From Forest Nursery Notes, Winter 2009

215. A survey of water and fertilizer management during cutting propagation. Santos, K. M., Fisher, P. R., and Argo, W. R. HortTechnology 18(4):597-604. 2008.

A Survey of Water and Fertilizer Management During Cutting Propagation

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ADDITIONAL INDEX WORDS. calibrachoa, greenhouse, leaching, nitrogen nutrient distribution, petunia, phosphorus, potassium, uptake efficiency, vegetative cuttings

SUMMARY. The objective of this study was to quantify water volume and nutrient content leached during propagation of herbaceous cuttings in commercial greenhouses. Nutrient concentrations in the fertigation solution, substrate, tissue, and leachate were measured between Jan. and Mar. 2006 at eight greenhouse locations in Michigan, Colorado, New Hampshire, and New Jersey. Grower management of the timing and concentration of nutrients applied to vegetatively grown calibrachoa (*Calibrachoa ×hybrida*) or petunia (*Petunia ×hybrida*) liner trays varied among the eight locations, ranging from 0.5 to 80 mg·L^{-1} nitrogen (N) in week 1 and from 64 to 158 mg·L^{-1} N in week 4. Over a 4-week crop period, applied nutrients averaged 4.9 g·m^{-2} N, 0.8 g·m^{-2} phosphorus (P), and 5.8 g·m^{-2} potassium (K), and leached nutrients averaged 1.1 g·m^{-2} N, 0.3 g·m^{-2} P, and 1.6 g·m^{-2} K. Leaching of nutrients and irrigation water was highly variable among locations. Leached water volumes ranged from 4.5 to 46.1 L·m^{-2} over 4 weeks and contained 0.29 to 1.81 g·m^{-2} N, 0.11 to 0.45 g·m^{-2} P, and 0.76 to 2.86 g·m^{-2} K. The broad range in current commercial fertigation practices, including timing of nutrient supply, concentration of applied fertilizer, and leaching volume, indicate considerable potential to improve efficiency of water and fertilization resources during propagation and reduce runoff.

Most horticultural production firms either propagate or buy seed, cuttings, or tissue-cultured propagules. These propagules are planted into small cells called plugs or liners, placed under high humidity to germinate or produce roots, and are subsequently grown to a saleable seedling plug or rooted liner, which requires 4 to 6 weeks in the case of most herbaceous cuttings. The plug or liner is then transplanted into the field or landscape or into a larger container for further growth before sale. The total value of sales of propagative plant material for cut flowers, potted flowering plants, annual bedding and garden plants, herbaceous perennials, foliage, and cut cultivated greens for 2005 was $439 million, 2% above the previous year (U.S. Dept. Agr., 2006). Annual bedding and garden plants accounted for 49% of all propagative material, or $214 million. These propagation numbers probably underestimate the economic value of the seedling and cutting industry when including vegetable, woody ornamental, and fruit production.

Agriculture accounts for over 80% of freshwater consumption in the United States and an increase in water use regulations necessitates improved irrigation strategies (Weibe and Gollehon, 2006). Greenhouse propagation involves considerable application of water for control of humidity, soil moisture, and as a means to apply water-soluble fertilizer. In a typical rooting environment for vegetative cuttings, water is initially supplied by either mist emitters or automated boom watering systems to minimize transpiration loss. The amount of water required is species-dependent. For example, artemisia (*Artemesia* spp.), gaura (*Gaura lindheimeri*), rosemary (*Rosemarinus officinalis*), or lavender (*Lavandula angustifolia*) cuttings rooting performance is reduced in high-mist environments (Dole and Gibson, 2006). Excessive water application can lead to increased use of water resources and associated production costs, reduce oxygen availability in the substrate, and thereby reduce rooting percentage (Geneve et al., 2004). Improved irrigation management may help reduce nutrient, pesticide, and trace element loads in irrigation runoff to surface waters as well as leaching of agricultural chemicals into groundwater supplies (Schaible and Aillery, 2003).

Annual nitrogen (N) fertilizer application rates as high as 3600 kg·ha^{-1} N were estimated for chrysanthemum (*Dendranthema ×grandiflorum*) (Nelson, 1998) and poinsettia (*Euphorbia pulcherrima*) potted crops (Yelanich and Biernbaum, 1994). Much of the excess N applied in crops grown with high fertilizer concentrations and heavy leaching can be lost into the environment, depositing as much as 100 mg of nitrate–nitrogen (NO_3-N) (243 mL or of effluent with a NO_3-N concentration of 411.6 mg·L^{-1}) per irrigation from a 6-inch-diameter pot into the soil profile (McAvoy et al., 1992). Soluble phosphate and micronutrients are also used more intensively per hectare in greenhouse

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Units

To convert U.S. to SI, multiply by	U.S unit	SI unit	To convert SI to U.S., multiply by
0.4047	acre(s)	ha	2.4711
29.5735	fl oz	mL	0.0338
0.0929	ft^2	m^2	10.7639
3.7854	gal	L	0.2642
9.3540	gal/acre	L·ha^{-1}	0.1069
40.7458	gal/ft^2	L·m^{-2}	0.0245
2.54	inch(es)	cm	0.3937
6.4516	inch^2	cm^2	0.1550
1.1209	lb/acre	kg·ha^{-1}	0.8922
1	mmho/cm	dS·m^{-1}	1
28.3495	oz	g	0.0353
28,350	oz	mg	3.5274×10^{-5}
305.1517	oz/ft^2	g·m^{-2}	0.0033
7.4892	oz/gal	g·L^{-1}	0.1335
0.001	ppm	g·L^{-1}	1000
1	ppm	mg·L^{-1}	1
(°F – 32) ÷ 1.8	°F	°C	(1.8 × °C) + 32

production than in field crop production (Nelson, 1990).

A similar net nutrient supply can be achieved with either low fertilizer and leaching rates (resource-efficient strategy) or high fertilizer and leaching rates (resource-inefficient); and commercial horticultural practices vary widely (Yelanich and Biernbaum, 1993). Fertilizers applied to both stock plants and during propagation of cuttings impact successful rooting of vegetative cuttings in propagation (Blazich, 1988; Gibson, 2003; Lebude et al., 2004; Rowe and Blazich, 1999). Biernbaum et al. (1995) and Kerr and Hanan (1985) found that the majority of fertilizer salts were rapidly removed from container media after leaching of one container capacity (Biernbaum et al., 1995) or one soil volume (Kerr and Hanan, 1985). Container capacity can be defined as the total amount of water present in the container after the substrate is saturated and then allowed to drain for 1 h.

Previous research on leaching in greenhouses (Groves et al., 1998; Ku and Hershey, 1997; Argo and Biernbaum, 1996; Yelanich and Biernbaum, 1994) has focused on potted plants rather than propagation. We are unaware of research on leaching and fertilizer concentration in plug and liner trays in which the water inputs relative to substrate volume may be much higher than in large containers. Based on the variability in growing practices within the industry, management practices need to be evaluated and critical areas such as the amount of water and nutrients lost should be quantified to determine points of potential improvement. Our objectives were to: 1) quantify levels of irrigation water leached during production of liner trays in multiple commercial greenhouse operations; 2) quantify nutrient levels in substrate, tissue, and leachate of these commercial crops; and 3) compare nutrient use efficiency at each location.

Materials and methods

Nutrient and irrigation data were collected in 2006 from eight greenhouse locations in Michigan, Colorado, New Hampshire, and New Jersey, which represent a range in climatic conditions within the northern United States. Two greenhouse locations were selected in each of four states, each of which had at least 3 ha in plug and liner production. Each greenhouse location represented an experimental unit. Although several locations had the capability to recirculate irrigation water, none were doing so with these crops because of disease susceptibility. The greenhouse businesses were leading propagators that had previously cooperated with the authors in on-site trials, and we were therefore confident about being able to collect reliable data. The timing for the experiments was determined based on the peak production season for U.S. propagation of annuals (January to March). The experiment was run for 1 week at each location (conditions described in Table 1) and four crops of vegetatively grown liner trays were related that were either 0 to 1, 1 to 2, 2 to 3, or 3 to 4 weeks of age. In this context, a "crop" refers to a specific age group in one location. In six locations, calibrachoa was selected; and in two locations, petunia was selected. Species selection depended on the crops grown and available at each location, and both species had a similar 4- to 5-week crop time in a liner tray (Blackmore Co., Belleville, MI). The cultivar within the species was consistent within a given location, but varied between locations.

Within each crop, there were five replicate measurements of each of the following variables located randomly within the crop: volume, pH (Pinnacle Corning pH Meter model 430; Nova Analytics Corp., Woburn, MA) and electrical conductivity (EC) (Orion model 130; Thermo Fisher Scientific, Waltham, MA) of applied nutrient solution (n = 5) (using five individual irrigation collection funnels); volume, pH, and EC of leached nutrient solution (using five leachate collection trays); substrate-pH and substrate-EC (using five liner propagation trays); and plant fresh and dry weights (combined root and shoot using five groups of three plants each). Within each crop, there was a single replicate measurement of each of the following: substrate nutrient levels (combined from five trays), leachate nutrient levels (n = 1) (combined from five leachate samples), tissue nutrient levels (from 15 combined plants), and tissue nutrient levels on unrooted ("week 0") plants.

Data were analyzed as a split plot design with location as the main plot, crop age as the subplot, and each tray as a random block. There were no significant differences between species or cultivar; therefore, location was assigned as the main factor in the model. Proc Mixed and Proc GLM in SAS (version 9.1; SAS Institute, Cary, NC) were used for statistical analysis and Tukey's honestly significant difference test was used for mean comparisons.

Quantify leached irrigation water volume

Growers recorded the number and schedule of irrigation events per day, N:P:K ratio, and concentration (parts per million) of fertilizer applied. The volume of applied irrigation solution was measured by randomly placing five "irrigation collection funnels" (0.47-L dark brown plastic bottles topped with open funnels, surface area = 24.4 cm^2 and stood 17 cm above the bottle) in each of the four crops, or a total of 20 bottles (five bottles/crop × four crops) per location. The irrigation collection funnels were left for 1 week, and growers were instructed to apply irrigation solution evenly across the crop surface and funnels as per normal practices. The data for irrigation water volume applied were not shown as a result of too much variability in the measurements.

The volume of solution leached from the propagation trays was measured by placing 20 15 × 45-cm "leachate collection trays" beneath five propagation trays per crop. The vent holes on the top of plug trays (in between the plug cells) were covered with water-resistant tape to prevent irrigation water from running directly into the leachate collecting tray. After 1 week, the collection trays were removed from beneath the propagation trays and the leachate volumes were measured.

Quantify nutrient levels in tissue, substrate, and leachate

From each of the five replicate samples per crop, 25 mL of applied irrigation water (from the irrigation collection funnels) and leachate (from the leachate collection trays) were collected. The pH and EC were recorded for each of those samples. The five samples from each crop were

Table 1. Cell count per tray, tray area, substrate components, crop, cultivar, start date, end date, and mean day and night temperature for eight commercial greenhouse locations surveyed.

Table 1. Cell count per tray, tray area, substrate components, crop, cultivar, start date, end date, and mean day and night temperature for eight commercial greenhouse locations surveyed.

Location	Cells (no./tray)	Tray area[z] (m^2)	Substrate components	Crop	Cultivar	Start date	End date	Mean day temp[y] (°C)	Mean night temp[y] (°C)
A	84	0.13	Peat/perlite	Petunia	Supertunia Mini Strawberry Pink Vein	8 Feb.	15 Feb.	20.0	22.0
B	84	0.13	Peat/perlite	Calibrachoa	Superbells Pink	6 Jan.	13 Jan.	21.1	20.4
C	105	0.15	Peat/perlite/polymer	Calibrachoa	Callie Rose Star	24 Feb.	2 Mar.	21.8	17.4
D	105	0.13	Peat/perlite	Calibrachoa	Minifamous Dark Violet	25 Jan.	1 Feb.	22.8	19.6
E	84	0.15	Peat/perlite	Petunia	Petunia Surfinia Purple Veined	24 Jan.	31 Jan.	21.1	20.8
F	105	0.15	Peat/perlite/soil	Calibrachoa	Colorburst Violet	8 Feb.	15 Feb.	19.4	17.0
G	105	0.13	Peat/polymer	Calibrachoa	Minifamous Caribbean Sunset	6 Jan.	13 Jan.	21.8	19.4
H	84	0.13	Peat/perlite/rockwool	Calibrachoa	Superbells Tequila Sunrise	23 Feb.	1 Mar.	22.3	18.8

[z]1 m^2 = 10.7639 ft^2.
[y]The day temperature was calculated by taking the average day temperature (sunrise to sunset) of each day during the trial. The night temperature was calculated by taking the average night temperature (sunset to sunrise) of each day during the trial. The day and night temperature were recorded by temperature data loggers (HOBO; Onset, Bourne, MA) [(1.8 × °C) + 32 = °F].

then combined into one sample per crop and sent to Quality Analytical Laboratories (Panama City, FL) for a complete nutrient analysis using inductively coupled plasma atomic emission spectrophotometry (ICAP 61E; Thermo-Jarrell Ash, Franklin, MA) to measure P, K, calcium (Ca), magnesium (Mg), sulfur (S), iron (Fe), manganese (Mn), boron (B), copper (Cu), zinc (Zn), molybdenum (Mo), aluminum, and sodium. The leachate and substrate solution samples were analyzed for NO_3-N and ammonium (NH_4) N using a Lachat QuikChem AE (Lachat Instruments, Loveland, CO). This instrument uses flow injection analysis to colorimetrically determine NO_3-N and NH_4-N concentration. For tissue samples, N was measured as total Kjeldahl N where all the protein is converted to NH_4 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.

Plug squeeze tests were performed ≈1 h after irrigation with nutrient solution by pressing down firmly on the top of the substrate surface and collecting the solution from the hole at the bottom of the pressed plug cell on each of the five replicate propagation trays per crop (Scoggins et al., 2002). The pH and EC were recorded individually for these samples.

The plug squeeze samples were then combined into a single replicate per crop for complete nutrient analysis. Five groups of three plants were removed from random locations within trays in each crop. The plants were washed in four separate baths of deionized water to remove any substrate from the root mass and to clean the foliage. Fresh weight of each replicate sample of three combined plants was taken, placed in a forced-air drying oven at 55 °C, and weighed again after all liquids evaporated (3 d) to measure dry weight. The dry tissue samples were combined by crop for a complete nutrient analysis. The container capacity (CC) was calculated for substrates at each location by measuring the total amount of water present in the container after the substrate has been saturated using subirrigation and allowed to drain for ≈1 h.

Compare nutrient use efficiency at each location

The resource use for each location was calculated using the following formulae:

Tissue nutrient uptake = [(final DW in $g \cdot m^{-2}$) × (final tissue % N, P, or K)] – [(initial DW in $g \cdot m^{-2}$) × (initial tissue % N, P, or K)], where DW = dry weight. [1]

Final nutrient concentration in substrate = (CC in $L \cdot m^{-2}$) × (final concentration N, P, or K in $g \cdot L^{-1}$). [2]

Total nutrient leached = total leachate volume in liters × total concentration N, P, or K in $g \cdot L^{-1}$). [3]

% N distribution = [(A)/(leachate N in grams + tissue uptake N in grams + final substrate N in grams)] × 100, where A = leachate N, tissue nutrient N, or final substrate N (Ku and Hershey, 1997). [4]

Results and discussion

Quantify leached irrigation water volume

The volume leached varied between locations, ranging from 0.6 to 6.0 L per propagation tray, which corresponded to 44,900 to 460,769 $L \cdot ha^{-1}$ over a 4-week crop period (Table 2). Six of the eight locations leached at least one CC over the 4-week crop cycle, and three locations leached 2.0 to 4.7 CC (Table 2). The greatest leaching also occurred during weeks 1 or 2 in six of the eight locations, and on average, significantly more water was leached during week 1 than in the subsequent 3 crop weeks (Table 3). The nature of vegetative propagation requires higher volumes of water to be applied to maintain humidity and plant turgidity until root formation. No previous research exists to provide a baseline to compare against; however, among these eight operations, we discovered less leaching at some indicating an excess at others. Given the rapid leaching of nutrients from soilless substrates after leaching of one CC (Biernbaum et al., 1995; Kerr and Hanan, 1985), a significant amount of preplant nutrients would have been

Table 2. Water leached by location over a 4-week crop cycle[z].

Location	Vol leached[y] ($L \cdot m^{-2}$)	Vol leached[x] ($L \cdot ha^{-1}$)	CC[w] ($L \cdot m^{-2}$)	CC leached[v] ($L \cdot m^{-2}$ per 4 wk)
A	7.7 cd[v]	77,215	9.8	0.8
B	46.1 a	460,769	9.8	4.7
C	14.2 b	141,686	10.5	1.3
D	4.5 d	44,900	11.8	0.4
E	8.7 bcd	87,333	8.6	1.0
F	13.7 b	136,667	10.6	1.3
G	14.7 bc	147,184	6.8	2.2
H	19.5 b	194,615	9.7	2.0
Avg	16.1	161,296	9.7	1.7
SD	12.1	121,487	1.4	1.3

[z]Leachate is quantified in terms of volume leached per tray, per hectare, or container capacities (CC) leached per tray.
[y]1 $L \cdot m^{-2}$ = 0.0245 gal/ft^2.
[x]1 $L \cdot ha^{-1}$ = 0.1069 gal/acre.
[w]One CC was defined as the total amount of water present in the container after the substrate was saturated and then allowed to drain for 1 h.
[v]Mean separation used Tukey's honestly significant difference test at $P \leq 0.05$.

leached early in the crop cycle before roots emerged and nutrients were taken up by the cuttings. These results indicate that irrigation volume was excessive at the beginning of the crop cycle when plant uptake would be reduced because of small leaf area and lack of plant roots.

Quantify nutrient levels in nutrient solution, tissue, substrate, and leachate

APPLIED NUTRIENTS. Fertilizer strategy varied widely among locations. Applied nutrient concentrations increased with crop age as measured with both EC and N level of the applied solution (Table 3). On average, 24, 85, 93, and 101 $mg \cdot L^{-1}$ N were applied during weeks 1 to 4, respectively, with a nutrient solution EC of 0.44, 0.88, 0.87, and 1.01 $dS \cdot m^{-1}$ (Table 3). Averaged across the 4 weeks, the nutrient concentrations in $mg \cdot L^{-1}$ were 76 N, 4 P, 65 K, 61 Ca, 17 Mg, 21 S, 2 Fe, 0.4 Mn, 0.2 B, 0.3 Cu, 0.4 Zn, and 0.05 Mo. Locations varied greatly in the applied N levels, particularly during the first 2 weeks (week 0 to 1 = 0 to 80 $mg \cdot L^{-1}$ N, week 1 to 2 = 0 to 195 $mg \cdot L^{-1}$ N, week 2 to 3 = 19 to 148 $mg \cdot L^{-1}$ N, and week 3 to 4 = 64 to 158 $mg \cdot L^{-1}$ N) (Table 3).

The total applied N, P, and K (sum of tissue uptake, nutrients leached, and final substrate nutrient content) during the 4-week crop cycle ranged by a factor of approximately four among locations, from 1.4 to 8.3 $g \cdot m^{-2}$ N, 0.3 to 1.2 $g \cdot m^{-2}$ P, and 2.7 to 10.1 $g \cdot m^{-2}$ K (Table 4), which represented 14 to 83 $kg \cdot ha^{-1}$ N, 3 to 12 $kg \cdot ha^{-1}$ P, and 27 to 101 $kg \cdot ha^{-1}$ K (Table 5). On an annual basis, the applied N level (averaging 637 $kg \cdot ha^{-1}$ N) was lower than the rate reported for potted chrysanthemum and poinsettia (Nelson, 1998; Yelanich and Biernbaum, 1994).

TISSUE UPTAKE. Tissue uptake ranged from 0.9 to 4.5 $g \cdot m^{-2}$ N, 0.2 to 0.6 $g \cdot m^{-2}$ P, and 1.5 to 4.6 $g \cdot m^{-2}$ K (Table 4), varying by a factor of 3 to 4 among locations. This range was partly the result of differences in dry weight (0.072 to 0.177 g per cutting), but principally caused by differences in tissue N concentration among locations. The change in cutting dry weight (DW) was calculated by subtracting the final tissue DW from the tissue DW at day 0 (the date of transplanting cuttings) (Table 4). Tissue percent N decreased from week 0 to week 4 (Table 4), but there was no significant change in P or K level. In an unpublished survey of tissue nutrient levels in visually healthy unrooted cuttings, we surveyed tissue from 291 petunia and 179 calibrachoa crops from 14 commercial locations. The mean ± 2 SDs were 3.8% to 7.5% N, 0.3% to 0.9% P, and 3.4% to 6.6% K in petunia or 3.4% to 6.3% N, 0.2% to 0.7% P, and 2.0% to 4.6% K in calibrachoa ($P \leq 0.05$). Initial percent N level in cuttings transplanted at location F and final percent N in locations C, E, G, and H were below the mean – 2 SD survey levels. Locations E, G, and H also had the three lowest total applied N. P levels were within the survey range, and final K level in location C was slightly below the mean –2 SD. There was no correlation between change in DW and tissue percent of N, P, or K.

SUBSTRATE NUTRIENTS. The optimal EC range for greenhouse substrate using a saturated media extraction (SME) is 0.75 to 2.(mmho/cm for plugs (Styer and Koranski, 1997). According to Scoggins, the media squeeze (or press extraction method) averages 0.1 $dS \cdot m^{-1}$ higher than the SME method for petunia; therefore, a substrate-EC lower than 0.85 or higher than 2.6 is beyond the acceptable limit whe performing a media squeeze in a petunia crop (Scoggins et al., 2002; Styer and Koranski, 1997). Substrate-EC at each location ranged from 0.2 to 3.2 $dS \cdot m^{-1}$ during week 1; 0.4 to 3.2 $dS \cdot m^{-1}$ during week 2; 0.3 to 1.4 $dS \cdot m^{-1}$ during week 3; and 0.4 to 2.3 $dS \cdot m^{-1}$ during week 4 (Table 3). On average, there was a significant de-crease in substrate-EC in weeks 1, 2, and 3 (2.0, 1.32, and 0.80 $dS \cdot m^{-1}$, respectively) with a rise in week 4 (Table 3). Substrate-EC during week 3 was below the acceptable limit (Styer and Koranski, 1997). Seven of the eight locations showed a significant drop in substrate-EC from week 1 to week 2 of propagation (Table 3). Most of the substrate-pH values were in an acceptable range (5.6 to 6.4; Argo and Fisher (2002)) and averaged 5.3 to 6.5 (data not shown). The N, P, and K content at the end of the 4-week crop cycle varied widely (between 0.14 and 2.92 $g \cdot m^{-2}$ N, 0.02 and 0.41 $g \cdot m^{-2}$ P, and 0.51 and 4.51 $g \cdot m^{-2}$ K; Table 4). The lowest substrate-N occurred in location E, which also had the lowest growth, N tissue uptake, and leachate N (Table 4).

LEACHATE NUTRIENTS. The leachate-EC during weeks 1, 2, 3, and 4 averaged 2.77, 1.50, 0.89, and 1.40 $dS \cdot m^{-1}$, respectively (Table 3). In contrast, applied nutrient solution-EC increased over weeks 1 to 4, suggesting that the high leachate-EC in week 1 resulted primarily from leaching of the preplant nutrient charge. Based on the nutrient analysis results for the leachate samples, on average, locations leached 1.09 $g \cdot m^{-2}$ N, 0.27 $g \cdot m^{-2}$ P, and 1.52 $g \cdot m^{-2}$ K over the 4-week crop cycle (Table 4).

Table 3. Nutrient solution applied over time at eight greenhouse locations[z].

Location	Crop age (weeks)	Irrigation method[y]	Applied N ($mg \cdot L^{-1}$)[x]	Applied solution EC ($dS \cdot m^{-1}$)[w]	Substrate EC ($dS \cdot m^{-1}$)	Leachate EC ($dS \cdot m^{-1}$)	Leach vol (L)[v]
A	1	Boom	80.2	0.7 a[u]	2.5 b	2.7 b	0.4 a
	2	Boom and hand	145.7	1.2 c	3.2 c	3.2 b	0.1 a
	3	Boom and hand	139.3	1.1 c	0.6 a	0.8 a	0.1 a
	4	Boom and hand	109.8	0.9 b	0.4 a	0.3 a	0.4 a
B	1	Boom	6.2	0.2 a	0.2 a	0.2 a	3.4 c
	2	Boom	82.2	0.8 b	0.6 bc	0.5 ab	1.2 b
	3	Hand	129.5	1.20 c	0.3 ab	0.5 ab	0.3 a
	4	Hand	112.8	1.0 c	1.0 c	1.2 b	1.0 b
C	1	Boom	67.8	0.9 a	1.8 b	2.0 b	0.9 b
	2	Boom	99.7	1.1 b	1.3 a	1.5 bc	0.1 a
	3	Boom	82.2	0.9 a	0.9 a	1.1 ac	0.8 b
	4	Boom	64.0	1.4 c	2.3 c	3.0 d	0.4 a
D	1	Boom	0.5	0.3 a	1.8 b	3.4 c	0.4 b
	2	Boom and hand	194.8	1.7 c	0.9 a	1.5 ab	0.0 a
	3	Boom and hand	148.0	1.4 b	0.8 a	0.6 a	0.0 a
	4	Boom and hand	157.6	1.4 b	2.0 b	1.9 b	0.2 ab
E	1	Boom	0.4	0.3 a	3.2 b	1.2 a	0.1 a
	2	Boom	2.1	0.6 b	0.7 a	1.0 a	0.7 b
	3	Boom and hand	93.5	0.8 c	1.0 a	0.9 a	0.1 a
	4	Boom and hand	105.5	0.9 c	0.7 a	0.7 a	0.4 a
F	1	Boom	5.0	0.3 a	3.1 c	4.8 c	0.3 b
	2	Boom and hand	0.0	0.2 a	2.5 b	2.9 b	0.0 a
	3	Hand	52.4	0.5 c	1.4 a	1.7 a	1.2 c
	4	Hand	72.7	0.7 b	2.1 b	2.0 a	0.5 b
G	1	Mist	6.8	0.4 a	0.9 bc	1.5 b	1.4 c
	2	Mist	11.7	0.5 a	0.4 a	0.4 a	0.4 b
	3	Hand	19.2	0.4 a	0.7 ab	0.5 a	0.0 a
	4	Hand	107.4	1.1 b	1.1 c	1.1 ab	0.1 ab
H	1	Boom	23.3	0.5 a	2.6 b	6.4 b	0.2 a
	2	Boom and hand	142.3	1.1 c	1.0 a	0.9 a	1.3 c
	3	Hand	79.3	0.7 b	0.7 a	1.1 a	0.4 ab
	4	Hand	78.3	0.7 b	0.9 a	1.1 a	0.7 b
	SE		21.3	0.06	0.16	0.30	0.11
Avg	1	a	23.8	0.44 a	2.00 a	2.77 c	0.88 c
Avg	2	ab	84.8	0.88 b	1.32 b	1.50 b	0.48 b
Avg	3	b	92.9	0.87 b	0.80 c	0.89 a	0.36 a
Avg	4	b	101.0	1.01 c	1.32 b	1.40 b	0.46 ab
Avg	All		75.6	0.8	1.4	1.6	0.5

[z]Data were analyzed by location (denoted A to H) and crop age (1, 2, 3, and 4 weeks after sticking of cuttings).
[y]Irrigation method included boom, stationary mist, or hand-watering or a combination of more than one method during the same week.
[x]The applied nitrogen concentration was measured on one sample for each crop and location combined from five replicate irrigation collection funnels; 1 $mg \cdot L^{-1}$ = 1 ppm.
[w]Electrical conductivity (EC) data were based on five replicate samples per crop age and location; 1 $dS \cdot m^{-1}$ = 1 mmho/cm.
[v]1 L = 0.2642 gal.
[u]Mean separation used Tukey's honestly significant difference test at $P \leq 0.05$.

However, leaching levels at individual locations were as high as 1.81 $g \cdot m^{-2}$ N, 0.45 $g \cdot m^{-2}$ P, and 2.86 $g \cdot m^{-2}$ K or as low as 0.29 $g \cdot m^{-2}$ N, 0.11 $g \cdot m^{-2}$ P, and 0.76 $g \cdot m^{-2}$ K (Table 4).

Compare nutrient use efficiency at each location

The fate of nutrients applied during vegetative cutting propagation can be divided into tissue, substrate, and leachate. Tissue uptake was calculated by change in percent nutrient × DW from week 0 to week 4, and uptake efficiency was calculated from Eq. 4, in which A = tissue uptake. More efficient growers would be defined as having a high tissue uptake and low level of nutrients leached on both a percentage and absolute basis. On average, locations had 50% N, 49% P, and 46% K nutrient uptake efficiencies (Table 5) with individual locations up to 77% N, 72% P, and 73% K uptake efficiency. In terms of leachate, the average percent nutrients leached among locations ranged from 23% N, 34% P, and 28% K with maximum leaching levels of 45% N, 45% P, and 55% K.

Several factors should be considered when evaluating the efficiency of nutrient management within an individual location. For example, location E had one of the higher nutrient uptake efficiencies (Table 5) and low nutrient leaching on a percentage (Table 5) and absolute (Table 4) basis along with moderate leached water volume (Table 2). However, location E also had excessively low tissue

Table 4. Initial and final percent nitrogen (N), phosphorus (P), and potassium (K) in the tissue[z].

Location[y]	Species	Concn in tissue (%) Initial	Concn in tissue (%) Final	Change in DW[x] (g/cutting)	Tissue uptake[w] ($g \cdot m^{-2}$)	Final substrate nutrient[v] ($g \cdot m^{-2}$)	Leached nutrient[u] ($g \cdot m^{-2}$)	Total applied[t] ($g \cdot m^{-2}$)
Nitrogen								
A	Petunia	6.1	4.4	0.15 ab	4.0 b	0.38	0.78 bc	5.1
B	Calibrachoa	3.9	3.8	0.07 e	1.7 ef	1.52	1.59 ab	4.8
C	Petunia	4.8	3.6	0.10 cde	2.3 cd	2.26	0.90 abc	5.4
D	Calibrachoa	4.0	3.8	0.09 de	2.9 c	2.92	0.95 abc	6.8
E	Petunia	4.2	2.9	0.07 e	0.9 f	0.14	0.29 c	1.4
F	Calibrachoa	3.0	3.6	0.18 a	4.5 a	2.08	1.69 a	8.3
G	Calibrachoa	5.4	2.3	0.11 cd	1.3 f	1.57	0.73 bc	3.6
H	Calibrachoa	4.6	3.2	0.12 bc	1.8 de	0.47	1.81 ab	4.0
Avg		4.5 a	3.4 b	0.11	2.4	1.42	1.09	4.9
SE		0.12	0.12	0.01	0.1		0.16	
Phosphorus								
A	Petunia	0.7	0.5		0.5 bc	0.02	0.35 ab	0.8
B	Calibrachoa	0.6	0.4		0.2 f	0.05	0.11 b	0.3
C	Petunia	0.6	0.5		0.3 cd	0.41	0.45 a	1.2
D	Calibrachoa	0.5	0.6		0.5 bc	0.05	0.15 b	0.7
E	Petunia	0.5	0.6		0.2 ef	0.10	0.15 b	0.5
F	Calibrachoa	0.4	0.5		0.6 a	0.17	0.23 ab	1.0
G	Calibrachoa	0.5	0.4		0.3 de	0.17	0.36 ab	0.9
H	Calibrachoa	0.7	0.5		0.3 cde	0.18	0.38 ab	0.9
Avg		0.5 a	0.5 a		0.4	0.14	0.27	0.8
SE		0.01	0.01		0.2		0.04	
Potassium								
A	Petunia	5.7	4.5		4.1 b	0.51	1.05 b	5.7
B	Calibrachoa	3.6	3.5		1.6 d	1.21	1.44 ab	4.3
C	Petunia	4.3	3.3		2.1 c	2.43	1.49 ab	6.0
D	Calibrachoa	4.0	4.7		3.8 b	4.51	1.86 ab	10.1
E	Petunia	5.0	4.1		1.5 cd	0.42	0.76 b	2.7
F	Calibrachoa	3.4	3.7		4.6 a	1.22	1.41 ab	7.2
G	Calibrachoa	4.6	2.5		1.7 cd	1.90	1.32 b	4.9
H	Calibrachoa	3.6	2.6		1.5 cd	0.85	2.86 a	5.2
Avg		4.3 a	3.6 a		2.6	1.63	1.52	5.8
SE		0.12	0.12		0.2		0.27	

[z]Change in dry weight (DW) for each species at each location. N, P, and K applied and distribution in the tissue, substrate, and leachate at each location.
[y]Each letter (A to H) represents an individual location.
[x]Change in dry weight (DW) per cutting was calculated by subtracting the DW at week 4 from the DW at week 0.
[w]1 $g \cdot m^{-2}$ = 0.0033 oz/ft^2; calculated by multiplying the dry weight of the vegetative cuttings at week 4 and week 0 by the percent N, P, or K at week 4 ("final" percent in tissue) and at week 0 ("initial" percent in tissue) and calculating the difference.
[v]Calculated by multiplying the $mg \cdot L^{-1}$ N, P, and K in the soil solution by the container capacity for each tray and then converting to $g \cdot m^{-2}$.
[u]Calculated by multiplying the $mg \cdot L^{-1}$ N, P, and K by the total volume of leachate over 4 weeks.
[t]The sum of the tissue uptake, nutrients leached, and final substrate nutrient content. Mean separation used Tukey's honestly significant difference test ($P \leq 0.05$).

percent N and low growth rate (Table 4) suggesting that inadequate N fertilizer was applied.

Conclusion

The variability in water and fertilizer use, and our observation that liners produced at all locations were saleable plant material, indicates that there is a broad range in practices and resource efficiencies that can be used to produce a horticulturally acceptable product. That situation presents an educational opportunity (to improve efficiency) by minimizing leaching and optimizing uptake and a challenge to convince growers of a need for change when current practices are already producing acceptable crops. We attribute management differences to grower decisions and technology rather than to differing geographic locations, because locations with similar greenhouse temperature and structures located only 10 km apart leached very different water levels. In follow-up discussions with the grower businesses in this study, these leaching and fertilizer data were helpful as a training tool and baseline to review practices that could minimize leaching and more closely match water and nutrient supply with plant need. Examples of management practices operations with high leaching rates implemented were to reduce the irrigation frequency during early propagation stages or to replace old mist nozzles with nozzles that supply smaller volumes of water. Further research should focus on optimizing strategies to supply necessary nutrients and water during the root initiation and growth stages and to measure the impact of

Table 5. Nitrogen, phosphorus, and potassium use efficiency for each location.

Location[z]	Species	Nutrient uptake efficiency[y] (%)	Final substrate nutrient[x] (%)	Nutrient leached[w] (%)	Total applied[v] (kg·ha^{-1})	Total leached[u] (kg·ha^{-1})
Nitrogen						
A	Petunia	77	7	15	51	8
B	Calibrachoa	36	31	33	48	16
C	Petunia	42	41	17	54	9
D	Calibrachoa	43	43	14	68	10
E	Petunia	69	10	21	14	3
F	Calibrachoa	55	25	20	83	17
G	Calibrachoa	36	44	20	36	7
H	Calibrachoa	44	12	45	40	18
Avg		50	27	23	49	11
Phosphorus						
A	Petunia	55	3	42	8	3
B	Calibrachoa	53	13	34	3	1
C	Petunia	29	34	37	12	4
D	Calibrachoa	72	7	21	7	1
E	Petunia	49	20	32	5	2
F	Calibrachoa	61	16	22	10	2
G	Calibrachoa	38	20	42	9	4
H	Calibrachoa	35	21	45	9	4
Avg		49	17	34	8	3
Potassium						
A	Petunia	73	9	18	57	10
B	Calibrachoa	38	28	34	43	14
C	Petunia	35	40	25	60	15
D	Calibrachoa	37	44	18	101	19
E	Petunia	56	16	29	27	8
F	Calibrachoa	64	17	20	72	14
G	Calibrachoa	35	39	27	49	13
H	Calibrachoa	29	16	55	52	29
Avg		46	26	28	58	16

[z]Each letter (A to H) represents an individual location.
[y]The percent nutrient uptake (also termed uptake efficiency) was calculated by dividing the total mg/tray (Table 4) by the change in tissue dry weight in milligrams (Table 4).
[x]The final percent nutrient in substrate was calculated by dividing the total mg/tray (Table 4) by the final substrate nutrient concentration (Table 4).
[w]The percent nutrient leached was calculated by dividing the total mg applied/tray (Table 4) by the nutrients leached in milligrams (Table 4).
[v]1 kg·ha^{-1} = 0.8922 lb/acre; calculated by converting the total mg/tray to kg·ha^{-1}.
[u]Calculated by converting the total mg/tray to kg·ha^{-1}.

grower training on improved resource efficiency.

Literature cited

Argo, W.R. and J.A. Biernbaum. 1996. Availability and persistence of macronutrients from lime and preplant nutrient charge fertilizers in peat-based root media. J. Amer. Soc. Hort. Sci. 121: 453–460.

Argo, W.R. and P.R. Fisher. 2002. Understanding pH management for container-grown crops. 1st Ed. Meister, Willoughby, OH.

Biernbaum, J.A., W.R. Argo, B. Weesies, A. Weesies, and K. Haack. 1995. Persistence and replacement of preplant nutrient charge fertilizers from highly leached peat-based root media. HortScience 30:763 (abstr.).

Blazich, F.A. 1988. Mineral nutrition and adventitious rooting, p. 61–69. In: David, T.D. B.E. Haissing, and N. Sankhla (eds.). Adventitious root formation in cuttings. Dioscorides Press, Portland, OR.

Dole, J.M. and J.L. Gibson. 2006. Cutting propagation: A guide to propagating and producing floriculture crops. 1st Ed. Ball Publishing, Batavia, IL.

Geneve, R., R. Gates, S. Zolnier, E. Wilkerson, and S. Kester. 2004. Environmental control systems for mist propagation of cuttings. Acta Hort. 630:297–301.

Gibson, J.L. 2003. Influence of mineral nutrition on stock plant yield and subsequent rooting of stem cuttings of scaevola, new guinea impatiens, and vegetative strawflower. North Carolina State University, Raleigh, NC. PhD Diss.

Groves, K.M., S.L. Warren, and T.E. Bilderback. 1998. Irrigation volume, application, and controlled-release fertilizer. II. Effect on substrate solution nutrient concentration and water efficiency in containerized plant production. J. Environ. Hort. 16:182–188.

Kerr, G.P. and J.J. Hanan. 1985. Leaching of container media. J. Amer. Soc. Hort. Sci. 110:474–480.

Ku, C.S.M. and D.R. Hershey. 1997. Growth response, nutrient leaching, and mass balance for potted poinsettia. I. Nitrogen. J. Amer. Soc. Hort. Sci. 122: 452–458.

Lebude, A., V.B. Goldfar, F. Blazich, F. Wise, and J. Frampton. 2004. Mist, substrate water potential and cutting water potential influence rooting of stem cuttings of loblolly pine. Tree Physiol. 24: 823–831.

McAvoy, R.J., M.H. Brand, E.G. Corbett, J.W. Bartok, Jr., and A. Botacchi. 1992. Effect of leachate fraction on nitrate loading to the soil profile underlying a greenhouse crop. J. Environ. Hort. 10:167–171.

Nelson, P.V. 1998. Greenhouse operations and management. 5th Ed. Prentice Hall, Englewood Cliffs, NJ.

Nelson, P.V. 1990. Developing root zone management strategies to minimize water and fertilizer waste: The United States perspective with emphasis on surface applied, nonrecirculating systems. Acta Hort. 272:175–184.

Rowe, D.B. and F.A. Blazich. 1999. Mineral nutrient and carbohydrate status of loblolly pine during mist propagation as influenced by stock plant nitrogen fertility. HortScience 34:1279–1285.

Schaible, G.D. and M.P. Aillery. 2003. Irrigation technology transitions in the mid-plains states: Implications for water conservation/water quality goals and institutional changes. Int. J. Water Resour. Dev. 19:67–88.

Scoggins, H.L., D.A. Bailey, and P.V. Nelson. 2002. Efficacy of the press extraction method for bedding plant plug nutrient monitoring. HortScience 37:108–112.

Styer, R.C. and D.S. Koranski. 1997. Plug and transplant production—A grower's guide. Ball Publishing, Batavia, IL.

U.S. Department of Agriculture. 200(Agricultural statistics for 2005. U.S. Dep Agr., Washington, D.C.

Weibe, K. and N. Gollehon. (eds.). 2006. Irrigation resources and water costs. 26 July 2006.<http://www.ers.usda.gov/publications/arei/eib16/Chapter2/2.1/>.

Yelanich, M.V. and J.A. Biernbaum. 1993. Root-medium nutrient concent tion and growth of poinsettia at three fertilizer concentrations and four leaching fractions. J. Amer. Soc. Hort. Sci. 118:771–776.

Yelanich, M.V. and J.A. Biernbaum. 1994. Fertilizer concentration and leaching affect nitrate–nitrogen leaching from potted poinsettia. HortScience 28:874–875.