Timing of Macronutrient Supply during Cutting Propagation of *Petunia*

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Abstract. The objective was to quantify the effect of the timing of macronutrient applications on nutrient uptake, growth, and development of *Petunia ×hybrida* Hort. Vilm.-Andr. ‘Supertunia Royal Velvet’ during vegetative propagation. Starting with unrooted cuttings (Day 0), fertigation was applied continuously at three time intervals (Day 0 to 7, Day 8 to 14, or Day 15 to 21) using either a “complete” (C) water-soluble fertilizer containing (in mg·L⁻¹) 75 NO₃-N, 25 NH₄-N, 12 phosphorus (P), 83 potassium (K), 20 calcium (Ca), 10 magnesium (Mg), 1.4 sulfur (S), 2 iron (Fe), 1 manganese (Mn), 1 zinc (Zn), 0.5 copper (Cu), 0.5 boron (B), and 0.2 molybdenum (Mo) or a micronutrient fertilizer (M) containing (in mg·L⁻¹) 1.4 S, 2 Fe, 1 Mn, 1 Zn, 0.5 Cu, 0.5 B, and 0.2 Mo in a complete factorial arrangement. With constant fertigation using the C fertilizer, plant dry weight (DW) doubled from Day 0 (sticking of unrooted cuttings) to Day 7 (0.020 g to 0.047 g), root emergence was observed by Day 4, and by Day 7, the average length of primary roots was 2.6 cm. During any week that the M fertilizer was substituted for the C fertilizer, tissue N–P–K concentrations decreased compared with plants receiving the C fertilizer. For example, plants receiving the M fertilizer between Day 0 and 7 had 20% lower tissue-N concentration at Day 7 compared with those receiving the C fertilizer. Although both shoot DW and leaf count increased once macronutrient fertilization was resumed after Day 7, final shoot DW and leaf count were lower than plants receiving C fertilizer from Day 0 to 21. Time to first root emergence was unaffected by fertigation. Constant application of C resulted in a higher shoot-to-root ratio at Day 21 than all other treatments. Results emphasize the importance of early fertigation on petunia, a fast-rooting species, to maintain tissue nutrient levels within recommended ranges.

Appropriate timing and concentration of nutrient supply in vegetative cutting propagation affects root development, uniformity of plant growth, uptake efficiency [(nutrient taken up/total nutrient applied–nutrients in substrate)*100], nutrient runoff, and transplant success. Root development can be divided into four stages: 1) cutting condition at “sticking” (insertion) into substrate; 2) callus formation; 3) root development; and 4) toning (Dole and

Gibson, 2006). Fertigation recommendations for vegetative cuttings are currently correlated with root developmental stages with a recommended initial application of 50 to 75 mg N/L at visible callus development (Stage 2) and subsequent applications of 100 mg N/L after root emergence (i.e., during Stage 3) (Dole and Gibson, 2006). Nutrient availability in the substrate becomes particularly important for uptake at Stage 3 after root emergence. Nutrients can be supplied to vegetative cuttings through a combination of preplant dry fertilizers in the substrate, supplemental application of water-soluble fertilizer, and/or incorporation of controlled-release fertilizers. Historically, fertilization through overhead mist was not recommended for short-term crops as a result of the potential for clogged emitters and algae growth (Dole and Gibson, 2006).

Based on a survey of eight U.S. commercial greenhouses, the concentration of fertilizer solutions applied during the propagation of vegetative petunia and calibrachoa cuttings

ranged from 0.5 to 80 and 64 to 158 mg·L⁻¹ N for 7 and 28 d after sticking into substrate, respectively (Santos et al., 2008). Timing of fertigation varied from constant application of N for 28 d to application of N 14 d after sticking (Santos et al., 2008). The variation in observed practices at these operations suggests that the current recommended fertilization strategies may need to be refined with further consideration of fertilizer timing and N concentration.

Mist irrigation is intended to maintain cutting turgidity during root development and often water is supplied in excess of evapotranspiration loss and container capacity (representing the volume of water held in a drained substrate) resulting in the potential for rapid leaching of fertilizer (Kerr and Hanan, 1985; Mudge, 1995; Santos et al., 2008). Propagators surveyed leached as much as 46 L·m⁻² in a 4-week crop cycle and six of eight operations leached over one container capacity during the same period (Santos et al., 2008). Nutrient leaching as a consequence of mist application during propagation is significant because soilless substrates have a limited ability to retain nutrients, especially when total leaching rates are greater than one container capacity (Biernbaum et al., 1995; Kerr and Hanan, 1985). During Stages 1 and 2 of root development, the loss of nutrients from leaching could deplete the substrate of nutrients by Stage 3 (root emergence), a critical stage for nutrient replenishment for the cutting. Therefore, commercial fertilizer application early in propagation before root formation may be required to recharge leached nutrients from the substrate. Water-soluble fertilizer applications before root emergence may also facilitate foliar uptake of nutrients (Tukey et al., 1958) and reduce observed tissue nutrient declines during preliminary phases of propagation (Svenson and Davies, 1995; Wilkerson and Gates, 2005).

Timing the supply of fertilizer to meet plant requirements at different root developmental stages has the potential to increase uptake efficiency and reduce nutrient runoff. Macronutrients, in absolute terms, are required in higher quantities compared with micronutrients only. Therefore, plant response to macronutrient supply is of particular interest before significant root growth (Phases 1 and 2 of rooting). The objective of this research was to evaluate the effect of timing of macronutrient supply on growth and nutrient uptake of petunia cuttings at 0 to 7, 8 to 14, and 15 to 21 d after sticking, in which these time periods correspond to mist fertigation during callus and root initial formation from Days 0 to 7 followed by hand fertigation during the root growth phase from Days 8 to 21.

Materials and Methods

The experiment was conducted at the University of Florida, Environmental Horticulture Research Greenhouse Complex in Gainesville, FL, from 27 Mar. 2007 to 18 Apr. 2007. Greenhouse and irrigation management were controlled by an environmental control system (Hortimax, Pijnacker, The Netherlands).

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Unrooted cuttings of *Petunia ×hybrida* Hort. Vilm.-Andr. ‘Supertunia Royal Velvet’ were air-freighted over 2 d from an off-shore vegetative cutting supplier, InnovaPlant in Costa Rica. Cuttings were immediately inserted into 21 × 50 cm, 102-count (19.6 mL/cell) propagation trays filled with 70% peat/30% perlite (by volume) substrate containing 2.1 kg·m⁻³ hydrated lime and 0.14 L·m⁻³ wetting agent (AquaGro 2000 M, Aquatrols, NJ). Substrate container capacity was 2.3 L/tray. The experimental unit was defined as an individual (21 × 50 cm; 102 count) propagation tray.

Mist was provided by bench risers fitted with 1.2 L·min⁻¹ JetRain nozzles (Dramm, Manitowac, WI) spaced 91.4 cm apart and alternated 30.5 cm and 40.6 cm above the crop until roots reached the side and bottom of each cell (14 d after sticking). Mist frequency was adjusted according to light, temperature, and root development stages. Average light levels were 216.4 μmol·m⁻²·s⁻¹ per day with average temperatures of 23 °C during the day and 19 °C at night. Before significant root growth (root length less than 3 cm), the mist frequency was every 17 to 28 min for 5 s triggered by an accumulated light threshold of 200 mmol·m⁻² of photosynthetically active radiation light. After root length was greater than 3 cm, the light threshold was increased to 500 mmol·m⁻² resulting in a mist frequency of every 50 to 60 min for 5 s.

Constant fertigation with a “C” water-soluble fertilizer containing (in mg·L⁻¹) 75 NO₃-N, 25 NH₄-N, 12 P, 83 K, 20 Ca, 10 Mg, 1.4 S, 2 Fe, 1 Mn, 1 Zn, 0.5 Cu, 0.5 B, and 0.2 Mo combined with a deionized water source was supplied through the mist system for the first 2 weeks and by hand for the last week (27 Mar. 2007 to 18 Apr. 2007). Fertilizer salts used were ammonium nitrate, ammonium phosphate, calcium nitrate, magnesium nitrate, potassium nitrate, boric acid, copper sulfate, iron EDDHA, manganese sulfate, sodium molybdate, and zinc sulfate. For Days 7, 14, and/or 21, as shown in Table 1, the alternative fertilizer treatment (“M”) contained only the micronutrient salts of the C fertilizer and was considered the control. Clear water was not used as the control because the objective was to evaluate the effect of macronutrient fertilizer supply only on growth and tissue nutrient trends in petunia. After 14 d, cuttings were irrigated with the fertilizer solutions twice

a week (i.e., with the same frequency for all treatments) by hand using a hose fitted with a 1000PL water breaker (Dramm) for the remaining 7 d. Fertilizer solutions were pumped from separate 378.6-L stock tanks beneath each bench. Irrigation volume applied was 4.0 and 2.3 L for 7 and 14 to 21 d after sticking, respectively, resulting in total leaching of 1.1 cc over 3 weeks. Average volume leached was 1.2 and 0.7 L per experimental unit 7 and 14 to 21 d after sticking, respectively.

The experiment was divided into four blocks, each consisting of the eight treatments described in Table 1. At the start of the experiment, each block contained six replicate trays per treatment combination. Two experimental units (trays) per treatment were collected from each block on each measurement date (0, 7, 14, and 21 d after sticking) and destructively sampled (n = 8).

Data were analyzed using Proc GLM in SAS (Version 9.1; SAS Institute, Cary, NC) as a randomized complete block design with each block consisting of varying intervals of C and M treatments. A separate analysis of variance was run for each measurement date, because the treatment combinations changed over time (C and M at Day 7, CC, CM, MC, and MM at Day 14, etc.). Means were analyzed using Tukey’s honestly significant difference test at *P* ≤ 0.05. Data collected from each experimental unit included SPAD chlorophyll index (Minolta SPAD 502; Spectrum Technologies, Plainfield, IL), number of leaves per cutting, plant height, longest root length, rooting stage, dry weight, and shoot and root tissue samples for nutrient analysis. Rooting stage for each treatment was determined using a rooting scale defined by Dole and Gibson (2006).

Tissue N concentration was measured as total Kjeldahl N where protein was converted to NH₄ using heat, a catalyst, sulfuric acid, and hydrogen peroxide. The sample was then run on a spectrophotometer (DR 4000; Hach, Loveland, CO) using Nesslerization for N determination. A Hach Digestahl apparatus was used for the conversion (digestion) and a spectrophotometer (DR 4000) for the analysis. Analysis of P, K, Ca, Mg, Na, Fe, Mn, Zn, Cu, B, and Mo was accomplished by dry ashing digestion followed by inductively coupled plasma (ICP) emission spectrometry by Quality Analytical Laboratories (Panama

City, FL) using a ICAP 61E (Thermo-Jarrell Ash, Franklin, MA). Samples consisted of either the total cuttings 7 d after sticking to provide sufficient tissue for complete nutrient analysis or separated roots and shoots 14 and 21 d after sticking. Cutting nutrient content was calculated by multiplying cutting dry weight in milligrams by the decimal fraction of the percent N, P, or K, respectively, and nutrient uptake was calculated by subtracting grams of N, P, or K on Day 0 from the measurement date (milligrams of N, P, or K on Day 7, 14, or 21).

Two additional experimental units per bench were randomly selected every 7 d (4, 7, and 18 Apr. 2007) for substrate and leachate nutrient sampling. The plug press method was used to sample substrate by pressing down firmly on the top of the substrate surface and the solution was collected from the hole at the bottom of the pressed plug cell (Scoggins et al., 2002). Solution leached from the propagation trays was measured in collection trays following the protocol described by Santos et al. (2008). Solutions were submitted for nutrient analysis using ICP to measure P, K, Ca, Mg, S, Fe, Mn, B, Cu, Zn, Mo, aluminum, and sodium. The leachate and substrate solution samples were analyzed for NO₃-N and ammonium (NH₄) N using a Lachat QuikChem AE (Lachat Instruments, Loveland, CO), and total N was calculated as NO₃-N plus NH₄.

Results and Discussion

Shoot and root growth. Macronutrient supply (C) during the first 7 d of production increased total dry weight by 21 d after sticking compared with fertilization with M during the first 7 d (Table 2; Fig. 1A). There was 100% rooting in all treatments with all cuttings tested at rooting Stage 2 (visible callus formation) on Day 4 and root development (Stage 3) occurring from Day 5 onward. At Day 7, total dry weight therefore consisted primarily of shoots only (roots were too small to separate and measure dry weight accurately). Total dry weight for plants receiving M treatments did not differ from constant C dry weight until 21 d after sticking, at which point treatments CMM, CMC, CCM, and CCC were consistently higher in total dry weight than other treatments (MMM, MMC, MCM, and MCC).

Shoot dry weight increased by Day 7 from 0.020 to 0.042 g/cutting; however, there was no difference in shoot dry weight between C and M plants (Table 2; Fig. 1A). Continued fertigation with the C fertilizer resulted in increased shoot dry weight compared with M supply by Days 14 and 21 (Table 2; Fig. 1B). Shoot dry weight was greater in CC (0.064 g/cutting) compared with that of treatments that received MC (0.051 g/cutting). The lowest shoot DWs at 21 d after sticking were found in MMM or MMC plants (0.069 or 0.065 g/cutting), respectively (Fig. 1B).

Continued application of C fertilizer at 21 d after sticking (CCC) resulted in reduced root DW compared with macronutrient supply during the first 7 d only (the CMM treatment; Fig. 1C). Treatments did not affect root length

Table 1. Fertilization treatments applied to *Petunia ×hybrida* over a 21-d crop cycle.^a

Treatment	0 to 7 days	8 to 14 days	15 to 21 days	Code
1	C	C	C	CCC
2	C	C	M	CCM
3	C	M	M	CMM
4	C	M	C	CMC
5	M	M	M	MMM
6	M	M	C	MMC
7	M	C	C	MCC
8	M	C	M	MCM

^a“C” represents constant fertigation with a “complete” water-soluble fertilizer containing (in mg·L⁻¹) 75 NO₃-N, 25 NH₄-N, 12 phosphorus (P), 83 potassium (K), 20 calcium (Ca), 10 magnesium (Mg), 1.4 sulfur (S), 2 iron (Fe), 1 manganese (Mn), 1 zinc (Zn), 0.5 copper (Cu), 0.5 boron (B), and 0.2 molybdenum (Mo). “M” represents fertilization with micronutrients only (1.4 S, 2 Fe, 1 Mn, 1 Zn, 0.5 Cu, 0.5 B, and 0.2 Mo). Treatment labels used in the text (listed under the “Code” column) are made up of three letters, in which the first letter corresponds to the fertilizer treatment on Week 1, the second letter for Week 2, and so forth.

Table 2. Analysis of variance summary of *P* values for fertilizer treatment effects on cumulative cutting dry weights and tissue nitrogen percent, content, and uptake per week from combined roots and shoots.^z

Variable	Time period		
	0 to 7 days	8 to 14 days	15 to 21 days
Root dry weight (g/cutting)	NA	0.2314	<0.0001
Shoot dry weight (g/cutting)	0.4165	0.0169	<0.0001
Total dry weight (g/cutting)	0.4165	0.1591	<0.0001
Shoot:root dry weight ratio	NA	0.0002	<0.0001
Tissue N concentration (mg/cutting)	0.0012	<0.0001	<0.0001
Tissue N content (mg/cutting)	0.0029	<0.0001	<0.0001
Tissue N uptake (mg/cutting per week)	0.0119	0.0004	0.0011

^zRoot growth was sufficient to measure root dry weight from Day 14 onward. Treatment labels are made up of one, two, or three letters, in which the first letter corresponds to the fertilizer treatment on Week 1, the second letter for Week 2, and so forth. For the period 0 to 7 days, treatment combinations were M (micronutrients only) and C (complete fertilizer). For the period 8 to 14 days, treatment combinations included MM, MC, CM, and CC; and for the period 15 to 21 days, MMM, MMC, MCM, MCC, CMM, CMC, CCM, and CCC. Least square means data are summarized in Figure 1 for dry weights and Figure 2 for tissue nitrogen.

NA = not applicable.

Fig. 1. Measured total dry weight (A), shoot dry weight (B), root dry weight (C), and shoot:root ratio (D) per cutting over time. Root dry weight was measured when root length was greater than 3 cm, corresponding to 14 d after sticking. Root emergence began at Day 4, regardless of treatment. Roots were not separated from shoots until 14 d after sticking. White bars correspond to each data collection interval and treatment calculated from the average of eight randomly selected trays (two trays per block) divided by the number of cuttings per tray (102). “C” represents the “complete” fertilizer treatment and “M” represents the micronutrient fertilizer treatment during a given week. Treatment labels are made up of one, two, or three letters, in which the first letter corresponds to the fertilizer treatment on Week 1, the second letter for Week 2, and so forth. Means were separated within each date using Tukey’s honestly significant difference test at $P \leq 0.05$.

($P = 0.767$ at Day 14 and 0.105 on Day 21) and average root length increased to 2.6, 12.2, and 17.9 cm/cutting by 7, 14, or 21 d after sticking, respectively.

For commercial production of rooted cuttings, a low shoot-to-root (S:R) ratio is desirable to reduce shipping costs, the need for chemical growth regulator application, and crop produc-

tion time required to produce a well-rooted, compact plant. Increasing the duration of C fertilization increased the S:R (Fig. 1D). The S:R ratio at Day 14 was higher in CC plants (4.5) compared with plants that received the other three treatments (which averaged 3.2). The S:R ratio continued to be highest at 21 d in the CCC treatment (4.1) compared with an average of 2.4 for the other seven treatments.

Constant C fertilizer application increased shoot height and leaf number (Table 3). Plant height averaged 1.7 cm to 2.1 cm/cutting and leaf number was 4.2 or 5.4 leaves/cutting on Days 0 and 7, respectively, regardless of fertilizer treatment. At 14 d, cuttings that received the CC treatment were taller than (4.5 cm) the cuttings that received the MM treatment (3.5 cm). At 21 d, CCC plants were the tallest of all treatments (8.3 cm) and MMM were the shortest (3.6 cm). Leaf number was highest in CC plants (8.1 leaves/cutting), whereas treatments CM or MC had the lowest leaf counts (6.5 leaves/cutting) after 14 d. After 21 d, leaf number remained highest in CCC or CCM plants (10.7 or 10.4 leaves/cutting). The lowest leaf counts were observed in plants receiving the MMM (7.0 leaves/cutting) or MMC (7.2 leaves/cutting) treatments. Treatments affected SPAD chlorophyll index only at 14 d after sticking ($P < 0.0001$), but with only a small range in SPAD index values [highest in MC plants (32.7) and lowest in CM (28.7)].

Nutrient concentration. Tissue nutrient concentration decreased from Day 0 to 7 in plants from all fertilizer treatments (Fig. 2A). With continuous application of the C fertilizer, tissue-N concentration dropped from 6.6% on Day 0 to 4.8% on Day 7, 5.0% on Day 14, and 4.3% on Day 21 (Fig. 2A). Percent P and K concentrations followed a similar trend to N under constant application of C with decreasing nutrient concentrations over the first 14 d followed by stable to slightly increasing concentrations (data not shown).

A greater decline in tissue nutrient concentration occurred during the first week when M was provided (Table 2; Fig. 2A). Cuttings that received M had 3.7% N, 0.3% P, and 2.7% K (1.6, 0.10, and 1.1 mg/cutting) at Day 7 compared with 4.8% N, 0.5% P, and 3.7% K (2.0, 0.20, and 1.5 mg/cutting) with the C fertilizer. The initial decrease in tissue nutrient concentrations could be attributed to dilution that resulted from an increase in total DW in conjunction with minimal uptake of nutrients (Blazich, 1988). Nutrients leached from the foliage, a phenomenon observed by Good and Tukey (1967), was not a factor in the initial tissue nutrient decline because a net loss of N per cutting was not observed during the first 7 d of propagation (Fig. 2B).

Application of C nutrient supply at any week in the crop cycle resulted in increased tissue N–P–K concentration at the end of that week compared with M (N data in Fig. 2C; P and K data not shown). Tissue nutrient concentrations increased once C application resumed; however, regardless of treatment, tissue N–P–K concentrations did not return to initial percent nutrient concentrations, suggesting that

Table 3. Summary analysis of variance results for effects of macronutrient fertilizer supply on plant height and leaf node number measured at Day 14 and 21.^z

Measurement day	Treatment	Plant ht (cm)	Leaf node number (leaves/cutting)
14 days	MM	3.5 b	6.5 b
	MC	4.0 ab	6.9 b
	CM	4.2 a	8.0 a
	CC	4.5 a	8.1 a
	<i>P</i> value	0.0026	0.0004
21 days	MMM	3.6 f	6.9 c
	MMC	3.8 ef	7.2 c
	MCM	4.8 de	8.6 b
	MCC	5.1 cd	8.9 b
	CMM	6.2 b	9.6 ab
	CMC	6.1 bc	9.6 ab
	CCM	6.5 b	10.4 a
	CCC	8.3 a	10.7 a
	<i>P</i> value	<0.0001	<0.0001

^z“C” represents the “complete” fertilizer treatment and “M” represents the micronutrient fertilizer treatment during a given week. Treatment labels are made up of one, two, or three letters, in which the first letter corresponds to the fertilizer treatment on Week 1, the second letter for Week 2, and so forth. Means were separated within each date using Tukey’s honestly significant difference test at $P \leq 0.05$.

Fig. 2. Nitrogen (N) content in the shoot and root by treatment over time expressed as percent of dry weight (A), milligrams per cutting (B), or (C) nitrogen uptake (milligrams per cutting per week). Nitrogen uptake was calculated using the following equation: [(Day 7, 14, or 21) DW in mg/cutting) $\times$ (the decimal fraction of the percent N at Day 7, 14, or 21)] – [(preceding week DW in mg/cutting) $\times$ (preceding tissue decimal fraction of the % N)] where DW = dry weight. “C” represents the “complete” fertilizer treatment and “M” represents the micronutrient fertilizer treatment during a given week. Treatment labels are made up of three letters; the first letter corresponds to the fertilizer treatment Week 1 and so forth. The mean separation used was Tukey’s honestly significant difference test at $P \leq 0.05$.

nutrient concentrations in the stock plant are very important to avoid nutrient deficiency symptoms in the unrooted cuttings (Rowe and Blazich, 1999). The goal throughout vegetative propagation is to maintain tissue nutrient concentrations within the recommended ranges to avoid slowed root and shoot development caused by nutrient deficiency. Gibson et al. (2007) observed deficiency symptoms in petunia at 2.1% N, 0.07% P, and 0.7% K, whereas Mills and Jones (1996) reported minimum sufficiency concentrations of 3.9% N, 0.47% P, and 3.1% K for petunia. In our study, 1.8% N, 0.2% P, and 1.5% K were observed for the MMM treatment at 21 d, indicating that N had dropped to a deficient concentration compared with both Gibson et al. (2007) and Mills and Jones (1996) standards. Compared with the Mills and Jones (1996) standards only, tissue P and K were also below minimum sufficiency standards for the MMM treatment on Days 7, 14, and 21.

Nitrogen content (dry weight $\times$ tissue concentration; Fig. 2B) and also content of P and K (data not shown) increased each week that C fertilizer was applied. N uptake was different between fertilizer treatments by Day 14 (Fig. 2C). Weekly N uptake increased over time for plants that received C fertilizer. A small amount of N uptake did occur in plants receiving continuous M, presumably from the peat substrate. By Week 3, N uptake in CCC-treated plants was nearly 10 $\times$ nutrient uptake of MMM cuttings receiving M (MMM) on Days 0 to 21 (2.8 versus 0.39 mg/cutting), respectively.

The fate of applied nutrients each week (leachate, substrate, or tissue; Fig. 3) showed increased tissue uptake and decreased leachate over time in the propagation cycle. The first week of propagation resulted in the least uptake efficiency [20%, calculated as (plant uptake/nutrients applied) $\times$ 100], which would be expected because root emergence did not occur until Day 4 and uptake would only occur through foliage and the cut stem. In commercial propagation conditions, the highest amount of leaching often occurs during the first 7 d of propagation because of the large water volume applied to maintain cutting turgidity (Santos et al., 2008). Uptake efficiency increased to 70% and 80% in Weeks 2 and 3 with the combination of a more developed root systems and reduced irrigation frequency.

Overall, the timing of macronutrient supply throughout a 21-d propagation cycle was found to affect growth, development, and nutrient uptake of petunia cuttings. Growth was dependent on macronutrient supply, particularly in terms of shoot dry weight (Fig. 1). Continuous application of C fertilizer also resulted in more rapid development, as quantified by more leaves per plant (Table 3), when compared with plants that received M indicating that some macronutrient (probably P or K) had reached a minimum critical concentration to limit growth. A high-quality “finished” rooted cutting requires adequate rooting, adequate shoot growth, and compact height. Therefore, under continuous C fertilizer, increased chemical or climate-controlled growth regulation

Fig. 3. Nitrogen (A), phosphorus (B), and potassium (C) in leachate, substrate, and tissue over time for plants receiving continuous complete ("C") fertilizer. Each bar represents the average of eight tray, divided by the number of cuttings per tray (102). Letters show mean comparisons across time within tissue, substrate, or leachate using Tukey's honestly significant difference at $P \leq 0.05$.

would be required to control the increased shoot growth or a lower constant macronutrient concentration could be applied. In the case of petunia 'Royal Velvet', the rate of fertilizer used in this experiment may have been too high and a reduction in fertilizer rate to a constant rate (for example, an average $76 \text{ mg} \cdot \text{L}^{-1}$ N was used in the survey by Santos et al., 2008) might control excessive shoot growth. The results from this experiment were based on a particular plant species and cultivar, whereas response to fertilization during propagation could vary with other crop types.

During the first 7 d of propagation regardless of nutrient supply, tissue nutrient concentrations dropped. This response can be attributed to dilution because of growth that occurred in the first 7 d in conjunction with minimal uptake. A decline in tissue nutrient concentration was also observed in poinsettia (*Euphorbia pulcherrima* Willd. ex Klotzsch) after 7 d under mist, and this decline was not correlated with three different rates of water volume applied (Wilkerson and Gates, 2005). A decline in tissue nutrient concentration also occurred in poinsettias that did not have any water applied to foliage 13 d after sticking (Svenson and Davies, 1995). The uniform decline in tissue nutrient concentrations during the first 7 d emphasizes the importance of

high initial tissue nutrient concentrations in unrooted cuttings for subsequent plant health. If the tissue nutrient concentrations are low in the unrooted cutting, fertilizer applications need to be started as soon as possible or a reduction in growth and quality may occur as tissue nutrient concentrations drop below recommended ranges and nutrient deficiencies begin to limit growth.

Complete fertilizer applications during this initial drop in tissue nutrient concentration were shown to sustain higher tissue nutrient concentrations compared with cuttings receiving M. The positive response to C fertilizer applications early in propagation could be attributed to uptake through foliar, cut stem, or root initials. High humidity environments such as propagation enable nutrients to stay in solution longer and are more available for foliar uptake (Clor et al., 1963; Dybing and Currier, 1961; Schonherr and Bukovac, 1972). Relative humidity and leaf water status have been shown to be key factors controlling foliar uptake (Bukovac and Wittwer, 1957; Tukey and Marczyński, 1984).

Conclusions

Overall, early nutrient supply had positive effects on growth and nutrient concentrations

of petunia. However, mist fertigation involves a tradeoff in terms of increased potential for algae growth, increased nutrient runoff if the fertigation solution is not recycled (as evidenced by the low uptake efficiency; Fig. 3), and potential for phytotoxicity or minimal response in certain species. Early mist fertigation would therefore be favored in combination with an irrigation system that includes capture and reuse of leachate in addition to water sanitation for algae and pathogen control (for example, copper ionization or chlorination) for fast-growing species in which nutrient dilution may rapidly occur, in species that readily absorb nutrients through the foliage (lacking a thick cuticle and not prone to salt damage), and where initial tissue nutrient concentrations are low in the unrooted cuttings. Areas that warrant further investigation include the response to early application of macronutrients in plant species other than petunia and understanding which sites (leaf, cut stem, or callus) are important pathways for nutrient uptake or loss before root emergence.

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