Morphology and Postharvest Performance of *Geogenanthus undatus* C. Koch & Linden ‘Inca’ after Application of Ancymidol or Flurprimidol

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Abstract. Excessive internode elongation and leaf senescence are common problems with foliage plants transferred to interiorscapes. The authors’ objective was to determine whether plant growth regulators applied late in the production cycle could control growth during production and improve interiorscape performance. In addition, the authors wanted to quantify the effect of irradiance on growth and morphology during the production phase and in the interiorscape. *Geogenanthus undatus* C. Koch & Linden ‘Inca’ plants were grown under one of two photosynthetic photon fluxes (PPF; 50 or 130 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$), and were treated with either α -(methylethyl)- α -[4-(trifluoromethoxy)phenyl]-5-pyrimidinemethanol (flurprimidol) or α -cyclopropyl- α -(4-methoxyphenyl)-5-pyrimidinemethanol (ancymidol) during the week 12 production, at 0.5, 1.0, or 1.5 mg/pot of active ingredient. The high PPF resulted in significantly higher leaf, stem, root, and total dry weight, and leaf area, but lower leaf area ratio (leaf area divided by total plant dry weight) compared with the low PPF. After production, plants were placed in a simulated interior environment for 4 months under a PPF of 15 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ and a photoperiod of 12 hours/day. Production PPF did not affect most growth parameters after 4 months in the interior environment, except for the root-to-shoot ratio. Under low-production PPF, root-to-shoot ratios were lower than under high-production PPF. For both growth regulators, the height and growth indexes were lower than for control plants, but flurprimidol offered greater control than ancymidol. Flurprimidol-treated plants had lower root dry weight and root-to-shoot ratios compared with ancymidol-treated and control plants. Applications of ancymidol or flurprimidol administered to *G. undatus* C. Koch & Linden ‘Inca’ late during the production cycle resulted in significant growth control and, therefore, superior plant performance throughout the postharvest period.

Geogenanthus undatus is a newly introduced cultivar of the species *G. undatus* C. Koch & Linden (seersucker plant), native to Peru (Graf, 1963). The species has a low-

growing habit with fleshy, broad, ovate metallic green leaves with parallel bands of pale gray and a characteristic quilted appearance. *Geogenanthus undatus* C. Koch & Linden ‘Inca’ has darker green leaves and a more compact habit than the species. The seersucker plant holds considerable potential for the interiorscape industry because of its adaptability to low-light environments. Although new species and cultivars are the lifeblood of the ornamental industry, cultural information is not often available at their market introduction. To produce high-quality marketable material, growers need production guidelines for irradiance, temperature, and nutrition regimes, as well as growth control.

The majority of tropical foliage plants are produced for use indoors. Generally, photo-

synthetic photon flux (PPF) in postharvest settings are suboptimal for plant growth, even for many shade-adapted species. Low PPF can cause foliar chlorosis or necrosis, premature leaf senescence, or internode stretching (Conover and Poole, 1981). These undesirable responses lead to frequent plant replacement, high costs, and consumer dissatisfaction. Growers often acclimate foliage plants to lower PPF during production to improve postharvest performance.

Production PPFs have been shown to affect growth parameters of foliage plants. Species-specific responses have been documented for various growth parameters, such as growth index, dry weight, and root-to-shoot ratio (Conover and Poole, 1981). In addition, production irradiance also affects acclimation. Because the majority of foliage plants are sold for the interiorscape market, postharvest performance is an important aspect of the overall evaluation of a particular species or cultivar for the foliage industry.

Plant growth regulator (PGR) type and concentration have been shown to affect postharvest performance of foliage plants (Cox and Whittington, 1988; Davis, 1987). Timing of application is considered critical to the efficacy of PGRs; they are generally applied early during the production cycle. However, by the time the plant is installed in the postharvest environment, the growth control exerted by the PGR may be less, and thus the PGR effect may not carry over to the interiorscape. If the PGR is applied later during the production cycle, and at an appropriate concentration, the growth control and related enhanced plant quality may be extended into the postharvest period. In the current study, drench applications of α -cyclopropyl- α -(4-methoxyphenyl)-5-pyrimidinemethanol (ancymidol) or α -(methylethyl)- α -[4-(trifluoromethoxy)phenyl]-5-pyrimidinemethanol (flurprimidol) were administered to *Geogenanthus* during the later part of the production cycle. The purpose of a late-production application was to ensure growth control throughout the postharvest period. In addition, we hoped that late application of PGRs would slow down growth during the latter part of production, allowing the plants to accumulate starch instead of allocating carbohydrates to new growth. Starch reserves could be used by the plants after transfer to a low irradiance environment and potentially improve their performance in interiorscapes.

The objectives of this study were to evaluate the effects of PPF and PGR on growth of *G. undatus* C. Koch & Linden ‘Inca’ during production, to determine whether the responses to the PGRs are similar at different irradiance levels, and, lastly, to evaluate the postharvest performance of *G. undatus* C. Koch & Linden ‘Inca’ in response to PPF and PGR applied late during the production cycle.

Materials and Methods

Production phase

Plant material. Tissue culture liners of *G. undatus* C. Koch & Linden ‘Inca’

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(Agri-Starts, Apopka, Fla.) were planted in square pots (volume, 793 cm³), using a peat-lite medium (Fafard 2P, 65% Canadian sphagnum peat–35% horticultural perlite; Fafard, Anderson, S.C.). Plants were grown in a double-polyethylene Quonset-style greenhouse, covered with a double layer of 50% shade cloth. The temperature control in the greenhouse was set at 21 °C day/18 °C night (Wadsworth Systems; Arvada, Colo.). Plants were grown on 12 ebb-and-flow benches (1.2 × 2.4 m²; Midwest GroMaster, St. Charles, Ill.). Fertilizer solutions were stored in plastic barrels (210 L) and pumped into the watertight trays of the ebb-and-flow system using submersible pumps (NK-2; Little Giant, Oklahoma City, Okla.). Media fertility levels were monitored weekly on a random sample of 12 to 24 plants using the pour-through method (Yeager, et al., 1997). Distilled water (50 mL) was poured into each pot and allowed to drain; leachate was collected, and pH and electrical conductivity (EC) were analyzed (Myron L Agrimeter AG-6; Metex Corporation Ltd., Toronto, Canada). Medium fertility levels were found to be within appropriate levels on all testing dates (EC, 1.3–1.6 dS·m⁻¹; pH, 5.5–6.5). Tissue and media samples were sent to MicroMacro Laboratories (Athens, Ga.) for analysis at the midpoint of production. Macro- and micronutrient levels in tissue were found to be within appropriate ranges, based on general recommendations for foliage plants (Reed, 1996).

Treatments. Two production irradiance levels were achieved by using a single layer of 50% black shade cloth placed over half the benches (designated low *PPF* treatment), whereas the remaining six benches received ambient irradiance levels and were designated as the high *PPF* treatment. The actual shade structure provided some additional shading. Measurement of the high and low irradiance levels were taken as instantaneous measurements (2 PM on 5 May 2004), and were found to be 130 μmol·m⁻²·s⁻¹ or 50 μmol·m⁻²·s⁻¹ respectively.

Drench applications of ancymidol [0.5, 1.0, 1.5 mg/pot of active ingredient (a.i.)] or flurprimidol (0.5, 1.0, 1.5 mg/pot a.i.; SePRO Corporation, Carmel, Ind.) were applied (59 mL/pot). Control plants received a drench of deionized water (59 mL/pot). Plant growth regulator treatment was administered during week 12 of production. Plant growth regulator dosages were determined based on previous work (Pennisi et al., 2003) and label recommendations.

Measurements. Morphological data were taken on all plants (height and two perpendicular widths, leaf tip to leaf tip) at the end of production. Height was measured from shoot base to the apex. These data were used to calculate growth index [size = (height + width₁ + width₂)/3].

After 16 weeks of production, plants were prepared for destructive sampling by removing growing media from roots, and by physical separation of roots, stems, and leaves. Whole-plant leaf areas were taken with a leaf

area meter (model 3100 Leaf Area Meter; LI-COR, Lincoln, Nebr.). For each plant, the roots, stems, and leaves were placed in separate bags and dried in a forced-air oven maintained at 80 °C for a week. Leaf area ratio (LAR) was calculated as leaf area divided by total plant dry weight.

Quantitative enzymatic starch analysis was performed separately for dry root, stem, and leaf tissue, according to the method of Io Bianco and Rieger (2002). The starch analysis was only performed on control and flurprimidol-treated plants.

At the end of production, physiological experiments were performed on 12 representative plants to determine photosynthesis at nine *PPFs*. Each plant was exposed to progressively higher *PPFs* (≈0, 10, 20, 30, 40, 50, 100, 400, and 700 μmol·m⁻²·s⁻¹). Carbon dioxide exchange concentrations were taken on the most recently matured leaf, midway between the mid rib and leaf edge, and midway between the petiole and leaf tip (CIRAS-1; PP-Systems, Amesbury, Mass.). Dark respiration (*R_d*), maximum light use efficiency (LUE), and light-saturated gross photosynthesis (*P_{gmax}*) were estimated from a nonlinear regression (SigmaPlot v.10 software package; Systat Software, Richmond, Calif.):

$$P_n = (P_{gmax})[1 - e^{(-LUE)(PPF)/P_{gmax}}] + R_d \quad [1]$$

where *P_n* is net photosynthetic concentration and, *P_{gmax}* is light-saturated gross photosynthetic concentration, LUE is maximum light use efficiency, and *R_d* is dark respiration (here expressed as a negative value, because it represents a CO₂ efflux from the plant). The light compensation point was determined by solving Eq. 1 for *PPF* and a *P_n* of 0 μmol·m⁻²·s⁻¹. The light saturation point was determined as the *PPF* at which *P_n* was 95% of light-saturated net photosynthesis [*P_n* = 0.95 × (*P_{gmax}* + *R_d*)]. The units for all parameters are micromoles per square meter per second, with the exception of the unitless LUE, which is a measure of the maximum moles of CO₂ fixed per mole of incoming light (the slope of the light response curve at a *PPF* of 0 μmol·m⁻²·s⁻¹).

Experimental design. Three subreplications were randomized within each bench (total of 21 plants/table). A subreplication consisted of seven plants: one plant from each of the three dosages of ancymidol, one plant from each of three dosages of flurprimidol, and one control plant. On each table, the three subreplications were designated as part of studies I (morphology and carbohydrate analyses), II (photosynthesis analysis), and III (postharvest analysis). The experimental design was a completely randomized split plot with 12 whole plots (benches), and the variables of PGR type and dosage nested within *PPF*.

Data were analyzed using the general linear model in Statistical Analysis Software v.9 (SAS Institute, Cary, N.C.) to test for two-way and three-way interactions and significant correlations (*P* < 0.05 was considered

statistically significant). PROC General Linear Model was used for the enzymatic starch analysis. Means separation analysis (Fisher's protected LSD) was used to analyze the data further. Significance of the main effects (*PPF*, PGR application) and their interaction were determined using analysis of variance, whereas more specific comparisons were made with contrast statements. Contrast statements were generated based on the fact that *PPF*, PGR type, and PGR concentration were treated as classification variables.

Postharvest phase

After 16 weeks of production, one or two plants from each experimental unit (one set of subreplications from eight benches, and two sets of subreplications from four benches) were placed in four growth chambers under simulated interior conditions [temperature, 21 °C day/18 °C night; *PPF*, 0.65 mol·m⁻²·d⁻¹ (15 μmol·m⁻²·s⁻¹); photoperiod, 12 h/d]. Plants were irrigated weekly and fertigated biweekly with a 100 mg·L⁻¹ N fertilizer solution [Peter's 24–8–16 Tropical Foliage (24N–3.4P–13.4K); Scotts, Marysville, Ohio]. The water and nutrient solutions were delivered through subirrigation.

After 18 weeks in growth chambers, morphological measurements were taken (height and two perpendicular widths, leaf tip to leaf tip). These data were used to calculate growth index. The number of senesced leaves per plant was recorded. Growing medium was washed from the roots. For each plant, the roots and shoots were separated and dried in a forced-air oven maintained at 80 °C for a week.

Experimental design. The experimental design for the postharvest study was a randomized split plot with 16 whole plots consisting of seven plants each (one from each PGR treatment). Furthermore, whole plots were arranged in a randomized complete block design, with each growth chamber representing a block holding four plots each (two from high *PPF* and two from low *PPF*). Statistical analysis was performed using the SAS software package v.9 and PROC MIXED procedure (SAS Institute, Cary, N.C.). Significance of the main effects (*PPF*, PGR application) and their interaction were determined using analysis of variance, whereas more specific comparisons were made with contrast statements. Contrast statements were generated based on the fact that *PPF*, PGR type, and PGR dosage were treated as classification variables, with *P* < 0.05 considered statistically significant. When main or interactive effects were significant, mean separation was accomplished through a series of *t* test comparisons among PGR treatments.

Results and Discussion

Production phase. All PGR treatments affected height of *G. undatus* C. Koch & Linden 'Inca' compared with controls (Tables 1 and 2), whereas *PPF* did not. Increasing the dosage of either ancymidol or flurprimidol had little effect on plant

Table 1. Separation of means based on irradiance and plant growth regulator treatments for growth parameters in *Geogenanthus undatus* C. Koch & Linden 'Inca'.

	H (cm)	GI (cm)	TDW (g)	RDW (g)	LA (cm ²)	LAR	R:S
PPF (μmol·m ⁻² ·s ⁻¹)							
130	11.3 a ^z	21.7 a	8.1 a	3.8 a	735 a	201 a	0.92 a
50	11.2 a	20.5 a	5.6 b	2.5 b	581 a	232 b	0.85 a
PGR (mg/pot a.i.)							
0	14.4 a	24.2 a	7.9 a	3.4	784 a	223 a	0.80 c
Ancymidol 0.5	11.6 b	21.3 b	7.1 abc	3.2	709 ab	224 a	0.80 c
Ancymidol 1.0	11.1 bc	20.8 bc	6.6 bc	3.0	647 b	218 ab	0.87 bc
Ancymidol 1.5	10.2 c	20.8 bc	6.0 c	2.5	615 bc	217 ab	0.74 c
Flurprimidol 0.5	10.9 bc	20.9 bc	7.3 ab	3.4	681 ab	213 bc	0.98 ab
Flurprimidol 1.0	10.5 bc	20.0 c	6.6 bc	3.3	649 b	217 ab	0.97 ab
Flurprimidol 1.5	10.2 c	19.7 c	6.3 bc	3.2	523 c	208 c	1.05 a

^zAny two means within a column not followed by the same letter are significantly different at $P < 0.05$ using a Fisher's protected LSD mean separation. Plant growth regulator (PGR) effects on root dry weight (RDW) were not analyzed, because of the absence of a significant PGR effect (Table 2).

An interaction did not exist between irradiance and PGR dosage for the growth parameters shown.

PPF, photosynthetic photon flux; H, height; GI, growth index; TDW, total dry weight; LA, leaf area; LAR, leaf area ratio; R:S, root-to-shoot ratio.

Table 2. Analysis of variance of main effects and contrast statements for the effects of photosynthetic photon flux (PPF) and plant growth regulator (PGR) on morphological response in *Geogenanthus undatus* C. Koch & Linden 'Inca'.

Effect ^z	Growth parameters								
	H	GI	TDW	RDW	SDW	LDW	LA	LAR	R:S
PPF	NS	NS	0.01	0.02	— ^y	—	0.07	<0.0001	NS
PGR treatment	<0.0001	<0.0001	0.03	NS	—	—	0.005	0.006	0.002
PPF × PGR treatment	NS	NS	NS	NS	0.04	0.05	NS	NS	NS
PGR all vs. control	<0.0001	<0.0001	0.005	—	<0.0001	0.0006	0.003	0.04	NS
PGR A vs. control	<0.0001	<0.0001	0.006	—	0.0007	0.007	0.02	NS	NS
PGR F vs. control	<0.0001	<0.0001	0.01	—	<0.0001	0.0002	0.001	0.005	0.004
PGR A vs. PGR F	NS	NS	NS	—	NS	NS	NS	0.01	<0.0001
Dosage effect	NS	0.04	0.04	—	NS	NS	0.02	NS	NS
Dosage effect, linear	NS	NS	0.01	—	NS	NS	0.005	NS	NS

^zUse of contrast statement analysis was based on significance of corresponding main effect, at a level of $P < 0.05$.

^y—, values not considered based on significance of a main or interactive effect of photosynthetic photon flux (PPF) and plant growth regulator (PGR) treatments.

^{ns}Nonsignificant effect at $P < 0.05$.

H, height; GI, growth index; TDW, total dry weight; RDW, root dry weight; SDW, stem dry weight; LDW, leaf dry weight; LA, leaf area; LAR, leaf area ratio; R:S, root-to-shoot ratio; PGR A, ancymidol; PGR F, flurprimidol.

height (Table 2). Drench applications of ancymidol also decreased height in four cultivars of sunflower (Starman et al., 1989). Whipker et al. (2004) found that flurprimidol caused a strong linear decrease in sunflower height up to a concentration of 2 mg a.i./15-cm pot. However, increasing concentration beyond 2 mg a.i./pot did not offer any further control of height. All PGR applications resulted in smaller plants, and this decrease was dosage dependent (Tables 1 and 2). As was the case for plant height, there was no difference between the two PGRs.

Studies of the interaction of PGRs and PPF have not been as common as experiments focused solely on the growth-controlling characteristics of PGRs (i.e., height, internode length). Thus, information on the combined effect of irradiance and PGR on dry weight is somewhat limited, especially when considering four separate dry weight quantities (leaf, stem, root, total). Photosynthetic photon flux alone has been shown to change dry weight accumulation and partitioning in shade-obligate plants. *Dracaena (Dracaena sanderana hort Sander ex. Mast.)*

exhibited quadratic responses in dry weight of root, stem, and shoot when grown under four different shading levels (47%, 63%, 80%, or 91%) (Vladimirova et al., 1997). Moderate shading (63% or 80%) allowed for the greatest accumulation of dry matter in all fractions, whereas the highest and lowest irradiance levels resulted in relative reductions in dry matter accumulation. Depending on irradiance requirements of the species in question, extremely high and low PPFs are likely to cause reductions in growth, resulting from inhibition of photosynthesis at either extreme.

Total dry weight was affected by both PPF and PGR concentration, but no significance was found for the interaction of these two variables (Tables 1 and 2). Low PPF reduced total biomass by 30% compared with high PPF, with a similar effect on root dry weight. *Geogenanthus* has not been widely grown, and therefore optimum production parameters are yet to be determined. Our data indicate that low PPF may delay accumulation of adequate dry matter for marketable *Geogenanthus* plants within a

reasonable production period. Both PGRs negatively affected total dry weight of *G. undatus* C. Koch & Linden 'Inca' and this reduction was correlated with the PGR dosage (Tables 1 and 2). Plant growth regulators did not have an effect on root dry weight. High PPF resulted in greater root dry weight than low PPF, regardless of PGR treatment (Tables 1 and 2). The interaction of PPF with PGR treatment was significant for leaf dry weight (Table 2), and the effects were similar as for stem dry weight. Under high PPF, control plants had higher leaf dry weight than plants treated with either PGR, and there was no effect of PGR concentration on leaf dry weight (Tables 2 and 3). Plant growth regulator applications did not affect leaf dry weight under low-irradiance conditions. Control plants grown in high PPF had 87% greater leaf dry weight than controls grown under low PPF.

Leaf area in *Geogenanthus* was unaffected by irradiance, but tended to be higher at high PPF ($P = 0.71$). This is in contrast to the general notion that leaf areas tend to increase under low irradiance during the process of light acclimation (Taiz and Zeiger, 2002). The application of either ancymidol or flurprimidol caused a decrease in leaf area, and this effect was similar for both PGRs (Tables 1 and 2). As with other morphological changes, leaf area tends to decrease as PGR dosage is increased (Thetford et al., 1995). Because of the tendency to increase leaf area, plants grown under a lower PPF tend to have a higher LAR than plants grown under high PPF (Makino et al., 1997). Both PPF and PGR dosage affected LAR, although an interaction between these two factors was not observed (Tables 1 and 2). As expected, plants grown under low PPF had a consistently higher LAR than high PPF plants of comparable PGR dosages. Flurprimidol reduced LAR compared with the control plants, whereas ancymidol did not (Tables 1 and 2).

The root-to-shoot ratio was increased by flurprimidol but not ancymidol (Tables 1 and 2). This is related to the decrease in leaf and stem dry weight of flurprimidol-treated plants, because root dry weight was unaffected by flurprimidol. Photosynthetic photon flux did not affect the root-to-shoot ratio.

Plant growth regulators have been shown to change carbon partitioning patterns and increase starch production in several species (Mehouachi et al., 1996; Pennisi et al., 2003). In general, the major starch storage organ varies by species (Davis et al., 1988). For this reason, we performed starch analysis separately on stems, leaves, and roots. Increased carbohydrate pools would allow for the continuation of maintenance respiration, which would be of particular importance for plants experiencing low PPF stress, as in a postharvest environment. However, the starch concentrations in leaves, stems, and roots were unaffected by production PPF or PGR treatments (data not shown).

Results from the photosynthesis–light response measurements did not indicate

differences among controls and treated plants, regardless of PPF or PGR treatment. A light response curve from a representative plant revealed that net photosynthesis in *G. undatus* C. Koch & Linden 'Inca' is low (Fig. 1). The light compensation point was $2.8 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$, the light saturation point was $64 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$, and the LUE was $0.159 \text{ mol}\cdot\text{mol}^{-1}$. These data are consistent with the slow growth observed during both production and postharvest phases. Shade-obligate plants have lower light compensation and saturation points than sun-obligate plants. In a study on four understory herbaceous plants [*Arisaema triphyllum* L. (Schott), *Erythronium americanum* Ker, *Podophyllum peltatum* L., and *Smilacina racemosa* L. (Desf.)], three of the four species were considered shade-obligate, whereas *E. americanum* was considered a sun plant (Hull, 2002). Light compensation points were lower for the shade-obligate species [*Podophyllum* ($11 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$), *Arisaema* ($5 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$), and *Smilacina* ($9 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$)], than for *Erythronium*

($16 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$). Although *Geogenanthus* had a lower light compensation point than all these species, it is close to that of *Arisaema*. Light saturation points for the shade-obligate species were also low in the understory herb study (*Podophyllum*, $117 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$; *Arisaema*, $133 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$; and *Smilacina*, $135 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$), and much higher for the sun species *Erythronium* ($326 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$). When comparing maximum photosynthesis, *Geogenanthus* had a P_{gmax} of $3.4 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$, which was close to that of *Smilacina* ($3.9 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$) and considerably lower than that of the sun species *Erythronium* ($14.7 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$).

Postproduction phase. After 18 weeks under simulated interior conditions, the height of *G. undatus* C. Koch & Linden 'Inca' was reduced by PGR applications (Tables 4 and 5, and Fig. 2). Both ancymidol and flurprimidol produced shorter plants compared with controls. Control plants were 60% taller than plants treated with 1.5 mg/pot a.i. of ancymidol, and 88% taller than plants treated with 1.5 mg/pot a.i. of flurprimidol

(Table 4). Furthermore, there was a difference between the two PGRs; flurprimidol-treated plants were shorter than ancymidol-treated plants. No main or interactive effect involving production PPF was significant with regard to plant height.

The effects of the PGRs are particularly evident upon examination of height increase in simulated interior conditions (i.e., the difference in plant height before and after the postharvest period; Tables 4, 5). The height of untreated plants increased more (5.9 cm) than that of treated plants, whereas plants treated with flurprimidol had only a very small height increase (<2.5 cm). Similarly, the growth index increase was lower in PGR-treated plants than in the control plants, and ancymidol-treated plants had a larger increase in growth index than flurprimidol-treated plants. These data indicate that the PGR treatments during late production had extended effects into the postharvest period, and that flurprimidol had a stronger effect during the postproduction phase than ancymidol.

In previous studies, shoot growth also was reduced by PGR applications, after a period in a low-PPF interior environment. Davis (1987) treated three species of foliage plants with paclobutrazol (25 $\mu\text{g}/\text{pot}$ a.i.), or 250 $\mu\text{g}/\text{pot}$ a.i.), and either immediately placed them in a simulated interior environment (PPF, $15 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$) or allowed them to grow for 2 months under optimal greenhouse conditions before being placed in the simulated interior. Paclobutrazol-treated *Zebrina* (*Z. pendula* Schnizl.), another member of the Commelinaceae family, experienced almost complete inhibition of growth when immediately placed in an interior environment. However, when greenhouse growth was allowed between PGR treatment and the interior, growth was less than that of control plants in the interior environment. Even though the two concentrations of paclobutrazol were an order of magnitude apart, growth for plants treated with these two concentrations was similar in the interior conditions. In a study using ancymidol drenches, foliage species were grown in a simulated postharvest environment (Blessington and Link, 1980). Height control of treated plants was maintained for *Philodendron* [*P. scandens* (Schott) Bunting], *Fatshedera* [*F. lizei* (Cochet) Guillaum], and *Tradescantia* (*T. fluminensis* Vell.), a member of the Commelinaceae family.

Shoot and total dry weights were unaffected by production PPF level, PGR type or concentration, or any interactions (Tables 4 and 5). It is interesting that differences were observed between control and treated plants for height and size, but not for total dry weight at the end of the postharvest period. This suggests that the differences in height and size were incited by stem elongation, rather than differences in biomass production. In contrast, at the conclusion of production, high-PPF plants had greater dry weight accumulation, whereas plant height

Table 3. Separation of means for growth parameters in *Geogenanthus undatus* C. Koch & Linden 'Inca' that exhibited an interaction between irradiance level and plant growth regulator (PGR) dosage.

PPF	PGR (mg/pot)	SDW (g)	LDW (g)
$130 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$	0.0	1.15 a	4.7 a ²
	Ancymidol 0.5	0.83 b	3.7 b
	Ancymidol 1.0	0.71 bc	3.7 ab
	Ancymidol 1.5	0.66 bcde	3.2 bc
	Flurprimidol 0.5	0.67 bcd	3.6 b
	Flurprimidol 1.0	0.59 cde	3.2 bc
	Flurprimidol 1.5	0.62 bcde	2.9 bc
$50 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$	0.0	0.57 cde	2.5 c
	Ancymidol 0.5	0.56 cde	2.8 bc
	Ancymidol 1.0	0.46 de	2.4 c
	Ancymidol 1.5	0.58 cde	2.5 c
	Flurprimidol 0.5	0.49 cde	2.4 c
	Flurprimidol 1.0	0.44 e	2.4 c
	Flurprimidol 1.5	0.46 de	2.2 c

²Any two means within a column not followed by the same letter are significantly different at $P < 0.05$ using a Fisher's LSD mean separation.

PPF, photosynthetic photon flux; PGR, plant growth regulator; SDW, stem dry weight; LDW, leaf dry weight.

Fig. 1. Growth response of *Geogenanthus undatus* C. Koch & Linden 'Inca' to photosynthetic photon flux (PPF) and plant growth regulators after 18 weeks in a simulated postharvest environment. Within panels, right to left: 0.0, 0.5, 1.0, and 1.5 mg a.i./pot treatments. (A) High PPF ($130 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$), ancymidol. (B) High PPF, flurprimidol. (C) Low PPF ($50 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$), ancymidol. (D) Low PPF, flurprimidol.

Table 4. Growth parameters of *Geogenanthus undatus* C. Koch & Linden 'Inca' as affected by plant growth regulator (PGR) type and dosage after an 18-week low photosynthetic photon flux (PPF) postharvest period.

PGR (mg/pot a.i.)	H (cm)	GI (cm)	TDW (g)	RDW (g)	R:S	SL	H increase (cm)	GI increase (cm)
Control 0.0	22.9 a ^y	30.2 a	9.4 ^z	2.96 a	0.55 a	5.9 ab	8.5 a	5.9 a
Ancymidol 0.5	17.1 b	25.7 b	9.7	2.97 a	0.50 ab	7.2 a	5.5 b	4.4 ab
Ancymidol 1.0	15.7 bc	23.7 bc	8.5	2.51 ab	0.44 abc	5.4 bc	4.6 b	2.9 bc
Ancymidol 1.5	14.3 cd	23.0 c	8.4	2.47 ab	0.46 abc	5.9 ab	4.2 bc	2.2 cd
Flurprimidol 0.5	12.5 de	21.4 cd	8.3	2.35 ab	0.43 abc	5.5 bc	1.6 d	0.5 d
Flurprimidol 1.0	12.8 e	20.5 d	7.5	2.05 b	0.40 bc	5.2 bc	2.3 cd	0.5 d
Flurprimidol 1.5	12.2 e	20.7 d	8.9	2.18 b	0.34 c	4.2 c	1.9 d	0.9 d

^zAnalysis of variance did not indicate any treatment effects on total dry weight (TDW); therefore, mean separation was not done for this parameter.

^yAny two values within a column not followed by the same letter are significantly different at $P < 0.05$ using pairwise *t* tests.

The interaction between photosynthetic photon flux and plant growth regulator (PGR) dosage for the growth parameters shown was nonsignificant. Growth index (GI) and height (H) increase refer to the increase in the postharvest environment.

a.i., active ingredient; RDW, root dry weight; R:S, root-to-shoot ratio; SL, senesced leaves.

Table 5. Analysis of variance of main effects and contrast statements for the effects of the photosynthetic photon flux (PPF) and plant growth regulator (PGR) on morphological response in *Geogenanthus undatus* C. Koch & Linden 'Inca' after 8 weeks in a low PPF postharvest environment.

Effect ^z	Growth parameters								
	H	GI	SDW	TDW	RDW	R:S	SL	H increase	GI increase
PPF	NS	NS	NS	NS	NS	0.04	NS	NS	NS
PGR treatments	<0.0001	<0.0001	NS	NS	0.04	0.05	0.009	<0.0001	<0.0001
PPF × PGR treatments	NS	NS	NS	NS	NS	NS	NS	NS	NS
All PGRs vs. control	<0.0001	<0.0001	—	—	0.03	0.01	NS	<0.0001	<0.0001
PGR A vs. control	<0.0001	<0.0001	—	—	NS	NS	NS	<0.0001	0.002
PGR F vs. control	<0.0001	<0.0001	—	—	0.005	0.003	NS	<0.0001	<0.0001
PGR A vs. PGR F	<0.0001	<0.0001	—	—	0.02	0.05	0.007	<0.0001	<0.0001
Concentration effect	NS	0.04	—	—	NS	NS	0.03	NS	NS
Concentration effect, linear	NS	0.02	—	—	NS	NS	0.01	NS	NS

^zUse of contrast statement analysis was based on significance of corresponding main effect at a level of $P < 0.05$.

^{ns}Nonsignificant effect at $P < 0.05$.

Growth index (GI) and height (H) increase refer to the increase in the postharvest environment.

SDW, shoot dry weight; TDW, total dry weight; RDW, root dry weight; R:S, root-to-shoot ratio; SL, senesced leaves; PGR A, ancymidol; PGR F, flurprimidol.

Fig. 2. Typical photosynthetic response to increasing photosynthetic photon flux (PPF) levels for *Geogenanthus undatus* C. Koch & Linden 'Inca'. The regression curve shown is the average of 12 representative curves. P_n , net photosynthetic concentration.

did not differ between the PPF treatments compared with low-PPF plants.

Root dry weight was reduced by flurprimidol but not by ancymidol (Tables 4 and 5). However, production PPF, or the interaction of production PPF with PGRs, did not affect root dry weight. Root dry weight has been shown to increase in rice (*Oryza sativa* L.) roots (Yim et al., 1997), but decrease in citrus seedlings (Mehouachi et al., 1996) in response to PGRs.

There was no interaction between production PPF and PGR treatment for root-to-shoot ratio, but their main effects were significant (Tables 4 and 5). Low-PPF plants had consistently greater root-to-shoot ratios (average, 0.51) than high-PPF plants (average, 0.38). This is in contrast to what would be expected, because low-light plants often invest a larger fraction of their carbon resources in the shoot (Taiz and Zeiger, 2002). Plant growth regulator effects on root-to-shoot ratios were related to effects on root dry weight; flurprimidol applications reduced both root dry weight and the root-to-shoot ratio, whereas ancymidol applications did not.

Leaf senescence was unaffected by PPF.

The number of dropped leaves also was unaffected by production PPF for two species of *Schefflera* (*S. arboricola* Hayata ex. Kanehira and *Brassaia actinophylla* Endl) after 3 months in a simulated interior environment (Braswell et al., 1982). However, PGRs have been shown to affect the number of senesced leaves in members of the Commelinaceae family. After application of paclobutrazol, *Z. pendula* plants had fewer senesced leaves (Davis, 1987). In the current study, flurprimidol-treated plants had fewer senesced leaves than ancymidol-treated plants (Tables 4 and 5). Although statistical significance was not found between PGR-treated plants and controls, in general the treated plants appeared to have fewer senesced leaves.

In conclusion, applications of ancymidol or flurprimidol administered to *G. undatus* C. Koch & Linden 'Inca' late during the production cycle resulted in significant growth control and, therefore, superior plant performance throughout the postharvest period. Production PPF did not play a major role in the overall response of the plants to the interior environment. Therefore, growers may use the high-production PPF ($130 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$), which results in a greater accumulation of dry weight than the low PPF ($50 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$). Furthermore, although PGRs effectively controlled height and growth index, the PGR concentration did not exert great influence over these parameters. Thus, the lower, more economical concentration can be used successfully. In general, flurprimidol exerted greater control over plant growth than ancymidol, and thus shows promise for use as a growth regulator in the foliage industry.

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