Nutrient Uptake in Poinsettia during Different Stages of Physiological Development

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ABSTRACT. 'Supjibi' poinsettias (*Euphorbia pulcherrima* Willd.) were grown hydroponically for 15 weeks in nutrient solutions with 100–15–100, 200–30–200, or 300–46–300 (in mg·L⁻¹ of N–P–K) to determine nutrient uptake patterns and accumulation rates. Results indicate that increasing fertilization rates from 100 to 300 mg·L⁻¹ of N and K did not significantly influence the plant dry mass or the nutrient concentration of P, K, Ca, Mg, Na, B, Cu, Fe, Mn, Mo, and Zn in poinsettias. NH₄-N concentration in the leaves, stems, and roots were lowest with the 100-mg·L⁻¹ N fertilization rate and increased as the N application rate increased to 200 and 300 mg·L⁻¹. Leaf P concentration levels from 1 week after potting through anthesis were above 1.3%, which exceeds the recommended level of 0.9%. When the plant tissue dry mass for each fertilizer rate was transformed by the natural log and multiplied by the mean tissue nutrient concentration of each fertilizer rate, there were no significant differences among the three fertilization rates when the total plant nutrient content was modeled for N, P, or K. Increasing the fertilizer application rate above 100 mg·L⁻¹ N and K and 15 mg·L⁻¹ P decreased total plant content of Ca, Mg, Mn, and Zn and increased the total plant Fe content. The results of the weekly nutrient uptake based on the total plant nutrient content in this study suggests that weekly fertilization rates should increase over time from potting until anthesis. Rates (in mg) that increase from 23 to 57 for N (with 33% of the total N supplied in the NH₄-N form), 9 to 18.5 for P, 19 to 57 for K, 6 to 15 for Ca, and 3 to 8 for Mg can be applied without leaching to poinsettias and produce adequate growth in the northern United States.

Applying excess amounts of fertilizer can cause leaching into groundwater. Growers are aware of the possibility of future environmental regulation that could restrict their current fertilization practices (Doerge et al., 1991; Pyle, 1991). Marketable poinsettias (*Euphorbia pulcherrima*) have been produced in experiments using reduced N application rates (98 mg·L⁻¹), a decreased leaching fraction of 0.15 (the volume of solution leached, divided by the total solution applied) (Yelanich and Biernbaum, 1993, 1994), or by changing irrigation practices from hand watering or capillary mats to using ebb-and-flow irrigation benches (Dole et al., 1994). Argo and Biernbaum (1995) grew poinsettias in five types of root media and found that after applying 392 mg·L⁻¹ N and 331 mg·L⁻¹ K by overhead irrigation for only the first 58 d, ample nutrients were available from the top 2.5-cm layer of the root medium by leaching down to the bottom root zone of the pot for the rest of the production period.

Nutrient uptake of roses (*Rosa hybrida* L.) grown in a recirculating hydroponic system was low when the plant was developing auxiliary buds following pinching, then uptake increased as the shoot elongated and leaves expanded, but decreased as flower buds developed (Evans and Paul, 1992; Tsujita and Taurins, 1991). The nutrient uptake pattern of snapdragons (*Antirrhinum majus* L.) also varied by developmental stage during vegetative growth, flower initiation, and visible bud. Hood et al. (1993) found NO₃-N and NH₄-N uptake patterns were similar during vegetative growth and flower initiation, then increased during visible bud development, although NO₃-N was the preferred form of N taken up by the plant. Uptake of P, K, Ca, Mg, and Mn decreased when flowers were initiated, but increased again during the visible bud. These studies indicated that uptake patterns of nutrients vary in

plants during progressive stages of physiological development. Correlating nutrient uptake in a crop to specific physiological stages of plant development is essential to develop a fertility program that maximizes nutrient uptake and accumulation while minimizing waste. To increase fertilizer use efficiency, there is a need to determine the nutrient uptake patterns of poinsettias during physiological development.

Materials and Methods

Terminal cuttings of 'Supjibi' poinsettia were taken on 4 Aug. 1993 and rooted under intermittent mist in perlite. Cutting bases were treated with rooting powder containing 0.1% indole-3-butyric acid (Hormodin 1; Merck Chemical, Rahway, N.J.). On 8

Fig. 1. Leaf, stem, and root dry mass of 'Supjibi' poinsettia plants over time. Average for all fertilization rates. Significant at $P \leq 0.001$ for leaf, stem, and root dry mass $\times$ week comparison. LSD ($\alpha = 0.05$) is 1.45. Plants were pinched at the end of week 3 (after data were recorded), short days began after week 5, and anthesis occurred on week 14. Mean of five replications and three fertilizer rates.

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Fig. 2. Weekly solution uptake of 'Supjibi' poinsettia plants. Average for the three fertilization rates. Significant at $P \leq 0.001$ for solution uptake $\times$ week comparison. LSD ($\alpha = 0.05$) is 56. Plants were pinched at the end of week 3 (after data was recorded), short days began after week 5, and anthesis occurred on week 14. Mean of five replications and three fertilizer rates.

Sept. (beginning of week 1), the plants were placed in a hydroponic system consisting of round 15 $\times$ 11-cm (diameter $\times$ height) (1.4-L) plastic tubs with fitted plastic lids (Dean's Foods 3# small curd cottage cheese containers; Franklin Park, Ill.). The containers' exterior were painted with metallic aluminium (Ace Hardware chrome aluminium #17006; Oak Brook, Ill.) to exclude light and prevent algae growth within the solution. A 5 $\times$ 1.5-cm (diameter $\times$ height) foam collar (ITP Backer Rod Insulation; Industrial Thermo Polymers, Ltd., Buffalo, N.Y.) supported each plant when it was placed in a 4.5-cm-diameter hole through the container's lid.

All plants were grown in a modified Hoagland's hydroponic solution (Hammer et al., 1978) containing (in $\text{mg}\cdot\text{L}^{-1}$): 50 $\text{NO}_3\text{-N}$, 8.25 $\text{H}_2\text{PO}_4\text{-P}$, 51 K, 50 Ca, 12 Mg, 16.75 S, 6.75 Na, 1.15 Fe, 0.125 Mn, 0.125 B, 0.005 Cu, 0.0125 Zn, and 0.025 Mo for the first week. After the first week, one base solution was used and was mixed at three rates: 100–15–100, 200–30–200, and 300–46–300 (in $\text{mg}\cdot\text{L}^{-1}$ of N–P–K). The other elements (in $\text{mg}\cdot\text{L}^{-1}$; 100 Ca, 50 Mg, 35.3 S, 11.5 Na, 6.6 Fe, 0.5 Mn, 0.5 B, 0.02 Cu, 0.05 Zn, and 0.1 Mo) were

the same for all three fertilization rates. The $\text{NH}_4\text{-N}$ comprised 25% of the N supplied, except for the lowest fertilization rate where it was 18%. Nutrient solutions were added and recorded to maintain the volume at 1.25 L and a pH of 6.0 ± 0.5 was corrected with 1 M HCl or 1 M NaOH once daily. The nutrient solution in each container was aerated with compressed air.

Greenhouse day/night temperature setpoints were 24/18 $^{\circ}\text{C}$. The plants were pinched on 29 Sept. (end of week 3) leaving four to five nodes. Plants were kept vegetative by supplying lighting from incandescent light bulbs from 2200 to 0200 hr daily until 13 Oct. (end of week 5), at which time they were grown under natural season long nights to induce flowering.

Five plants and solutions of each fertilizer rate were randomly selected weekly from 8 Sept. until 22 Dec. for analysis. In addition, nutrient solutions were sampled weekly from week 3 to 15 from the plants that were harvested during the final week of the experiment. Sixty-milliliter samples of each of the three nutrient solution were collected, initially when the 1.25 L of solution was added to the containers and again 1 week later when the solution was changed. The volume of the remaining solution also was recorded. The hydroponic solutions were analyzed for pH (glass Ag/AgCl electrode; Orion, Boston), electrical conductivity (EC) (Solu-bridge; Beckman Instruments, Cedar Grove, N.J.), $\text{NO}_3\text{-N}$ (ion-sensitive electrode; Orion), $\text{NH}_4\text{-N}$ by the Nessler's procedure (Jackson, 1958), P colorimetric procedure (Murphy and Riley, 1962), and K, Ca, and Na by flame emission and Mg by atomic absorption using a Varian SpectrAA-10 spectrometer (Varian Techtron Pty., Mulgrave, Victoria, Australia).

The nutrient content was calculated for each element at the start and end of each week by analyzing the solution and multiplying the nutrient concentration by the number of milliliters of hydroponic solution in the container. Weekly uptake rates were calculated as the difference between the initial and final content.

Five plants from each fertilizer rate were collected weekly at the end of the week when the hydroponic solutions were changed,

Fig. 3. The uptake of (A) $\text{NO}_3\text{-N}$, (B) $\text{NH}_4\text{-N}$, (C) K, and (D) Ca by fertilizer rate over time. Significant at $P \leq 0.001$, 0.001, 0.001, and 0.001, respectively, for $\text{NO}_3\text{-N}$, $\text{NH}_4\text{-N}$, K, and Ca for the fertilization rate $\times$ week comparison. LSD ($\alpha = 0.05$) are 8.8, 4.3, 14.8, and 5.7, respectively, for $\text{NO}_3\text{-N}$, $\text{NH}_4\text{-N}$, K, and Ca. Plants were pinched at the end of week 3 (after data was recorded), short days began after week 5, and anthesis occurred on week 14. Mean of five replications.

starting 7 d after planting. Plant height was recorded by measuring from the container rim to the top of the leaf canopy. Plants were harvested and divided into leaf, stem, and root portions; dried in a forced-air oven at 70 °C for 72 h; and dry mass was measured and ground to pass through a 20-mesh Wiley Mill. Ground tissue samples (150 mg) were digested in 3 mL H₂O₂ and 1 mL HClO₄ (Adler and Wilcox, 1985) and diluted with distilled water to a volume of 25 mL for analysis. The NH₄-N was determined by Nessler's procedure (Jackson, 1958), and P, K, Ca, Mg, Na, Fe, B, Mn, Zn, Cu, and Mo were determined using an inductively coupled Ar plasma emission spectrophotometer (Perkin Elmer, Norwalk, Conn.).

Data for the hydroponic solutions and tissue nutrient levels were analyzed using analysis of variance by general linear model procedures (SAS Inst., Cary, N.C.). Significantly different means were separated by least significant differences (LSD) at $P \leq 0.05$.

DATA ANALYSIS. Poinsettia leaf, stem, and root tissue dry mass for each fertilizer rate and replicate (except week 13 when the dry mass of the plants sampled were abnormally low and dry mass for this week was deleted from the calculations) were transformed using the natural log of the dry mass to stabilize the variance (Snedecor and Cochran, 1989). For each fertilizer rate, the dry mass of the three tissue types (leaf, stem, and root) was regressed using the SAS stepwise procedure of PROC REG (SAS Inst.) to determine the best fit model. The full model used was as follows:

$$\ln DW_{t,j} = \beta_0 + \beta_1 Wk + \beta_2 Wk^2 + \beta_3 Wk^3 + \beta_4 Wk^4 + \beta_5 Wk^5$$

where DW_t = dry mass of each plant part, *i* = tissue type (leaf, stem, or root), *j* = fertilizer rate (100–15–100, 200–30–200, or 300–46–300 mg·L⁻¹ of N–P–K), Wk = week after potting, and β_{*k*} = estimated coefficients (*k* = 0 to 5).

Terms significant at the 0.15 level were selected for inclusion in the final model.

Weekly mean tissue (leaf, stem, and root) nutrient concentration values for each fertilizer rate were multiplied by the corresponding best fit dry mass model to calculate weekly whole-plant nutrient content of each element. Whole-plant nutrient content values were regressed using the PROC REG procedure to determine the best fit linear or quadratic model for each element. Variables in the model were time (week) and indicator variables for the fertilization rate, with the full model being as follows:

$$\text{Content}_i = \beta_0 + \beta_1 Wk + \beta_2 Wk \times \text{Rate}_{200} + \beta_3 Wk \times \text{Rate}_{300} + \beta_4 Wk^2 + \beta_5 Wk^2 \times \text{Rate}_{200} + \beta_6 Wk^2 \times \text{Rate}_{300} + \beta_7 Wk^3 + \beta_8 Wk^3 \times \text{Rate}_{200} + \beta_9 Wk^3 \times \text{Rate}_{300}$$

where Content_{*i*} = total plant nutrient content of each element (mg or μg); *i* = nutrient being regressed (NH₄-N, P, K, Ca, Mg, Na, B, Cu, Fe, Mn, Mo, Zn); Wk = week after potting; Rate₂₀₀ = 1 if fertilization rate = 200–30–200 mg·L⁻¹ of N–P–K, 0 otherwise; Rate₃₀₀ = 1 if fertilization rate = 300–46–300 mg·L⁻¹ of N–P–K, 0 otherwise; and β_{*k*} = estimated coefficients (*k* = 0 to 9).

Terms of the model were judged to be significant or nonsignificant and included in the final model based on a comparison of *F* values at α = 0.05.

DEFINITIONS. The stages of development were based on the work of Rose et al. (1994). Vegetative stage: 35 d of long days (16

Fig. 4. Nutrient uptake ratios for (A) NO₃-N, (B) NH₄-N, (C) P, (D) K, and (E) Ca by fertilizer rate over time. Significant at $P \leq 0.001$, 0.001, 0.001, 0.001, and 0.01, respectively, for NO₃-N, NH₄-N, P, K, and Ca for the fertilizer rate × week comparison. LSD ($\alpha = 0.05$) are 6.2, 11.4, 15.5, 7.1, and 5.2, respectively, for NO₃-N, NH₄-N, P, K, and Ca. Plants were pinched at the end of week 3 (after data was recorded), short days began after week 5, and anthesis occurred on week 14. Mean of five replications.

h) after potting (to the end of week 5). Inductive stage: 28 d of short days (< 14 h) between floral induction (week 6) and visible bud (week 9). Bract development stage: 28 d of short days between visible bud (week 10) and anthesis (week 14) (pollen dehiscence). Bract coloration occurred between weeks 9 and 10.

Results and Discussion

PLANT GROWTH. Leaf, stem, and root dry mass increased significantly as the plants grew, the period of the greatest increase in leaf dry mass occurred after the vegetative stage (after week 5) when the new axillary shoots began to grow (Fig. 1). Fertilizer application rate did not affect individual leaf, stem, or root dry mass. The total plant dry mass of >16 g was similar to that reported by Dole et al. (1994) for poinsettias irrigated with either 175 or 250 mg·L⁻¹ N by microtubes (15.1 g) or Ebb-and-flow benches (15.3 g).

NUTRIENT UPTAKE. Weekly uptake of the nutrient solution varied over time with lower volumes being used by the plants during the early vegetative stages of growth when the plants were small and increased as the axillary shoots grew (Fig. 2). The

cumulative volume of nutrient solution used by the plants was 5.4 L, which was similar to the 5.2 to 5.4 L used by 'Lilo' poinsettias during Fall 1990 (Rose, 1993). Uptake of NO₃-N, NH₄-N, K, and Ca were significantly different by week and fertilizer application rate (100, 200, or 300 mg·L⁻¹ N and K) (Fig. 3). The largest differences in NO₃-N uptake was during the first seven weeks of growth, with uptake increasing as the fertilization rate increased. During the last 2 weeks of the inductive stage (week 8) through anthesis (week 15), NO₃-N uptake followed a similar trend for all fertilization rates and decreased as the plants reached anthesis. The uptake of NH₄-N increased to 37 mg with the higher N and K fertilization rates and also followed a trend of increasing through the vegetative and inductive stages before declining as the plant reached anthesis (Fig. 3 A and B). Potassium uptake was similar for all three fertilization rates (100, 200, or 300 mg·L⁻¹ N and K) for the 15 weeks measured (Fig. 3C). Potassium uptake was lowest for the first 7 weeks of growth before increasing. Calcium uptake rate increased for the first 8 weeks of growth and remained in the 10 to 25-mg/week range thereafter (Fig. 3D).

Uptake of P and Mg were significantly different only by week and were not affected by the N-P-K fertilizer application rate (data not shown). Phosphorus uptake increased through the fourth week of growth, declining after the terminal growth was removed before increasing to 22 mg by week 12. Magnesium uptake was similar for most of the growing season (<15 mg), but uptake declined at week 15 as the plants reached anthesis. The increase in NH₄-N, P, and K uptake during periods of rapid growth of the axillary shoots was similar to reports with poinsettia (Rose et al., 1994; Tsutsui and Aoki, 1981), roses (Evans and Paul, 1992; Tsujita, 1992; Tsujita and Taurins, 1991), and snapdragons (Hood et al., 1993).

Nutrient budgets were calculated for the entire 15 weeks of the experiment and compared nutrient uptake and total plant content over time for N, P, K, Ca, and Mg (data not shown). Mean values accounted for 55% to 99% of the nutrients that had been applied. Nitrogen had the highest percentage that was unaccounted for at the 300 mg·L⁻¹ fertilization rate, with 45% of the applied N being unaccounted. More than 89% of the P and 82% of the K were accounted for throughout the experiment, with the lowest accountability for both elements occurring with the 300 mg·L⁻¹ fertilization rate. The ranges were similar to those previously reported which accounted for 50% to 100% of N and 90% to 100% of P and K, except for K at the 300-mg·L⁻¹ N and K fertilization rate (Riga et al., 1988; Sharpe et al., 1988; E. Smaling, personal communication), especially considering the week-to-week variation in the random sampling of plants.

NUTRIENT UPTAKE RATIO. Nutrient uptake ratios are a method of comparing nutrient uptake levels (Clark, 1990; Tsujita, 1992). The ratio is the amount of a nutrient taken up by the plant divided by the amount of the element that was available during the week. The peaks in uptake ratios with the 100-mg·L⁻¹ N and K fertilization rate indicate that the plants used a higher percentage of the available NO₃-N, NH₄-N, K, P, and Ca (Fig. 4 A-E) at that rate. The highest uptake ratios for NO₃-N, NH₄-N, and K occurred during weeks 8 through 12 and for P during weeks 4 through 13. Fertilization rate did not affect the uptake ratio of Mg, with uptake ratio <14% (data not shown). The uptake ratios of between 80% to 100% for the available NH₄-N and P at the 100-mg·L⁻¹ N and K fertilization rate indicates the plants used a majority of the available NH₄-N and P and higher application rates may be appropriate when adapting rates for plants being grown in soilless root medium.

PLANT TISSUE NUTRIENT CONCENTRATION. Tissue NH₄-N concentration was significantly different by the week × tissue type × fertilizer application rate (100, 200, or 300 mg·L⁻¹ N and K)

Fig. 5. Concentration of NH₄-N in (A) leaf, (B) stem, and (C) root tissue by fertilizer rate over time. Significant at $P \leq 0.05$ for the tissue NH₄-N concentration for the fertilizer × week comparison. LSD ($\alpha = 0.05$) is 0.35. Plants were pinched at the end of week 3 (after data was recorded), short days began after week 5, and anthesis occurred on week 14. Mean of five replications.

Table 1. Regression coefficients of models for leaf, stem, and root dry mass accumulation of poinsettia plants over the 15-week production period. Dependent variable = $\ln(\text{dry mass} \times 1000)$.

Independent variable	Fertilizer rate (mg·L ⁻¹ of N-P-K)		
	100-15-100	200-30-200	300-46-300
Leaf tissue			
Intercept	6.94***	6.98***	7.01***
Week	0.1727***	0.1584***	0.1540***
R ²	0.9018	0.8456	0.8764
Regression F statistic	670.34	399.80	517.76
Stem tissue			
Intercept	5.40***	5.50***	5.43***
Week	0.2943***	0.2726***	0.2782***
Week ²	-0.0075***	-0.0074***	-0.0079***
R ²	0.9135	0.8675	0.8855
Regression F statistic	380.13	235.76	278.47
Root tissue			
Intercept	5.63***	5.67***	5.67***
Week	0.3796***	0.3565***	0.3550***
Week ²	-0.0142***	-0.0131***	-0.0129***
R ²	0.8480	0.8455	0.8632
Regression F statistic	200.90	197.02	227.22

***Significant at $P \leq 0.001$. Mean of five replications.

interaction. The concentration of $\text{NH}_4\text{-N}$ increased for the first 4 to 6 weeks for all three tissue types (Fig. 5 A-C), with the leaf and root tissue concentrations of 3% to 4.5% exceeding that of the stem concentration of 2% to 3%. For all tissue types, $\text{NH}_4\text{-N}$ concentration was lowest with the 100-mg·L⁻¹ N fertilization rate and increased with the 200- and 300-mg·L⁻¹ N fertilization rates. Recommendations for nutrient analysis involve sampling only the most recently matured leaves. The method used in this study involved dividing the entire plant into leaf, stem, and root portions, which made calculations of total-plant nutrient content possible, but may dilute the nutrient concentration values that can be used to compare with other studies (Rose et al., 1994; Tsutsui and Aoki, 1981). Even with the sampling method used, leaf $\text{NH}_4\text{-N}$ concentration levels for all three fertilizer rates were above the critical level of 3.5% (Ecke et al., 1990). Marketable poinsettias were also produced with shoot N concentrations above 3.0% for 'Celebrate 2' and 'Lilo' plants grown with 100 and 200 mg·L⁻¹ of N (Rose, 1993).

Tissue nutrient concentration of P, K, Ca, Mg, Na, B, Cu, Fe, Mn, Mo, and Zn were significantly different only by week and tissue type (leaf, stem, and root) interaction, but not by fertilizer application rate (data not shown). Tissue P concentration was not affected by increases in the P fertilization rate from 15 to 30 and to 46 mg·L⁻¹ P. Tissue P concentration increased in the leaves during the vegetative stage and in the roots and stems during the vegetative and inductive stages. Leaf P concentration decreased to 1.3% during the bract development stage, while the root and stem P concentration remained stable. Leaf P concentration levels during weeks 2 to 15 were >1.3%, which is higher than the normal range of 0.3% to 0.6% recommended by Ecke et al. (1990) and exceeds what they considered to be the toxic level of 0.9%. Leaf P concentrations of 0.85% to 1.29% were also reported for 'Gutbier V-14 Glory' poinsettias grown with four irrigation methods and N levels of 175 or 250 mg·L⁻¹ (Dole et al., 1994). 'Annette Hegg Dark Red' and 'Red Sails' poinsettias grown with 0.18 kg P/m³ supplied from either triple superphosphate or superphosphate incorporated

Table 2. Regression coefficients of models for macronutrient content of poinsettia plants over the 15-week production period.

Independent variable	$\text{NH}_4\text{-N}$ (mg)	P (mg)	K (mg)	Ca (mg)	Mg (mg)	Na (μg)
Intercept	30.54*** (6.477) ^c	5.49* (2.126)	37.10*** (4.459)	24.01*** (12.345)	9.34*** (11.543)	20116.00*** (5.133)
Week	21.54*** (14.768)	8.70*** (10.878)	17.96*** (6.977)	5.99*** (9.766)	3.10*** (12.152)	5065.51*** (4.179)
Week ²	1.23*** (13.085)	0.34*** (6.563)	1.33*** (8.040)	0.31*** (7.921)	0.17*** (10.656)	363.10*** (4.658)
Rate ₂₀₀ × week	NS	NS	NS	-1.87*** (-9.187)	-0.96*** (-11.310)	NS
Rate ₃₀₀ × week	NS	NS	NS	-3.08*** (-15.137)	-1.55*** (-18.307)	NS
R ²	0.9959	0.9897	0.9861	0.9878	0.9927	0.9608
Adjusted R ²	0.9957	0.9892	0.9855	0.9866	0.9920	0.9591
Regression F statistic	5484.575	2152.694	1594.441	867.316	1457.231	552.036

^cValues for *t* statistic given in parentheses.

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

Fig. 6. Regression line model of weekly plant Ca content by fertilizer rate. Plants were pinched at the end of week 3, short days began after week 5, and anthesis occurred on week 14. $Ca_{100} = 24.01 + 5.99 \text{ Wk} + 0.31 \text{ Wk}^2$, $Ca_{200} = 24.01 + 4.12 \text{ Wk} + 0.31 \text{ Wk}^2$, $Ca_{300} = 24.01 + 2.91 \text{ Wk} + 0.31 \text{ Wk}^2$. The adjusted R^2 was 0.9866.

into the root medium also had $>0.9\%$ P in the leaf tissue (Eddy, 1994). This suggests that the acceptable range for P in poinsettia tissue can exceed 0.9%.

PLANT TISSUE NUTRIENT MODELING. The regression line models for the leaf, stem, and root tissue dry mass transformed by the natural log are presented in Table 1. Only the week class variable was significant for estimating leaf tissue dry mass. The leaf tissue dry mass model accounted for between 84% and 90% of the sample variation, with the 100-mg-L⁻¹ N and K fertilization rate having the highest R^2 . Both week and week² class variables were significant for estimating stem and root tissue dry mass. The 100-mg-L⁻¹ N and K fertilization rate had the highest R^2 of 0.91 for stem tissue dry mass, while for the root tissue the highest R^2 of 0.86 was the 300-mg-L⁻¹ N and K fertilization rate.

The regression line models for total plant macronutrient content over time are presented in Table 2. The macronutrient models for NH₄-N, P, K, Ca, Mg, and Na all accounted for $\geq 96\%$ of the sample variation. There were no significant differences among the three fertilizer rates when the total plant nutrient content was modeled for NH₄-N, P, or K. The class variables week and week² were significant for the NH₄-N, P, and K models, accounting for 99%, 98%, and 98%, respectively, of the variation in the total-plant NH₄-N, P, and K content. The similar NH₄-N, P, and K content as the fertilizer rate increased indicates little or no luxury consumption occurred. Similar results for N in poinsettias were reported by Rose et al. (1994) and Tsutsui and Aoki (1981).

Week, fertilization rate $\times$ week, and week² variables were significant in the models for Ca and Mg, with total-plant Ca and Mg contents decreasing as the N-P-K fertilization rate increased (Figs. 6 and 7). High ratios of NH₄-N to NO₃-N have been reported to limit plant growth (Gaffney et al.,

1982), cause bract necrosis of poinsettias, and decrease Ca content (Nell and Barrett, 1985; Woltz and Harbaugh, 1985), but for this study the percentage of N supplied in the NH₄-N form was $<25\%$. Competition from K has also been reported to decrease Ca content in poinsettias (T. Blom and W. Brown, unpublished data; Stromme et al., 1994) and Mg content (Cox and Seeley, 1980, 1984; Mengel and Kirkby, 1978). The K to Ca ratios used in this study were 1:1, 2:1, and 3:1, which corresponded to the three K fertilization rates of 100, 200, and 300 mg-L⁻¹ K and a Ca rate of 100 mg-L⁻¹, respectively. T. Blom and W. Brown (unpublished data) reported that increasing the K to Ca ratio from 1:1 to 4:1 decreased bract Ca in 'Supjibi' poinsettia plants from 0.57% to 0.37%. This suggests the common practice of applying K at the rate of 250 to 300 mg-L⁻¹ at every watering (Berghage et al., 1987; Ecke et al., 1990) has a negative effect on the Ca level in poinsettias and can contribute to the incidence of bract necrosis.

The regression line models for total plant micronutrient content over time are presented in Table 3.

The micronutrient models for B, Cu, Fe, and Mn accounted for $>93\%$ of the sample variation, while models for Mo and Zn accounted for 90% and 80%, respectively, of the variation. The sample variation for the micronutrients were accounted for with one of two types of models. The best fit model for B, Cu, and Mo included only the week and week² variables. The best fit models for Fe and Mn included the week, week², and fertilization rate $\times$ week variables. The best fit models for Zn included the week and fertilization rate $\times$ week variables. Increases in the N-P-K fertilization rate resulted in an increase in the total plant Fe content (Fig. 8), while Mn (Fig. 9) and Zn (Fig. 10) contents decreased.

Increasing the N fertilization rate from 175 to 250 mg-L⁻¹ resulted in an increase in leaf Fe concentration for 'Gutbier V-14

Fig. 7. Regression line model of weekly plant Mg content by fertilizer rate. Plants were pinched at the end of week 3, short days began after week 5, and anthesis occurred on week 14. $Mg_{100} = 9.34 + 3.10 \text{ Wk} + 0.17 \text{ Wk}^2$, $Mg_{200} = 9.34 + 2.14 \text{ Wk} + 0.17 \text{ Wk}^2$, $Mg_{300} = 9.34 + 1.55 \text{ Wk} + 0.17 \text{ Wk}^2$. The adjusted R^2 was 0.9920.

Table 3. Regression coefficients of models for micronutrient content of poinsettia plants over the 15 week production period.

Independent variable	B (μg)	Cu (μg)	Fe (μg)	Mn (μg)	Mo (μg)	Zn (μg)
Intercept	249.03** (3.154) ^c	74.09** (2.780)	4547.99*** (5.698)	-402.10 (-0.254)	-5.39 (-0.051)	5401.55*** (10.735)
Week	72.54** (2.970)	-9.06 (-1.099)	1844.03*** (7.331)	6255.40*** (12.541)	34.74 (1.159)	918.41*** (12.913)
Week ²	11.91*** (7.580)	4.32*** (8.153)	37.52* (2.363)	-139.98*** (-4.446)	9.21*** (4.365)	NS
Rate ₂₀₀ × week	NS	NS	255.00** (3.055)	-533.35*** (-3.222)	NS	-299.67*** (-4.087)
Rate ₃₀₀ × week	NS	NS	455.53*** (5.457)	-915.28*** (-5.530)	NS	-302.27*** (-4.123)
R ²	0.9723	0.9416	0.9751	0.9524	0.9030	0.8037
Adjusted R ²	0.9711	0.9390	0.9728	0.9480	0.8987	0.7903
Regression F statistic	789.414	362.679	421.419	215.174	209.398	60.054

^aValues for *t* statistic given in parentheses.

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

Glory' poinsettias (Dole et al., 1994). Potassium and NO₃-N have been reported to have competitive effects on Fe, while Fe uptake is enhanced by NH₄-N (Lingle et al., 1963; Sideris and Young, 1956). In this study, NH₄-N levels were increased from 18, 50 and 75 mg·L⁻¹, respectively, for the 100, 200, and 300-mg·L⁻¹ N fertilization rates and may account for the increased Fe content.

Competition from other cations has been associated with decreased uptake of Mn, while Zn can be affected by other cations and high P levels (Mengel and Kirkby, 1978). The increased application rate of K and P at 300 and 46 mg·L⁻¹, respectively, may account for the decreased total plant Mn and Zn content.

The weekly nutrient uptake based on the regression line models of total plant nutrient content for each element at the 100N-15P-100K-mg·L⁻¹ fertilization rate was calculated for the entire 15-week production period (Table 4). The amount of weekly uptake

increased over time for N, P, K, Ca, Mg, B, Cu, Fe, and Mo. Weekly nutrient uptake declined over time with Mn and remained at the same level with Zn. The weekly uptake rates based on the nutrient content are the amount of nutrients that were incorporated into the plant and the values can be used as the basis of recommending fertilization rates for poinsettia growers.

Conclusions

Results of this study indicate that varying fertilization rates did not significantly influence the leaf, stem, or root tissue nutrient concentration of P, K, Ca, Mg, Na, B, Cu, Fe, Mn, Mo, and Zn in poinsettia. The NH₄-N concentration in the leaves, stems, and roots was lowest with the 100-mg·L⁻¹ N fertilization rate and increased as the N application rate increased to 200 and 300 mg·L⁻¹. Even though there was a difference in leaf NH₄-N concentration among the three fertilizer rates, all values were above the critical level for N of 3.5% recommended by Ecke et al. (1990).

When the plant tissue dry mass for each fertilizer rate were transformed by the natural log and multiplied by the mean tissue nutrient concentration of each fertilizer rate, there were no significant differences among the three fertilization rates when the total plant nutrient content was modeled for N, P, or K. Increasing the fertilizer application rate above 100 mg·L⁻¹ N and K and 15 mg·L⁻¹ P resulted in a decreased total plant content of Ca, Mg, Mn, and Zn while increasing the total plant Fe content.

The uptake ratios for NO₃-N, K, Ca, and Mg all were <50% of the amount that was available at the 100-mg·L⁻¹ N and K fertilization rate. The level of nutrients provided by the 100 mg·L⁻¹ N and K fertilization rate in this study were adequate for plant growth. The high uptake ratios for the available NH₄-N and P at the 100-mg·L⁻¹ N and K fertilization rate of 80% to 100% indicated that the plants used most of the available nutrients and that application rates higher than 18 mg·L⁻¹ NH₄-N and 15 mg·L⁻¹ P are required for poinsettias during the period of time between the inductive and bract development stages of growth. To compensate for the higher NH₄-N

Fig. 8. Regression line model of weekly plant Fe content by fertilizer rate. Plants were pinched at the end of week 3, short days began after week 5, and anthesis occurred on week 14. $\text{Fe}_{100} = 4547.99 + 1844.03 \text{ Wk} + 37.52 \text{ Wk}^2$. $\text{Fe}_{200} = 4547.99 + 2099.03 \text{ Wk} + 37.52 \text{ Wk}^2$. $\text{Fe}_{300} = 4547.99 + 2299.56 \text{ Wk} + 37.52 \text{ Wk}^2$. The adjusted R² was 0.9728.

Fig. 9. Regression line model of weekly plant Mn content by fertilizer rate. Plants were pinched at the end of week 3, short days began after week 5, and anthesis occurred on week 14. $Mn_{100} = -402.10 + 6255.40 \text{ Wk} - 139.98 \text{ Wk}^2$, $Mn_{200} = -402.10 + 5722.05 \text{ Wk} - 139.98 \text{ Wk}^2$, $Mn_{300} = -402.10 + 5340.12 \text{ Wk} - 139.98 \text{ Wk}^2$. The adjusted R^2 was 0.9480.

requirement, the percentage of N supplied by $\text{NH}_4\text{-N}$ should be increased, but to levels <33% as recommended by Ecke et al. (1990) and Nell and Barrett (1985).

The recommendation of 250 to 300 $\text{mg}\cdot\text{L}^{-1}$ N and K at every watering for poinsettias when grown in soilless root medium (Berghage et al., 1987; Ecke et al., 1990) is excessive during the early stages of plant growth. The results of the weekly nutrient uptake based on the total plant nutrient content in this study, suggests that weekly fertilization rates should increase over time from potting until anthesis. Rates (in mg) that increase from 23 to 57 for N (with 33% of the total N supplied in the $\text{NH}_4\text{-N}$ form), 9 to 18.5 for P, 19 to 57 for K, 6 to 15 for Ca, and 3 to 8 for Mg can be applied without leaching to poinsettias and produce adequate growth in the northern United States.

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Fig. 10. Regression line model of weekly plant Zn content by fertilizer rate. Plants were pinched at the end of week 3, short days began after week 5, and anthesis occurred on week 14. $Zn_{100} = 5401.55 + 918.41 \text{ Wk}$, $Zn_{200} = 5401.55 + 618.74 \text{ Wk}$, $Zn_{300} = 5401.55 + 616.14 \text{ Wk}$. The adjusted R^2 was 0.7903. Regression estimates for Zn_{200} and Zn_{300} overlap.

Table 4. Weekly^z nutrient uptake based on total plant content over the 15-week production period.

Week	Development stage	NH ₄ -N (mg)	P (mg)	K (mg)	Ca (mg)	Mg (mg)	B (μg)	Cu (μg)	Fe (μg)	Mn (μg)	Mo (μg)	Zn (μg)
1	Vegetative	22.8	9.0	19.3	6.3	3.3	84	-5	1882	6115	44	918
2	Vegetative	25.2	9.7	22.0	6.9	3.6	108	4	1957	5835	62	918
3	Vegetative	27.7	10.4	24.6	7.5	4.0	132	13	2032	5556	81	918
4	Vegetative	30.1	11.1	27.3	8.1	4.3	156	21	2107	5276	99	918
5	Vegetative	32.6	11.7	29.9	8.7	4.6	180	30	2182	4996	118	918
6	Inductive	35.0	12.4	32.6	9.4	5.0	204	38	2257	4716	136	918
7	Inductive	37.5	13.1	35.3	10.0	5.3	227	47	2332	4436	154	918
8	Inductive	39.9	13.8	37.9	10.6	5.7	251	56	2407	4156	173	918
9	Inductive	42.4	14.4	40.6	11.2	6.0	275	64	2482	3876	191	918
10	Bract	44.9	15.1	43.2	11.8	6.4	299	73	2557	3596	210	918
11	Bract	47.3	15.8	45.9	12.4	6.7	323	82	2632	3316	228	918
12	Bract	49.8	16.5	48.6	13.0	7.0	346	90	2707	3036	246	918
13	Bract	52.2	17.1	51.2	13.6	7.4	370	99	2782	2756	265	918
14	Bract	54.7	17.8	53.9	14.3	7.7	394	108	2857	2476	283	918
15	Bract	57.1	18.5	56.6	14.9	8.1	418	116	2932	2196	302	918
Mean		39.9	13.8	37.9	10.6	5.7	251	56	2407	4156	173	918

^zWeekly values based on the nutrient content of plants grown with the 100N-15P-100K mg·L⁻¹ fertilization rate. Plants were pinched at the end of week 3, short days began after week 5, and anthesis at week 14.

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