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

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***Abstract.* Using incubation and container culture with subirrigation for up to 28 days, three experiments were conducted with six liming materials of different particle sizes and six blended preplant nutrient charge (PNC) fertilizers. Liming material, particle size, and incorporation rate had an effect on the initial pH (3.5 to 6.1) and the final stable pH (4.8 to 7.8) with one type of Canadian sphagnum peat that did not contain an incorporated PNC. Saturated media extract (SME) Ca and Mg concentrations were <25 and 15 mg·liter^{-1}, respectively, for both pulverized and superfine dolomitic lime at incorporation rates up to 7.2 kg·m^{-3}. For the blended PNC fertilizers in media containing lime, initial electrical conductivity (EC) and SME nutrient concentrations ranged from (EC) 1.0 to 2.9 dS·m^{-1}, (mg·liter^{-1}) 60 to 300 N, 4 to 105 PO_4-P, 85 to 250 K, 120 to 400 Ca, and 60 to 220 Mg. However, within two days, the rapid stratification of fertilizer salts within the pot caused macronutrient concentrations to increase in the top 3 cm of root medium (top layer) by an average of 180% and decrease in the remaining root medium in the pot (root zone) by an average of 57% compared to that measured in the medium at planting. Nutrient concentrations in the top layer continued to increase even when those in the root zone fell below acceptable levels recommended for an SME. The importance of fertilizer salt stratification within a pot lies in the reduced availability of nutrients to the plant and illustrates the limited persistence of the PNC fertilizers. Testing nutrients in container media several days after planting rather than in freshly mixed media may be more representative of the starting point for a nutritional management program.**

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

In general, unamended acidic peat-based root media do not contain sufficient nutrients for plant growth (Bunt, 1988; Nelson, 1991). Current recommendations for the incorporation of fertilizer materials other than limestone into root media before planting include sources of N, PO_4-P, K, Ca, Mg, SO_4-S, and trace elements (Table 1). These guidelines come from the early soilless container media recommendations, including the Cornell Peat-lite media (Boodley and Sheldrake, 1972), the Pennsylvania State Univ. media (White, 1974), Glasshouse Crops Research Institute media (Bunt, 1988), and floriculture textbooks (Nelson, 1991). The most commonly recommended macronutrient fertilizers include $Ca(NO_3)_2$, KNO_3, superphosphate or triple superphosphate, and gypsum (Bunt, 1988; Nelson, 1991; Warncke and Krauskopf, 1983). Commercially available preplant nutrient charge (PNC) fertilizers are ground and preblended for particle size uniformity and sometimes mixed with granular wetting agents to provide greenhouse and nursery operators with a complete product (Table 2). In general, the nutrient content of the blended PNC fertilizers is within the range of the original soilless container media recommendations found in Table 1.

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

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

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

	Cornell Peat-lite A and B[z]	Cornell foliage media[z]	Penn. State media[y]	Nelson potting media[x]	GCRI-1 potting media[w]	GCRI-2 potting media[w]
	All incorporation rates in kg·m^{-3} of root media					
PNC fertilizers	0.9 kg KNO_3 0.6 kg 0–8.6–0[v]	0.9 kg KNO_3 0.6 kg 0–8.6–0[v] 1.6 kg 10–4–8[u]	0.6 kg KNO_3 1.2 kg 0–8.6–0[v] 0.6 kg 20–8–15[u]	0.6 kg KNO_3[t] 0.6 kg $Ca(NO_3)_2$[t] 2.7 kg 0–8.6–0[v] or 1.3 kg 0–19.8–0[s] 0.9 kg gypsum 0.3 kg $MgSO_4$[t]	0.8 kg KNO_3 0.4 kg NH_4NO_3 1.5 kg 0–8.6–0[v]	0.8 kg KNO_3 0.9 kg urea-formaldehyde 1.5 kg 0–8.6–0[v]
Recommended lime rate[r]	3.0 kg ground	4.9 kg dolomitic	3.0 kg dolomitic	6.0 kg dolomitic	2.25 kg each ground and dolomitic	2.25 kg each ground and dolomitic
	Nutrient (kg·m^{-3} of root medium)					
Total N	0.12	0.28	0.20	0.18	0.25	0.45
PO_4-P	0.05	0.12	0.15	0.23	0.13	0.13
K^+	0.33	0.46	0.31	0.22	0.29	0.29
Ca	0.12	0.12	0.23	0.64	0.29	0.29
Mg	0.00	0.00	0.00	0.03	0.00	0.00
SO_4^{2-}-S	0.07	0.07	0.14	0.35	0.18	0.18

[z]Boodley and Sheldrake, 1972.
[y]White, 1974.
[x]Nelson, 1991.
[w]Glasshouse Crops Research Institute (Bunt, 1988).
[v]N–P–K content of single superphosphate ($3Ca(H_2PO_4)_2{\bullet}H_2O + 7CaSO_4{\bullet}2H_2O + 2HF$).
[u]N–P–K content of blended fertilizer. The exact formulation of this fertilizer is unknown and is not included in the nutrient content calculation for Ca, Mg, or SO_4-S.
[t]The incorporation of these materials is optional (Nelson, 1991) but is included in the nutrient content calculations.
[s]N–P–K content of triple superphosphate ($10Ca(H_2PO_4)_2{\bullet}H_2O + 2HF$).
[r]The lime recommendation is not included in the nutrient content calculation.

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

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

Materials and Methods

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

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

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

Experiments 2 and 3 were conducted at Michigan State Univ., East Lansing, in a well-ventilated glass greenhouse with constant air circulation and cement floors. The root medium used was a 60% (by

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

	Blended preplant nutrient charge (PNC) fertilizers					
	MSU I[z]	MSU II[y]	GC I[x]	GC II[x]	GC III[x]	UM[w]
Fertilizer materials	KNO_3 $Ca(NO_3)_2$ 0–19.0–8[w] gypsum $MgSO_4$	KNO_3 $Ca(NO_3)_2$ 0–19.0–8[w] gypsum $MgSO_4$	KNO_3 $Ca(NO_3)_2$ 0–19.0–8[w] gypsum $MgSO_4$	KNO_3 $Ca(NO_3)_2$ steamed-bone meal gypsum $MgSO_4$	KNO_3 KH_2PO_4 gypsum $MgSO_4$	KNO_3 $(NH_4)H_2PO_4$ urea-formaldehyde K_2SO_4 0–19.8–0[v] gypsum $MgSO_4$
Rate ($kg{\cdot}m^{-3}$)	3.9	2.7	3.9	6.2	0.9	2.7
			Elemental analysis (%)			
Total N	4.4	6.3	4.4	3.2	4.0	10.0
PO_4-P	6.2	4.5	6.0	3.9	1.3	4.4
K^+	5.7	8.3	5.5	3.6	11.6	4.2
Ca	12.9	11.4	8.6	3.7	6.0	4.0
Mg	0.8	1.1	0.7	0.5	3.0	2.5
SO_4^{2-}-S	5.7	4.9	5.6	3.9	8.8	7.0
			Nutrient ($kg{\cdot}m^{-3}$ of root medium)			
Total N	0.17	0.17	0.17	0.19	0.04	0.27
PO_4-P	0.23	0.12	0.23	0.24	0.01	0.12
K^+	0.22	0.22	0.21	0.22	0.10	0.11
Ca	0.50	0.30	0.33	0.23	0.05	0.11
Mg	0.03	0.03	0.03	0.03	0.03	0.07
SO_4^{2-}-S	0.22	0.13	0.21	0.24	0.08	0.19

[z]MSU I was 0.6 kg KNO_3 and $Ca(NO_3)_2$, 1.2 kg 0–19.8–0 and gypsum, and 0.3 kg $MgSO_4/m^3$ of media, respectively.
[y]MSU II was 0.6 kg KNO_3, $Ca(NO_3)_2$, 0–19.8–0, gypsum, and 0.3 kg $MgSO_4/m^3$ of media, respectively.
[x]Greencare I, II, and III, respectively, Greencare Fertilizers, Chicago.
[w]Uni-mix Plus II, Peter's Fertilizer, Marysville, Ohio.
[v]N–P–K content of triple superphosphate ($10Ca(H_2PO_4)_2{\cdot}2H_2O + 2HF$).

volume) Canadian sphagnum peatmoss (Fisons black bale professional grower grade)/20% perlite/20% rockwool (Partek North American, Brunswick, Ohio) and contained 0.3 kg of a wetting agent/m^3 (Aquagro L; Aquatrols, Cherry Hill, N.J.) in addition to the indicated PNC and lime treatments. Incorporation rates and nutrient contents for the PNC fertilizers are presented in Table 2. After mixing, media remained in plastic bags with the tops open to the air for gas exchange for 2 days before the pots were filled. Hybrid impatiens plugs ('Super Elfin Violet' Impatiens wallerana) from a 512 plug tray were planted into 11.5 × 11.5-cm (0.7-liter) plastic pots containing media with the lime and PNC treatments, placed onto a flood subirrigation bench, and irrigated daily with RO purified water (pH = 6.0, EC = 0.1 $dS{\cdot}m^{-1}$, alkalinity to pH 4.5 of <20 mg $CaCO_3$/liter, and 20 and 7 mg Ca and Mg/liter, respectively). At a typical irrigation, the benches were filled in 2 min to a 2-cm depth and allowed to drain, which took an additional 5 min.

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

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

Comparison 1. The three blended PNC fertilizers used were GC I (Greencare I; Greencare Fertilizers, Chicago), UM (Uni-mix Plus II; Scotts, Marysville, Ohio), and MSU I (PNC fertilizer blended at MSU) incorporated at 3.9, 2.7, and 3.9 $kg{\cdot}m^{-3}$, respectively. In addition to the PNC, a dolomitic hydrated limestone [97% $Ca(OH)_2$ MgO], National Lime and Stone, Carey, Ohio) was incorporated at 1.5 $kg{\cdot}m^{-3}$, which supplied an additional 0.5 kg Ca and 0.3 kg Mg/m^3 of medium. The bulk particle size of the hydrated lime allowed 97% to pass a 45-μm (#325) screen. Root media were sampled initially and at 2, 7, 14, 21, and 28 days after planting. The comparison consisted of three PNC fertilizers with three replications at six sampling dates.

Comparison 2. An evaporation barrier was placed on pots containing the GC I, UM, and MSU I media and consisted of an 11.5-cm plastic cover with a 0.5-cm hole melted in the middle for the plant stem and cut from the perimeter to the center so the cover could be inserted after planting. Root media in the covered pots were sampled at 14 and 28 days after planting. The comparison of the uncovered and covered root-zone nutrient concentrations was analyzed as a 3 × 2 factorial with three replications at the two sampling dates. Top-layer data were analyzed as a single factorial, with replication made across PNC treatments.

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

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

Results and Discussion

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

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

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

	Sampling day				
pH	0	3	7	13	21
Lime grind (LG)	***	***	***	***	***
Rate (R)	**	***	***	***	***
LG × R	**	***	*	NS	NS
s_ε[z]	0.01	0.01	0.01	0.01	0.01
Ca/Mg					
Lime grind (LG)	***/***	NS/NS	**/NS	***/***	***/**
Rate (R)	***/***	**/NS	**/**	***/***	**/*
LG × R	**/***	*/NS	**/**	***/***	**/*
s_ε	0.01/0.01	0.02/0.06	0.02/0.02	0.01/0.01	0.02/0.01

[z]Square root of the mean square error from the ANOVA of the transformed data.

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

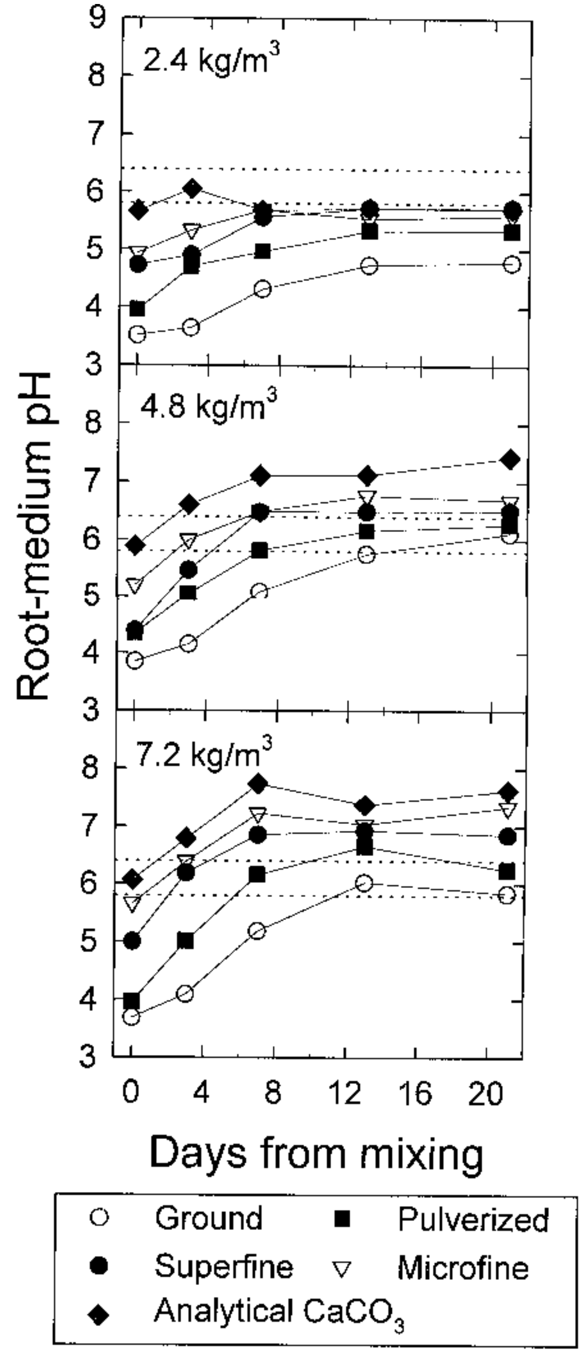

Fig. 1. Experiment 1. The pH of peat amended with ground, pulverized, superfine, or microfine dolomitic carbonate lime ($CaCO_3$ $MgCO_3$), and analytical grade $CaCO_3$ incorporated at either 2.4, 4.8, or 7.2 kg·m^{-3}, respectively, and measured over 21 days. Dotted lines (.....) indicate recommended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

Experiment 2. In general, initial pH and water-soluble nutrient concentrations of root media containing GC I, UM, and MSU I were at or above those considered optimal for the SME (Warncke and Krauskopf, 1983) (Fig. 3, remaining data not shown). In comparison, Argo (1993) reported that initial pH of five commercial peat-based root media ranged from 6.0 to 6.6; EC, from 1.6 to 3.6 dS·m^{-1}; and initial nutrient concentrations, from (mg·liter^{-1}) 65 to 180 N, 3 to 25 PO_4-P, 70 to 328 K, 120 to 580 Ca, and 34 to 130

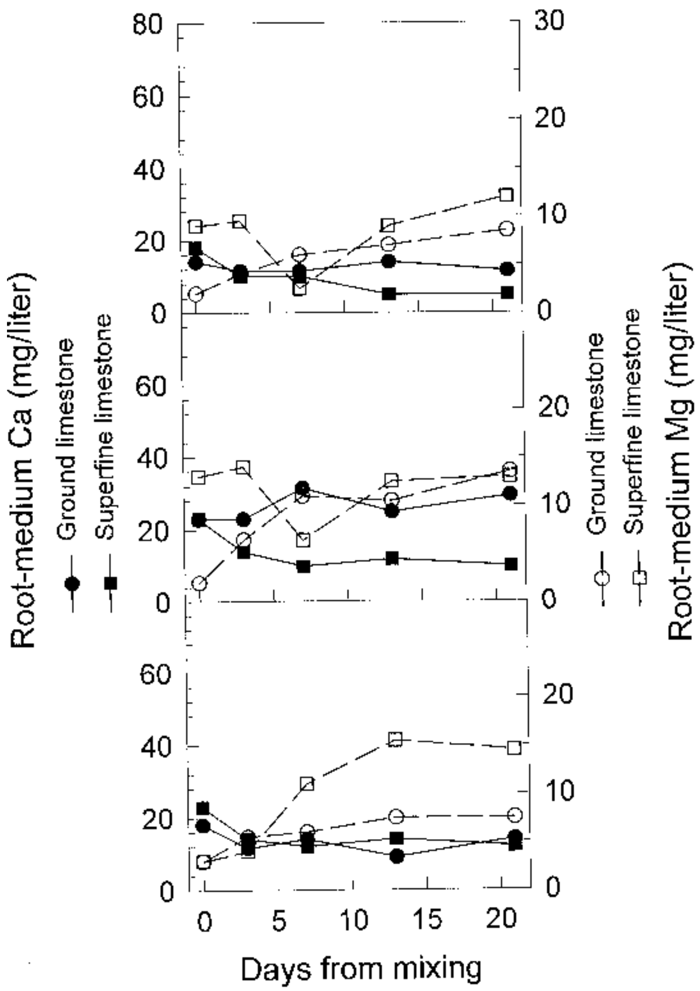

Fig. 2. Experiment 1. Calcium and Mg concentrations of peat amended with ground or superfine dolomitic carbonate lime ($CaCO_3$ $MgCO_3$) incorporated at either 2.4, 4.8, or 7.2 kg·m^{-3}, respectively, and measured over 21 days. Minimum acceptable concentrations for Ca is 80 mg·liter^{-1} and Mg is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

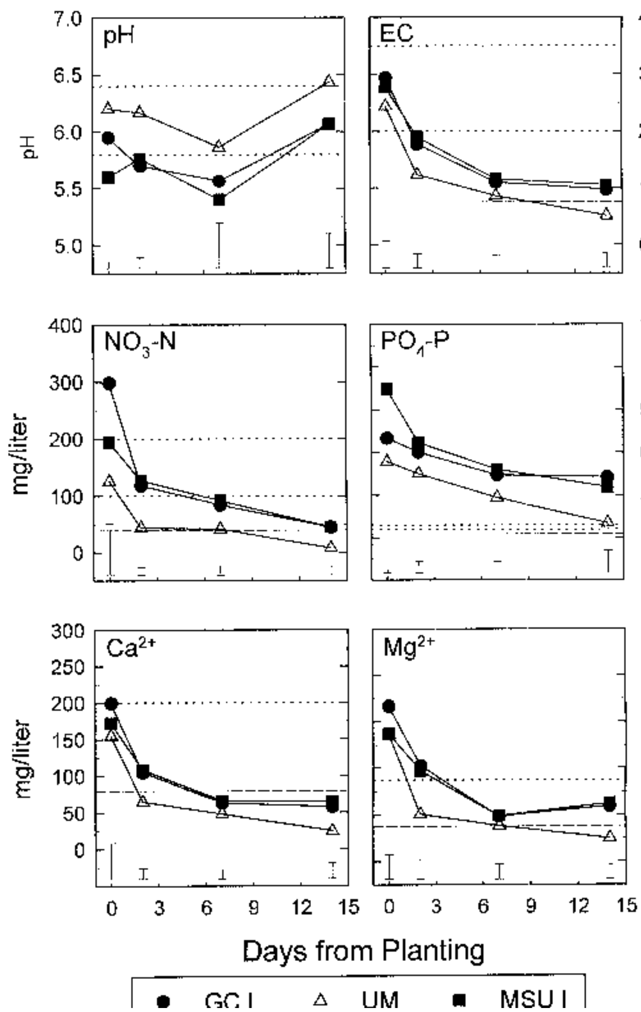

Fig. 3. Experiment 2. Root-zone pH, EC, NO_3-N, PO_4-P, Ca, and Mg concentrations of uncovered subirrigated hybrid impatiens with media containing the blended PNC fertilizers Greencare I, Uni-mix Plus II, and MSU I from planting until day 14. The liming material used was a microfine dolomitic hydrated lime [$Ca(OH)_2$ MgO] incorporated at 1.5 kg·m^{-3}. Dotted lines (.....) indicate recommended optimal concentration(s), the lower dashed line (---) indicates acceptable concentrations for the SME (Warncke and Krauskopf, 1983). Vertical error bars are mean separation using LSD.

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

In addition to the lime, there are also recommendations for the water-soluble nutrient concentrations that can be expected from the incorporation of gypsum, superphosphate, $Ca(NO_3)_2$, and KNO_3 (Warncke, 1976; Warncke and Krauskopf, 1983). Using MSU I as an example (Table 2) and not including the lime in the calculation, the predicted water-soluble nutrient concentration would be (mg·liter^{-1}) 150 N, 25 P, 105 K, and 270 Ca, as measured with the SME. The actual concentration of nutrients measured in media containing MSU I was (mg·liter^{-1}) 220 N, 105 P, 240 K, and 170 Ca. Warncke (1976) used field soil in five of the six media with the incorporated PNC fertilizers. Perhaps the absence of soil and the greater water-holding capacity of the peat/rockwool/perlite medium used in this experiment affected the partitioning between exchangeable, insoluble, and water-extractable nutrients, which resulted in the difference between the predicted and measured nutrient concentrations.

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

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

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

		EC	NO_3-N	PO_4-P	K^+	Ca	Mg
Top layer	EB day 14	**	**	**	***	**	**
	EB day 28	*	NS	**	*	*	NS
			Day 14				
Root zone	EB	***	***	*	***	***	***
	PNC fertilizer	***	***	NS	***	***	***
	EB × PNC	NS	NS	NS	**	*	**
	s_ε[z]	0.02	0.08	0.16	0.04	0.01	0.04
			Day 28				
	EB	***	**	***	***	***	***
	PNC fertilizer	*	***	**	*	*	NS
	EB × PNC	NS	**	NS	NS	NS	NS
	s_ε	0.03	0.10	0.03	0.06	0.05	0.06

[z]Square root of the mean square error from the ANOVA of the transformed data.
NS,*,**,***Nonsignificant or significant at $P < 0.05$, 0.01, or 0.001, respectively.

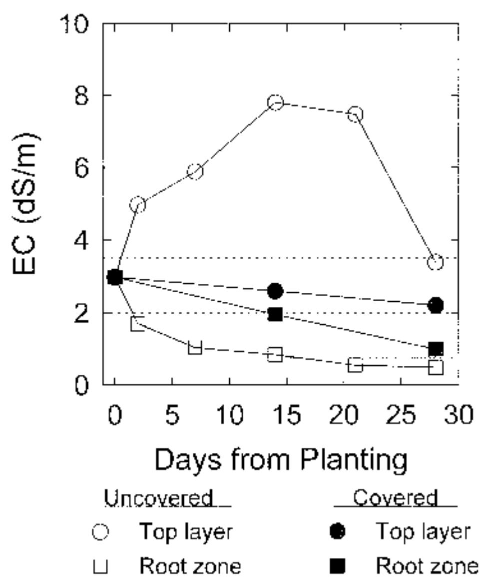

Fig. 4. Experiment 2. Comparison of root-zone and top-layer electrical conductivity (EC) for pots grown without and with an evaporation barrier averaged over media containing three PNC fertilizers from Expt. 2. Dotted lines (....) indicate recommended optimal concentration(s), and lower dashed lines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

to that in uncovered pots (Table 4, Fig. 4).

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

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

Irrigation method also may affect the persistence of the PNC fertilizers in the root zone. Argo and Biernbaum (1995a, 1995b) found that fertilizer salt stratification also occurred with top-watered poinsettias grown with 33% and 25% leaching, respectively. Because of the leaching effects of the water, nutrients contained in the top layer provided a source of nutrients (buffering capacity) for the root zone for up to 6 weeks once fertilization was stopped (Argo and Biernbaum, 1995b). Thus, the persistence of PNC fertilizers with top-watering methods may be different than that measured in this experiment with subirrigation.

The use of a microfine dolomitic hydrated lime $Ca(OH)_2$ MgO,1.5 $kg \cdot m^{-3}$ compared to a superfine dolomitic carbonate lime ($CaCO_3$ $MgCO_3$, 4.5 or 7.5 $kg \cdot m^{-3}$) did not affect either the initial concentrations of Ca or Mg or the persistence of these ions in the root zone up to 28 days after planting (data not shown), even though more Ca and Mg were added to the root medium containing the carbonate lime treatments (1120 mg Ca and 680 mg Mg per pot at 7.5 $kg \cdot m^{-3}$) than the same hydrated lime treatments (350 mg Ca and 210 mg Mg per pot at 1.5 $kg \cdot m^{-3}$). The initial pH of media containing the hydrated lime was 6.0 and remained fairly stable for the entire experiment (Fig. 5). In comparison, the initial pH of the media with the carbonate lime was 4.5 and required 14 days to reach the same pH as the media containing the hydrated lime. As in Expt. 1, the continued reaction of the carbonate lime (increasing pH) did not affect medium Ca and Mg concentrations measured with the SME. Instead, the main effect of the different liming materials on nutrient availability from GC I was due to pH effects on PO_4-P solubility (Fig. 5).

The solubility of PO_4-P can be based on medium pH, EC, and

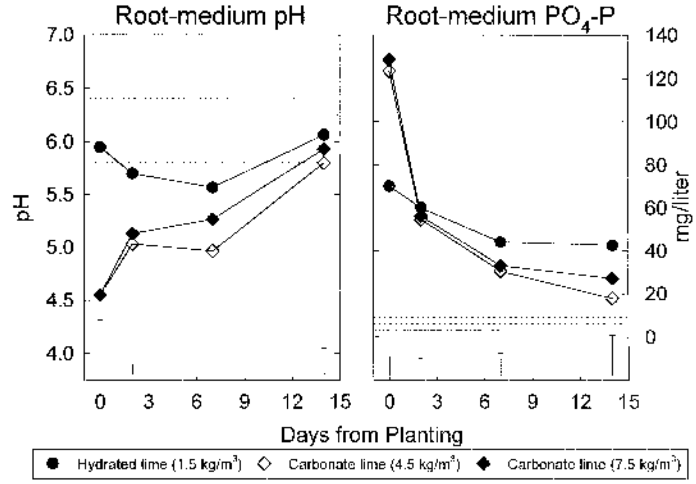

Fig. 5. Experiment 2. Root-zone pH and PO_4-P concentrations in media containing GC I with either a microfine dolomitic hydrated lime $Ca(OH)_2$ MgO incorporated at 1.5 $kg\cdot m^{-3}$ or a superfine dolomitic carbonate lime ($CaCO_3$ $MgCO_3$) incorporated at 4.5 or 7.5 $kg\cdot m^{-3}$. Dotted lines (....) indicate recommended optimal concentration(s), the lower dashed line (---) indicates acceptable concentrations for the SME (Warncke and Krauskopf, 1983). Vertical error bars are mean separation using LSD.

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

Experiment 3. At the initial soil test, EC, PO_4-P, Ca, and Mg concentrations (Fig. 6), as well as NO_3-N and K concentrations (data not shown) were at or above optimum concentrations for an SME in media containing GC I and MSU II. In media containing GC II, initial PO_4-P concentrations were below acceptable levels for an SME because of the limited solubility of the P source (steamed bone meal). Initial nutrient concentrations in media containing GC III were within acceptable levels for an SME but were lower than those of the other PNC fertilizers. The total amount of nutrients incorporated with GC III was lower than that in the other PNC fertilizers (except for Mg) (Table 2). In fact, GC III is similar in N, K, and SO_4-S content to the recommended initial nutrient content of several seedling media (Boodley and Sheldrake, 1972; Bunt, 1988; White, 1974), but with significantly lower PO_4-P and Ca.

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

Reducing the incorporation rate or limiting the solubility of the nutrient also affected the amount lost to the top layer. For example, decreasing the amount of PO_4-P incorporated into the medium by 50% (GC I vs. MSU II) decreased initial PO_4-P concentrations by 38% (Fig. 6). After 14 days, the concentration of PO_4-P in the root zone was above optimal levels for the SME with both PNC fertilizers, and the increase in the concentration of PO_4-P of media containing MSU II was less than that of media containing GC I. In another example, media containing GC I and GC II had similar amounts of incorporated PO_4-P (Table 2). Initial PO_4-P concentrations of media containing GC II were only 5% of the initial concentration of media containing GC I (Fig. 6), and the corre-

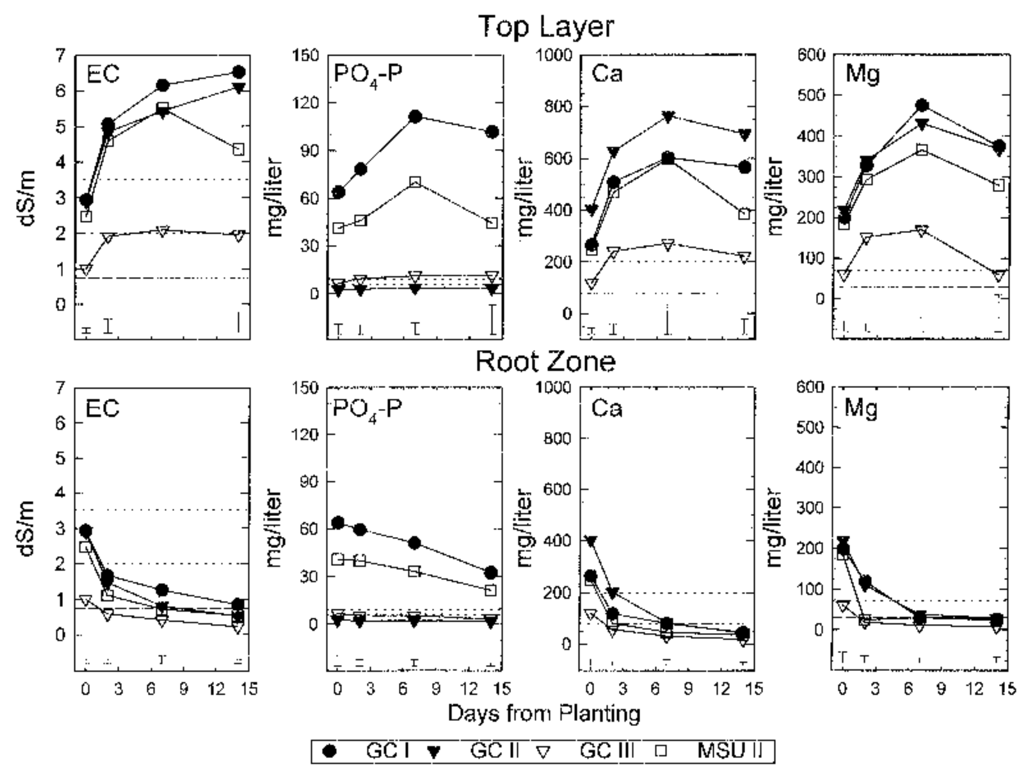

Fig. 6. Experiment 3. Root-zone EC, PO_4-P, Ca, and Mg concentrations of subirrigated hybrid impatiens with media containing the blended PNC fertilizers Greencare I, Greencare II, Greencare III, and MSU II from planting until day 14. The liming material used was a microfine dolomitic hydrated lime $Ca(OH)_2$ MgO) incorporated at 1.5 $kg\cdot m^{-3}$. Dotted lines (....) indicate recommended optimal concentration(s), the lower dashed line (---) indicates acceptable concentrations for the SME (Warncke and Krauskopf, 1983). Vertical error bars are mean separation using LSD.

sponding increase in the top-layer PO_4-P concentrations with GC II was less than with media containing GC I. Soilless media have a limited ability to retain PO_4-P against leaching (Yeager and Barrett, 1985) and subirrigation or top watering under production conditions (Argo, 1993), which may result in insufficient PO_4-P concentrations later in crop development. Limiting the solubility of the PO_4-P carrier (bone meal) may increase its persistence over time. However, there was some marginal leaf necrosis observed 14 days after planting on the plants grown in media containing GC II, and the odor of the steamed bonemeal during formulation of the PNC was objectionable (L. Metcalf, Greencare Fertilizers, Chicago, personal communications).

Based on discussions with four commercial peat-based media suppliers, PNC fertilizer incorporation rates from 10 years ago were similar to those used in MSU I/GC I. Typical incorporation rates during the past two years for N, P, and K fertilizer have been reduced by as much as half. If a complete water-soluble fertilizer is applied on a constant basis starting at the initial irrigation, it is questionable whether the high initial nutrient concentrations measured in media containing GC I, GC II, UM, MSU I, or MSU II are necessary because of the rapid loss of nutrients from the root zone when subirrigation was used.

In Expts. 2 and 3, the use of dolomitic hydrated lime $Ca(OH)_2$ MgO) offered a method of rapidly obtaining a root-medium pH of 6.0. At an incorporation rate of 1.5 kg of the hydrated lime per m^3, initial pH was 6.0 and remained relatively stable for up to 28 days in a peat/perlite/rockwool medium. In comparison, the initial pH of the same medium containing up to 7.5 kg of superfine dolomitic carbonate lime ($CaCO_3$ $MgCO_3$)/m^3 was 4.6 and required up to 14 days to equilibrate to 6.0.

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

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

Recognition of the rapid decrease in nutrient concentrations after planting is important for the proper interpretation of root-medium analysis. When PNC fertilizers have been incorporated, nutrient concentrations in fresh medium taken from a mixing line or a bag will be higher than that of media placed in a container, irrigated, and allowed to dry for several days before sampling. Moistening and incubating the media for several days to 2 weeks in a closed container likely will give a better estimate of the starting pH, but not EC or macronutrient concentrations. In our opinion, a sample taken two to four days after planting is more representative of the starting point of a nutritional program. Based on these experiments, the EC and nutrient concentrations of media several days after planting likely will fall within the lower acceptable range for nutrient concentrations based on the SME (Warncke and Krauskopf, 1983). However, because of the preliminary nature of these experiments, specific grower recommendations about PNC fertilizers, liming materials, rates, and sampling methods cannot be made.

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