Blackout Reduces Height of Easter Lily but End-of-day Red Light Treatment Using Light-emitting Diodes Does Not

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ADDITIONAL INDEX WORDS. growth regulation, *Lilium longiflorum*, photoperiod, R:FR, twilight

SUMMARY. One principle for reducing undesirable stem extension in greenhouse production is to counteract the decrease in red-to-far red ratio that occurs naturally during twilight periods. This study evaluated three lighting treatments on the morphology of easter lily (*Lilium longiflorum*): 1) a 1-hour end-of-day treatment providing $20 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ of monochromatic red light (EOD R), 2) blackout curtains closed 45 to 75 minutes before sunset and kept closed until 0 to 60 minutes after sunrise (BO), and 3) a control with natural twilight (CTRL). Plants under the BO treatment were 11% shorter than CTRL, while plants exposed to EOD R did not differ in height compared with BO or CTRL. There were no treatment effects on any other measured parameters, including aspects of flowering.

Height control is crucial for easter lily (*Lilium longiflorum*) production to attain acceptable aesthetics and to enable shipping to retailers in standard-sized boxes. To manage plant height, easter lily growers have commonly relied on plant growth regulators (PGRs) (Franciscangeli et al., 2007; Jiao et al., 1986; Wulster et al., 1987) and temperature control (Blom and Kerec, 2003; Erwin and Heins, 1995; Erwin et al., 1989; Wilfret, 1987). Non-chemical methods of controlling height are increasingly becoming desirable alternatives for height control as PGRs face increasing environmental concerns and tighter regulations (Bergstrand, 2017).

Various environmental manipulation strategies to control easter lily have been demonstrated, although they each have challenges that may be barriers to commercial adoption. For example, doubling the intensity

(without changing photoperiod) resulted in height reductions of 17% (13.4 cm) in one study (Kohl and Nelson, 1963). Similarly, halving the intensity from emergence to flowering increased total height by $\approx 40\%$ (Heins et al., 1982a). Higher light intensities can be achieved by maintaining high light transmission through greenhouse coverings, reducing light-blocking overhead structures, or through supplemental lighting, but the energy and infrastructure costs of the latter are trade-offs. Another method to reduce height of many plant species, including easter lily, is to provide a negative day vs. night temperature differential (DIF) (i.e., by providing warmer temperatures during the night compared with the day). For example, raising night temperature from 14 to 30 °C after flower initiation (determined through meristem examination) reduced the height of easter lily from 43.8 to 31.3 cm (29%) when day temperature was held at 14 °C (Erwin et al., 1989), although the additional

energy required for nighttime heating must be considered for this height control strategy. Reducing the temperature of irrigation solution, when applied to the shoot apex, was found to reduce easter lily height linearly by $1.75 \text{ cm}\cdot\text{°C}^{-1}$ between 18 and 2 °C (Blom et al., 2004). However, focused applications of cooled water to the shoot apex may be challenging to scale-up to commercial production, and irrigation temperature had no effect when applied directly to the substrate.

Light-emitting diodes (LEDs) are a promising tool for manipulating plant morphology due to the customizable nature of LED spectra, as targeted light spectral modifications can have substantial photomorphological effects. For example, the red [R (600–700 nm)] to far red [FR (700–800 nm)] photon flux ratio (R:FR) can dramatically affect plant morphology in sole-source lighting scenarios (Carvalho and Foltá, 2014; Demotes-Mainard et al., 2016; Hernández et al., 2016; Holmes and Smith, 1977a; Kong et al., 2018; Mah et al., 2018). The challenge remains to design suitable and cost-effective growth control treatments using LEDs in greenhouse production environments, where targeted supplemental light treatments must overcome the background intensity and quality characteristics of natural light to elicit photomorphogenic effects.

One notable feature of the solar spectrum on Earth is that the R:FR tends to decrease at the ends of the natural photoperiod (Hughes et al., 1984). This leads to the question of whether this short-duration decrease in R:FR at the end of day (EOD) reduces plant compactness, as many species exhibit “shade avoidance” responses when exposed to low R:FR (Demotes-Mainard et al., 2016; Smith and Whitelam, 1997). In easter lily, a typical response to additional

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Units

To convert U.S. to SI, multiply by	U.S. unit	SI unit	To convert SI to U.S., multiply by
10.7639	fc	lx	0.0929
0.3048	ft	m	3.2808
3.7854	gal	L	0.2642
2.54	inch(es)	cm	0.3937
6.4516	inch ²	cm ²	0.1550
1	μmho/cm	μS·cm ⁻¹	1
28.3495	oz	g	0.0353
1	ppm	mg·L ⁻¹	1
(°F – 32) ÷ 1.8	°F	°C	(°C × 1.8) + 32
(°F ÷ 1.8) + 255.37	°F	K	(K – 255.37) × 1.8

FR includes increased stem elongation (Blom and Kerec, 2003; Blom et al., 1995).

During the daytime (i.e., solar elevation $> 10^{\circ}$ – 15°), the R:FR of natural sunlight is ≈ 1.15 , but during twilight (solar elevation $< 10^{\circ}$ – 15° until darkness), the R:FR gradually drops $\approx 35\%$ (Holmes and Smith, 1977b). The dynamics of light intensity and quality at twilight are impacted by weather, time of year, latitude, and light pollution (Kishida, 1986; Spitschan et al., 2016). Although few studies directly investigate whether the changes in light quality during twilight actually influence stem elongation, Lund et al. (2007) found that height of chrysanthemum (*Chrysanthemum × morifolium*) increased as R:FR was reduced from 2.4 to 0.7 or 0.4 to mimic twilight (using LEDs), under very low photosynthetic photon flux density [*PPFD* (400–700 nm)] by maintaining either R at $1 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ or FR at $1 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ for 30 min at the end of photoperiod in growth chambers. A previous growth chamber study showed that four bedding plant species grown under a light spectrum with R:FR of 0.7 vs. 1.1 had longer stems (Mah et al., 2018), although it is uncertain whether this result would still be observed if R:FR was altered during twilight only.

Instead of competing with the native intensity and spectrum characteristics of sunlight in a greenhouse environment, targeted spectral treatments from artificial sources (such as LEDs) can be applied near the EOD; i.e., at the tail end of the photoperiod just before darkness, to manipulate crop morphology in greenhouse environments. During the twilight periods, artificial lighting can easily modify the spectrum received by plants, as *PPFD* of natural light is low during that time. Based on solar measurements in Guelph, ON across several months, *PPFD* of natural light dropped below $10 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ after sunset, and diminished to less than $2 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ when apparent solar elevation was just 2° below the horizon (Mah, 2019). Altering the light spectrum at EOD using FR-absorbing filters has been shown to reduce height of vegetable seedlings, although increasing the R:FR at the EOD was less effective at reducing height than the same R:FR applied

over the entire photoperiod (Cerny et al., 2004). Nonetheless, EOD treatments using LEDs still warrant investigation, as they may require less infrastructure or energy than all-day treatments, and do not have the drawback of simultaneously reducing *PPFD* associated with FR-absorbing filters.

Adding narrow-band FR at EOD has been shown to have a strong promoting effect on internode elongation in numerous species (Casal and Smith, 1989; Chia and Kubota, 2010; Ilias and Rajapakse, 2005; Vince-Prue, 1977; Zahedi and Sarikhani, 2016), including easter lily (Blom et al., 1995). However, these experiments tended to compare EOD FR to EOD R treatments, while far fewer experiments have compared EOD R lighting to control treatments that are more relevant to greenhouse environments. In one experiment, adding 15 min of R ($2.1 \text{ W}\cdot\text{m}^{-2}$) at EOD in a greenhouse using filtered fluorescent light reduced the height of petunia (*Petunia × hybrida*) from 12.8 to 10.2 cm (20%) compared with the ambient control (Ilias and Rajapakse, 2005).

Blackout strategies (BO) have been in use for over a decade in easter lily production to suppress stem elongation (Blom et al., 2004; Miller, 1992). By shortening the natural daylength to 8 h, BO reduced height of ‘Nellie White’ easter lily by 15% (44.8 vs. 38.0 cm) (Blom et al., 1995), up to 26% (52.4 vs. 39.0 cm) (Blom and Kerec, 2003), or even 45% (36.8 vs. 20.4 cm) (Heins et al., 1982b). It has been suggested that BO curtains control stem elongation by eliminating the dynamic changes in R:FR during twilight, therefore preventing any stem-lengthening associated with the natural decrease in R:FR at EOD (Blom et al., 1995), and also by shortening the photoperiod (Kohl and Nelson, 1963). However, most studies that investigated photoperiod for easter lily height control used incandescent lights, which have a R:FR of ≈ 0.6 (Craig and Runkle, 2016), to extend the photoperiod of the treatments (Roh and Wilkins, 1977a, 1977b; Smith and Langhans, 1962), or compared BO with natural days without controlling for light quality changes at twilight (Blom and Kerec, 2003; Blom et al., 1995;

Heins et al., 1982b). In these cases, photoperiod and spectral factors were confounded. The spectrum of photoperiod extension lighting is a known factor for manipulating easter lily growth, with 28% greater height when photoperiod extension lighting was provided by incandescent lamps vs. high-pressure sodium lamps (Heins et al., 1982a). Nonetheless, at least one study (in growth chambers) demonstrated that a short photoperiod (8 h) dramatically reduced easter lily height by 29% (24.8 cm) compared with a 16-h photoperiod with the same *PPFD* and light quality (Kohl and Nelson, 1963). Shorter photoperiod with the same *PPFD* also resulted in lower dry weight, attributed to the reduced daily light integral (DLI), while leaf number was unaffected. Combining a short photoperiod (8 h) with high *PPFD* resulted in shorter plants than either high *PPFD* or short photoperiod alone (Kohl and Nelson, 1963).

The objective of this study was to evaluate the efficacy of EOD BO and low fluence rates of EOD R on height and flowering of greenhouse-grown easter lily. The hypothesis was that both EOD R and BO would reduce height compared with a control, given that both strategies should prevent the plants from experiencing the natural drop in R:FR at the EOD. Unlike most BO studies that shorten the photoperiod to 8 h, this study proposed to close the BO curtains shortly before sunset to minimize reductions in natural DLI while still cutting off the natural reductions in R:FR during the twilight period.

Materials and methods

PLANT MATERIAL. On 27 Oct. 2017, 450 bulbs (8 to 9 inches circumference) of ‘Nellie White’ easter lily arrived at Meyer’s Farms in Niagara-on-the-Lake, ON, Canada. Bulbs were planted singly in plastic pots (15 cm diameter, 14 cm tall), then filled with an all-purpose growing medium (BM6; Berger, Saint-Modeste, QC, Canada), moistened, and cooled to $\approx 7^{\circ}\text{C}$. Planted bulbs were vernalized until 7 Dec. 2017 (i.e., for 41 d), at which time they were transported to the University of Guelph, Guelph, ON, Canada (lat. 43.5°N , long. 80.2°W).

GROWING CONDITIONS. The potted bulbs were placed on benches in a greenhouse with no supplemental lighting and held at (mean $\pm$ SD) 13.8 ± 0.7 °C until emergence (18 d). On 8 Dec. 2017, each pot was top-irrigated with ≈ 200 mL of solution made with 20N–3.4P–16.6K water-soluble fertilizer (20–8–20 All Purpose High Nitrate; Master Plant-Prod, Brampton, ON, Canada) in deionized water with a nitrogen concentration of $200 \text{ mg}\cdot\text{L}^{-1}$. Thereafter, until the start of the experiment, plants were top irrigated, as needed, with a fertilizer solution composed of 15N–0P–12.5K water-soluble fertilizer (15–0–15 CAL-POT Special, Master Plant-Prod) in water comprised of well and deionized water [mixed to have an electrical conductivity (EC) of $500 \text{ }\mu\text{S}\cdot\text{cm}^{-1}$], with a N concentration of $165 \text{ mg}\cdot\text{L}^{-1}$. This resulted in a solution EC of $\approx 1600 \text{ }\mu\text{S}\cdot\text{cm}^{-1}$.

On 25 Dec. 2017, 180 uniform plants were selected as sample plants. These were distributed in three adjacent research greenhouse compartments (6.2×7.6 m) running east to west containing three flood benches each, with long sides of the benches oriented in an east–west direction and with 20 plants per bench. Plants were spaced 20 cm apart on-center, in a 10×2 grid at the geometric center of each benchtop. Single rows of border plants (taken from the remaining 270 plants) were placed around all four sides of each treatment plot, also with 20-cm spacing between pot centers. From this time onwards, plants were subirrigated, with the 15N–0P–12.5K solution described above. This solution was stored in a 700-L underground reservoir (one per compartment), and irrigation runoff was returned to the reservoir. A few sample plants from each plot were weighed daily. An irrigation event was triggered when individual pot weights were less than 700 g. At this time, the drains in the flood benches were plugged, and the benches were filled with fertilizer solution to a depth of about 5 cm. The benches were drained when individual pot weight increased to over 1100 g (i.e., a 400 g increase in weight). The temperature and pH of the solutions, measured before each irrigation event, were (mean $\pm$ SD) 15 ± 1 °C and 7.3 ± 0.2 , respectively. The nutrient solution reservoir tank was refilled as

Table 1. Mean day and night temperatures and relative humidity during the light-treatment period for ‘Nellie White’ easter lily, applied from emergence to flowering (25 Dec. 2017 to 22 Apr. 2018).

Greenhouse	Day temp (°C) ^z	Night temp (°C)	Relative humidity (%)
	(mean ± SD)		
A	17.8 ± 1.4 ^y	16.9 ± 0.3	56 ± 14
B	17.3 ± 0.9	16.9 ± 0.3	63 ± 4
C	17.4 ± 1.3	16.9 ± 0.3	59 ± 7

^zThe bounds of day and night were defined by astronomical sunrise and sunset using calculations from the National Oceanic and Atmospheric Administration.

^yData were logged at 15-min intervals; $(1.8 \times ^\circ\text{C}) + 32 = ^\circ\text{F}$.

Fig. 1. Spectral photon flux density distributions of (A) supplemental light from light-emitting diodes provided by a mix of blue (440-nm peak), white (5700K broad spectrum), and red (660-nm peak), and (B) end-of-day red light treatment. Supplemental light was provided to all treatments, including control, during the daytime.

needed. Each greenhouse section was independently controlled using an environmental control system (Titan; Argus Controls Systems, Surrey, BC, Canada) at constant temperature

and relative humidity of 17 °C and 60% respectively. A constant temperature regime was used to eliminate any effects that a day/night temperature differential may have had on stem

elongation. Environmental data, logged in 15-min intervals, are summarized in Table 1.

Three lighting treatments were provided in each greenhouse compartment, with one treatment allocated to each bench: Blackout curtains, which closed 45 to 75 min before sunset and opened 0 to 60 min after sunrise (BO), a 1-h end-of-day red light treatment providing $20 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ at pot level using red LEDs (EOD R), and a control treatment with natural twilight (CTRL). Each bench was equipped with automatic blackout capability (top and side curtains). Only the side curtains on the EOD R treatment were closed, half-way, at dusk, which prevented light contamination onto neighboring benches while still allowing light from the evening sky to reach the plants within the EOD R treatment. The top and side curtains on the BO treatment benches were fully closed, and the curtains on the CTRL treatment benches were not used.

Each plot was provided (mean $\pm$ SD) $153 \pm 8 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ of supplemental lighting using two programmable LED light fixtures per bench (LX601; Heliospectra AB, Gothenburg, Sweden), affixed 1.35 m above the bench, separated by 1.60 m (on-center), oriented with the long sides of the fixtures parallel with the long sides of the bench and centered over the plots. The LED fixtures had three channels controlling “blue” (450-nm peak), “red” (660-nm peak), and “white” (5700 K correlated color temperature) LEDs, with full width half maxima of 20 and 17 nm for B and R LEDs, respectively. The supplemental lighting spectrum provided a spectral photon flux ratio of blue [B (400–500 nm)], green [G (500–600 nm)], and red [R (600–700 nm)] of B21:G13:R66 (Fig. 1). The supplemental lighting was programmed to turn on and off daily at the same time as the BO curtains opened and closed, respectively. The EOD R treatment provided (mean $\pm$ SD) $19.8 \pm 0.9 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ using only the red channel and was scheduled to run daily for 60 min, starting 30 min after the blackout curtains closed.

The lighting and BO schedules were adjusted in 30-min increments throughout the trial as the natural daylength increased to ensure the EOD R treatment always extended

at least 15 min past sunset (Fig. 2), resulting in an average photoperiod in the BO treatment of 9.6 h and an average supplemental DLI of $5.3 \text{ mol}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$, measured at pot level. The average natural photoperiod was 11.0 h and average outdoor DLI was $18.0 \text{ mol}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$, based on pyranometer measurements (logged by the Argus control system) over the treatment period (25 Dec. 2017 to 22 Apr. 2018). Assuming 35% transmission of incident sunlight at bench level, based on our previous measured data for these greenhouse compartments (not published), the average canopy-level natural DLI was $6.3 \text{ mol}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$, resulting in an average total DLI (i.e., natural + supplemental) of $11.6 \text{ mol}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$ (Table 2). The average total DLI provided was about equal to the minimum recommended DLI of $12 \text{ mol}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$ for producing a high-quality easter lily (Faust, 2003).

Spectral photon flux distribution for supplemental lighting and the EOD R treatment were measured, at night, with a radiometrically calibrated spectrometer (XR FLAME-S; Ocean Optics, Dunedin, FL) equipped

with a 1.5-m long, 400- μm diameter-optical fiber for ultraviolet-visible range, with a CC-3 (3900 μm) cosine corrector, tethered to a laptop running SpectraSuite software (Ocean Optics) using the PARSpec subroutine. Light measurements were taken at pot height, on a 2×10 grid, matching the locations of each of the sample pots.

PLANT MEASUREMENTS. Starting in the middle of Jan. 2018, every trial plant was investigated daily for visible bud formation, and the date of a visible bud was recorded for each plant. Starting 1 Apr. 2018, every trial plant was investigated before 12:00 PM daily for flowering, defined as when the first flower of a plant opened. Upon flowering, the date was recorded, and both nondestructive and destructive measurements were conducted for the respective plant the same day. Total height (pot rim to highest part of plant) and stem height (pot rim to base of inflorescence) were measured. Leaves on the stem (including senesced leaves) and total flower buds were counted, and leaf area was measured with a scanning leaf area meter (LI-3100; LI-COR,

Fig. 2. Lighting treatment schedule for height control of ‘Nellie White’ easter lily from emergence to flowering (25 Dec. 2017 to 22 Apr. 2018). In the blackout (BO) treatment, curtains were raised 0 to 60 min after sunrise and were lowered 45 to 75 min before sunset. The end-of-day red (EOD R) treatment ran for a 60-min duration, starting 30 min after BO-treatment curtains closed to avoid light contamination between treatments. The system schedules were manually updated as days lengthened to ensure the EOD R always extended at least 15 min after sunset. The control (CTRL) treatment provided natural twilight conditions. Supplemental lighting (SL) was powered on in all treatments during the same time periods that BO curtains were open.

Table 2. Blackout (BO) treatment and supplemental lighting (SL) schedule applied to ‘Nellie White’ easter lily from emergence to flowering. Supplemental lighting was applied to all treatments, including control. An end-of-day red (EOD R) treatment ran for a 1-h duration starting 30 min after BO-treatment curtains closed. Mean daily light integral (DLI) are provided for ambient and supplemental light in each schedule change period.

Date range ^z	BO open and SL turned on	DLI (mol·m ⁻² ·d ⁻¹)			
		Outdoor	Indoor ^y	Supplemental	Total ^x
25 Dec. to 16 Jan.	8:00 AM to 4:00 PM	10.7	3.7	4.4	8.1
17 Jan. to 10 Feb.	8:00 AM to 4:30 PM	11.9	4.2	4.7	8.9
11 Feb. to 7 Mar.	7:30 AM to 5:00 PM	17.0	5.9	5.2	11.1
8 Mar. to 29 Mar.	7:00 AM to 5:30 PM	25.5	8.9	5.8	14.7
30 Mar. to 22 Apr.	6:30 AM to 6:00 PM	25.8	9.4	6.3	15.7
Daily avg		18.0	6.3	5.3	11.6

^zDates are inclusive.

^yIndoor DLI refers to ambient sunlight at bench level, calculated assuming 35% transmission.

^xTotal represents the combined canopy-level DLI of the control treatment from natural and supplemental sources. The BO treatment reduced DLI by ≈ 0.18 mol·m⁻²·d⁻¹ and the EOD R treatment increased DLI by ≈ 0.07 mol·m⁻²·d⁻¹.

Table 3. Growth and morphology of ‘Nellie White’ easter lily under three light treatments applied from emergence to flowering for the purpose of height control. The three treatments were the following: a control treatment with natural twilight (CTRL), blackout curtains that closed 45 to 75 min before sunset and opened 0 to 60 min after sunrise (BO), and 1-h end-of-day red light treatment providing 20 μ mol·m⁻²·s⁻¹ at pot level using red LEDs (EOD R).

Growth or morphology measurement ^z	Treatment			P
	CTRL	BO	EOD R	
	(mean $\pm$ SE) ^y			
Total height (cm)	35.9 $\pm$ 1.5 a ^x	32.0 $\pm$ 1.1 b	34.8 $\pm$ 1.3 ab	0.045
Stem height (cm)	19.8 $\pm$ 1.1 a	16.3 $\pm$ 0.8 b	18.9 $\pm$ 0.9 ab	0.022
Buds (no.)	7.5 $\pm$ 0.2	7.4 $\pm$ 0.1	7.4 $\pm$ 0.1	
Leaves (no.)	86.2 $\pm$ 0.8	84.6 $\pm$ 0.7	85.1 $\pm$ 0.2	
Leaf area (cm ²)	1,550 $\pm$ 110	1,490 $\pm$ 60	1,520 $\pm$ 30	
Leaf dry wt (g)	10.6 $\pm$ 0.4	10.6 $\pm$ 0.1	10.4 $\pm$ 0.1	
Stem dry wt (g)	14.1 $\pm$ 0.5	13.0 $\pm$ 0.3	13.8 $\pm$ 0.2	
Bulb dry wt (g)	20.1 $\pm$ 0.4	20.5 $\pm$ 1.6	19.4 $\pm$ 0.9	
Total dry wt (g)	44.8 $\pm$ 0.7	43.9 $\pm$ 1.9	42.9 $\pm$ 0.3	
Time from emergence to visible bud (d)	70.1 $\pm$ 0.3	70.0 $\pm$ 0.3	70.3 $\pm$ 0.1	
Time from emergence to first open flower (d)	109 $\pm$ 2	108 $\pm$ 3	111 $\pm$ 1	

^zTotal height was measured from the rim of the pot to the highest point on the plant. Stem height was measured from the rim of the pot to the base of the inflorescence. Stem dry weight includes flowers. Visible bud was determined when buds were visible to the eye without touching the plant; 1 cm = 0.3937 inch, 1 cm² = 0.1550 inch², 1 g = 0.0353 oz.

^yAll reported values are mean $\pm$ SE (n = 3) where each experimental unit represents an average of 20 plant subsamples.

^xValues with different lowercase letters in the same row are significantly different according to Tukey's honestly significant difference post hoc test ($P < 0.05$).

Lincoln, NE). The tissues of each plant (exclusive of adventitious roots) were then divided into 1) bulb, 2) stem and flowers, and 3) leaves, and oven-dried to constant weight at 70 °C.

STATISTICAL ANALYSIS. This study was a randomized complete block design with three treatments and three blocks. Greenhouse compartment was the block (n = 3), and plot (one plot per bench) was the experimental unit (n = 9) with 20 treatment plants (i.e., subsamples) per plot. Statistical analysis was performed in RStudio (RStudio, Boston, MA) using “R” software (version 3.3.1; R Foundation for Statistical Computing, Vienna, Austria). Analysis of variance was performed on each metric, and Tukey's honestly

significant difference post hoc test was performed using the “agricolae” package (de Mendiburu, 2016). Significance for all analyses was defined at $P \leq 0.05$.

Results and discussion

Of the metrics measured, only plant height showed treatment effects (Table 3). The BO treatment reduced total height compared with CTRL by 11% (4.0 cm), while there were no treatment effects in the EOD R-treated plants. The results match the general results of previous studies in which BO also reduced easter lily height, although the results were not as dramatic compared with the 15% to 45% height reductions found in literature (Blom and Kerec, 2003; Blom et al., 1995; Heins et al.,

1982b). These studies all shortened the photoperiod to 8 h vs. the 9.6-h (average) photoperiod in the present study. The differences in total height between BO and CTRL treatments were primarily attributable to internode length because stem height was 18% (3.6 cm) shorter in BO compared with CTRL, while there were no treatment effects on leaf number.

The hypothesis that both EOD R and BO would reduce easter lily height was not supported, as only BO reduced height compared with CTRL, suggesting that the natural reductions in R:FR at the EOD was not the only factor related to BO-mediated growth control. The photoperiods between the treatments differed, however, as EOD R extended the natural photoperiod

and BO shortened it (Fig. 2). The shortened photoperiod in the BO treatment may have contributed to the reduction in height compared with CTRL. Kohl and Nelson (1963) demonstrated, using a static light spectrum from a mixture of fluorescent and incandescent sources in growth chamber studies, that ‘Ace’ easter lily height was reduced by either shorter photoperiod (8 vs. 16 h) or higher light intensity (1000 vs. 500 fc), as opposed to the combination of these factors (i.e., DLI). Because BO strategies simultaneously reduce the photoperiod and increase the average intensity (as they eliminate light exposure at the times of day when *PPFD* values are naturally very low), the stem-shortening effect of the BO treatment may have resulted from the combination of both shorter photoperiod and higher average natural *PPFD*. An investigation of how different BO-controlled photoperiods affect greenhouse production of easter lily may be worthwhile. Although shorter photoperiods can reduce easter lily height, a lower percentage of dry weight has been observed when the shorter photoperiod also had lower DLI (Kohl and Nelson, 1963). The present study revealed no difference in dry weight between BO and natural photoperiod, possibly because this BO treatment did not reduce the photoperiod or DLI as much as other studies, which typically use 8-h photoperiods. More specifically, based on pyranometer data, the closed BO curtains in the present study reduced the natural DLI by $\approx 3\%$, whereas a shorter 8-h photoperiod (e.g., from 8:00 AM to 4:00 PM) during the same growing season would have reduced the natural DLI by $\approx 11\%$.

When the depth of the pot (14 cm) was included, the final height for all treatments averaged less than 53.3 cm, meaning that the plants from all treatments could fit in a standard 22-inch (i.e., 55.9 cm) shipping box. Given that this was achieved without using DIF strategies or PGRs, it is likely that increasing the mean DLI to $\approx 12 \text{ mol}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$ through the use of supplemental lighting contributed to keeping plants relatively short, as the DLI met the general recommendation for “high quality” easter lily (Faust, 2003). For comparison, the control groups of greenhouse-grown easter lily in other studies are normally

substantially taller; for example control plants forced at a similar temperature of 18 °C with natural daylight resulted in stem heights of 36.9 or 49.7 cm (Expts. 1 and 2 in Blom et al., 2004), which is roughly double the 16- to 20-cm stem heights in the present study. The notion that the plants in the present study may have been pampered in terms of DLI also leads to the question of whether BO and EOD R treatments may have shown greater effects on plant height if the plants were forced under a lower DLI.

In conclusion, this study corroborates previous research that BO can reduce plant height and suggests that factors other than eliminating twilight-associated drop in R:FR contribute to BO-related inhibition of stem elongation in easter lily. Although the BO effect on height in the present study was not as dramatic as other BO studies, there was also no sacrifice of plant quality (i.e., no reduction in dry weight or flower bud number). Under the conditions used, a low fluence rate of R at the EOD was not efficacious in reducing height of easter lily.

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