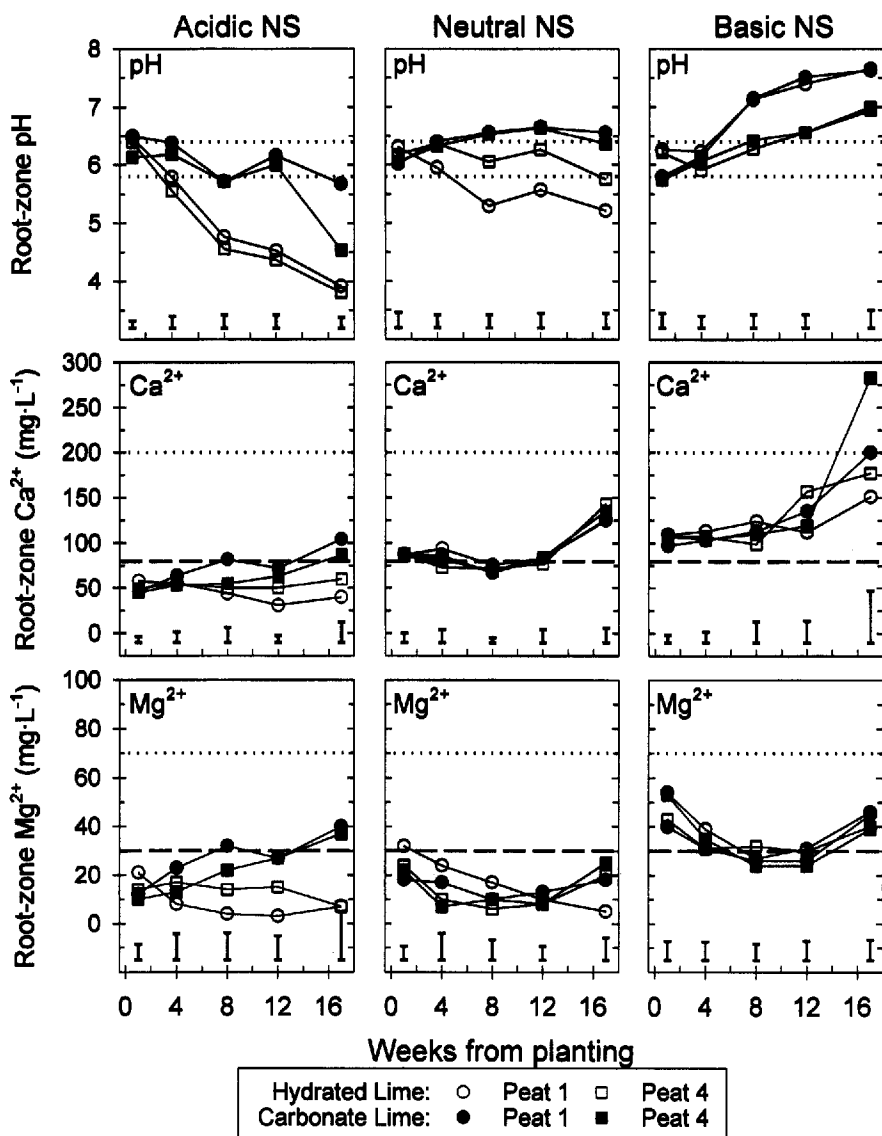


Fig. 3. Medium pH, Ca^{2+} , and Mg^{2+} concentrations in the root zone of plants grown in two media containing either hydrated dolomitic lime [$\text{Ca}(\text{OH})_2$ and $\text{Mg}(\text{OH})_2$] or carbonate dolomitic lime (CaCO_3 and MgCO_3) with three nutrient solutions between weeks 1 and 17 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.

root-medium Ca²⁺ concentrations had decreased to an average of 44% of the initial concentration (Fig. 2, Table 3). After the week 1 sampling date, the Ca²⁺ 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 Ca²⁺ 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 Ca²⁺ 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 Ca²⁺ 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 r² between the week-4 and -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 Ca²⁺ in the NS and shoot-tissue Ca was reported by Argo and Biernbaum (1996a) with impatiens grown with 12 NS. Our results add further support to the conclusion of Argo and Biernbaum (1996a) that 1) the main factor affecting the uptake of Ca into the plant is the concentration of Ca²⁺ in the NS, as affected by the WSF and IWS; and 2) other ions in the NS (NH₄⁺-N, K⁺, Mg²⁺, or SO₄⁻S) do 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 Ca²⁺ concentration (carbonate lime treatment Ca was 165 mg·L⁻¹; hydrated lime treatment average was 155 mg·L⁻¹) or affect Ca²⁺ concentrations

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, Ca²⁺, and Mg²⁺ concentrations at 1, 4, 8, 12, and 17 weeks after planting in Expt. 2.

	df	Week 1		Week 4		Week 8		Week 12		Week 17	
		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 ²	2	14.4	***	4.4	*	148.5	***	332.8	***	669.1	***
M × L	1	0.2	NS	0.2	NS	1.0	NS	5.8	*	22.4	***
NS × L	2	3.4	NS	4.7	*	16.2	***	67.3	***	38.2	***
M × NS	2	1.0	NS	2.3	NS	20.7	***	41.9	***	18.9	***
M × NS × 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 Ca²⁺											
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	
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 × L	1	2.1	NS	0.1	NS	0.7	NS	16.3	***	4.3	*
NS × L	2	2.1	NS	0.5	NS	7.9	**	18.4	***	14.7	***
M × NS	2	2.4	NS	0.6	NS	0.6	NS	2.3	NS	2.1	NS
M × NS × 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 Mg²⁺											
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	
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 × L	1	5.3	*	2.6	NS	1.3	NS	9.1	**	2.4	NS
NS × L	2	2.8	NS	1.2	NS	15.0	***	18.0	***	19.4	***
M × NS	2	2.9	NS	5.8	**	5.3	**	10.5	***	6.4	**
M × NS × 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	

²Nutrient solution.

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

through week 4 compared to the same media with hydrated lime (Fig. 3, Table 4). However, after week 8, Ca²⁺ 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 week-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% NH₄⁺-N WSF with RO water) with the lime. Decreasing the percentage of NH₄⁺-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. Niemiera and Wright (1986) found similar results when nitrification within the medium was inhibited. Thus, if a less acidic

WSF is used in conjunction with a low alkalinity (CaCO_3 at $<120 \text{ mg}\cdot\text{L}^{-1}$) and low Ca^{2+} IWS 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 $160 \text{ mg}\cdot\text{L}^{-1}$ 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 $64 \text{ mg}\cdot\text{L}^{-1}$ in the coir medium to $163 \text{ mg}\cdot\text{L}^{-1}$ 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 ($30 \text{ mg}\cdot\text{L}^{-1}$) 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 $72 \text{ mg}\cdot\text{L}^{-1}$ (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 week-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 is the concentration of Mg^{2+} in the NS, as affected by the WSF and IWS and 2) other ions in the NS ($\text{NH}_4^+\text{-N}$, K^+ , Ca^{2+} , or $\text{SO}_4\text{-S}$) 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 week-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 ($<120 \text{ mg}\cdot\text{L}^{-1}$) and low Mg^{2+} IWS 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 $50 \text{ mg}\cdot\text{L}^{-1}$ 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 sphag-

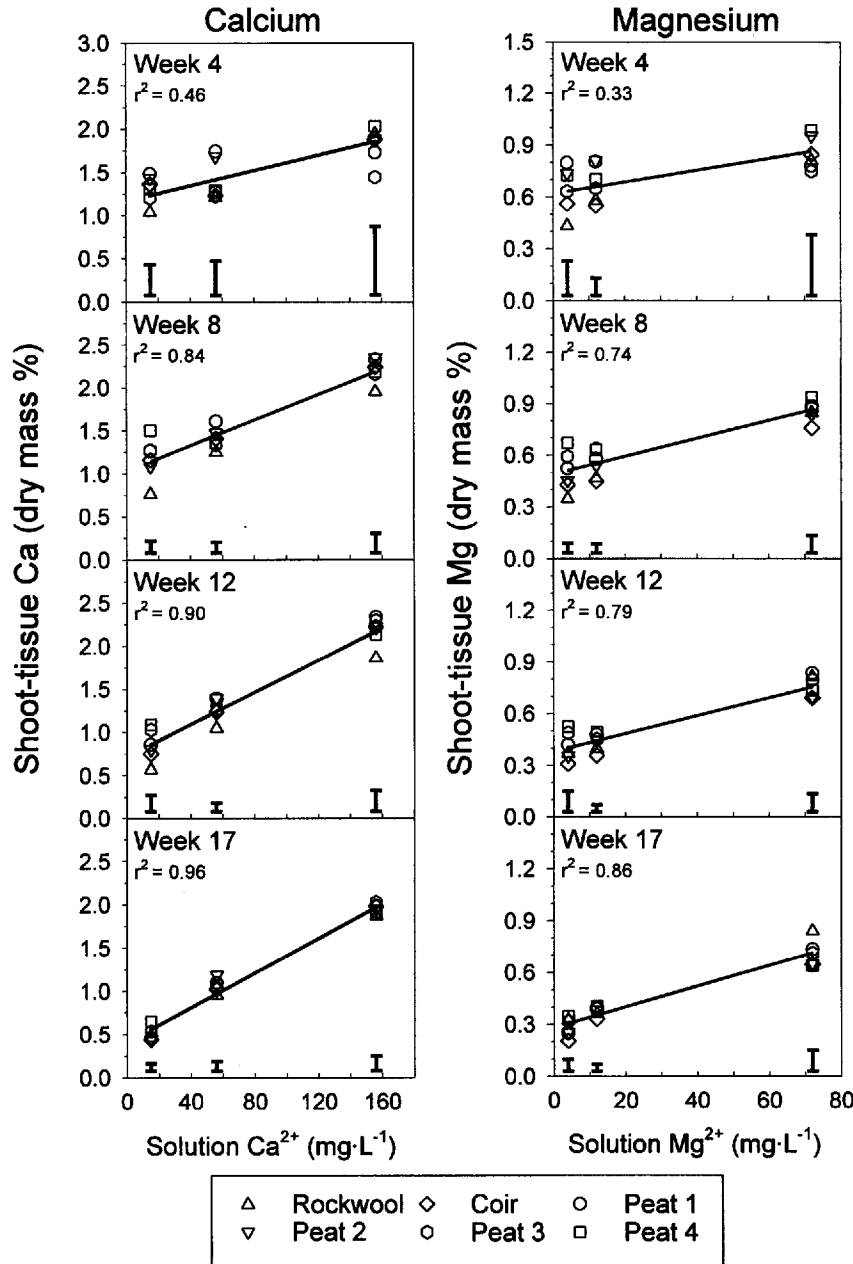


Fig. 4. The effect of applied Ca^{2+} and Mg^{2+} concentration on the shoot-tissue Ca and Mg concentrations in impatiens grown in six root media at 4, 8, 12, and 17 weeks after planting in Expt. 1. The solid line (—) represents the predicted shoot-tissue Ca concentration based on linear regression analysis.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

num 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 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 6 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

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.

Variable	Week				Units
	4	8	12	17	
Shoot-tissue Ca					
Intercept	1.17 ± 0.14 ^a *	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 (%) per mg·L ⁻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 (%) per mg·L ⁻¹

^aNinety-five percent confidence intervals were calculated as the parameter SE × t(0.025, n distribution).

*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.

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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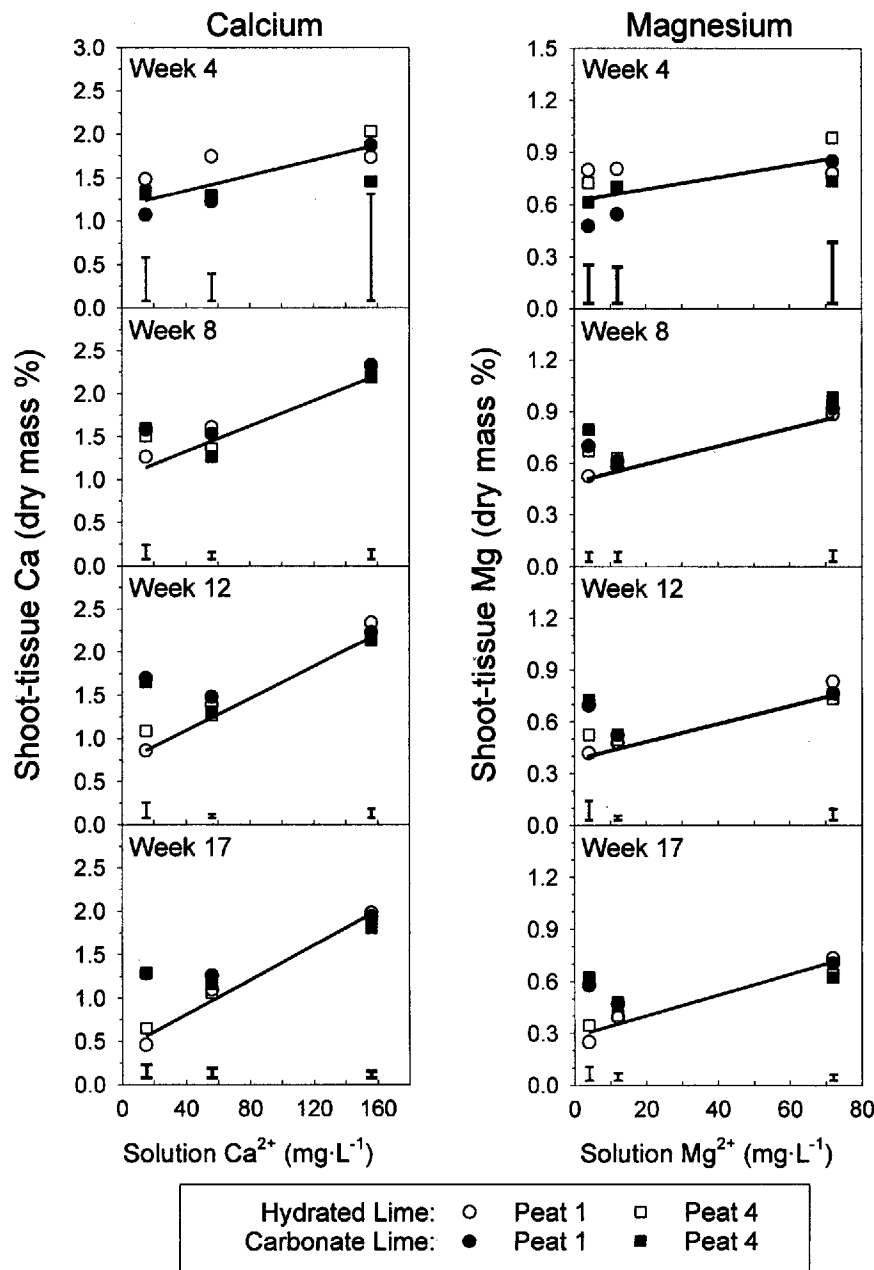


Fig. 5. The effect of applied Ca²⁺ and Mg²⁺ concentration on the shoot-tissue Ca and Mg concentrations in impatiens grown in two root media containing either hydrated dolomitic lime [Ca(OH)₂ and Mg(OH)₂] or carbonate dolomitic lime (CaCO₃ and MgCO₃) at 4, 8, 12, and 17 weeks after planting in Expt. 2. 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.

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