Phosphorus Restriction as an Alternative to Chemical Plant Growth Retardants in *Angelonia* and New Guinea Impatiens

Josh B. Henry¹, Ingram McCall, and Brian E. Whipker

ADDITIONAL INDEX WORDS. *Angelonia angustifolia*, floriculture, *Impatiens hawkeri*, nutrition, PGR, phosphate

SUMMARY. Chemical plant growth retardants (PGRs) are commonly used to produce compact bedding plants. Few PGRs are labeled for sensitive species because of the concern of excessive restriction of stem elongation or phytotoxicity. Growers are therefore presented with a dilemma: produce untreated plants that may be too tall or risk applying a PGR that can potentially lead to irreversible aesthetic damage to the plant. Nutrient restriction, specifically of phosphorus (P), may be used to control plant height. This study was conducted to determine if restricting P fertilization yielded comparable growth control to plants produced with PGRs. Two cultivars each of new guinea impatiens (*Impatiens hawkeri*) and angelonia (*Angelonia angustifolia*) were grown using five fertilizers that varied by P concentration (0, 2.5, 5, 10, and 20 ppm). Half of the plants from each P fertilizer concentration were treated with paclobutrazol at 4 and 5 weeks after transplant for angelonia and new guinea impatiens, respectively. On termination of the experiment, data were collected for height, diameter, and dry weight, which were used to determine a growth index (GI). Angelonia GI values were maximized with 7–9 ppm P, whereas new guinea impatiens GI was maximized with 8–11 ppm P. Concentrations of 3–5 ppm P provided similar height control to plants grown with nonlimiting P and a paclobutrazol application. Concentrations of ≤ 2.5 ppm P resulted in low-quality plants with visual symptoms of P deficiency. These results indicate that a narrow range of P concentrations may be used to control stem elongation and keep plants compact.

Excessively large bedding plants are less desirable than compact plants as they are difficult to handle and prone to breakage (van Iersel and Nemali, 2004). Damaged plants are often unmarketable, so growers implement management practices that limit plant height and promote overall compactness. Growers typically manage excessive stem elongation with chemical growth regulators such as PGRs (Whipker, 2017). A concern associated with PGRs is that they are not labeled for all crops. PGRs also have the potential to cause phytotoxicity in sensitive species, leading to unmarketable plants. Although PGRs

may still adequately control height in these sensitive plants, damage may occur to the flowers or foliage. This is the case for vinca (*Catharanthus roseus*), which develops symptoms of black spotting in response to the PGR paclobutrazol (Barrett and Nell, 1987). New guinea impatiens will develop chlorosis due to applications of chlormequat chloride and may exhibit flower bud abortion and excessive stunting from applications of paclobutrazol, flurprimidol, or uniconazole (Currey et al., 2016; Justice and Faust, 2015). Phytotoxicity often varies by cultivar and the quantity of active ingredient that is applied to the plant.

Nutrient restriction is an alternative way to control growth in greenhouse crops (Gibson et al., 2007; Henry et al., 2017; Justice and Faust, 2015). Phosphorus restriction has a direct effect on limiting internode elongation, resulting in more compact plants (Nelson et al., 2012). Past research determined that growers can use lower P concentrations during bedding plant seedling production to grow compact plants with a greater root to shoot ratio than those grown with nonlimiting P concentrations (Huang and Nelson, 1994). Phosphorus restriction may be successfully implemented for seedling production, which takes only a few weeks, whereas growing to flowering may take several months (McMahon, 2011). Over time, P concentrations in the substrate may be depleted, leading to reallocation of tissue P and deficiency symptom development. This is especially true for bedding plants produced in soilless substrates which have limited P-holding capacity (Marconi and Nelson, 1984). Present research suggests using 5–15 ppm P to maximize growth of bedding plants grown in soilless substrates (Henry et al., 2017), although few studies have been published regarding low P as an alternative to conventional PGRs.

Studies by Hansen and Nielsen (2000, 2001) investigated low P fertility as an alternative to PGRs using 0.3–31 ppm P with several floriculture species, including argyranthemum (*Argyranthemum frutescens*), aster (*Aster novi-belgii*), pentas (*Pentas lanceolata*), and hybrid rose (*Rosa* × *hybrid*). For most of these species, significant height control was only observed when limiting P fertilization to ≤ 1.5 ppm (Hansen and Nielsen, 2000, 2001). A study by Justice and Faust (2015) indicated that limiting P

Department of Horticultural Science, North Carolina State University, P.O. Box 7609, Raleigh, NC 27695

This paper is a portion of a thesis submitted by Josh B. Henry in fulfilling a degree requirement.

We are grateful for the funding support provided by the Fred C. Gloeckner Foundation, the USDA Floriculture and Nursery Research Initiative, American Floral Endowment Altman Family Scholarship, and The Garden Club of America. We would also like to express our gratitude to Dümmer Orange for providing cuttings, and for peatmoss provided by Sun Gro Horticulture.

¹Corresponding author. E-mail: josh.bradly.henry@gmail.com.

https://doi.org/10.21273/HORTTECH03939-17

Units

To convert U.S. to SI, multiply by	U.S. unit	SI unit	To convert SI to U.S., multiply by
29.5735	fl oz	mL	0.0338
7.8125	fl oz/100 gal	mL/100 L	0.1280
3.7854	gal	L	0.2642
2.54	inch(es)	cm	0.3937
0.5933	lb/yard ³	kg·m ⁻³	1.6856
28.3495	oz	g	0.0353
28,350	oz	mg	3.5274×10^{-5}
7.4892	oz/gal	g·L ⁻¹	0.1335
1	ppm	mg·L ⁻¹	1
(°F – 32) ÷ 1.8	°F	°C	(°C × 1.8) + 32

fertilization in a liquid fertilization program could provide height control for hybrid impatiens (*Impatiens xhybrida*). This study demonstrated that moderate height control was achieved when limiting P fertilization from 12 to 6 ppm P, but greater height control was observed between 6 and 3 ppm P (Justice and Faust, 2015). Other findings suggest that 5 ppm P or less can provide significant growth control for bedding plant production (Henry et al., 2017). However, no study has compared the effect of P fertility directly with that of a PGR. The objective of this study was to determine if restricting P fertilization could result in comparable growth control for bedding plants grown with higher P concentrations in combination with a standard PGR application.

Materials and methods

Angelonia and new guinea impatiens were selected for this study to represent crops with low and high sensitivity to PGRs, respectively. Angelonia ('Sungelonia Blue' and 'Sungelonia White') and new guinea impatiens ('Pure Beauty Red on Pink' and 'Tamarinda Dark Red') cuttings (Dümmen Orange, Columbus, OH) were stuck on 3 May 2016 in 128-cell plug trays with cell dimensions of

1 × 1 × 1.5 inches (length × width × depth) and a cell volume of 25 mL. The substrate used for all aspects of the experiment was an 80:20 (v:v) mix of canadian sphagnum peatmoss (Conrad Fafard, Agawam, MA) and horticultural coarse perlite (Perlite Vermiculite Packaging Industries, North Bloomfield, OH), amended with mesh size #100 dolomitic limestone (Rockydale Agricultural, Roanoke, VA) at 15 lb/yard³ and wetting agent (AquaGro 2000 G; Aquatrols, Cherry Hill, NJ) at 1 lb/yard³. This custom substrate was used to limit P contamination that may be present in commercial substrate mixes.

Cuttings were rooted under mist for 2 weeks without fertilization. Mist frequency varied depending on cutting turgidity and substrate saturation. Plants were propagated and grown in a glass-glazed greenhouse at North Carolina State University, Raleigh (lat. 35°N), under natural photoperiod. Greenhouse day/night temperature set points were 75/65 °F. Rooted 24-d-old angelonia were transplanted on 27 May and 21-d-old new guinea impatiens were transplanted on 24 May into 5-inch round azalea pots (Dillen, Middlefield, OH) with dimensions of 5 × 3.6 inches (diameter × depth) and a volume of 800 mL.

Fertilization treatments began the day of transplant for each species. Five fertilizer concentrations of 0, 2.5, 5, 10, or 20 ppm P were used. Fertilizers were custom blends of the following individual technical grade salts (Fisher Scientific, Pittsburg, PA): calcium nitrate tetrahydrate [Ca(NO₃)₂·4H₂O], potassium nitrate (KNO₃), monopotassium phosphate (KH₂PO₄), potassium sulfate (K₂SO₄), magnesium sulfate heptahydrate (MgSO₄·7H₂O), magnesium nitrate [Mg(NO₃)₂], iron chelate (Fe-DTPA), manganese chloride tetrahydrate (MnCl₂·4H₂O), zinc chloride heptahydrate (ZnCl₂·7H₂O), copper chloride dihydrate (CuCl₂·2H₂O), boric acid (H₃BO₃), and sodium molybdate dihydrate (Na₂MoO₄·2H₂O) (Table 1). Phosphorus (referring to phosphate-phosphorus) concentrations were varied among treatments, whereas other essential nutrients were adjusted to remain as constant as possible (Table 1). Nitrate-nitrogen (NO₃-N) and potassium (K) were held at 150 ppm, with all other essential microelements remaining constant (Henry, 2017). Fertilizer solution was mixed in 100-L barrels and applied through drip irrigation as needed at every irrigation with an estimated 10% leaching fraction. Plants grown with higher P concentrations typically had greater growth and

Table 1. Fertilizer salts used to formulate fertilizer stock solutions, with their respective molecular weight, the weight of each salt used per liter of stock solution, and the amount of stock solution used for each phosphorus fertilizer treatment (0, 2.5, 5, 10, and 20 ppm phosphorus). Fertilizer stock solutions consisting of individual salts of each macronutrient and iron were used, whereas a single micronutrient stock solution mix consisting of manganese, zinc, copper, boron, and molybdenum salts was used to supply these nutrients.

Fertilizer salt	Molecular wt (g) ^z	Wt of salt (g·L ⁻¹) ^z	Phosphorus fertilizer concn (ppm) ^z				
			0	2.5	5	10	20
			Stock solution used (mL/100 L) ^z				
Individual salts							
Ca(NO ₃) ₂ ·4H ₂ O	236.15	354.24	213.9	213.9	213.9	213.9	213.9
KNO ₃	101.10	128.52	196.9	196.9	234.8	276.4	251.0
MgSO ₄ ·7H ₂ O	246.48	295.80	96.9	96.9	117.0	150.0	140.0
KH ₂ PO ₄	136.09	81.66	—	13.4	26.9	53.8	107.6
K ₂ SO ₄	174.26	100.00	116.2	110.0	60.2	—	—
Mg(NO ₃) ₂	256.41	256.41	89.4	89.4	65.3	38.8	55.0
Fe-DTPA	40.00	40.00	100.0	100.0	100.0	100.0	100.0
Micronutrient mix			45.0	45.0	45.0	45.0	45.0
MnCl ₂ ·4H ₂ O	197.91	7.92	—	—	—	—	—
ZnCl ₂ ·7H ₂ O	136.28	0.90	—	—	—	—	—
CuCl ₂ ·2H ₂ O	170.48	1.13	—	—	—	—	—
H ₃ BO ₃	61.83	6.18	—	—	—	—	—
Na ₂ MoO ₄ ·2H ₂ O	241.90	0.05	—	—	—	—	—

Ca(NO₃)₂·4H₂O = calcium nitrate tetrahydrate; KNO₃ = potassium nitrate; KH₂PO₄ = monopotassium phosphate; K₂SO₄ = potassium sulfate; MgSO₄·7H₂O = magnesium sulfate heptahydrate; Mg(NO₃)₂ = magnesium nitrate; Fe-DTPA = iron chelate; MnCl₂·4H₂O = manganese chloride tetrahydrate; ZnCl₂·7H₂O = zinc chloride heptahydrate; CuCl₂·2H₂O = copper chloride dihydrate; H₃BO₃ = boric acid; Na₂MoO₄·2H₂O = sodium molybdate dihydrate.

^z 1 g = 0.0353 oz, 1 g·L⁻¹ = 0.1335 oz/gal, 1 L = 0.2642 gal, 1 ppm = 1 mg·L⁻¹, and 1 mL/100 L = 0.1280 fl oz/100 gal.

were, therefore, irrigated more frequently than those grown with lower P concentrations. Solution was delivered via sump pumps (model 1A; Little Giant Pump Co., Oklahoma City, OK) connected to 0.75-inch irrigation tubing fitted with drip rings (Dramm USA, Manitowoc, WI).

Treatments were completely randomized by cultivars with 16 individual plants of each cultivar grown with each of the five P concentrations. Each species was treated with a single application of paclobutrazol (Piccolo 10 XC; Fine Americas, Walnut Creek, CA) halfway through the study. Eight angelonia plants from each of the five P concentrations were treated with a substrate drench of paclobutrazol at a concentration of 4 mg a.i. per pot, within a total volume of 4 fl oz per pot. This drench was applied 4 weeks after transplant and followed published recommendations for paclobutrazol applications for angelonia (Schoellhorn, 2002). Eight new guinea impatiens plants from each of the five P concentrations were treated with a foliar spray of 7.5 ppm paclobutrazol applied using a volume of 200 mL·m⁻². This spray was applied 5 weeks after transplant and followed published recommendations for paclobutrazol applications for new guinea impatiens (Whipker, 2017). Each cultivar had eight single plant replicates for each of five P concentrations with or without a paclobutrazol application.

Growth data were collected at the end of the study, 8 weeks after transplant for angelonia and 10 weeks after transplant for new guinea impatiens. Measurements were collected for plant height by measuring the highest point of the foliage with a ruler from the rim of the pot. Plant diameter was recorded by averaging the widest point and its perpendicular axis. The number of axillary branches was counted. The plants were severed at the substrate surface, and plant shoot tissues were dried for at least 72 h at 158 °F. After drying, plant shoot dry weight was determined.

STATISTICAL ANALYSIS. Height, diameter, and dry weight were analyzed and used to calculate GI (Henry et al., 2017).

$$GI = \frac{\text{height} + \frac{\text{diameter1} + \text{diameter2}}{2} + \text{dry weight}}{3} \quad [1]$$

All data were analyzed using SAS (version 9.4; SAS Institute, Cary, NC) and GraphPad Prism (version 7.02; GraphPad Software, La Jolla, CA). Data were subjected to the general linear model procedure (PROC GLM) to conduct analysis of variance. The regression procedure (PROC REG) was used to regress the data to determine the best-fit linear or quadratic models for each growth parameter based on P concentrations with and without PGR applications. The nonlinear regression procedure (PROC NLIN) was used to determine best-fit quadratic plateau models for each growth parameter (Henry et al., 2017). Quadratic plateau models are a segmented regression model in which there is an initial quadratic curve that increases or decreases until a point at which the data maintain a similar horizontal trend as the explanatory variable value increases. This model was found to be well suited for this study as many plant growth parameters increased up to a certain point after which they no longer increased or decreased with increasing P concentrations.

Models obtained from PROC REG and PROC NLIN were compared using GraphPad Prism and selected based on the difference between corrected Akaike information criterion (AICc) values (Spiess and Neumeyer, 2010). AICc may be used to determine nonlinear regression model fit, as traditional measures of fit, such as the adjusted coefficient of determination, are poorly suited to measure the fit of nonlinear regression models (Spiess and Neumeyer, 2010). Models with the lowest AICc

were selected. X_0 values were determined and provided for growth plateaus of quadratic plateau models. The X_0 value indicated the point at which the model reached its respective maximum value and plateaued. This value indicated the P concentration at which each growth parameter reached its maximum, past which point no change in growth occurred. When applicable, the regression equations were used to determine the P concentrations that would result in the maximum paclobutrazol-treated model value for the nontreated model. This comparison was made when the paclobutrazol-treated model had lower maximum growth than the nontreated model, and was visually illustrated in the graphs by the intersection of the paclobutrazol-treated maximum value with the regression model of nontreated plants (Figs. 1 and 2).

Results and discussion

Main effects were each considered independently because of plant growth interactions among P concentration, PGR application, and cultivar. A P concentration of 20 ppm in combination with a PGR application was considered the control in this study as a standard production practice used by growers. These crops are often produced with PGR applications, so growth parameters were compared within cultivars and between plants grown with and without paclobutrazol applications. Regression models were used to determine the P concentration at which each growth parameter was maximized. The quadratic plateau model provided the best fit in most instances (Figs. 1 and 2). In these instances, the plateau for paclobutrazol-treated plants could be followed to the point

where it intersected with the model for nontreated plants. Similarly, the peak for selected paclobutrazol-treated quadratic models could be followed to the intersection with the nontreated model. These intersections demonstrated the P concentrations required by nontreated plants to result in similar growth to control plants (Figs. 1 and 2). The differences in these values will be discussed for each cultivar.

The ‘Sungelonia Blue’ angelonia grown without paclobutrazol reached a maximum height of 48 cm at 5 ppm P, whereas paclobutrazol-treated plants reached a maximum height of 44 cm with 4 ppm P (Fig. 1A). The intersection of the paclobutrazol-treated plateau with the regression model of nontreated plants indicated that similar height could be achieved by growing ‘Sungelonia Blue’ with 3 ppm P and no PGR application. This demonstrates that similar levels of height control can be achieved by limiting P fertilization to 3 ppm P. Higher concentrations of 11 and 10 ppm P were required to maximize diameter for plants grown with and without a paclobutrazol application, respectively (Fig. 1C). Concentrations of 16–20 ppm P were required to maximize branching (Fig. 1E). Maximum branching was higher in plants grown without a PGR, with 59 branches per plant compared with 51 branches per plant in paclobutrazol-treated plants (Fig. 1E). Higher P concentrations of ≥ 17 ppm P were also required to maximize dry weight (Fig. 1G). This illustrates how plants typically continue to exhibit luxury consumption of P (Nelson et al., 2012) and accumulate additional biomass past the point at which plants reached their maximum dimensions.

The GI for ‘Sungelonia Blue’ indicated that overall growth was maximized with 9 ppm P in paclobutrazol-treated plants and 9 ppm P in nontreated plants (Fig. 1I). The intersection of the paclobutrazol-treated plateau with the regression model for nontreated plants indicated that similar GI could be achieved by growing ‘Sungelonia Blue’ with 7 ppm P and no PGR application (Fig. 1I). The analysis of these parameters illustrates that growers can significantly limit the fertilizer P concentration to control height; however, a higher P concentration may be desired when considering the overall growth of the crop.

Fig. 1. Best-fit regression models for height (A and B), diameter (C and D), number of branches (E and F), dry weight (G and H), and growth index (GI) (I and J) of ‘Sungelonia Blue’ and ‘Sungelonia White’ angelonia, respectively. Growth index was calculated by averaging the height, diameter, and dry weight, where $GI = [\text{height} + (\text{diameter 1} + \text{diameter 2})/2 + \text{dry weight}]/3$. Models represent plants grown with or without a plant growth retardant (PGR) drench of 4 mg (1.4×10^{-4} oz) a.i. paclobutrazol per pot. The intersection of the two dotted lines indicates the phosphorus (P) concentration that can be used to grow each cultivar without paclobutrazol while maintaining similar growth to the largest paclobutrazol-treated plants, whenever applicable. The X_0 value indicates the P concentration required to maximize a quadratic plateau regression model and the point at which the model plateaued. The peak x value indicates the P concentration required to maximize a quadratic regression model; 1 ppm = $1 \text{ mg} \cdot \text{L}^{-1}$, 1 cm = 0.3937 inch, and 1 g = 0.0353 oz.

The ‘Sungelonia White’ angelonias reached an average maximum height with 5 ppm P for paclobutrazol-treated plants and 4 ppm P for nontreated plants (Fig. 1B). The intersection of the paclobutrazol-treated plateau with the regression model of nontreated plants indicated that similar height could be achieved with 3 ppm P and no PGR application. As with the results of ‘Sungelonia Blue’, higher P concentrations were required to maximize the other growth parameters. For instance, 8–10 ppm P was required to maximize diameter (Fig. 1D), 16–18 ppm P to maximize branching (Fig. 1F), and 15–16 ppm P to maximize dry weight (Fig. 1H). The GI needed to maximize overall growth was 9 ppm for paclobutrazol-treated plants and 7 ppm for nontreated plants (Fig. 1J). The intersection of the paclobutrazol-treated plateau with the regression model of nontreated plants indicated that similar growth could be achieved with 6 ppm P and no PGR application (Fig. 1J).

Paclobutrazol-treated ‘Pure Beauty Red on Pink’ new guinea impatiens were 15% shorter than nontreated plants and required 10 ppm P to reach maximum height (Fig. 2A). The intersection of the paclobutrazol-treated plateau with the regression model of nontreated plants indicated that similar height could be achieved with 5 ppm P and no PGR application (Fig. 2A). This demonstrates that by applying half of the P required to attain maximum height without a PGR application, growers can obtain 15% shorter plants for this cultivar. Maximum GI was obtained with 10 ppm P for paclobutrazol-treated plants and 12 ppm P for nontreated plants (Fig. 2I). To provide growth control comparable to that of the paclobutrazol-treated plants, a concentration of 7 ppm P would be required (Fig. 2I).

The ‘Tamarinda Dark Red’ new guinea impatiens required similar P concentrations as ‘Pure Beauty Red on Pink’ for most growth parameters. Height was maximized with 8–11 ppm P (Fig. 2B). The paclobutrazol-treated maximum height was attained in nontreated plants with 4 ppm P (Fig. 2B), indicating that this cultivar needed similar P levels to control height as were required by ‘Pure Beauty Red on Pink’. Some parameters such as dry weight and branching

required as high as 15 and 16 ppm P, respectively, to reach maximum values (Fig. 2F and 2H). The GI was maximized with 11 ppm P for paclobutrazol-treated and nontreated plants (Fig. 2J). This provides additional support that growers can limit their P fertilization to achieve comparable growth control to a single application of paclobutrazol. By determining the intersection of the paclobutrazol-treated plateau with the regression model of nontreated plants, it was found that similar growth could be achieved with 7 ppm P and no PGR application (Fig. 2J).

For both crops grown in this study, low P fertilization resulted in comparable growth control to plants grown with 20 ppm P in combination with a PGR. According to regression analysis, new guinea impatiens grown with 5 ppm P and no PGR had comparable height to those grown with a concentration of 20 ppm P in combination with a PGR (Fig. 2A and 2B). Both angelonia cultivars had similar height with 3 ppm P and no PGR compared with plants grown with 20 ppm P and a PGR (Fig. 1A and 1B). These results deviate from the findings of Hansen and Nielsen (2000, 2001) as significant height control was not achieved among crops such as argyranthemum, aster, and pentas when lowering P fertilization from 31 to 4.7 ppm. Hansen and Nielsen (2000, 2001) found that 1.5 ppm P controlled height when compared with their highest concentration of 31 ppm P. In contrast, 2.5 ppm P used in our study led to plants that were stunted and developed mild symptoms of P deficiency (personal observation). Plants grown with 2.5 ppm P were smaller in both height and diameter and plants did not grow sufficiently for the canopy

to cover the pot. Plants grown without P had severe symptoms of P deficiency, although symptoms appeared most prominent on 'Tamarinda Dark Red' (personal observation).

Results from Hansen and Nielsen (2000, 2001) indicated that growing plants with 1.5 ppm provided significant growth control with no detrimental effects on appearance or flowering. The inconsistency between our studies may be explained by the difference in substrate composition. Hansen and Nielsen (2000, 2001) used kiln-dried clay as the substrate, which was treated with a P buffer. This buffer supplied P at a constant concentration that released steadily on each irrigation, rather than being supplied through a liquid fertilizer (Oh et al., 2016). The low P concentrations used in these studies would likely result in detrimental P deficiency symptoms in the typical peat-based substrates used in commercial bedding plant production. In our study, a peat- and perlite-based substrate was used in combination with a liquid fertilization program, which is more typical of the practices used in commercial bedding plant production (Marconi and Nelson, 1984). The methods in this study replicate commercial production practices, so results may be used directly to provide fertilizer recommendations to growers who apply liquid fertilizer with every irrigation.

The results of this study demonstrate that concentrations >2.5 ppm P should be used to control growth while inhibiting visual P deficiency symptoms, whereas concentrations >10–15 ppm maximized most growth parameters such as height. These findings are similar to those reported by Justice and Faust (2015), who found that 6 ppm P provided moderate height control, 3 ppm P provided significant height control, and 0 ppm P resulted in P deficiency

symptoms. Our study confirmed that low P fertilization provided comparable growth control to a PGR application; however, it is important to acknowledge that the low margin for error could limit the practicality and successful implementation of P restriction in a commercial setting (Justice and Faust, 2015).

Conclusions

When considering growth control, it is the ultimate decision of the grower to determine which specific growth parameter should be targeted. In this study, 3–5 ppm P was required to provide comparable height control to that of a common PGR. The total growth measured in terms of GI demonstrated that slightly higher concentrations of 6–7 ppm P should be used to provide comparable overall growth control compared with a single application of paclobutrazol. Although concentrations as low as 3 ppm P could be used to control height, we do not recommend this P concentration in a commercial production setting. The potential for error is too great when a simple miscalculation or improperly calibrated fertilizer injector could be the difference between beneficial height control and deficiency symptom development. At these low concentrations, a difference of 1 ppm P could unintentionally render a crop unsalable. Thus, growers should maintain 5–10 ppm P. This range should provide sufficient P to prevent visual P deficiency symptoms while limiting excessive stem elongation and providing moderate growth control.

Literature cited

- Barrett, J.E. and T.A. Nell. 1987. Efficacy and phytotoxicity of paclobutrazol and XE-1019 on vinca. *J. Amer. Soc. Hort. Sci.* 107:335–338.
- Currey, C.J., N.J. Flax, and K.J. Walters. 2016. Foliar sprays of flurprimidol, paclobutrazol, and uniconazole suppress height of seed-propagated new guinea impatiens. *HortTechnology* 26:20–25.
- 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 Publ.*, Batavia, IL.
- Hansen, C.W. and K.L. Nielsen. 2000. Non-chemical growth regulation of ornamental plants. *Grøn Viden* 121:1–4.
- Hansen, C.W. and K.L. Nielsen. 2001. Reduced phosphorus availability as

Fig. 2. Best-fit regression models for height (A and B), diameter (C and D), number of branches (E and F), dry weight (G and H), and growth index (GI) (I and J) of 'Pure Beauty Red on Pink' and 'Tamarinda Dark Red' new guinea impatiens, respectively. Growth index was calculated by averaging the height, diameter, and dry weight, where $GI = [\text{height} + (\text{diameter } 1 + \text{diameter } 2)/2 + \text{dry weight}]/3$. Models represent plants grown with or without a plant growth retardant (PGR) spray of 7.5 ppm paclobutrazol. The intersection of the two dotted lines indicates the phosphorus (P) concentration that can be used to grow each cultivar without paclobutrazol while maintaining similar growth to the largest paclobutrazol-treated plants, whenever applicable. The X_0 value indicates the P concentration required to maximize a quadratic plateau regression model and the point at which the model plateaued. The peak x value indicates the P concentration required to maximize a quadratic regression model; 1 ppm = 1 mg·L⁻¹, 1 cm = 0.3937 inch, and 1 g = 0.0353 oz.

a method to reduce chemical growth regulation and to improve plant quality, p. 314–315. In: W.J. Horst, M.K. Schenk, A. Bürkert, N. Claassen, H. Flessa, W.B. Frommer, H. Goldbach, H. Olf, V. Römhild, B. Sattelmacher, U. Schmidhalter, S. Schubert, N. von Wirén, and L. Wittenmayer (eds.). Plant nutrition—Food security and sustainability of agroecosystems. Springer, Dordrecht, The Netherlands.

Henry, J.B. 2017. Beneficial and adverse effects of low phosphorus fertilization of floriculture species. North Carolina State Univ., Raleigh, NC, MS Diss.

Henry, J.B., I. McCall, B. Jackson, and B. E. Whipker. 2017. Growth response of herbaceous ornamentals to phosphorus fertilization. *HortScience* 52:1362–1367.

Huang, J. and P.V. Nelson. 1994. Phosphorus supply control of bedding plant

seedling root/shoot ratio. *HortScience* 29:502 (abstr.).

Justice, A. and J.E. Faust. 2015. Phosphorus-restriction as a potential technique to control *Impatiens* stem elongation. *Acta Hort.* 1104:9–13.

Marconi, D. and P. Nelson. 1984. Leaching of applied phosphorus in container media. *Scientia Hort.* 22:275–285.

McMahon, R.W. 2011. An introduction to greenhouse production. 3rd ed. Curriculum Materials Service, Columbus, OH.

Nelson, P.V., C-Y. Song, J. Huang, C.E. Niedziela, Jr., and W.H. Swallow. 2012. Relative effects of fertilizer nitrogen form and phosphate level on control of bedding plant seedling growth. *HortScience* 47:249–253.

Oh, Y., P.V. Nelson, D.L. Hesterberg, and C.E. Niedziela. 2016. Efficacy of a

phosphate-charged soil material in supplying phosphate for plant growth in soil-less root media. *Intl. J. Agron.* Article ID 8296560. 11 Feb. 2017. <<https://www.hindawi.com/journals/ija/2016/8296560>> doi:10.1155/2016/8296560.

Schoellhorn, R. 2002. Angelonia, the warm season snapdragon. *Greenhouse Prod. News* 12(3):77–78.

Spiess, A. and N. Neumeyer. 2010. An evaluation of R^2 as an inadequate measure for nonlinear models in pharmacological and biochemical research: A Monte Carlo approach. *BMC Pharmacol.* 10:6.

van Iersel, M.W. and K.S. Nemali. 2004. Drought stress can produce small but not compact marigolds. *HortScience* 39:1298–1301.

Whipker, B. 2017. Plant growth regulators for annuals. Ball Publ., West Chicago, IL.