Effects of Daily Light Integral and Canopy Density on Shoot Growth and Development in a Poinsettia (*Euphorbia pulcherrima* Willd. ex. Klotsch) Stock Plant Canopy

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Abstract. Poinsettia stock plants consist of a dense canopy of competing shoots, and the growth and development of these individual shoots have not been previously quantified. The effects of air temperature, daily light integral (DLI), and canopy density (CD) were investigated on poinsettia (*Euphorbia pulcherrima* Willd. ex. Klotsch) 'Freedom Red' shoot development in a stock plant canopy. Plants were grown at two constant temperatures (20.3 or 25.7 °C), five CD (43, 86, 129, 172, or 215 shoots/m²), and three DLI treatments (2.6, 4.4, or 7.7 mol·m⁻²·d⁻¹ for the September planting and 4.0, 6.0, or 10.6 mol·m⁻²·d⁻¹ for the January planting). Shoot position at the final data collection was used to assign shoots to different levels within the canopy; Level 1 = the four highest shoots, Level 2 = the next four highest shoots, and so forth for Levels 3, 4, and 5. Temperature did not significantly affect leaf unfolding rate (LUR), shoot fresh mass (FM), or shoot caliper, whereas DLI and CD affected shoot growth and development. LUR and FM increased as DLI increased from 2.6 to 10.6 mol·m⁻²·d⁻¹, whereas LUR and FM decreased on the uppermost shoots in the canopy, e.g., Level 1 shoots, as CD increased from 43 to 129 shoots/m². Therefore, higher CD required higher DLI to achieve similar LUR and FM. Shoot caliper on Level 1 shoots increased from 6.3 to 7.4 mm as CD decreased from 129 to 43 shoots/m²; and shoot caliper increased from 5.8 to 7.6 mm as DLI increased from 4.0 to 10.6 mol·m⁻²·d⁻¹. The DLI environment needs to be managed to accommodate greater CD, to sustain growth and development of individual shoots within the canopy of poinsettia stock plants.

Commercial production of flowering poinsettias begins with the propagation of shoot tip cuttings that are harvested from stock plants having many stems in a dense canopy. The cuttings are removed from the stock plants on a weekly schedule. A typical unrooted poinsettia cutting for the North American market consists of a 5.0- to 6.5-cm stem, two to three mature leaves, and three to four immature leaves. The caliper at the base of the stem is typically 4 to 6 mm (Ecke et al., 2004). Individual shoots require 6 to 8 weeks to develop from an axillary bud to a shoot with commercial cutting specifications.

Previous studies on poinsettia growth and development have concentrated on the branching (Faust and Heins, 1996), plant height (Berghage and Heins, 1991; Clifford et al., 2004), bract size, and flowering dates (Liu and Heins, 2002). These studies typically describe the growth and development of the dominant shoots in a canopy with a relatively low canopy density (shoots/m²), i.e., low competition for

sunlight. Thus, the results describe optimal rates of growth and development. In contrast, poinsettia stock plants consist of a relatively dense canopy of competing shoots, which appear to be developing at less than optimal rates. Stock plant crops are scheduled so that the canopies reach the point of closure, i.e., when the leaves of neighboring plants overlap, before the cutting harvest season. If a stock plant canopy does not reach canopy closure, then production space is wasted. If a stock plant canopy reaches canopy closure far in advance of the harvest season, then labor is wasted removing cuttings until there is market demand while not increasing branching.

Previous studies on stock plant management techniques are relatively few and have primarily focused on the effect of pinching techniques on cutting yield (Grueber, 1985). The growth and development of individual shoots within the stock plant canopy have not been quantified. Therefore, the objective of this study was to measure the effects of temperature, CD, and DLI on shoot growth and development within a poinsettia stock plant canopy. These data can provide insight into the management of greenhouse environments and cultural practices for the production of commercial poinsettia cuttings.

Poinsettia (*Euphorbia pulcherrima* Willd. ex. Klotsch) 'Freedom Red' unrooted cuttings were propagated on 18 Sept. and 9 Jan. with one cutting per pot in 771-cm³ square pots, 12.7 cm tall and 8.9 cm wide (TLC Polyform, Morrow, GA) filled with a peat-based growing medium (3B; Fafard Inc., Belton, SC). The propagation environment consisted of an overhead mist system, bottom heat that provided a 22 °C media temperature, and a 50% shade curtain that was engaged when outdoor solar radiation exceeded 800 μmol·m⁻²·s⁻¹. Four weeks after the start of propagation, each cutting was pinched by removing one fully expanded, mature leaf and three immature leaves, leaving seven to eight nodes on the stem. At the time of pinching, 14 plants per experimental unit were placed on a bench with four center plants surrounded by 10 guard row plants (Fig. 1). Four center plants occupied 929 cm². Plants were irrigated based on plant demand and were fertilized during each irrigation with 300 mg·L⁻¹ nitrogen using 15N-2.2P-12.5K (Peters Excel Cal-Mag; The Scott's Company, Marysville, OH).

Temperature and DLI treatments began on the pinch day, whereas CD treatments began 9 d after the pinch day when shoots had emerged and could be removed. The temperature treatments were created by using two planting dates, September and January resulting in an average daily temperature of 20.3 ± 1.2 °C (21.0 °C day and 19.6 °C night temperature) for the September planting or 25.7 ± 1.7 °C (26.6 °C day and 24.7 °C night temperature) for January planting. Each of the plantings was done in separate greenhouses. Within each greenhouse, i.e., planting date, three DLI treatments were provided with ambient photosynthetic photon flux (PPF) (no shade curtain) or one of two different shade curtains that provided PPF reduction of 43% (XLS 15 F Firebreak; Ludwig Svensson, Charlotte, NC) or 64% (XLS 15 F Firebreak on top of SLS 10 Ultra plus; Ludwig Svensson). Curtains were supported by rectangular polyvinyl chloride tube frames (0.94, 1.52, and 1.73 m height, width, and length, respectively) placed over the plants. DLI treatments were equivalent to 2.6, 4.4, and 7.7 mol·m⁻²·d⁻¹ for the September planting and 4.0, 6.0, and 10.6 mol·m⁻²·d⁻¹ for the January planting. These DLIs accommodate a wide range of DLI experienced by a stock plant canopy, including in winter when outside DLI could be low as 4 mol·m⁻²·d⁻¹ (Ecke et al., 2004). Air temperature was measured with an environmentally controlled computer (Argus Controls Environmental Systems, B.C., Canada), and DLI was measured underneath each shade treatment with line quantum sensors (400 to 700 nm) connected to an Apogee Nanologger (Apogee Instruments, Logan, UT). Non-inductive photoperiods were provided with a 1000-W enhanced spectrum metal halide bulb (AgroSun Bulbs Hydrofarm, Petaluma, CA) that delivered 0.14 to 0.43 mol·m⁻²·d⁻¹ at canopy height from 2200 to 0200 hr. The CD treatments were created by removing shoots to

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Fig. 1. (A) Schematic diagram of an individual plant representing the assignment of levels within a canopy, based on the position of shoots from highest to the lowest, and (B) its relationship to the canopy density treatments. (C) Representation of an experimental unit with 14 such individual plants, of which four center plants were taken for data collection.

allow one, two, three, four, or five shoots to develop on each plant within the experimental unit. The measured shoots grew within the 30.5 × 30.5-cm (929 cm²) area in the center of each experimental unit, which was equivalent to CD of 43, 86, 129, 172, or 215 shoots/m². For example, one shoot was allowed to develop per plant within the 43-shoots/m² treatment, whereas two shoots were allowed to develop on each plant within the 86-shoots/m² treatment. Two CD × DLI treatments were present within each temperature treatment.

All shoots were harvested for data collection from the four center plants within each experimental unit, 8 weeks after pinching. Shoot FM and height were recorded 8 weeks after the pinch date. Shoot height was measured from the growing media surface to the shoot meristems, whereas FM reflected the mass of entire individual lateral shoots measured immediately after removal from plant.

Comparisons across CD were performed by assigning shoots to levels based on the shoot position in the canopy as being highest to the lowest as at 8 weeks of pinching (Fig. 1). The four highest shoots per experimental unit (comprised of each shoot from four plants) averaged 32.9 cm and were assigned to Level 1. Level 2 represented four shoots below the Level 1 that averaged 28.6 cm, Level 3 represented four shoots below Level 2 that averaged 24.8 cm, Level 4 represented four shoots below Level 3 that averaged 22.4 cm, and Level 5 represented four shoots below Level 4 that averaged 19.8 cm. The number of levels assigned varied with the CD treatments as a result of the availability of shoots. For example, Level 1 occurred on all five CD treatments, because all CD treatments contained at least four shoots per experimental unit. However, Level 2 only occurred on CD ranging from 86 to 215 shoots/m²

(shoots ranging from eight to 20 per experimental unit), because lowest CD treatment (42 shoots/m²) had only four shoots per experimental unit.

LUR was calculated for each individual shoot as the linear slope of the number of leaves unfolded over time. Shoot caliper was measured using a digital vernier caliper, 6.2 cm below the shoot tip for the shoots in the January planting because this is a common length for commercial cuttings.

The experimental design was a split-split plot with temperature, created by two different planting dates, in the whole plot, split by DLI and further split by CD. The effect of CD on Level 5 could not be analyzed because only the 215-shoots/m² treatment had 20 shoots to represent this level. The experiment was analyzed with SAS Version 8.0 (SAS Institute, Cary, NC) using the Mixed procedure independently run for each level. Marginal least significant difference means were presented when there were no significant interactive effects.

Results and Discussion

Temperature did not significantly affect LUR or FM; therefore, data were pooled for further analysis. Pooling resulted in a split-plot design with DLI in the whole plot and CD in the subplot. Temperature effects on poinsettia growth and development have been previously described with quadratic polynomial regressions (Berghage et al., 1990; Berghage and Heins, 1991) because these curves increase from a base temperature, reach a plateau at an optimal temperature, and decrease thereafter. The temperatures delivered in this study (20.3 ± 1.2 and 25.7 ± 1.7 °C) were near the optimal temperature range for poinsettia (Berghage et al., 1990) where

temperature changes have less effect on rate changes. Additionally, temperature was the whole plot portion of the split plot treatments and had fewer df making it more difficult to obtain statistically significant effects.

LUR increased as DLI increased from 2.6 to 10.6 mol·m⁻²·d⁻¹ on Levels 1 to 4 (Fig. 2), whereas Level 5 did not respond to any factor (data not shown), and upper levels within the canopy had greater LUR than lower levels within the canopy. LUR decreased with an increase in CD as evident at Level 1 (Fig. 1A), whereas no CD response was observed at Levels 2 to 4 (Fig. 2B–D). However, a similar LUR was measured for Level 1 shoots growing at 2.6 mol·m⁻²·d⁻¹ (Fig. 2A), Level 2 shoots growing at 4.4 mol·m⁻²·d⁻¹ (Fig. 2B), Level 3 shoots growing at 6.0 mol·m⁻²·d⁻¹ (Fig. 2C), and Level 4 shoots growing at 7.7 mol·m⁻²·d⁻¹ (Fig. 2D). This suggests that as CD increased, a higher DLI was required to produce a similar LUR. Although some LUR models use only average daily temperatures to predict development rates (Karlsson et al., 1988), previous studies have used a combination of temperature and DLI to predict LUR where light also limited plant development (Faust and Heins, 1993; Liu and Heins, 1998; Volk and Bugbee, 1991). Effects of radiation can be difficult to discern from temperature responses, because higher radiation typically results in higher plant temperatures. However, plant temperatures deviate most greatly from air temperatures under high solar radiation, whereas the vapor pressure deficit is low such as occurs at cooler air temperatures and high relative humidity (Faust and Heins, 1998), which were not the case during these experiments.

FM followed a similar response as LUR (Fig. 3) that is, increasing as DLI increased or decreasing with Levels 1 to 5. Additionally, CD significantly affected FM only among Level 1 shoots (Fig. 3A). These results are in agreement with previous work on single stem rose production that demonstrated that the specific fresh mass of cut roses increased with increasing DLI or reduced canopy density (Bredmose, 1998).

Only the shoots at Level 1 (highest) within the canopy were affected by CD, although these shoots were positioned at the top of the canopy and thus received direct solar radiation (Figs. 2 and 3). For example, LUR and FM at Level 1 decreased as CD increased from 43 to 129 shoots/m² (Figs. 2A and 3A). This suggests that the additional shoots at lower levels in the canopy were sinks for the carbohydrates produced by Level 1 shoots. For Level 1 shoots, the CD treatments 129 shoots/m² or greater had similar LUR and FM (Figs. 2A and 3A; averages are presented). Shoots positioned at Levels 2 to 4 were unaffected by CD (Figs. 2B–D and Figs. 3B–D; averages are presented). These levels also had fewer observations and a narrowing range of CD treatments, which decreased the df in the analysis of variance resulting in CDs that were not significantly different. Grouping cuttings into levels based on shoot height have merit in the fact that the levels correspond to the order

Fig. 2. The effects of daily light integral (DLI) on leaf unfolding rate at different levels of the canopy (Level 1 to 5 being highest to lowest) of poinsettia 8 weeks after treatment application for (A) Level 1 at a canopy density (CD) treatments of 43 shoots/m² (●), 86 shoots/m² (○), and at mean averages for CD of 129 to 215 shoots/m² (▼); (B) Level 2 at CD treatments of 86 to 215 shoots/m² (△); (C) Level 3 for CD treatments of 129 to 215 shoots/m² (■); and (D) Level 4 for CD treatments of 172 to 215 shoots/m² (□). No significant effect of DLI or CD was observed at Level 5 (data not shown). Vertical bars represent $\pm$ SE.

Fig. 3. The effects of daily light integral (DLI) on final shoot fresh mass at different levels of the canopy (Level 1 to 5 being highest to lowest) of poinsettia 8 weeks after treatment application for (A) Level 1 at canopy density (CD) treatments of 43 shoots/m² (●), 86 shoots/m² (○), and at mean averages from CD of 129 to 215 shoots/m² (▼); (B) Level 2 at CD treatments 86 to 215 shoots/m² (△); (C) Level 3 for CD treatments of 129 to 215 shoots/m² (■); and (D) Level 4 for CD treatments of 172 to 215 shoots/m² (□). No significant effect of DLI or CD was observed at Level 5 (data not shown). Fitted trends are a raise to max single two parameter equation for A and B and a linear polynomial equation for C and D with its respective r^2 . Vertical bars represent $\pm$ SE.

and rate at which the shoots will be harvested for cuttings. Commercially, cuttings are harvested from the top of the canopy,

and therefore, the Level 1 cuttings would be harvested in the first week, then the Level 2 cuttings would become the new Level 1

cuttings during the next week and would be harvested at that time.

DLI and CD affected shoot caliper only within Level 1 (Table 1), where shoot caliper increased from 6.3 to 7.4 mm as CD decreased from 129 to 43 shoots/m². At Level 1, shoot caliper increased from 5.8 to 7.6 mm as DLI increased from 4 to 10.6 mol·m⁻²·d⁻¹. Within each level, all shoot calipers measured in CD treatments 129 shoots/m² or greater were similar. Marginal mean comparisons of Level 2 showed that shoot caliper increased as DLI increased from 6.0 to 10.6 mol·m⁻²·d⁻¹, whereas CD had no effect. Level 3 had no significant main effects; however, a significant interaction existed, so cell means were compared. Within Level 3, shoot caliper was greatest at a DLI of 10.6 mol·m⁻²·d⁻¹ with CD treatments of 129 and 172 shoots/m². No shoot caliper differences were observed within Levels 4 and 5. Although the influence of DLI on shoot caliper among the levels within the canopy was not investigated, increase in shoot caliper in response to increasing DLI was reported in other species (Currey et al., 2012).

Stock plants can be grown for varying lengths of time. "Fast-crop" stock plants receive just one pinch and produce ≈ 10 cuttings per 929 cm², whereas two- and three-pinch stock plants produce 15 and 25 cuttings per 929 cm², respectively (Ecke et al., 2004). The data presented in this article suggest that the DLI requirements for a poinsettia stock plant increase as the CD increases; thus, fast-crop (single-pinch) stock plants should be produced with a DLI of at least 6.0 mol·m⁻²·d⁻¹, whereas 10 mol·m⁻²·d⁻¹ is beneficial for two- and three-pinch stock plant production. Higher DLIs allow for increased growth and development of the top four levels of shoots, which essentially represents 4 weeks of cutting production. In addition, we expect that harvest intensity, i.e., the number of cuttings harvested per week, will increase with higher DLI, because the shoots achieve market specifications faster under higher DLI environments.

In our experiments, the plants in all treatments had reached canopy closure within 6 weeks of the initial pinch date. In commercial stock plant production, the crop is typically spaced so that the plants reach canopy closure in the week or 2 immediately before the onset of the peak harvest season. Thus, fast-crop (one pinch) stock plants are spaced closer together than a two- or three-pinch stock plants. The goal is to schedule the stock plants to reach maximum production capacity just as the seasonal market opens up.

CD can be manipulated by removing mature leaves or shoots in the stock plant canopy. This technique essentially increases the light interception of the remaining shoots by reducing competition for light. Leaf removal on stock plants has been demonstrated to benefit cutting yield of geraniums (Wilkins, 1988). Shoot removal or canopy thinning can be performed if there are excessive shoots within the canopy, i.e., more shoots than cuttings needed. Our data also underscore the importance of removing shoots that have become mature even if there is no market for them.

Table 1. Effects of daily light integral (DLI) and canopy density (CD) at different levels of the canopy (Level 1 to 5 representing highest to lowest, respectively) on shoot caliper measured 6.2 cm below the meristem in shoots of poinsettia 8 weeks after treatment application for January planting.^z

Level	Daily light integral (mol·m ⁻² ·d ⁻¹)	Canopy density (shoots/m ²)					Means DLI
		43	86	129	172	215	
		Shoot caliper (mm)					
1 ^y	4.0	6.4	5.6	5.5	5.5	5.2	5.8 c
	6.0	7.8	7.2	6.1	6.1	5.9	6.6 b
	10.6	7.9	7.7	7.4	7.4	7.3	7.6 c
	Means CD	7.4 a	6.8 b	6.3 c	6.3 c	6.3 c	
2 ^y	4.0 ^x		5.0	5.1	5.1	4.6	4.9 b
	6.0		5.9	5.7	5.3	5.6	5.6 b
	10.6		6.8	6.5	6.6	6.1	6.5 a
	Means CD						
3	4.0			4.2 bcd ^x	3.9 cd	4.2 bcd	4.1
	6.0			4.4 bcd	4.4 bcd	4.7 bc	4.5
	10.6			5.8 a	5.6 a	4.8 bc	5.4
	Means CD						
4 ^w	4.0				3.3	3.9	3.6
	6.0				4.3	3.8	4.1
	10.6				4.4	4.0	4.2
	Means CD						
5	4.0					3.1	3.1
	6.0					— ^v	
	10.6					3.8	3.8
	Means CD						

^zAt Level 1, DLI and CD were statistically significant; therefore, marginal comparisons are shown represented by letters. DLI was the only significant factor for Level 2; therefore, only DLI marginal comparisons are made. At Level 3, the DLI × CD interaction was statistically significant; therefore, the cell means are compared. No significant treatment effects were observed at Level 4 or 5.

^yMeans following the same letters within rows (DLI) or columns (CD) represent no significant difference within the main effect (LSD 5% level).

^xAt Level 3, means following the same letters within a level represent no significant difference (LSD 5% level).

^wAt Levels 4 to 5, no significant differences within treatments (LSD 5% level).

^vData were not recorded because no shoots existed for this treatment.

LSD = least significant difference.

These shoots eventually become larger than the desired specifications and shade lower shoots in the canopy, which effectively reduces the productivity of the stock plant and therefore need to be removed on a regular schedule.

Previous research has described the growth and development of the primary poinsettia shoots in the finished plant environment. These shoots are at the top of the canopy and have little competition for light. In contrast, the current study describes the growth and development of all the shoots within a relatively dense canopy. The canopy density affects the growth of the best positioned shoots in the canopy (Level 1) as well as all the shoots located beneath the primary shoots (Levels 2 to 5). The results provide commercial stock plant producers with an increased understanding of

how the stock plant canopy grows and develops, which has practical implications for both the management of the DLI delivered to the canopy and the management of the canopy to alter the delivery of light to individual developing shoots. Specifically, DLI should be optimized, providing at least 10 mol·m⁻²·d⁻¹, mature shoots should be removed from the canopy so that only shoots that are of ideal size for cutting harvest are positioned at the top level of the canopy, and stock plants should be spaced so that they reach canopy closure immediately before the peak harvest season.

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