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 postharvest handling (Karlovic 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 (Kohanbash 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 postharvest 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 Horticubes; Smithers-Oasis, Kent, OH), were obtained...
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 40SC; SePro Corporation, Carmel, IN) and dinitrofenuran (Safan 20 SG; Valent USA Corporation, Walnut Creek, CA) were inserted diagonally into the root zone of representative plants in each experimental unit. The greenhouse was cooled using a fan system when the air temperature was below 22 °C; while the greenhouse heating was on at temperatures below 18 °C. Temperatures during nighttime were the same for all treatments. The greenhouse was exposed to WD 21 to 29 d and from 53 to 58 d after pinching. The rapid increase in plant height shortly after pinching can be explained by elongation of lateral branches. Free-branching poineettia 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 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 77 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 poineettia 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 m·m⁻³·d⁻¹ to twice 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 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 poineettia 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 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 poineettia 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).

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WD supports previous suggestions on the successful regulation of plant growth through the target range (Figs. 1 and 2). The treatment in which final plant height was the acceptable height range. Tukey’s HSD test ($\alpha = 0.05$). The solid horizontal line represents the target height, while the dotted lines indicate PGR applications (both drench and spray applications were made on both days), while the horizontal arrows indicate two sigmoidal curves indicate the target height range. The vertical arrows indicate PGR applications (WD) treatments as monitored using height tracking curves for 77 d. Growth retardants and WD were a mixture of daminozide and chlormequat chloride or drench with paclobutrazol) and water deficit (WD) cycles. Bars (means ± SD) with the same letter are not significantly different according to $R^2 = 0.56; P = 0.0008$), and bract size ($R = 0.46; P = 0.0085$). The reduction in canopy spread as

Irrigation and WD application. After hand watering was stopped, the automated soil moisture sensor-controlled irrigation system successfully maintained the $\theta$ in the control and PGRs treatments close to 0.40 m$^3$·m$^{-3}$. The mean $\theta$ maintained by the irrigation system in the control and PGR treatments was 0.406 ± 0.003 m$^3$·m$^{-3}$ (mean ± SD). When WD was started, $\theta$ decreased gradually because of evapotranspiration. After WD had reached 0.20 m$^3$·m$^{-3}$, $\theta$ during the remainder of the WD periods was 0.207 ± 0.004 m$^3$·m$^{-3}$. At the end of the WD periods, multiple irrigations quickly returned $\theta$ to 0.40 m$^3$·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 mol·m$^{-2}$·d$^{-1}$).

After lowering the $\theta$ threshold in the WD treatment to 0.20 m$^3$·m$^{-3}$, plants were not irrigated until $\theta$ decreased to this threshold (DWU = 0 mL/plant). After the substrate $\theta$ had reached 0.20 m$^3$·m$^{-3}$, WD plants were irrigated to maintain $\theta$ at 0.20 m$^3$·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 $\theta$ threshold was changed back to 0.40 m$^3$·m$^{-3}$ to end the WD, DWU peaked as the irrigation system watered frequently to increase $\theta$ back to 0.40 m$^3$·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. 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 ± SD) with the same letter are not significantly different according to Tukey’s 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).
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 \( \leq 40\% \). 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 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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