Photosynthetic Daily Light Integral During Root Development Influences Subsequent Growth and Development of Several Herbaceous Annual Bedding Plants

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Abstract. Vegetatively propagated bedding plants are produced during the late winter and early spring when outdoor photosynthetic daily light integral (DLI) is low, especially in northern latitudes. Our objective was to quantify how propagation DLI influences subsequent growth and development of annual bedding plants. Cuttings of *Angelonia angustifolia* Benth. ‘AngelMist White Cloud’, *Nemesia fruticans* (Thunb.) Benth. ‘Aromatica Royal’, *Osteospermum ecklonis* (DC.) Norl. ‘Voltage Yellow’, and *Verbena ×hybrida* Ruiz ‘Aztec Violet’ were harvested and propagated in a glass-glazed greenhouse. After callusing ($\approx 5 \text{ mol}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$ for 7 days), cuttings of each species were placed under one of three different fixed-woven shade cloths providing $\approx 38\%$, 61% , or 86% shade or no shade with 16 h of supplemental light for 14 days. Rooted cuttings were then transplanted into 11-cm containers and grown in a common greenhouse of $21 \pm 1^\circ\text{C}$ and DLI of $\approx 12 \text{ mol}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$ to identify any residual effects on subsequent growth and development during the finish stage. As DLI during propagation increased, time to first open flower decreased for *Angelonia*, *Nemesia*, *Osteospermum*, and *Verbena*. For example, time to flower for *Angelonia* and *Osteospermum* was hastened by 23 and 19 days, respectively, as DLI during propagation increased from 1.2 to $12.3 \text{ mol}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$. Our research can be used to predict growth and flowering under varying propagation DLIs for the cultivars of *Angelonia*, *Nemesia*, *Osteospermum*, and *Verbena* in the study.

Vegetatively propagated herbaceous bedding plants are produced in two distinct phases: a young plant stage, in which shoot-tip cuttings are rooted as liners, and a finish plant stage, in which the rooted young plants are transplanted into a larger finish container where they are grown until they become marketable (Klopmeier, 2003). Vegetative propagation of bedding plants occurs from mid to

late winter and early spring when average daily ambient photosynthetic DLI is typically low, especially in northern latitudes (Currey et al., 2012; Lopez and Runkle, 2008). During this time, outdoor DLI can range from 5 to $20 \text{ mol}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$ (Korczynski et al., 2002). Shading, glazing materials, obstructions, and structures can further reduce DLI within propagation facilities to 2.5 to $10 \text{ mol}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$ (Oh et al., 2010) and can be as low as $1 \text{ mol}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$ during extended periods of overcast weather (Lopez and Runkle, 2008).

Many studies have been performed on the effects of increasing DLI during the young plant stage on root and shoot biomass, liner, and plug transplant quality (Currey et al., 2012; Enfield, 2002; Graper and Healy, 1991; Lopez and Runkle, 2008; Pramuk and Runkle, 2005; Rapaka et al., 2005; Torres and Lopez, 2011) or during the finish plant stage on flowering (Fauser et al., 2005; Islam et al., 2005; Loehrlein and Craig, 2004). Generally, increases in DLI during the propagation of seedlings and cuttings increased biomass accumulation, root growth, and transplant quality and hastened subsequent flowering. For example, increasing propagation DLI from 4.1 to $14.2 \text{ mol}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$ during the seedling stage increased shoot dry mass per internode linearly by 64%, 64%, 47%, and 68% and plants subsequently flowered 4, 10, 12, and

12 d earlier in *Tagetes patula* L., *Celosia argentea* var. *plumosa* L., *Impatiens walleriana* Hook. f., and *Viola ×wittrockiana* Gams., respectively (Pramuk and Runkle, 2005). When *Petunia ×hybrida* Vilm.-Andr. and *Viola* seedlings were provided with supplemental light (≈ 4 to $5 \text{ mol}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$) during the last two-thirds or entire young plant stage, shoot dry mass and number of leaves increased, whereas subsequent time to flower decreased. Similarly, increasing propagation DLI from 1.2 to $10.7 \text{ mol}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$ increased the root and shoot dry mass of *Impatiens hawkeri* Bull. ‘Harmony White’ cuttings by 1038 and 82%, respectively, and subsequent time to flower decreased from 85 to 70 d, respectively (Lopez and Runkle, 2008).

When outdoor DLI is low, the only way to increase DLI is to provide supplemental lighting from high-intensity discharge lamps (Oh et al., 2010). Lopez and Runkle (2008) indicated that DLI should be maintained between 4 to $6 \text{ mol}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$ when *Impatiens hawkeri* and *Petunia* cuttings are stuck and during callusing. The DLI should increase between 6 and $8 \text{ mol}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$ during root development and toning to obtain rapid, uniform rooting and high-quality rooted transplants that flower earlier, especially when cuttings are rooted during the darkest periods of the year. When ambient DLI is 8 to $10 \text{ mol}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$ or less, Oh et al. (2010) recommend using supplemental lighting during the two true leaf stage to produce good-quality plugs, rapid flowering, and energy savings.

One report (Lopez and Runkle, 2008) quantifies the effects of ambient DLI during vegetative cutting propagation on subsequent growth and development during the finish stage. However, the effects of using supplemental lighting to increase DLI during cutting propagation of a broader range of specialty herbaceous annual bedding plants has not been published. Therefore, our objective was to quantify the impact of supplemental DLI during cutting propagation on subsequent growth and development of four annual bedding plant species.

Materials and Methods

Plant material and culture. Cuttings of *Angelonia angustifolia* ‘AngelMist White Cloud’, *Nemesia fruticans* ‘Aromatica Royal’, *Osteospermum ecklonis* ‘Voltage Yellow’, and *Verbena ×hybrida* ‘Aztec Violet’ were planted in 15-cm (1.7-L volume) round containers filled with substrate comprised of (by volume) 80% sphagnum peatmoss and 20% perlite (Fafard 1P; Conrad Fafard, Inc., Agawam, MA) on 9 May 2010. Plants were irrigated with acidified water supplemented with water-soluble fertilizer to provide (in $\text{mg}\cdot\text{L}^{-1}$): 200 nitrogen (N), 26 phosphorus (P), 163 potassium (K), 50 calcium (Ca), 20 magnesium (Mg), 1.0 iron (Fe), 0.5 manganese (Mn) and zinc (Zn), 0.24 copper (Cu), boron (B), and 0.1 molybdenum (Mo). Nutrients were supplied from a combination of two fertilizers, 900 $\text{mg}\cdot\text{L}^{-1}$ (Peters Excel® Cal-Mag 21N–2.2P–16.5K; The Scotts Co.,

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Marysville, OH) and 300 mg·L⁻¹ formulation (Peters Excel© 15N–2.2P–12.5K). Irrigation water was supplemented with 93% sulfuric acid (Brenntag, Reading, PA) at 0.08 mg·L⁻¹ to reduce alkalinity to 100 mg·L⁻¹ and pH to a range of 5.8 to 6.2. Stock plants were maintained in a vegetative state by regularly pinching shoots and applying foliar sprays of solutions containing 250 mg·L⁻¹ ethephon (Florel; Lawn and Garden Products, Inc., Fresno, CA). Ethephon sprays stopped at least 3 weeks before cutting harvest.

Stock plants were grown in a glass-glazed greenhouse in West Lafayette, IN (lat. 40° N) with an exhaust fan and evaporative-pad cooling and radiant hot-water heating controlled by an environmental computer (Maximizer Precision 10; Priva Computers Inc., Vineland Station, Ontario, Canada). The greenhouse day and night air temperature set points were 23 °C and were measured with an enclosed thermocouple (Watchdog 2450 Weather Station; Spectrum Technologies, Inc., Plainfield, IL). The photoperiod was a constant 16 h (0600 to 2200 HR) consisting of natural daylengths with day-extension lighting from high-pressure sodium lamps (HPS) that delivered a supplemental photosynthetic photon flux (PPF) density of 100 μmol·m⁻²·s⁻¹ at plant height [as measured with a quantum sensor (LI-COR Biosciences, Lincoln, NE)] from 1700 to 2200 HR. The greenhouse mean air temperature for stock plants was 23.2 ± 1.2 °C and the mean DLI was 11.6 ± 2.0 mol·m⁻²·d⁻¹ (average daily temperature ± the temperature SD).

Cutting harvest. On 4 Sept. 2010, 16 Oct. 2010, and 11 Jan. 2011, 40 uniform 2.5-cm shoot-tip cuttings were harvested from each species of stock plant. The cuttings were then placed in 105-cell propagation trays (individual cell volume 28 mL; T.O. Plastics, Inc., Clearwater, MN) filled with a propagation substrate composed of (v/v) 50% soilless substrate (Fafard 1P) and 50% coarse perlite (Strong-Lite Coarse Perlite; Sun Gro Horticulture, Bellevue, WA). Cuttings were sprayed to runoff with a solution containing 300 mg·L⁻¹ non-ionic surfactant (CapSil; Aquatrols, Paulsboro, NJ) so water would not accumulate on the plant foliage.

Propagation environment and culture. All cuttings were rooted in a glass-glazed greenhouse under a 16-h photoperiod with an air temperature set point of 23 °C, and the DLI was maintained at ≈5 mol·m⁻²·d⁻¹ during callusing. Enclosed resistance-based sensors placed below the mist and sensors (External Temperature Sensor; Spectrum Technologies, Inc.) inserted into the substrate were used to measure air and substrate temperatures, respectively, in each treatment every 30 s and averages were logged every 15 min by a data logger (Watchdog 2800 Weather Station; Spectrum Technologies, Inc.). Two amplified quantum sensors placed above the mist nozzles (SQ-212; Apogee Instruments, Inc., Logan, UT) measured PPF every 30 s under each light treatment and the average of each sensor was logged every 15 min by a data logger (Watchdog 2800 Weather

Station). For the three periods from harvest through callusing, the average air temperatures were 21.3 ± 0.5, 20.9 ± 0.8, and 20.7 ± 1.1 °C; the average substrate temperatures were 22.7 ± 0.5, 22.6 ± 0.9, and 22.4 ± 1.5 °C; and the average DLIs were 5.0 ± 0.9, 4.7 ± 1.2, and 4.8 ± 0.7 mol·m⁻²·d⁻¹, respectively.

After 7 d of callusing, 10 cuttings of each species were placed under DLI treatments that were created using no shade or shade-cloth providing ≈38%, 61%, or 86% or no shade (XLS F-14, -15, or -16; Ludvig Svensson, Inc., Charlotte, NC) under ambient daylight supplemented with 79 ± 8, 44 ± 5, 33 ± 5, or 13 ± 2 μmol·m⁻²·s⁻¹, respectively, delivered from HPS lamps from 0600 to 2000 HR. Every 20 min, 4 s of mist was applied consisting of acidified water supplemented with a water-soluble fertilizer (Jack's LX 16N–0.94P–12.3K Plug Formula for High Alkalinity Water; J.R. Peters, Inc., Allentown, PA) providing (in mg·L⁻¹) with each misting event: 50 N, 5 P, 39 K, 9 Ca, 4.7 Mg, 0.05 B, 0.025 Cu, 0.25 Fe, 0.125 Mn, 0.025 Mo, and 0.125 Zn. Six days after transfer of cuttings, misting frequency was reduced to every 30 min beginning and ending 2 h before and after the photoperiod, respectively; 8 d after cutting, transfer misting was reduced to begin and end 1 h before and after the photoperiod. Ten days after the placement of cuttings under DLI treatments, the use of mist was discontinued and cuttings were hand-irrigated daily with acidified water supplemented with water-soluble fertilizer as described in the previous "Plant Material and Culture" section. Environmental data were measured as previously described and are reported in Table 1.

Plant finishing culture. After 21 d in propagation DLI treatments, nine plants of each species from each DLI treatment were transplanted on 25 Sept. 2010, 6 Nov. 2010, and 1 Feb. 2011 into 11-cm diameter round containers (602-mL volume) filled with a peat-based substrate (Fafard 1P). Plants were hand-watered with water supplemented with water-soluble fertilizer (combination of fertilizers as previously described) to provide (in mg·L⁻¹): 200 N, 26 P, 163 K, 50 Ca, 20 Mg, and micronutrients. Leaf temperature was measured using infrared temperature sensors (Temperature/Transmitter model OS136-1; Omega Engineering Inc., Stamford, CT). The plants were grown at 21 °C under a 16-h photoperiod (as described previously) and environmental data are reported in Table 2.

Data collection. Time to flower from the time of transplant, number of flower buds (greater than 2 mm in diameter), number of lateral branches (greater than 2 cm in length), the number of nodes below the first open flower, and plant height from the substrate level to the tip of the longest shoot were recorded on the date the first flower opened on each plant. For *Verbena*, each inflorescence was recorded as a flower. Shoot dry mass was recorded after drying in an oven at 70 °C for 1 week.

Data analysis. The experiment used a randomized complete block design in a factorial

arrangement. The factors were DLI (12 levels) and species (four levels). The experiment was repeated twice over time with nine samples (individual cuttings) per species per DLI per propagation date. Cuttings were randomly assigned to each DLI treatment, and DLI treatments were randomized between propagation dates within the greenhouse. Data were analyzed using regression analyses (Sigma Plot 11.0; Systat Software, Inc., San Jose, CA) with DLI as the independent variable.

Results

Flowering. The number of days from transplant to first open flower decreased linearly as propagation DLI increased for *Angelonia* and *Osteospermum*. For example, subsequent time to flower was hastened by 23 and 19 d, respectively, as DLI during propagation increased from 1.2 to 12.3 mol·m⁻²·d⁻¹ (Figs. 1A and 1C). As DLI increased from 1.2 to 12.3 mol·m⁻²·d⁻¹, a quadratic decrease in the number of days from transplant to the first open flower was observed for *Verbena* and *Nemesia* (Figs. 1B and 1D). The number of buds at first open flower for *Angelonia*, *Nemesia*, and *Verbena* was not influenced by the DLI during propagation (data not shown). However, in *Osteospermum*, bud number decreased by 14.1 as propagation DLI increased from 1.2 to 12.3 mol·m⁻²·d⁻¹. The number of nodes below the first open flower for *Angelonia*, *Nemesia*, and *Verbena* was not influenced by propagation DLI (data not shown). However, the number of nodes below the first open flower for *Osteospermum* decreased by 15.7 as propagation DLI increased from 1.2 to 12.3 mol·m⁻²·d⁻¹ (data not shown).

Growth. Shoot dry mass at flowering of all species decreased as propagation DLI increased. For example, as propagation DLI increased from 1.2 to 12.3 mol·m⁻²·d⁻¹, shoot dry mass of *Angelonia*, *Nemesia*, and *Osteospermum* decreased linearly by 0.9, 1.5, and 3.4 g, respectively (Fig. 1E–G). As DLI during propagation increased from 1.2 to 12.3 mol·m⁻²·d⁻¹, final plant height at flowering decreased for *Angelonia* and *Osteospermum* by 61 and 35 mm, respectively (Figs. 2A and 2C). Height of *Verbena* was an exception to this trend and was unaffected by propagation DLI (Fig. 2D). Branch number of *Angelonia*, *Osteospermum*, and *Verbena* decreased as propagation DLI increased from 1.2 to 12.3 mol·m⁻²·d⁻¹ by 1.8, 10.9, and 1.0, respectively (Figs. 2A, 2B, and 2D). However, branch number of *Nemesia* was unaffected by propagation DLI.

Discussion

To properly schedule bedding plants to flower within a predetermined and narrow market window for spring sales, greenhouse operations must intensively manage environmental factors such as temperature and light (Heins et al., 2000). Therefore, knowledge of how DLI during propagation influences crop timing and quality is crucial because an

Fig. 1. (A–H) Relationships between mean photosynthetic daily light integral during propagation and time to flower from transplant and shoot dry mass at first flowering for *Angelonia*, *Nemesia*, *Osteospermum*, and *Verbena*. Each symbol represents the mean of nine plants in each treatment and error bars represent sds of the mean. Regression lines are presented for significant correlations only with corresponding r^2 and R^2 presented. NS, *, **, *** indicate nonsignificant or significant at $P \leq 0.05$, 0.01, or 0.001, respectively.

Table 1. Average daily greenhouse air and substrate temperature (°C) and daily light integral (DLI; mol·m⁻²·d⁻¹) during root development (from callusing to transplant) of seven vegetatively propagated annuals under ~38%, 61%, or 86% shade (XLS-14, -16, or -18; Ludvig Svensson, Inc., Charlotte, NC) or no shade (0%).²

Propagation date	Shade (%)	Temperature (°C)		DLI (mol·m ⁻² ·d ⁻¹)
		Air	Substrate	
4 Sept. 2010	0	22.2 ± 0.8	22.6 ± 0.5	12.3 ± 1.5
	38	21.9 ± 0.8	22.1 ± 0.3	7.2 ± 1.2
	61	22.1 ± 0.7	22.2 ± 0.7	5.6 ± 1.2
	86	21.9 ± 0.8	23.7 ± 1.1	2.0 ± 0.4
17 Oct. 2010	0	22.4 ± 0.3	23.1 ± 0.4	10.6 ± 1.4
	38	22.3 ± 0.6	22.4 ± 0.4	6.4 ± 0.8
	61	21.6 ± 0.8	22.0 ± 0.3	3.6 ± 0.4
	86	21.9 ± 0.5	22.1 ± 0.3	1.4 ± 0.2
11 Jan. 2011	0	21.8 ± 0.6	22.4 ± 0.6	9.0 ± 0.9
	38	21.9 ± 0.7	21.9 ± 0.2	4.9 ± 0.8
	61	21.8 ± 0.6	22.0 ± 0.3	2.8 ± 0.8
	86	22.4 ± 0.7	23.0 ± 0.6	1.2 ± 0.4

²Treatments consisted of ambient daylight supplemented with 79 ± 8, 44 ± 5, 33 ± 5, or 13 ± 2 μmol·m⁻²·s⁻¹ (average ± SD), respectively, provided by high-pressure sodium lamps from 0600 to 2000 HR.

increasing number of greenhouse growers are vegetatively propagating annual bedding plants. Additionally, species-specific and, in some cases, cultivar-specific guide lines are needed to efficiently schedule and root vegetatively propagated bedding plant crops to meet market dates.

Management of DLI during seed and cutting propagation and finishing can reduce production time and increase crop quality (Currey et al., 2012; Fausey et al., 2005; Faust et al., 2005; Lopez and Runkle, 2008; Oh et al., 2010). Results from this study are in agreement with findings of Lopez and Runkle (2008) who quantified the effects of ambient DLI during propagation on subsequent development of *Impatiens hawkeri* and *Petunia*. In both studies, time to flower decreased as DLI during propagation increased. For example, in the current study, as DLI (supplemented with HPS lamps) during propagation

increased from 1.2 to 12.3 mol·m⁻²·d⁻¹, time to flower decreased linearly for *Angelonia* and *Osteospermum* by 23 and 19 d. Similarly, Lopez and Runkle (2008) reported that as ambient propagation DLI increased from 1.4 to 10.7 mol·m⁻²·d⁻¹, time to flower decreased by 21 and 22 d for *Petunia* 'Tiny Tunia Violet Ice' and 'Supertunia Mini Purple', respectively.

Shoot dry mass is often considered an indicator of plant quality (Fausey et al., 2005; Lopez and Runkle, 2008; Oh et al., 2010; Pramuk and Runkle, 2005). Shoot dry mass is a reliable quantitative measurement of plant size and fullness. Although increasing propagation DLI resulted in decreased flowering time (which is also a quality parameter), the quality of the plants may be reduced by some standards as a result of the decrease in shoot dry mass. This tradeoff between rapid flowering and quality is consistent with several

other studies (Lopez and Runkle, 2008; Oh et al., 2010; Pramuk and Runkle, 2005). For example, the shoot dry mass for *Petunia* 'Tiny Tunia Violet Ice' and 'Supertunia Mini Purple' at first open flower decreased by ~1.5 and 1.0 g as propagation DLI increased from ~1 to 11 mol·m⁻²·d⁻¹. Shoot dry mass at first open flower may be reduced as a result of increased propagation DLI, which in certain instances may be desirable. For example, a decreased shoot dry mass may be desirable when using a smaller finishing container. An alternative method of achieving a smaller finished plant is the use of a chemical plant growth retardant such as ethephon, which can induce floral senescence, abscission, and abortion, thus delaying time to flower and promoting shoot growth. However, caution must be exercised because exogenous ethephon applications may result in smaller root systems (unpublished data). Therefore, applications should not be made until cuttings are in the final stages of rooting after adequate root growth has occurred.

The effect of DLI on height or stem elongation at the first open flower was not consistent among the species in this study. For example, height of *Angelonia* and *Osteospermum* and stem elongation of *Nemesia* at the first open flower decreased as propagation DLI increased from 1.2 to 12.3 mol·m⁻²·d⁻¹. However, stem elongation of *Verbena* was not significantly influenced by propagation DLI. Similarly, Lopez and Runkle (2008) reported the height at the first open flower of *Petunia* and *Impatiens hawkeri* was not influenced by propagation DLI.

In addition to time to flower, increasing DLI in propagation impacted other flowering characteristics. We observed variability in flower bud number in response to propagation DLI among species, which is consistent with results from Lopez and Runkle (2008). In the current study, flower bud number was

Fig. 2. (A–H) Relationships between mean photosynthetic daily light integral during propagation and height and branch number at first flowering for *Angelonia*, *Nemesia*, *Osteospermum*, and *Verbena*. Each symbol represents the mean of nine plants in each treatment and error bars represent $\pm$ SE of the mean. Regression lines are presented for significant correlations only with corresponding r^2 and R^2 presented. NS, *, **, *** indicate nonsignificant or significant at $P \leq 0.05$, 0.01, or 0.001, respectively.

Table 2. Average daily greenhouse air and leaf temperature ($^{\circ}\text{C}$) and daily light integral (DLI; $\text{mol}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$) during the subsequent finish stage of four vegetatively propagated annuals under $\approx 38\%$, 61% , or 86% shade (XLS-14, -16, or -18; Ludvig Svensson, Inc., Charlotte, NC) or no shade (0%).^a

Propagation date	Transplant date	Temperature ($^{\circ}\text{C}$)		DLI ($\text{mol}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$)
		Air	Leaf	
4 Sept. 2010	25 Sept. 2010	20.9 ± 0.87	22.6 ± 1.3	11.9 ± 3.3
17 Oct. 2010	06 Nov. 2010	21.2 ± 0.43	21.9 ± 1.2	11.6 ± 3.0
11 Jan. 2011	01 Feb. 2011	22.0 ± 0.76	22.4 ± 1.9	11.8 ± 1.9

^aTreatments consisted of ambient daylight supplemented with 45, 28, 11, or $81 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ on average provided by high-pressure sodium lamps from 0600 to 2000 HR.

not influenced by increasing propagation DLI in any species with the exception of *Osteospermum*. Although flower bud number of *Osteospermum* at first open flower decreased as propagated DLI increased, we do not believe that increased flower bud number is a reflection of greater floral induction. Rather, plants propagated under lower DLIs (less than $6 \text{ mol}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$) flowered ≈ 20 to 40 d after transplant and had more branches with terminal flowers. Similarly, Lopez and Runkle (2008) reported that flower bud number of *Petunia* ‘Double Wave Spreading Rose’ and three cultivars of *Impatiens hawkeri* was not influenced by propagation DLI, whereas flower bud number of *Petunia* ‘Tiny Tunia Violet Ice’ and ‘Super-tunia Mini Purple’ decreased as propagation DLI increased.

The number of nodes beneath the first flower in *Osteospermum* decreased as propagation decreased. With these data, we are able to classify *Osteospermum* as having a facultative irradiance (FI) response based on a reduced node number below the inflorescence in response to increasing DLI (Erwin and Warner, 2002; Mattson and Erwin, 2005). However, there were no differences in the number of flower buds or nodes below the first flower or inflorescence for *Angelonia*, *Nemesia*, and *Verbena*. This would suggest that cuttings were induced to flower at the

same time and to a similar degree based on node number and flower number, respectively. Additionally, the fact that flowering occurred in as little as 2 weeks after transplant for cuttings propagated under high DLIs suggests that floral induction and initiation had likely occurred before or early in propagation. However, there were no significant differences in plant temperature during propagation under different DLIs (data not shown) and cuttings were finished in a common environment. Preliminary data indicate that cuttings propagated under higher DLIs have higher photosynthetic rates. For example, photosynthesis of ‘Magnum Salmon’ *Impatiens hawkeri* was 2.0 , 4.5 , and $6.3 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$, respectively, for cuttings propagated under ≈ 2.5 , 8.5 , and $15.6 \text{ mol}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$, respectively (unpublished data). Therefore, flower bud development for *Angelonia*, *Nemesia*, and *Verbena* may have been a function of carbohydrate source rather than temperature. Developing flower buds are carbohydrate sinks. For example, development and retention of flower buds of *Capsicum annuum* L. was related to carbohydrate accumulation (Aloni et al., 1996). Lopez and Runkle (2008) hypothesized that low DLIs are needed to accumulate more photosynthates or increase net photosynthesis to promote flower bud initiation or continued development of initiated buds and our data from this study may strengthen that hypothesis.

Conclusions

Data from this study may be used to predict how propagation DLI can influence subsequent growth and development of *Angelonia*, *Nemesia*, *Osteospermum*, and *Verbena* (i.e., time to flower, shoot dry mass, height, bud number, and branch number). Further studies are needed to quantify the effects of the interaction between propagation and finishing DLI across a wider range of plant species. This will help to create guidelines that commercial growers can follow to maximize efficiency during the propagation and finish environments to produce high-quality liners and flowering plants.

Lopez and Runkle (2008) recommend a propagation DLI of between 6 and $8 \text{ mol}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$ for *Petunia* and *Impatiens hawkeri* after roots have initiated to ensure uniform cuttings with accelerated flowering. However, when the results of the current study are taken together with those reported by Currey et al. (2012), we recommend greenhouse propagators maintain a DLI of $\approx 10 \text{ mol}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$ during root development with the use of supplemental lighting after callusing to increase both growth and quality of rooted cuttings and reduce subsequent time to flower.

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