Relative Effects of Fertilizer Nitrogen Form and Phosphate Level on Control of Bedding Plant Seedling Growth

Paul V. Nelson¹

Department of Horticultural Science, North Carolina State University, Box 7609, Raleigh, NC 27695-7609

Cheon-Young Song

Korea National College of Agriculture and Fisheries, 11 Dongwhari Bongdam Hwasunsi Kyonggido, R.O. Korea 445-890

Jinsheng Huang

Department of Environmental Horticulture, University of Florida, Gainesville, FL 32611

Carl E. Niedziela, Jr.

School of Natural Sciences and Mathematics, Ferrum College, PO Box 1000, Ferrum, VA 24088

William H. Swallow

Department of Statistics, North Carolina State University, Raleigh, NC 27695-8203

Additional index words. *Gomphrena globosa*, *Impatiens wallerana*, *Solanum esculentum*, *Petunia ×hybrida*, *Tagetes erecta*, nitrate-to-ammonium ratio, low phosphorous stress

Abstract. Fertilizers with a high proportion of nitrogen (N) in the nitrate (NO_3^-) form are used in the ornamental industry to promote compactness in plants. Although the common belief is that it is the high proportion of NO_3^- that causes compactness, these formulations also contain no or a low level of phosphate, which can also cause compactness. This study was conducted to assess the relative effects of NO_3^- to ammonium (NH_4^+) ratio and phosphate supply, as found in high NO_3^- fertilizers, on seedling shoot growth. A series of fertilizers was formulated in which the level of phosphate and proportion of N in the NO_3^- form were varied factorially. Additionally, commercial fertilizers varying in these same two nutrient components were tested to verify the results obtained using the formulated fertilizers. Test plants included gomphrena (*Gomphrena globosa* L.), impatiens (*Impatiens wallerana* Hook. F.), petunia (*Petunia ×hybrida* Juss.), marigold (*Tagetes erecta* L.), and tomato (*Solanum esculentum* Mill.) grown as plug seedling crops. A strong inverse relationship occurred between the supply of phosphate and extent of compactness. The relationship between proportion of N in the NO_3^- form and compactness was comparatively small. In most comparisons within the study, shoot size increased with increasing proportion of NO_3^- , contrary to common belief. These data indicate that it is the limited phosphate level in high NO_3^- fertilizers that accounts for compactness rather than the high proportion of N in the NO_3^- form.

Many ornamental greenhouse crops are grown under some form of stress or growth regulation that limits the full potential for their shoot volume production. This is universally true for young plants produced in plug seedling

trays and bedding plant flats where limited horizontal space tends to increase vertical growth. Commercial methods of shoot control have included restricted watering (Schnelle et al., 1993), low fertility, which mainly translates into N stress (Styer and Koranski, 1997), temperature manipulation (Berghage and Heins, 1991), and chemical growth retardants (Gaston et al., 2001; Tayama et al., 1992). The respective problems associated with these procedures in the order just presented are desiccation of tissue and possible leaf abscission, chlorotic foliage, and high cost of growth regulators and their very limited registration for use on vegetable seedlings.

In addition to the four forms of shoot control, greenhouse production managers often use the form of N to control shoot size (Styer

and Koranski, 1997). The belief is that fertilizers with high proportions of NO_3^- produce compact shoots (smaller leaves and shorter internodes), whereas those with high proportions of NH_4^+ yield large shoots. This is achieved by using high NO_3^- fertilizers such as 15N–0P–12.5K, 14N–0P–11.6K, and 17N–0P–14.1K formulated from combinations of calcium nitrate [$\text{Ca}(\text{NO}_3)_2$], potassium nitrate (KNO_3), and magnesium nitrate [$\text{Mg}(\text{NO}_3)_2$]. Our experience with forms of N has not shown a relationship with shoot size. Because high NO_3^- fertilizers typically contain little or no phosphate, we hypothesized that it is a low phosphorus (P) stress brought on by using these fertilizers that accounts for suppression of shoot growth rather than their high proportion of NO_3^- .

Plant species vary greatly in their response to NO_3^- and NH_4^+ (Haynes and Goh, 1978). There are reports of 100% NO_3^- limiting plant growth in some species, including *Ageratum houstonianum* Mill. (Jeong and Lee, 1992), carnation (*Dianthus caryophyllus* L.) (Green et al., 1973), and wheat (*Triticum aestivum* L.) (Cox and Reisenauer, 1973). In contrast, most species grow better with mixtures of NH_4^+ and NO_3^- , with up to 50% of N in the NH_4^+ form (Gaffney et al., 1982; Jeong and Lee, 1992; Schrock and Goldsberry, 1982). Minimal effect of the NO_3^- to NH_4^+ ratio on plant shoot growth had been observed on *Impatiens wallerana* Hook F. (Argo and Biernbaum, 1997) and *Lobelia erinus* L. ‘Cobalt’ (Jeong and Lee, 1992). These variable results could be the result of an unchecked impact of the fertilizer $\text{NH}_4^+:\text{NO}_3^-$ ratio on root substrate pH and subsequent effects on nutrient availability.

Bedding plant growth can also be controlled by limiting the supply of phosphate in root media (Gibson et al., 2007; Huang and Nelson, 1994). Plants receiving a low level of phosphate resulted in compact shoots. It was found that growth inhibition by P deficiency is selective, affecting shoots much more than roots for many species, resulting in an often-desirable higher root-to-shoot ratio (Goldstein et al., 1988; Huang and Nelson, 1994; Loneragan and Asher, 1967; Trull et al., 1997).

The objective of this study was to assess the relative effects of NO_3^- to NH_4^+ ratio and phosphate supply, as found in high NO_3^- fertilizers, on vegetable and bedding plant seedling shoot growth.

Materials and Methods

Treatments and cultural practices. Two experiments were conducted in glass greenhouses in Raleigh, NC, at 35° north latitude. The 15 fertilizer treatments established in the first experiment can be separated into four groups (Table 1). The phosphate series at low NO_3^- (Treatments 1, 2, 3, and 4) all contained 60% of total N as NO_3^- but varied in phosphate-P levels where the equivalent elemental P levels were 0%, 3.3%, 6.6%, and 21.8% of N, respectively. The phosphate series at high NO_3^- (Treatments 5, 6, 7, and 8) contained 100% of total N as NO_3^- with the same phosphate-P levels as Treatments 1, 2, 3, and 4, respectively.

Received for publication 14 Oct. 2011. Accepted for publication 13 Nov. 2011.

This research was funded in part by a grant from Bedding Plants Foundation, Inc., Lansing, MI, and by the North Carolina Agricultural Research Service (NCARS), Raleigh, NC.

Use of trade names does not imply endorsement by the NCARS of products named nor criticism of similar ones not mentioned.

¹To whom reprint requests should be addressed; e-mail paul_nelson@ncsu.edu.

Table 1. Fertilizer formulations applied in Expts. 1 and 2.^z

Treatment no.	Expt.	N-P-K	NO ₃ ⁻ (% N) ^y	P (% N)	Ionic concentrations in fertilizer solutions						
					NH ₄ ⁺	NO ₃ ⁻	H ₂ PO ₄ ⁻	K ⁺	Ca ²⁺	SO ₄ ²⁻	Mg ²⁺
(mm)											
Phosphate series at low NO ₃ ⁻											
1	1, 2	20-0-16.6	60	0	2.8	4.3	0	2.1	0	0.35	0
2	1, 2	20-0.7-16.6	60	3.3	2.8	4.3	0.11	2.1	0.055	0.35	0
3	1, 2	20-1.3-16.6	60	6.6	2.8	4.3	0.21	2.1	0.11	0.35	0
4	1, 2	20-4.4-16.6	60	21.8	2.8	4.3	0.70	2.1	0.35	0.35	0
Phosphate series at high NO ₃ ⁻											
5	1	15-0-12.5	100	0	0	7.1	0	2.1	2.5	0	0
6	1	15-0.5-12.5	100	3.3	0	7.1	0.11	2.1	2.6	0	0
7	1	15-1-12.5	100	6.6	0	7.1	0.21	2.1	2.6	0	0
8	1, 2	15-3.3-12.5	100	21.8	0	7.1	0.70	2.1	2.9	0	0
NO ₃ ⁻ series at high phosphate											
4	1, 2	20-4.4-16.6	60	21.8	2.8	4.3	0.70	2.1	0.35	0.35	0
9	1, 2	20-4.4-16.6	87	21.8	0.9	6.2	0.70	2.1	1.9	0	0
10	1, 2	20-4.4-16.6	93	21.8	0.5	6.6	0.70	2.1	2.4	0	0
8	1, 2	15-3.3-12.5	100	21.8	0	7.1	0.70	2.1	2.9	0	0
Commercial series											
11	1	17-0-14.1	80	0	1.4	5.7	0	2.1	0.59	0	0.48
12	1, 2	15-0-12.5	87	0	0.9	6.2	0	2.1	1.8	0	0
13	1	14-0-11.6	92	0	0.6	6.5	0	2.1	1.1	0	0.88
14	1	13-0.9-10.8	95	6.9	0.4	6.7	0.22	2.1	1.2	0	0.95
15	1, 2	15-3.3-12.5 ^x	87	21.8	0.9	6.2	0.70	2.1	2.2	0	0

^zAll treatments were applied at 100 mg·L⁻¹ N and 83 mg·L⁻¹ K.

^yNitrate and P levels in the fertilizer solutions were expressed as a percentage of the total N in the solution.

^xThe 15-3.3-12.5 treatment was the 15-0-12.5 commercial fertilizer amended with Ca(H₂PO₄)₂ to provide phosphate while maintaining the N to K ratio. N = nitrogen; P = phosphorus; K = potassium.

The NO₃⁻ series at high phosphate (Treatments 4, 9, 10, and 8) contained the highest phosphate-P levels (21.8% of N) but varied in NO₃⁻ levels (60%, 87%, 93%, and 100% of total N, respectively). We self-formulated the non-commercial fertilizers to avoid unknown proprietary contents and NH₄⁺ that are present in some calcium nitrate sources.

The commercial fertilizer series (Treatments 11 to 15) included five high NO₃⁻ fertilizers (80% to 92% of N as NO₃⁻) from Masterblend International (Elwood, IL). Treatments 11 to 13 contained no phosphate, and Treatments 14 and 15 contained phosphate-P levels of 6.9% and 21.8% of N, respectively.

Potassium was 83% of N level in all 15 treatments. Test plants included gomphrena (*Gomphrena globosa* 'Gnome Purple') and tomato (*Solanum esculentum* 'Better Boy').

A second experiment was conducted to assess reproducibility of the first for gomphrena and to extend the test plant crops to impatiens (*Impatiens wallerana* 'Super Elfin White'), petunia (*Petunia ×hybrida* 'Madness White'), and marigold (*Tagetes erecta* 'Antigua Yellow'). Nine treatments were incorporated from the phosphate series at low NO₃⁻ (Treatments 1 to 4), NO₃⁻ series at high phosphate (Treatments 4, 8, and 9), and commercial fertilizer series as described for the first experiment (Table 1). The commercial fertilizer group only included Treatments 12 and 15.

In both experiments, seed were sown in 288-cell plug trays in a 3 sphagnum peat-moss:1 perlite substrate (v/v) amended with dolomitic limestone and Micromax micronutrient mix (The Scotts Company, Marysville, OH) at 3 and 0.45 g·L⁻¹, respectively. Seeds were sown on 10 Oct. and 14 Dec. for Expts.

Fig. 1. Effect of fertilizer (A) phosphorus (P) levels expressed as a percentage of total N at two NO₃⁻ proportions of total nitrogen (N) and (B) NO₄⁻ proportions of total N on the height; also (C) P levels expressed as a percentage of total N at two NO₃⁻ proportions of total N and (D) NO₄⁻ proportions of total N on the dry weight of seedling shoots of tomato and gomphrena at the end of plug stage 3 in Expt. 1. Vertical bars represent SE (n = 3).

1 and 2, respectively. After seeds were sown, trays were placed in a dark germination chamber at constant 24 °C. When radicles emerged and hooked downward (end of Stage 1), plug trays were removed from the chamber and placed on a greenhouse bench. For a 10-d

period beginning at cotyledon separation, seedlings were fertilized with 20N-4.4P-16.6K commercial fertilizer at 50 mg·L⁻¹ N. At that point, nutrient treatments were initiated and continued until the normal end of plug seedling production, 34 and 37 d in Expts. 1 and 2,

respectively. All fertilizer treatments were applied at 100 mg·L⁻¹ N.

Data collection. At the end of each experiment, substrates were sampled 1 h after fertilization. Substrate samples were squeezed by hand through one layer of cheesecloth. Extracted substrate solutions were analyzed for pH, electrical conductivity (EC), NO₃⁻, NH₄⁺, phosphate-P, Ca²⁺, Mg²⁺, and K⁺. EC and pH were measured using a Model 695 pH/conductivity/TDS/temperature meter (Extech Instruments, Waltham, MA). Colorimetric analysis was performed for NO₃⁻ (Cataldo et al., 1975), NH₄⁺ (Chaney and Marbach, 1962) and phosphate-P (concentrations under 10 µg·mL⁻¹; Murphy and Riley, 1962; and concentrations above 10 µg·mL⁻¹; Chapman and Pratt, 1961) on a Model Lambda 3 ultraviolet/VIS spectrophotometer (Perkin and Elmer, Norwalk, CT). Potassium (K), calcium (Ca), and magnesium (Mg) analysis was performed using an atomic absorption spectrometer Analyst 100 (Perkin-Elmer, Norwalk, CT).

Plants were harvested at the end of each experiment for shoot height and dry mass measurements. Fifty shoots from each plot were washed in 0.2 N HCl for 30 s, rinsed in deionized water, dried at 70 °C, weighed, and ground to 1-mm particle size in a stainless steel Wiley Laboratory Mill Model 4 (Thomas Scientific, Philadelphia, PA) for tissue analysis. Total N was analyzed using a Kjeldahl procedure (Fleck and Davidson, 1974). Ground tissue was dry-ashed at 500 °C, dehydrated in HCl, and dissolved in 0.5 N HCl. Tissue P, K, Ca, and Mg were measured by the same procedures used for substrate solution analyses.

Experimental design and statistical analysis. In Expt. 1, the phosphate series at both low and high NO₃⁻ (Treatments 1 to 8) were analyzed together as a two-factor factorial with two NO₃⁻ levels and four phosphate levels arranged in three blocks for a total of eight treatment combinations (24 experimental units). The NO₃⁻ series at high phosphate (Treatments 4, 8, 9, and 10) were analyzed separately with four treatments arranged in three blocks (12 experimental units). The commercial series (Treatments 11 to 15) with the addition of Treatment 4 were also analyzed separately with six treatments arranged in three blocks (18 experimental units).

In Expt. 2, the phosphate series at the low NO₃⁻ level (Treatments 1 to 4) were analyzed separately with four treatments arranged in three blocks (12 experimental units). The NO₃⁻ series at high phosphate (Treatments 4, 8, 9, and 10) were analyzed separately with four treatments arranged in three blocks (12 experimental units). The commercial series (Treatments 10 and 13) with the addition of Treatment 4 were also analyzed separately with three treatments arranged in three blocks (nine experimental units).

Data were analyzed using SAS 9.1 (SAS Inst., Cary, NC) with analysis of variance (ANOVA) by PROC ANOVA and means separation by least significant difference where appropriate. Shoot height and dry weight values were regressed against shoot tissue P concentration using SAS's PROC GLM to obtain

the best-fit linear vs. quadratic model for each species. Terms of the model to include were determined using $\alpha = 0.05$.

Results and Discussion

Formulated fertilizer series. In Expt. 1, results from the ANOVA indicated that tomato height was affected only by main treatment effects of phosphate-P fertilization and N form. Tomato shoot dry weight as well as height and dry weight of gomphrena were significantly affected by phosphate-P fertilization, N form, and their interaction.

When N was supplied in Expt. 1 with either 60% or 100% in the NO₃⁻ form to tomato, and 100% in the NO₃⁻ form to gomphrena, height increased with each increase in treatment

phosphate level (Fig. 1A). With 60% of N in the NO₃⁻ form, gomphrena height increased with increased phosphate-P up to 6.6% of the total N level and remained at that level with 21.8%. Height of tomato and gomphrena was either equal or greater in treatments that supplied N as 100% NO₃⁻ compared with 60% NO₃⁻. In Figure 1B, phosphate-P was supplied at 21.8% of the N level, whereas the percentage of N in the NO₃⁻ form increased from 60% to 100%. As the NO₃⁻ proportion increased, height increased in tomato and gomphrena. However, the effect of increasing the proportion of NO₃⁻ on height was much smaller than the effect of raising phosphate.

A large increase in shoot dry weight of tomato and gomphrena occurred when phosphate-P was supplied at a rate equal to 3.3%

Fig. 2. Effect of fertilizer (A) phosphorus (P) levels expressed as a percentage of total nitrogen (N) and (B) NO₃⁻ proportions of total N on the height; also (C) P levels expressed as a percentage of total N and (D) NO₃⁻ proportions of total N on the dry weight of seedling shoots of gomphrena, impatiens, marigold, and petunia at the end of plug Stage 3 in Expt. 2. Vertical bars represent SE (n = 3).

Table 2. Effects of commercial fertilizers, varying in percentage of total N in the NO₃⁻ form and phosphate level, on height and dry weight of seedling shoots of gomphrena and tomato at the end of plug Stage 3 in Expt. 1.

Treatment no.	N-P-K ^z	NO ₃ ⁻ (% N) ^y	P (% N)	Gomphrena		Tomato	
				Ht (cm)	Dry wt (mg)	Ht (cm)	Dry wt (mg)
11	17-0-14.1	80	0	2.7	41	12.2	62
12	15-0-12.5	87	0	2.9	39	13.4	62
13	14-0-11.6	92	0	3.6	44	13.7	65
14	13-0.9-10.8	95	6.6	4.8	54	16.9	73
15	15-3.3-12.5 ^x	87	21.8	4.5	54	15.9	66
4	20-4.4-16.6 ^w	60	21.8	4.1	43	16.3	65
LSD _{0.05}				0.2	3	0.3	2

^zAll treatments were applied at 100 mg·L⁻¹ N and 83 mg·L⁻¹ K.

^yNitrate and P levels in the fertilizer solutions were expressed as a percentage of the total N in the solution.

^xThe 15-3.3-12.5 treatment was the 15-0-12.5 commercial fertilizer amended with Ca(H₂PO₄)₂ to provide phosphate while maintaining the N to K ratio.

^wThe 20-4.4-16.6 treatment was not a commercial fertilizer but was included to compare the commercial fertilizers with high NO₃⁻ levels (80% to 92% of total N) to a fertilizer with relatively low NO₃⁻ levels (60% of total N).

N = nitrogen; P = phosphorus; K = potassium; LSD = least significant difference.

of the N level compared with zero phosphate-P in both the 60% and 100% NO_3^- series (Fig. 1C). Further increases of phosphate did not result in taller plants. At all phosphate levels, the increase from 60% to 100% of N in the NO_3^- form resulted in increased dry weight. In the treatments in which NO_3^- form of N was increased from 60% to 100% of N, whereas phosphate-P was held constant at 21.8% of N (Fig. 1D), dry weight of tomato and gomphrena increased with increasing proportion of NO_3^- .

In the Expt. 2 phosphate series at low NO_3^- (Fig. 2A), height increased in gomphrena, impatiens, and petunia with each increase in phosphate and increased in marigold with each phosphate-P increase up to 6.6% phosphate-P above which it remained constant. In the NO_3^- series at high phosphate-P (Fig. 2B), increased NO_3^- proportion resulted in increased height in marigold, had little effect in gomphrena and petunia, and showed a decrease in impatiens. Again, the phosphate effect was much greater than the NO_3^- effect.

Dry weight response in Expt. 2 largely followed height in the phosphate series at low NO_3^- (Fig. 2C), increasing in all four species with increasing phosphate. When phosphate-P was held constant at 21.8% of the fertilizer N level and the proportion of N in the NO_3^- form was increased from 60% to 100% (Fig. 2D), there was a small increase in dry weight in marigold and impatiens and no net effect in gomphrena and petunia. Like in the first experiment, the effect of NO_3^- proportion on height and dry weight was very small compared with the effect of phosphate level.

Commercial fertilizer series. Within the commercial series of fertilizers in Expt. 1 (Table 2), Treatments 11, 12, and 13 contained no phosphate-P; however, the proportion of N in the NO_3^- form increased in the order of the treatment number. Height and dry weight of tomato and gomphrena increased with increasing proportion of NO_3^- . Phosphate was supplied in Treatments 14 and 15 and these resulted in large increases in height and dry weight in both species compared with the treatments without phosphate.

When phosphate was added to Treatment 12 in Expts. 1 and 2 (Tables 2 and 3, respectively) to raise the phosphate-P level from zero to 21.8% of the N level (Treatment 15), large increases in height and dry weight occurred in all five species tested. In both experiments, the larger heights and dry weights resulting from phosphate addition in Treatment 15 were closer to those in Treatment 4 (a $20\text{N}-10\text{P}_2\text{O}_5-20\text{K}_2\text{O}$ fertilizer with 60% of N in the NO_3^- form and phosphate-P at 21.8% of N) than to those in Treatment 12 (without phosphate-P). This further indicated that height and dry weight suppression in Treatment 12 was controlled by low phosphate rather than high NO_3^- proportion.

Correlation of tissue phosphorus level with growth. Expts. 1 and 2 shoot heights (Figs. 3A and 3C, respectively) and dry weights (Figs. 3B and 3D, respectively) for all treatments within each experiment were plotted against

Table 3. Effects of commercial fertilizers, varying in percentage of total N in the NO_3^- form and phosphate level, on height and dry weight of seedling shoots of gomphrena, impatiens, marigold, and petunia at the end of plug Stage 3 in Expt. 2.

Treatment no.	N-P-K ^z	NO_3^- (% N) ^y	P (% N)	Gomphrena		Impatiens		Marigold		Petunia	
				Ht (cm)	Dry wt (mg)	Ht (cm)	Dry wt (mg)	Ht (cm)	Dry wt (mg)	Ht (cm)	Dry wt (mg)
12	15-0-12.5	87	0	1.3	23	1.0	13	3.8	44	0.5	7
15	15-3.3-12.5 ^x	87	21.8	3.3	31	4.3	29	5.4	62	2.2	24
4	20-4.4-16.6 ^w	60	21.8	3.6	30	5.2	25	4.9	53	2.6	24
				LSD _{0.05}							
				0.1	3	0.4	2	0.3	7	0.3	2

^zAll treatments were applied at 100 mg L^{-1} N and 83 mg L^{-1} K.

^yNitrate and P levels in the fertilizer solutions were expressed as a percentage of the total N in the solution.

^xThe 15-3.3-12.5 treatment was the 15-0-12.5 commercial fertilizer amended with $\text{Ca}(\text{H}_2\text{PO}_4)_2$ to provide phosphate while maintaining the N to K ratio.

^wThe 20-4.4-16.6 treatment was not a commercial fertilizer but was included to compare the commercial fertilizers with high NO_3^- levels (87% of total N) to a fertilizer with relatively low NO_3^- levels (60% of total N).

N = nitrogen; P = phosphorus; K = potassium; LSD = least significant difference.

Fig. 3. Effect of shoot tissue phosphorus (P) concentration on the (A) height and (B) dry weight of seedling shoots of tomato and gomphrena in Expt. 1 and (C) height and (D) dry weight of seedling shoots of gomphrena, impatiens, marigold, and petunia in Expt. 2 at the end of plug Stage 3. Regression lines were generated for the best fit model ($n = 3$). The regression equations for the graphs were (A) $y_{\text{gomphrena ht}} = -4.34x^2 + 6.53x + 2.28$ ($r^2 = 0.89$), $y_{\text{tomato ht}} = -9.61x^2 + 14.2x + 11.6$ ($r^2 = 0.90$); (B) $y_{\text{gomphrena dry wt}} = -42.7x^2 + 58.5x + 33.4$ ($r^2 = 0.65$), $y_{\text{tomato dry wt}} = -31.3x^2 + 37.9x + 59.3$ ($r^2 = 0.44$); (C) $y_{\text{gomphrena ht}} = -5.82x^2 + 9.24x + 0.127$ ($r^2 = 0.92$), $y_{\text{impatiens ht}} = -2.72x^2 + 6.71x + 0.434$ ($r^2 = 0.94$), $y_{\text{marigold ht}} = -4.77x^2 + 6.85x + 2.87$ ($r^2 = 0.92$), $y_{\text{petunia ht}} = -1.50x^2 + 3.58x + 0.329$ ($r^2 = 0.96$); and (D) $y_{\text{gomphrena dry wt}} = -20.5x^2 + 34.2x + 17.3$ ($r^2 = 0.86$), $y_{\text{impatiens dry wt}} = -20.4x^2 + 39.5x + 7.75$ ($r^2 = 0.90$), $y_{\text{marigold dry wt}} = -39.8x^2 + 59.9x + 33.5$ ($r^2 = 0.62$), $y_{\text{petunia dry wt}} = -28.8x^2 + 46.8x + 4.81$ ($r^2 = 0.95$).

their associated shoot tissue P concentrations. Both variables were found to increase with increasing tissue P concentrations greatly above the minimum critical tissue P levels of 0.25% to 0.30% of dry weight reported for general floral crops during mid- to late stages of production (Dole and Wilkins, 2004; Mills and Jones, 1996). Tomato height and dry weight were maximum in Expt. 1 at tissue P concentrations of $\approx 0.7\%$ and 0.6% , respectively. Height and dry weight of gomphrena were maximized at approximate tissue P concentrations between 0.7% and 0.8% in Expt. 1 and 0.8% and 0.9% in Expt. 2. In Expt. 2, maximum height and dry weights of marigold, petunia, and impatiens occurred in the tissue P ranges

of 0.7% to 0.8%, 0.8% to 1.1%, and 1.0% to 1.3%, respectively. Clearly, the minimum critical tissue P concentrations for these young bedding plants, based on maximum growth, are in the range of 0.6% to 1.3% and sometimes higher.

Typically, a broad luxury consumption plateau exists for P tissue concentrations above the minimum critical level. In this plateau, growth does not change with rising tissue P concentrations. If a luxury consumption plateau exists for tissue P concentrations in these young bedding plants, it is above 0.6% to 1.3%. Thus, tissue P concentrations that do not promote increased growth for many other floral crops with a low minimum critical level will

stimulate increased growth for young plants. This relationship of tissue P to growth is very important for commercial growers of plug seedlings and bedding plants because they need to produce compact plants. This can be accomplished by maintaining tissue P concentrations that are below the minimum critical levels and in the zone of moderate P deficiency.

Conclusions

These data support the commonly held industry concept that shoot height can be suppressed by applying high NO_3^- fertilizers. At the same time, they refute the industry explanation for this phenomenon, i.e., that it is the proportion of NO_3^- to NH_4^+ that controls height. High NO_3^- fertilizers are either devoid or low in phosphate. This study demonstrated that the low phosphate level in these fertilizers strongly induced compactness, whereas the higher proportions of N in the NO_3^- form had a comparatively weak effect on compactness. In most cases in this study, increased proportion of NO_3^- caused the reverse effect, i.e., increased plant size.

Literature Cited

Argo, W.R. and J.A. Biernbaum. 1997. Lime, water source, and fertilizer nitrogen form affect medium pH and nitrogen accumulation and uptake. *HortScience* 32:71–74.
Berghage, R.D. and R.D. Heins. 1991. Quantification of temperature effects on stem elongation in poinsettia. *J. Amer. Soc. Hort. Sci.* 116:14–18.

Cataldo, D.A., M. Haroon, L.E. Schrader, and V.L. Youngs. 1975. Rapid colorimetric determination of nitrate in plant tissue. *Commun. Soil Sci. Plant Anal.* 6:71–80.
Chaney, A.L. and E.P. Marbach. 1962. Modified reagents for determination of urea and ammonium. *Clin. Chem.* 8:130–132.
Chapman, H.D. and P.F. Pratt. 1961. *Methods of analysis for soils, plants, and waters*. Univ. Calif., Div. Agr. Sci., Berkeley, CA.
Cox, W.J. and H.M. Reisenauer. 1973. Growth and ion uptake by wheat supplied nitrogen as nitrate, or ammonium, or both. *Plant Soil* 38:363–380.
Dole, J.M. and H.F. Wilkins. 2004. *Floriculture principles and species*. Pearson Prentice Hall, Upper Saddle River, NJ.
Fleck, A. and J. Davidson. 1974. Micro determination of nitrogen. *Crit. Rev. Anal. Chem.* 4:141–154.
Gaffney, J.M., R.S. Lindstrom, A.R. McDaniel, and A.J. Lewis. 1982. Effect of ammonium and nitrate nitrogen on growth of poinsettia. *HortScience* 17:603–604.
Gaston, M.L., P.S. Konjoian, L.A. Kunkle, and M.F. Wilt (eds.). 2001. *Tips on regulating growth of floriculture crops*. O.F.A. Services, Columbus, OH.
Gibson, J.L., D.S. Pitchay, A.L. Williams-Rhodes, B.E. Whipker, P.V. Nelson, and J.M. Dole. 2007. *Nutrient deficiencies in bedding plants*. Ball Publishing, Batavia, IL.
Goldstein, A., D. Baertlein, and R. McDaniel. 1988. Phosphate starvation inducible metabolism in *Lycopersicon esculentum*. I. Excretion of acid phosphate by tomato plants and suspension-cultured cells. *Plant Physiol.* 87:711–715.
Green, J.L., W.D. Holley, and B. Thaden. 1973. Effects of the $\text{NH}_4^+:\text{NO}_3^-$ ratio, chloride, N-serve, and simazine on carnation flower production and plant growth. *Proc. Fla. State Hort. Soc.* 86:383–388.
Haynes, R.J. and K.M. Goh. 1978. Ammonium and nitrate nutrition of plants. *Biol. Rev. Camb. Philos. Soc.* 53:465–510.
Huang, J. and P.V. Nelson. 1994. Phosphorus supply control of bedding plant seedling root/shoot ratio. *HortScience* 29:502 (abstr.).
Jeong, B.R. and C.W. Lee. 1992. Ammonium and nitrate nutrition of 11 bedding plant species. *Acta Hort.* 319:505–510.
Loneragan, J. and C. Asher. 1967. Response of plants to phosphate concentration in solution culture: II. Rates of phosphate absorption and its relation to growth. *Soil Sci.* 103:311–318.
Mills, H.A. and J.B. Jones. 1996. *Plant analysis handbook II*. Micro Macro Publishing, Athens, GA.
Murphy, J. and J.P. Riley. 1962. A modified single solution for the determination of phosphate in natural waters. *Anal. Chim. Acta* 27:331–336.
Schnelle, M.A., B.D. McCraw and J.M. Dole. 1993. Height control for flowering and vegetable transplants. Oklahoma State Univ. Extension Facts No. 7614.
Schrock, P.T. and K.L. Goldsberry. 1982. Growth responses of seed geranium and petunia to N sources and growing media. *J. Amer. Soc. Hort. Sci.* 107:348–352.
Styer, R.C. and D.S. Koranski. 1997. *Plug and transplant production: A grower's guide*. Ball Publishing, Batavia, IL.
Tayama, H.K., R.A. Larson, P.A. Hammer, and T.J. Roll (eds.). 1992. *Tips on the use of chemical growth regulators on floriculture crops*. Ohio Florists' Assoc., Columbus, OH.
Trull, M.C., M.J. Guiltinan, J.P. Lynch, and J. Deikman. 1997. The responses of wild-type and ABA mutant *Arabidopsis thaliana* plants to phosphorus starvation. *Plant Cell Environ.* 20:65–92.