Controlled Water Deficit as an Alternative to Plant Growth Retardants for Regulation of Poinsettia Stem Elongation

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Abstract. Production of poinsettias (*Euphorbia pulcherrima*) often involves intensive use of plant growth retardants (PGRs) to regulate height. Height control is necessary for visual appeal and postharvest handling. Since PGRs do not always provide consistent height control and can have unwanted side effects, there is interest in alternative methods of height control. Since turgor potential drives cell expansion, and thus stem elongation, drought stress has potential for regulating plant height. Through soil moisture sensor-controlled irrigation, the severity of drought stress can be both monitored and controlled. The objective of our study was to compare poinsettia ‘Classic Red’ height control using PGRs (spray, mixture of daminozide and chlormequat at 1000 mg·L⁻¹ each and drench, 0.25 mg·L⁻¹ paclobutrazol) with the use of controlled water deficit (WD). Graphical tracking of plant height, using a final target height of 43.5 cm, was used to determine when to apply PGR or controlled WD. In the WD treatment, substrate volumetric water content (θ) was reduced from 0.40 to 0.20 m³·m⁻³ when actual height exceeded the expected height. PGR applications (spray or drench) reduced poinsettia height to 39 cm, below the final target level of 43.5 cm. WD resulted in a height of 44.5 cm, closest to the target height, while control plants were taller (49.4 cm). There was no effect of PGR drenches or WD on bract size, while spraying PGR reduced bract size by $\approx$ 40%. Bract chroma was unaffected by WD or PGR treatments. There was no difference in shoot dry weight between PGR- and WD-treated plants. Lateral growth was reduced by the PGR treatments, but not by WD. These results indicate that controlled WD can be used to regulate poinsettia height.

Poinsettias are one of the most economically valuable pot plants in the United States and around the world (Trejo et al., 2012; U.S. Department of Agriculture, 2014). In 2013, poinsettias had a wholesale value of over \$146 million in the United States (U.S. Department of Agriculture, 2014). Height control is important for the production of marketable, compact poinsettias (Fisher and Heins, 1995; Heins et al., 1999). Poinsettia height control is also important for transportation and post-harvest handling (Karlović et al., 2004; Niu et al., 2002). Optimal poinsettia height may vary depending on cultivar, intended use, and grower or consumer preference. To control poinsettia height, growers typically use PGRs to suppress stem elongation. PGRs reduce stem elongation by antagonizing or inhibiting biosynthesis of gibberellins (Brown et al., 1997; Lodeta et al., 2010).

Although widely used in poinsettia production and effective at suppressing elongation (Ecke et al., 2004), use of PGRs also has disadvantages. Apart from adding to the cost of production (Mata and Botto, 2009), PGRs are among the agrochemicals that can contribute to environmental pollution (Berghage and Heins, 1991). Because of their pollution potential, the use of PGRs has restrictions in some countries (Moe et al., 1992a). Also, if applied in excess, PGRs negatively affect plant quality and growth through phytotoxicity (Gibson et al., 2003) and stunting (Hamid and Williams, 1997).

Several nonchemical methods of height control have been described. Previous work has shown the possibility of controlling plant height by reducing temperature or by manipulating night and daytime temperatures (Berghage and Heins, 1991; Moe et al., 1992a). However, lowering temperature also reduces photosynthesis and metabolic processes, including growth rate, which can delay the crop maturity (Moe et al., 1992b). In addition, it may be difficult to cool the greenhouse enough during the day to reduce the temperature below nighttime temperatures, which may be needed to get effective height control. This is especially difficult in warm climates and in mid to late summer, when the radiative heat load is

large. Other studies have shown that manipulation of light quality can be used to control poinsettia growth (Cockshull et al., 1994; Mata and Botto, 2009). However, manipulating light quality in greenhouses is not yet common practice. Low amounts of phosphate fertilizer also can promote more compact growth (Nelson et al., 2012), but there are no guidelines on how to manipulate fertilization practices to produce plants with a specific height.

The use of WD to control plant growth is not new (Hendriks and Ueber, 1995). However, it has been difficult for growers to control the severity of WD, and thus the impact on growth. If the WD is not severe enough, there may be little impact on stem elongation, while severe levels of WD can negatively affect plant quality. With the advent of precision irrigation systems such as those controlled by soil moisture sensors (Kohanbashi et al., 2013), there is a potential for successful use of controlled WD to control stem elongation. Such irrigation systems can maintain specific θ levels to impose a controlled WD. We have previously shown that the combination of height tracking with regulated WD can be used to control poinsettia elongation (Alem et al., 2015).

The use of WD to control stem elongation is based on the role of water in cell expansion and growth. Water is needed for turgor pressure, which drives cell expansion and stem elongation. Suppressions of growth due to drought stress may also occur as a result of changes in cell wall properties, such as cell wall extensibility and the minimum turgor required for cell expansion (van Volkenburgh, 1999). Hence, regulated WD can be used to control plant height (Cameron et al., 2006). This technique is inexpensive and not likely to cause plant damage if managed carefully. In addition, using WD for plant height control is environmentally friendly and eliminates potential pollution caused by PGRs. Plants grown under controlled WD may also be more acclimated to survive stressful post-harvest handling and conditions (Cameron et al., 2008).

We chose poinsettias as the model species because graphical tracking curves can be used to determine when a crop requires height control (Fisher and Heins, 2002; Harwood and Hadley, 2004). Graphical tracking requires regular measurement of plant height and comparing these with the expected height range at that date. When plants are taller than desired, height control is needed. The objectives of this experiment were to 1) test whether controlled WD can be used to control poinsettias height, 2) determine the effect of WD on quality characteristics such as bract color and size, and 3) compare the effects of WD on plant quality to those of PGRs.

Materials and Methods

Plant material and growing conditions. Poinsettia ‘Classic Red’ cuttings, rooted in phenolic foam blocks (Oasis Horticultubes; Smithers-Oasis, Kent, OH), were obtained

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from a commercial greenhouse on 4 Aug. 2011 and transplanted into 15-cm pots filled with peat:perlite (80:20 v:v) substrate (Fafard 1P; Fafard, Agawam, MA). Controlled-release fertilizer (Osmocote 14-14-14, The Scotts Co., Marysville, OH; 14N-6.1P-11.6K) was incorporated into the substrate at a rate of 7.7 g·L⁻¹ before transplanting. Plants were watered by hand for 10 d until sufficient root development was achieved. Two weeks after transplanting, plants were sprayed with buprofezin (Talus® 40SC, SePRO Corporation, Carmel, IN) and drenched with a mixture of imidacloprid (Marathon 60 Wettable Powder; OHP, Mainland, PA) and dinotefuran (Safari 20 SG; Valent USA Corporation, Walnut Creek, CA) to control whiteflies. Plants were pinched to a height of 21.6 cm (measured from the bench) 33 d after transplanting (Sept. 6) to encourage branching and development of compact plants (Berghage et al., 1989; Faust and Heins, 1996). Five to seven nodes were left to develop into branches. Plant density was 10 plants/m².

Plants were grown in a glass-covered greenhouse in Athens, GA, without supplemental lighting or black cloth application. The greenhouse was cooled using a pad and fan system when the air temperature was above 22 °C, while the greenhouse heating was on at temperatures below 18 °C. Temperature set points were the same for day and night. Because of the large radiative heat load, actual greenhouse temperature on most days was well above the 22 °C cooling set point during late summer and early fall.

Hand irrigation was stopped 10 d after transplanting. For the rest of the trial, a soil moisture sensor-controlled irrigation system, similar to the one described by Nemali and van Iersel (2006) was used to maintain θ at the desired thresholds. The irrigation system used two capacitance soil moisture sensors (EC-5; Decagon, Pullman, WA) per plot (six pots on the same irrigation line). The two sensors were inserted diagonally into the root zone of two representative plants in each experimental unit. The capacitance soil moisture sensors were connected to multiplexers (AM16/32; Campbell Scientific, Logan, UT), which were connected to a datalogger (CR10X; Campbell Scientific). The datalogger measured the voltage output from the soil moisture sensors every 10 min using a 2.5 VDC excitation voltage. The voltage readings were converted to θ using a substrate-specific calibration (θ = voltage $\times$ 1.8862 - 0.5624, r^2 = 0.95). Whenever the average θ in a plot dropped below the threshold θ (0.40 or 0.20 m³·m⁻³ during WD application), the datalogger sent a signal to a relay controller (SDM-CD16AC; Campbell Scientific), which opened a solenoid valve (DV, Rain Bird, Azusa, CA) for 20 s, applying 11 mL/plant. Plants were irrigated with pressure-compensating drip emitters (WPCJ10; Netafim USA, Fresno, CA).

By maintaining θ at a steady level, the irrigation system replaces the water that is lost through evapotranspiration. Thus, the amount of water applied reflects evapotranspiration or water use, except for periods when

θ is decreasing from 0.40 to 0.20 m³·m⁻³ or increasing from 0.20 to 0.40 m³·m⁻³. The datalogger recorded the number of times each of the plots was irrigated each day. The daily water use (DWU) was calculated by multiplying the number of daily irrigations by 11 mL/irrigation. No leaching was observed during the study.

Treatments. Final target plant height was set at 43.5 $\pm$ 2.5 cm. Pinching height (21.6 cm) and the final target height were entered in an Excel spreadsheet (obtained from the Department of Environmental Horticulture, University of Florida, Gainesville, FL) to develop sigmoid growth tracking curves that were used to monitor plant height. The spreadsheet generated two sigmoid curves; upper and lower limit curves that defined the target height range at any given date. Plant height measurements taken over the course of the experiment were plotted in the growth tracking curves.

Control plants were maintained at a θ of 0.40 m³·m⁻³ for the entire experiment, with no PGR application. Substrate volumetric water content was also kept at 0.40 m³·m⁻³ in the two PGRs treatment (spray and drench). In the spray treatment, plants were sprayed with a mixture of daminozide (B-Nine, OHP Inc., Mainland, PA) and chlormequat chloride (Cycocel, OHP Inc., Mainland, PA), each at a concentration of 1000 mg·L⁻¹ of a.i. Sprays were applied to thoroughly wet the shoots. The drench treatment received 100 mL of 0.25 mg·L⁻¹ of a.i. (paclobutrazol, Bonzi, Syngenta Crop Protection, Greensboro, NC) applied to the substrate. Applications of PGRs were made when the plant height exceeded the upper limit of the height tracking curves. In the WD treatment, θ was maintained at 0.40 m³·m⁻³ when plant height was within the target height curve range. When height control was needed, the plants were exposed to WD by allowing θ to drop to 0.20 m³·m⁻³. Once θ reached 0.20 m³·m⁻³, it was kept at this level until plant height was back within the height tracking curve limits.

Data collection. Plant height was measured at $\approx$ 10-d intervals from pinching to 77 d after pinching. At the end of the experiment (84 d after pinching), three fully-expanded, uppermost bracts were sampled from each plant and their size determined using a leaf area meter (LI-3100, LI-COR, Lincoln, NE). In addition, bract chroma (a measure of color intensity) was measured using a colorimeter (XL-20; Gardner Instruments Laboratory, Bethesda, MD). More positive values indicate more intense redness of the bract. The spread of the canopy was approximated by averaging two perpendicular widths at the top of the canopy. To quantify overall shoot growth, the two plants from each plot with soil moisture sensors inserted in their root zone were harvested, dried in an oven at 80 °C, and weighed to determine shoot dry weight.

Experimental design and data analysis. The experimental design was a randomized complete block with eight blocks and four treatments (control, WD, PGR spray, and PGR drench). The experimental unit was

a group of six plants irrigated with a single solenoid valve. The data were analyzed for block and treatment effects using a general linear models procedure with the block by treatment interaction as the error term (proc GLM, SAS v. 9.3, SAS Institute, Cary, NC). Treatment means of final plant height, bract size and color, shoot dry weight, and canopy spread were separated using Tukey's HSD test (α = 0.05). Plant height measurements, taken repeatedly on the same plants, were analyzed using repeated measures (proc MIXED, SAS), with LSMEANS used to separate paired differences in plant height among treatments on different measurement dates. Regression analysis was used to test for correlations between different growth parameters.

Results and Discussion

Plant height. The rapid increase in plant height shortly after pinching can be explained by elongation of lateral branches. Free-branching poinsettia cultivars typically develop branches before pinching. Because these branches are already growing at the time of pinching, initial elongation can be more rapid than predicted by the sigmoidal height curves. As a result, plant height in all treatments exceeded the target height at 9 d after pinching. The height of control plants continued to increase during the 77 d after pinching, with plants reaching a final height of 49.4 cm, 3.4 cm taller than the upper limit of the target range (Figs. 1 and 2). To control plant height, both spray and drench PGR treatments were applied at 14 d after pinching. Both PGR treatments reduced plant height by 1.8 cm compared with the control treatment by 31 d after pinching. However, plant height still exceeded the target height for that stage of growth and additional PGR drench and spray applications were made at 34 d after pinching. That resulted in plant heights within the target range at 41 and 50 d after pinching. However, plant height was below the target range at 61 d after pinching and was 1.6 cm below the lower limit of the target range at the end of the study. In retrospect, the second PGR application may not have been necessary to achieve the desired plant height. Growers face the same challenge with the use of PGRs: it is difficult to predict the long-term impact of PGR applications on elongation, especially because different poinsettia cultivars respond differently to PGR applications (Currey and Lopez, 2011) and elongation depends on environmental conditions such as temperature and light levels (Moe et al., 1992b).

In the WD treatment, θ was lowered to 0.20 m³·m⁻³ twice to suppress growth, from 21 to 29 d and from 53 to 58 d after pinching (Fig. 1). Substrate θ was not lowered at the same time as the first PGR application, because the greenhouse was unattended from 15 to 20 d after transplanting. The combination of the two WD periods brought the plant height within the target range at 61 d after pinching and it remained there till the end of the study. The WD treatment was the only

Fig. 1. Poinsettia 'Classic Red' height response to plant growth retardant (PGR) applications (spray with a mixture of daminozide and chlormequat chloride or drench with paclobutrazol) and water deficit (WD) treatments as monitored using height tracking curves for 77 d. Growth retardants and WD were applied to control stem elongation, with the aim of reaching a final target height of 43.5 ± 2.5 cm. The two sigmoidal curves indicate the target height range. The vertical arrows indicate PGR applications (both drench and spray applications were made on both days), while the horizontal arrows indicate periods of WD application. ns, not significant.

Fig. 2. The final plant height of poinsettias that were kept well watered (control), and treated with spray (mixture of daminozide and chlormequat) or drench (paclobutrazol) or exposed to two water deficit (WD) cycles. Bars (means $\pm$ SD) with the same letter are not significantly different according to Tukey's HSD test ($\alpha = 0.05$). The solid horizontal line represents the target height, while the dotted lines represent the acceptable height range.

treatment in which final plant height was within the target range (Figs. 1 and 2). The successful regulation of plant growth through WD supports previous suggestions on the

feasibility of using regulated WD to control plant height as an alternative to PGRs application (Cameron et al., 2008; Röber and Hafez, 1981).

Irrigation and WD application. After hand watering was stopped, the automated soil moisture sensor-controlled irrigation system successfully maintained the θ in the control and PGRs treatments close to $0.40 \text{ m}^3 \cdot \text{m}^{-3}$. The mean θ maintained by the irrigation system in the control and PGR treatments was $0.406 \pm 0.003 \text{ m}^3 \cdot \text{m}^{-3}$ (mean $\pm$ SD). When WD was started, θ decreased gradually because of evapotranspiration. After θ had reached $0.20 \text{ m}^3 \cdot \text{m}^{-3}$, θ during the remainder of the WD periods was $0.207 \pm 0.004 \text{ m}^3 \cdot \text{m}^{-3}$. At the end of the WD periods, multiple irrigations quickly returned θ to $0.40 \text{ m}^3 \cdot \text{m}^{-3}$ (Fig. 3).

Daily water use. Generally, DWU increased gradually from transplanting to a maximum in late October (59 d after pinching) and decreased gradually thereafter (days 61–83; Fig. 4). The decrease in DWU during the latter part of the study is likely to combine effect of lower seasonal light levels and shading of the canopy by the bracts. Alem et al. (2015) reported similar seasonal fluctuations in DWU of poinsettia and the importance of light levels in determining DWU of greenhouse crops is well established (e.g., Baille et al., 1994; Kim et al., 2011; Löfkvist et al., 2009). DWU also fluctuated day to day, depending on weather conditions and was particularly low on very overcast days (e.g., days 1, 33, 60, 70, and 82; daily light integral $< 6 \text{ mol} \cdot \text{m}^{-2} \cdot \text{d}^{-1}$).

After lowering the θ threshold in the WD treatment to $0.20 \text{ m}^3 \cdot \text{m}^{-3}$, plants were not irrigated until θ had decreased to this threshold (DWU = 0 mL/plant). After the substrate θ had reached $0.20 \text{ m}^3 \cdot \text{m}^{-3}$, WD plants were irrigated to maintain θ at $0.20 \text{ m}^3 \cdot \text{m}^{-3}$, replacing the water lost by evapotranspiration. DWU was much lower under WD conditions than in the control treatment (e.g., days 28, 29, 57, and 58). Several factors contribute to this lower DWU under WD conditions: less evaporation from a drier substrate surface, less transpiration from the drought-stressed plants, and smaller canopy size as a result of the WD. Immediately after the θ threshold was changed back to $0.40 \text{ m}^3 \cdot \text{m}^{-3}$ to end the WD, DWU peaked as the irrigation system watered frequently to increase θ back to $0.40 \text{ m}^3 \cdot \text{m}^{-3}$ (Fig. 4).

Plant growth and morphology. Control plants had a greater shoot dry weight than the WD- and PGR-treated plants (Fig. 5). Thus, it seems that practices that suppress stem elongation also reduce overall growth and shoot biomass accumulation. Although plants that were exposed to WD were taller than PGR-treated plants (Fig. 2), these treatments had similar shoot dry weight (Fig. 5). It is not clear why the taller, WD-treated plants had similar shoot dry weight as PGR-treated plants. Possible reasons are that PGR-treated plants may have had thicker stems or more branches with more foliage.

Canopy spread was similar in the control and WD treatments, but lower in the two PGR treatments (Fig. 5). Canopy spread was positively correlated with final plant height ($R = 0.43$; $P = 0.014$), shoot dry weight ($R = 0.56$; $P = 0.0008$), and bract size ($R = 0.46$; $P = 0.0085$). The reduction in canopy spread as

Fig. 3. Substrate volumetric water content for one experimental unit of the control and water deficit (WD) treatments collected every 2 h. The substrate volumetric water content was maintained at $0.40 \text{ m}^3 \cdot \text{m}^{-3}$ in the control and the WD treatments when growth suppression was not required. The arrows indicate periods when WD (substrate volumetric water content of $0.20 \text{ m}^3 \cdot \text{m}^{-3}$) was applied to suppress growth.

Fig. 4. Daily water use (DWU) of poinsettias in the control [θ of $0.40 \text{ m}^3 \cdot \text{m}^{-3}$] and water deficit (WD) treatments. In the WD treatments, θ alternated between 0.40 and $0.20 \text{ m}^3 \cdot \text{m}^{-3}$, depending on whether plant height exceeded the target height. Horizontal arrows indicate the periods that the θ threshold was decreased to $0.20 \text{ m}^3 \cdot \text{m}^{-3}$. Peaks in irrigation volume in the WD treatment (day 30 and 59) represent days when the θ threshold was changed back to $0.40 \text{ m}^3 \cdot \text{m}^{-3}$ and the irrigation system watered frequently to increase θ .

result of PGR application was attributed to the inhibition of cell elongation by the PGRs.

Bract size was similar in the control, WD, and PGR drench treatments, but lower in the PGR spray treatment (Fig. 5). Compared with WD and PGR drench treatments, bract size in

the PGR spray treatment was reduced by $\approx 40\%$. The reduction in bract size by the PGR sprays can be considered to be a quality reduction (Niu et al., 2002). Bract size reduction by PGRs applied as spray might be due to the late second application, after the

Fig. 5. Mean shoot dry weight, canopy width, and bract size of poinsettias treated with plant growth retardant (PGR) drenches (paclobutrazol) or sprays (mixture of daminozide and chlormequat) or controlled water deficit (WD) (substrate volumetric water content of $0.20 \text{ m}^3 \cdot \text{m}^{-3}$) to regulate stem elongation. Control plants were kept well watered for entire growing period (substrate volumetric water content of $0.40 \text{ m}^3 \cdot \text{m}^{-3}$). Bars (mean $\pm$ SD) with the same letter are not significantly different according to the Tukey's test ($\alpha = 0.05$).

onset of bract initiation (Barrett, 1996; Fisher and Heins, 1997; Hartley, 1992). Controlled WD did not reduce bract size although WD reduced stem elongation. However, in subsequent work, we have found that WD can reduce bract size (Alem et al., 2015) while Barrett and Nell (1982) reported that lengthening the irrigation interval and allowing the substrate to dry out more between irrigations reduced bract dry weight. The exact effect of WD on bracts likely depends on the timing, duration, and severity of the WD, as has been reported by Nowak and Strojny (2001).

Color intensity plays an important role in appearance, and thus consumer preference (Goreta et al., 2008). Contrary to previous reports that PGR application can increase bract color intensity (Lodeta et al., 2010), there was no difference in bract chroma among the treatments (results not shown).

Conclusions

Soil moisture sensor-controlled irrigation systems can be used to apply regulated WD to

control poinsettia stem elongation. This was shown to be an effective method of height control. Although application of WD to control poinsettia stem elongation did not cause any negative side effects on poinsettia quality in this study, other studies have shown reductions in bract size. The use of WD should be avoided following bract initiation to reduce the risk of unwanted effects on plant quality. Regulated WD has potential to reduce the need for PGR applications and can be used as an alternative or supplemental method of height control in poinsettia production.

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