Abstract. Supplemental radiation (SR), traditionally provided by high-pressure sodium (HPS) lamps, is recommended for greenhouse production of seedlings during radiation-limiting conditions. Light-emitting diodes (LEDs) have emerged as an appealing alternative to HPS lamps primarily because they can provide SR at improved energy efficiencies, they have longer fixture lifetimes, and the radiation spectrum can be tailored to potentially manipulate plant morphology by targeting radiation absorption of specific photoreceptors. We grew seedlings of three annual bedding plants and two vegetable transplants in greenhouses at 20 °C under a 16-h photoperiod under six SR treatments: five that delivered a photosynthetic photon flux density (PPFD) of 90 μmol·m⁻²·s⁻¹ from HPS lamps (HPS90), or LEDs [four treatments composed of blue (B; 400–500 nm), red (R; 600–700 nm), far red (FR; 700–800 nm), and/or white LEDs] and one that delivered 10 μmol·m⁻²·s⁻¹ from HPS (HPS10) lamps as a control with matching photoperiod. The LED treatments, defined by the percentages of B, green (G; 500–600 nm), and R radiation, were B₁₀R₉₀, B₅G₅R₈₅, B₁₂G₂₀R₆₈, and B₁₂G₂₀R₆₈+FR (FR at 12 μmol·m⁻²·s⁻¹). At transplant, leaf area and seedling height were similar among 90 under B₄₅R₅₅ and B₁₂G₂₀R₆₈ radiation, were B₁₀R₉₀, B₅G₅R₈₅, B₁₂G₂₀R₆₈, and B₁₀G₅R₈₅ treatments. Seedlings of each species grown under the HPS 10 mol·m⁻²·s⁻¹ treatments in all species except snapdragon (Antirrhinum majus), in which seedlings grown under B₁₂G₂₀R₆₈+FR had 62% greater leaf area than those grown under B₅G₅R₈₅ and were 47%, 18%, 38%, and 62% taller than those grown under HPS₉₀, B₁₀G₅R₈₅, B₁₂G₂₀R₆₈, and B₁₀R₉₀, respectively. After transplant and finishing under the same SR treatments, snapdragon flowered on average 7 days earlier under the B₁₂G₂₀R₆₈+FR treatment than the other LED treatments, whereas geranium (Pelargonium × hortorum) grown under B₅G₅R₈₅ and B₁₂G₂₀R₆₈+FR flowered 7 to 9 days earlier than those under the B₁₀G₅R₈₅ and B₁₀R₉₀ treatments. Seedlings of each species grown under the HPS₁₀ treatment accumulated less dry weight and took longer to flower compared with seedlings under the other SR treatments. We conclude that radiation quality of SR has relatively little effect on seedling growth and subsequent flowering although in some crops, flowering may be earlier when SR includes FR radiation.

The photosynthetic daily light integral (DLI) is the cumulative quantity of photons within the photosynthetically active waveband (400–700 nm) incident on a square meter during a 24-h period and is usually expressed as moles per square meter and day. During commercial seedling production, a minimum DLI of 10–12 mol·m⁻²·d⁻¹ has been recommended to achieve suitable seedling quality and reduced time to flower after transplant (Lopez and Runkle, 2008; Pramuk and Runkle, 2005). Commercial production of annual (bedding plant and vegetable) seedlings primarily occurs during the winter and early spring, and in the northern United States, the mean outdoor DLI is as low as 5–10 mol·m⁻²·d⁻¹ (Korzynski et al., 2002); inside a greenhouse, values are typically 30% to 50% lower. Therefore, SR from electric lamps is commonly used by commercial growers to increase the DLI to increase root and shoot growth. Supplemental radiation is typically delivered by conventional high-intensity discharge lamps, mostly from HPS lamps, and usually operates during cloudy conditions and at night. Light-emitting diodes have increasing potential to be used for SR applications as the technology develops, particularly as their intensity and efficacy increase and costs decrease (Bourget, 2008; Wallace and Both, 2016).

Unlike conventional lamps and excluding LEDs coated with phosphors, LEDs emit narrow wavebands based on their chip composition and can therefore emit specific wavebands of interest for a range of plant applications (Mitchell et al., 2015). Early focus of LED use in horticulture was on the application of R (600–700 nm) radiation because it is strongly absorbed by chlorophyll extracts and was the first color to become feasible for horticultural radiation (Bula et al., 1991). Growth under R radiation alone in sole-source radiation (SSR) experiments produced plants with elongated hypocotyls and petioles or decreased chlorophyll development, which could be alleviated with the addition of a relatively low flux of B (400–500 nm) radiation (Hoenecke et al., 1992; Tripathy and Brown, 1995). Unlike broad-spectrum radiation sources, the LED spectral output can be tailored to emit only or mostly photosynthetic or photomorphogenic radiation (Morrow, 2008).

Plant growth and development are controlled by photoreceptors that regulate hypocotyl and internode extension, leaf expansion, chlorophyll orientation, and flowering in response to specific wavebands of radiation. For example, the cryptochrome receptors, cry1 and cry2, respond to wavelengths from 390 to 480 nm and regulate stem extension, guard cell opening, anthocyanin accumulation, and, in at least some species, flower induction (Ahmad et al., 2002). In Arabidopsis, cryptochromes mediate hypocotyl elongation through B radiation regulation of gibberellic acid metabolism (Zhao et al., 2007). Phytochrome, a family of proteins that primarily absorb R and FR (700–800 nm) radiation, signals shade avoidance and flowering control through gene-regulated control of transcription networks (Folta and Carvalho, 2015). Phytochrome exists in R-absorbing (inactive) and FR-absorbing (active) forms, and the incident radiation quality (particularly the R:FR) establishes a phytochrome photoequilibrium (PPE). In conditions depleted of R radiation, such as under a plant canopy, the PPE becomes low, which signals stem and petiole elongation (Franklin and Whitelam, 2005). With the narrow emission spectra of LEDs, one can target these photoreceptors to potentially control plant morphology, which can influence quality attributes important for commercial production of ornamental and vegetable seedlings.

Early plant experiments with R and FR LEDs and B radiation from blue fluorescent lamps showed that including B or FR radiation in SSR studies could affect plant morphology, increase plant growth, or both. Brown et al. (1995) grew 21-d-old pepper (Capsicum annuum ‘Hungarian Wax’) seedlings under SSR from metal halide lamps, only R radiation from LEDS (peak = 660 nm), 1% blue fluorescent + 99% R LEDs, and R LEDs + 59 μmol·m⁻²·s⁻¹ from FR LEDs (peak = 735 nm), each providing a PPDF...
of 300 μmol·m⁻²·s⁻¹ for 12 h·d⁻¹. Plants grown under R + B from fluorescent lamps were shorter than those grown under R radiation alone, whereas those grown under R + FR radiation were tallest. Plants grown without B radiation had negatively affected leaf expansion and dry weight accumulation. In wheat (Triticum aestivum) grown under R LEDs (peak = 600 nm) at 350 μmol·m⁻²·s⁻¹ for 24 h·d⁻¹, adding 10% B radiation increased plant growth and seed quantity, resulting in plants that were comparable with those grown under white fluorescent lamps (Goins et al., 1997).

Far red LEDs have been used in plant applications for extending growth of leaves and stems, as well as to regulate flowering of at least some long-day plants. For example, by adding FR to B and R SSR treatments from LEDs, Park and Runkle (2017) were able to increase biosynthesis in seedlings of four annual bedding plants; those grown under increasing amounts of FR radiation displayed greater leaf expansion that subsequently increased radiation capture. In addition, stem length of tomato (Solanum lycopersicum) rootstock seedlings increased from an end-of-day FR radiation treatment from LEDs (Chia and Kubota, 2010). Red + FR radiation has been provided by incandescent bulbs to promote flowering in long-day plants, and R + white + FR LEDs effectively promoted flowering while consuming less energy (Meng and Runkle, 2010). Red + FR radiation has been provided in supplemental radiation treatments to promote flowering of at least some long-day plants.

Materials and Methods

Plant material. Seeds of geranium (Pelargonium × hortorum ‘Pintuo Premium Salmon’), pepper ‘Long Red Slim Cayenne’, petunia (Petunia × hybrida ‘Single Dreams White’), snapdragon ‘Montego Yellow’, and tomato ‘Supersweet’ were sown into 128-cell plug trays (2.7 × 2.7 cm; 12.0-mL volume) at a commercial greenhouse (C. Raker and Sons, Inc., Litchfield, MI) and delivered to the Plant Science Research Greenhouses at Michigan State University (East Lansing, MI) 4 (replication 1) or 5 (replication 2) after seeds were sown. For each species, six 128-cell trays were cut in half and the 12 half trays were randomly assigned to six radiation treatments in adjacent greenhouse sections. Seedling trays of each species were placed at about the same position in each section and rotated systematically every 2 d to minimize positional effects within each treatment. Seedlings were irrigated as necessary with water-soluble fertilizer providing (in mg·L⁻¹) 60 N, 23 P, 60 K, 27.7 Ca, 4.6 Mg, 1.3 Fe, 0.6 Mn, 0.6 Zn, 0.6 Cu, 0.4 B, and 0.1 Mo (MSU Plug Special; GreenCare Fertilizers, Inc., Kankakee, IL).

Radiation treatments. Different SR treatments were delivered to each greenhouse section continuously for 16 h·d⁻¹ (0600 to 2200 μμ) at a PPFD of 90 ± 10 μmol·m⁻²·s⁻¹ (five sections) or 10 ± 2 μmol·m⁻²·s⁻¹ (one section) as measured at plant height in nine different horizontal positions by a portable spectroradiometer (PS-200; StellarNet Inc., Tampa, FL) (Fig. 1). Two of the SR treatments were delivered by HPS lamps using either one 150-W fixture (LU150; Acuity Lighting, Conyers, GA) or four 400-W fixtures (LR48877; P.L. Light Systems, Beavemess, ON, Canada) to deliver a target PPFD of 10 (HPS10) or 90 (HPS90) μmol·m⁻²·s⁻¹, respectively. The fourth remaining SR treatments were delivered by commercial 200-W LED fixtures that contained R (peak = 660 nm), B (peak = 453 nm), white (which was the source of G radiation), or FR (peak = 737 nm) LEDs, three of which were wrapped in a layer of flexible, neutral-density mesh (general-purpose aluminum; New York Wire, Grand Island, NY) to reduce radiation intensity (by approximately 35%) without affecting SR spectral output or incident solar radiation. Each LED fixture was mounted horizontally 1.9 m above the bench height, and the 400- and 150-W HPS fixtures were mounted 1.3 and 2.5 m above the plants, respectively. Glass walls between greenhouse sections were coated with a heavy layer of whitewash to prevent radiation treatment contamination.

The four LED treatments were defined by their 100-nm waveband ratios of B, G (500–600 nm), and R radiation (subscript values indicate the percentage of each waveband) and were B₁₀G₃₀R₆₈, B₁₀G₃₅R₆₈, and B₁₂G₂₀R₆₈ + FR. The B₁₀G₉₀ and B₁₀G₃₅R₆₈ treatments were delivered by top-lighting fixtures (GP-TOPlight DR/W-LB2013 and GP-TOPlight DR/W-MB2013; Philips, Eindhoven, the Netherlands). The B₁₂G₃₅R₆₈ treatment was delivered by top-lighting fixtures providing 20% B + 80% R radiation (GP-TOPlight DR/B-LB2013; Philips) with two layers of neutral-density mesh to reduce radiation intensity (by approximately 57%), along with 18 B-emitting LED research modules (GreenPower LED research module blue; Philips) hung 60 cm above the benches to provide the target PPFD. The fourth LED treatment, B₁₂G₃₅R₆₈ + FR, was provided by top-lighting fixtures that emitted FR radiation at 12 μmol·m⁻²·s⁻¹ (GP-TOPlight DR/W/FR_2-HB2013; Philips) and did not require mesh to obtain the target PPFD. The estimated PPE established under each treatment was calculated with spectroradiometer software (SpectraWiz; StellarNet Inc.) that used the formula described by Sager et al. (1988) and ranged from 0.84 to 0.88 (Fig. 1).

Environmental conditions. The experiment was performed in six glass-glazed greenhouse sections oriented west to east and measuring 4.0 m by 4.6 m, with a 2.2-m-high gutter and 3.5-m peak. The set point for air temperature was 20 °C during the day and night, and was maintained by steam heating, exhaust fans, and roof vents controlled by a greenhouse environmental control system (Integro 725; Priva North America, Vineyard, ON, Canada). In each section, air temperature was recorded by an aspirated thermocouple (Type E; Omega Engineering, Stamford, CT) above canopy height. Leaf surface temperature was measured by an infrared thermocouple (Type K, OS36-01; Omega Engineering) placed 15 cm above one seedling tray in each section during the
Table 1. Means (± SD) of temperature and photosynthetic daily light integral (DLI) as measured in greenhouses by aspirated thermocouples, infrared sensors, and quantum sensors during the seedling phase under ambient radiation, with supplemental radiation treatments delivered by high-pressure sodium (HPS) lamps or light-emitting diodes (LEDs). For the LED treatments (all delivered at 90 μmol·m⁻²·s⁻¹), subscript values that follow each waveband of blue (B; 400–500 nm), green (G; 500–600 nm), red (R; 600–700 nm), and far red (FR; 700–800 nm) radiation indicate their percentages. Numbers in subscript after HPS treatments denote their intensity (μmol·m⁻²·s⁻¹).

| Treatment initiation | Supplemental radiation treatment | Daytime air temp (°C) | Daytime canopy temp (°C) | Air–canopy temp (°C) | DLI (μmol·m⁻²·d⁻¹) |
|----------------------|---------------------------------|-----------------------|-------------------------|---------------------|-------------------|
| 4 Nov.               | HPS₁₀                           | 19.2 ± 0.9            | 14.0 ± 2.6              | 5.2                 | 3.8 ± 1.7         |
|                      | HPS₉₀                           | 19.5 ± 1.2            | 17.2 ± 3.3              | 2.3                 | 7.0 ± 1.7         |
|                      | B₁₀G₉₀                          | 19.4 ± 1.0            | 15.9 ± 2.9              | 3.4                 | 7.3 ± 1.6         |
|                      | B₁₀G₉₀R₉₀ + FR                   | 20.0 ± 0.6            | 17.1 ± 2.9              | 2.8                 | 7.6 ± 1.6         |
| 29 Dec.              | HPS₁₀                           | 19.0 ± 0.7            | 15.1 ± 3.1              | 7.5                 | 3.5 ± 1.2         |
|                      | HPS₉₀                           | 19.7 ± 1.1            | 15.3 ± 2.5              | 4.1                 | 7.7 ± 1.0         |
|                      | B₁₀R₉₀                          | 18.8 ± 0.9            | 14.3 ± 2.0              | 4.5                 | 7.7 ± 0.9         |
|                      | B₁₀G₉₀R₉₀ + FR                   | 18.8 ± 1.5            | 13.2 ± 1.8              | 5.6                 | 8.7 ± 1.1         |
|                      | B₁₂G₂₀R₆₈ + FR                   | 19.7 ± 0.8            | 14.7 ± 1.9              | 5.1                 | 7.2 ± 1.0         |
|                      | B₄₅R₅₅                          | 20.7 ± 0.8            | 12.1 ± 1.9              | 8.5                 | 7.2 ± 0.9         |

Table 2. Means (± SD) of temperature and photosynthetic daily light integral (DLI) as measured in greenhouses by aspirated thermocouples, infrared sensors, and quantum sensors from transplant to flowering under ambient radiation, with supplemental radiation treatments delivered by high-pressure sodium (HPS) lamps or light-emitting diodes (LEDs). For the LED treatments (all delivered at 90 μmol·m⁻²·s⁻¹), subscript values that follow each waveband of blue (B; 400–500 nm), green (G; 500–600 nm), red (R; 600–700 nm), and far red (FR; 700–800 nm) radiation indicate their percentages. Numbers in subscript after HPS treatments denote their intensity (μmol·m⁻²·s⁻¹).

| Transplant date     | Supplemental radiation treatment | Daytime air temp (°C) | Daytime canopy temp (°C) | Air–canopy temp (°C) | DLI (μmol·m⁻²·d⁻¹) |
|---------------------|---------------------------------|-----------------------|-------------------------|---------------------|-------------------|
| 25 Nov.             | HPS₁₀                           | 19.0 ± 0.7            | 13.3 ± 1.1              | 5.6                 | 3.5 ± 1.4         |
|                      | HPS₉₀                           | 19.8 ± 1.3            | 16.7 ± 3.1              | 3.2                 | 7.6 ± 1.1         |
|                      | B₁₀R₉₀                          | 19.2 ± 1.0            | 16.0 ± 2.8              | 3.1                 | 7.6 ± 1.1         |
|                      | B₁₀G₉₀R₉₀ + FR                   | 18.9 ± 0.9            | 15.4 ± 3.4              | 3.5                 | 8.4 ± 1.5         |
|                      | B₁₀G₉₀R₆₈ + FR                   | 19.8 ± 0.9            | 16.2 ± 2.7              | 3.6                 | 7.4 ± 1.1         |
| 20 Jan.             | HPS₁₀                           | 19.8 ± 1.4            | 15.2 ± 2.9              | 4.6                 | 5.6 ± 2.3         |
|                      | HPS₉₀                           | 20.7 ± 1.7            | 21.1 ± 5.2              | 0.4                 | 9.1 ± 1.9         |
|                      | B₁₀R₉₀                          | 19.7 ± 1.2            | 18.9 ± 3.4              | 0.7                 | 9.6 ± 1.9         |
|                      | B₁₀G₉₀R₆₈ + FR                   | 19.0 ± 1.2            | 16.6 ± 4.2              | 2.4                 | 10.4 ± 1.7        |
|                      | B₁₂G₂₀R₆₈ + FR                   | 20.4 ± 1.2            | 17.8 ± 4.2              | 2.6                 | 9.3 ± 1.9         |
|                      | B₄₅R₅₅                          | 21.4 ± 1.0            | 14.7 ± 3.7              | 6.7                 | 9.2 ± 1.8         |

Fig. 2. Plant height of five seedling crops grown under ambient greenhouse radiation and supplemental lighting from two high-pressure sodium (HPS) or four light-emitting diode (LED) treatments delivering different percentages of blue (B; 400–500 nm), green (G; 500–600 nm), red (R; 600–700 nm), and far red (FR; 700–800 nm) radiation. All treatments delivered a photosynthetic photon flux density of 90 μmol·m⁻²·s⁻¹, except HPS₁₀, which delivered 100 μmol·m⁻²·s⁻¹. For the LED treatments, subscript values denote the waveband proportions. NS = nonsignificant; means sharing a letter are not statistically different by Tukey’s honest significant difference test at P ≤ 0.05. Error bars indicate standard error.
Tomato seedlings grown under B45R55 had more leaves at transplant than those grown under B10R90, B10G5R85, and HPS10 SR, whereas those under each of the 90 μmol·m⁻²·s⁻¹ SR treatments had more leaves than those grown under HPS10 (Fig. 3). There were no other differences in leaf number among the other crops grown under the 90 μmol·m⁻²·s⁻¹ SR treatments except for snapdragon seedlings, in which those grown under B45R55 had 37% less leaf area than seedlings grown under B12G30R68 + FR. Leaf area under HPS10 SR was 63%, 64%, and 75% less than that of seedlings grown under HPS90 SR in pepper, tomato, snapdragon, and petunia, respectively. There were no differences in average leaf area (the quotient of total leaf area and average leaf number) among the 90 μmol·m⁻²·s⁻¹ SR treatments (data not presented).

**Seedling dry weights.** In all crops tested, dry shoot weight was significantly less in seedlings grown under the HPS10 treatment than those grown under the LED and HPS90 SR treatments (Fig. 4). Seedlings grown under HPS10 accumulated 53%, 68%, 69%, 75%, and 79% less dry weight in geranium, pepper, tomato, petunia, and snapdragon, respectively, compared with those grown under HPS90. Among the 90 μmol·m⁻²·s⁻¹ SR treatments, only pepper seedlings exhibited a difference in dry weight among LED SR treatments: those under B10R90 SR accumulated less dry matter than seedlings grown under HPS90 SR.

Root dry weights of tomato, petunia, pepper, and snapdragon were 40%, 57%, 68%, and 76% less, respectively, when grown under HPS10 than those grown under HPS90 SR. Tomato seedling root weight was greater under HPS90 SR and B12G30R68 + FR LED SR compared with that in the HPS10 treatment, whereas weights under the remaining LED SR treatments were similar. In all crops tested, there were no differences in dry root weights among the 90 μmol·m⁻²·s⁻¹ SR treatments.

**Days to first flower.** Seedlings grown under HPS10 continuously (during the seeding and transplant phases) took the longest to

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**Experimental design and data analysis.** The experiment was performed twice, with seed sowings in Nov. and Dec. 2015. Data were analyzed with the mixed-model procedure (PROC MIXED) in SAS 9.4 (SAS Institute, Cary, NC), and pairwise comparisons between treatments were performed with Tukey’s honest significant difference test ($P \leq 0.05$).

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**Results**

Seedling height. At transplant, seedlings of petunia, snapdragon, tomato, and pepper were shorter when grown under the HPS10 treatment compared with those grown under HPS90. Height of geranium seedlings was similar under all treatments (Fig. 2). Tomato, pepper, and petunia seedlings grown under any 90 μmol·m⁻²·s⁻¹ SR treatment were similar in height; however, petunia seedlings grown under B10G5R85 were similar in height to those grown under HPS10 SR. Snapdragon seedlings grown under B12G30R68 + FR were the tallest among treatments, followed by those grown under B10R90, and those under the remaining 90 μmol·m⁻²·s⁻¹ treatments were similar in height.

Leaf number and leaf area of seedlings. Tomato seedlings grown under B45R55 had more leaves at transplant than those grown under B10G5R85, B10G5R85, and HPS10 SR, whereas those under each of the 90 μmol·m⁻²·s⁻¹ SR treatments had more leaves than those grown under HPS10 (Fig. 3). There were no other differences in leaf number among the other crops grown under the 90 μmol·m⁻²·s⁻¹ SR treatments except for snapdragon seedlings, in which those grown under B45R55 had 37% less leaf area than seedlings grown under B12G30R68 + FR. Leaf area under HPS10 SR was 63%, 64%, and 75% less than that of seedlings grown under HPS90 SR in pepper, tomato, snapdragon, and petunia, respectively. There were no differences in average leaf area (the quotient of total leaf area and average leaf number) among the 90 μmol·m⁻²·s⁻¹ SR treatments (data not presented).

Seedling dry weights. In all crops tested, dry shoot weight was significantly less in seedlings grown under the HPS10 treatment than those grown under the LED and HPS90 SR treatments (Fig. 4). Seedlings grown under HPS10 accumulated 53%, 68%, 69%, 75%, and 79% less dry weight in geranium, pepper, tomato, petunia, and snapdragon, respectively, compared with those grown under HPS90. Among the 90 μmol·m⁻²·s⁻¹ SR treatments, only pepper seedlings exhibited a difference in dry weight among LED SR treatments: those under B10R90 SR accumulated less dry matter than seedlings grown under HPS90 SR.

Root dry weights of tomato, petunia, pepper, and snapdragon were 40%, 57%, 68%, and 76% less, respectively, when grown under HPS10 than those grown under HPS90 SR. Tomato seedling root weight was greater under HPS90 SR and B12G30R68 + FR LED SR compared with that in the HPS10 treatment, whereas weights under the remaining LED SR treatments were similar. In all crops tested, there were no differences in dry root weights among the 90 μmol·m⁻²·s⁻¹ SR treatments.

Days to first flower. Seedlings grown under HPS10 continuously (during the seeding and transplant phases) took the longest to

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placed in paper envelopes and into a drying oven (NAPCO 630; NAPCO Scientific Co., Tualatin, OR) at 80 °C for at least 48 h then measured for shoot and root dry weight. From the remaining seedlings, 10 each (five from each block) of geranium, petunia, and snapdragon from each treatment were transplanted into 10-cm pots containing 70% peatmoss, 21% perlite, and 9% vermiculite (SUREMIX; Michigan Grower Products Inc., Galesburg, MI) and returned to their respective SR treatment. Pots were irrigated with line-fed water-soluble fertilizer providing (in mg L⁻¹) 125 N, 12 P, 100 K, 65 Ca, 12 Mg, 1 Fe and Cu, 0.5 Mn and Zn, 0.3 B, and 0.1 Mo (MSU RO Water Special; GreenCare Fertilizers, Inc.) as necessary and rotated positionally every 2 d. Date of first open flower or inflorescence, height at first flower (measured from the media surface to the tallest leaf for geranium and shoot tip for petunia and snapdragon), and the total number of open flowers for petunia or inflorescences with open flowers for geranium and snapdragon, 7–10 d after flowering, were recorded.
flower (Fig. 5). On average, snapdragon, petunia, and geranium under the HPS10 treatment flowered 19, 23, and 24 d later than those grown under the HPS90 treatment. Petunia transplants grown under 90 μmol·m⁻²·s⁻¹ SR treatments took a similar number of days to flower, whereas among LED SR treatments, snapdragon flowered earliest when grown under the B12G20R68 + FR treatment. Geranium transplants grown under B10R90 and B10G5R85 took longer to flower than those grown under B12G20R68 + FR and B12G55, but flowering time was similar to that of plants grown under HPS90.

**Plant height at first flower.** Snapdragon plants were of similar height at flowering under all SR treatments. Petunia plants grown under HPS90 were taller at first flower than those grown under HPS90, B10R90, and B10G55, but their height was similar to that of those grown under B10G5R85 and B12G20R68 + FR. Petunia grown under B10R90 were shorter at first flower than those grown under B12G20R68 + FR, but were of similar height to those grown under the remaining treatments. Geranium was shorter at first flower when grown under the B12G55 treatment compared with those under the HPS10, HPS90, and B12G20R68 + FR treatments.

**Total flower number.** Snapdragon grown under HPS90 and B12G20R68 + FR had more inflorescences (8) than those grown under HPS10 (5), whereas inflorescence number among 90 μmol·m⁻²·s⁻¹ treatments was similar. Petunia grown under B12G20R68 + FR SR had more flowers (25) than those grown under HPS10 and B10G5R85 (13 and 12, respectively). Similarly, geranium had the most inflorescences when grown under the B12G20R68 + FR treatment and the least under HPS10 (3 and 1, respectively). The B10R90 treatment was the only 90 μmol·m⁻²·s⁻¹ SR treatment for which the plant inflorescence number was similar to that of those grown under HPS10.

**Discussion**

One of our objectives was to determine whether SR that emitted a relatively high percentage (45%) of B radiation would inhibit extension growth of seedlings. Previously, we observed little or no effect of radiation quality of SR treatments on seedling growth and morphology when SR emitted 10% to 20% B radiation (Poel and Runkle, 2017). Blue radiation can suppress stem extension and leaf expansion through a cryptochrome-mediated pathway altering gene expression (Folta and Childers, 2008) and perhaps through other B radiation–mediated photoreceptors. For example, Wollaeger and Runkle (2015) grew seedlings of impatiens (Impatiens walleriana), salvia (Salvia splendens), petunia, and tomato under LED SSR with six B:R ratios (from 100:0 to 0:100), and as little as 10 μmol·m⁻²·s⁻¹ of B radiation (6.25% of the PPFD) inhibited extension growth, whereas cryptochrome receptors were likely saturated with B radiation at 40 μmol·m⁻²·s⁻¹ because plants receiving more than 25% B radiation were similar in height.

Despite the increased ratio of B radiation in the B12G55 treatment, there were few differences or consistent responses in leaf expansion and plant height under the 90 μmol·m⁻²·s⁻¹ treatments. Snapdragon seedlings grown under B12G55 were 26% and 37% shorter than those grown under B10R90 and B12G20R68 + FR, respectively; however, the addition of FR radiation may be a confounding factor in this second comparison. There were no differences in plant height or leaf area in the other four species tested among the 90 μmol·m⁻²·s⁻¹ treatments. A similar lack of response in stem elongation and leaf expansion was reported under SR with 0% to 16% B radiation delivered with R radiation to tomato (Hernandez and Kubota, 2012), and when cucumber (Cucumis sativus) seedlings were grown under a relatively high DLI (16.2 mol·m⁻²·d⁻¹) (Hernandez and Kubota, 2014). By contrast, seedlings of snapdragon, vinca (Catharanthus roseus), impatiens, geranium, petunia, and marigold (Tagetes patula) were more compact when grown under LED SR delivering 15% and 30% B radiation with R radiation compared with those grown under HPS, but there were no differences in plant height between the two B + R LED SR treatments (Randall and Lopez, 2014). The lack of a clear B radiation response in our and other SR studies could be attributed to the saturation of B radiation–absorbing photoreceptors (e.g., cryptochrome) from background ambient sunlight. All plants received a DLI of ≈3–5 mol·m⁻²·d⁻¹ from sunlight (Tables 1 and 2), which equates to ≈0.7–1.2 mol·m⁻²·d⁻¹ of B radiation, potentially enough to saturate B radiation photoreceptors across all treatments.
We were also interested in the effects of SR treatments (especially the different percentages of B radiation) on plant growth after transplant. After 12 weeks under SR, geranium plants grown under $B_{45}R_{55}$ were 27% shorter at flowering than those grown under HPS$_{90}$, but were similar to those under the other two LED treatments without FR radiation. Snapdragon were of the same height at flowering under all SR treatments, and petunia plants were generally similar under the 90 mol·s$^{-1}$·m$^{-2}$·d$^{-1}$ SR treatments, whereas the other LED treatments delivered different intensities of B, G, and R radiation. The authors attributed the reduced leaf area to flower development in some long-day plants (Runkle and Heins, 2001). Snapdragon grown under the $B_{12}G_{30}R_{68}$ + FR treatment flowered 8 d earlier than those under the remaining LED SR treatments although time to flower was similar to that of those under the HPS$_{90}$ treatment. Under an FR-radiation-intercepting filter creating a high R:FR, flower initiation was delayed in campanula (Campanula carpatica) and coreopsis (Coreopsis grandiflora), and flower development was inhibited in viola (Viola ×wittrockiana) (Runkle and Heins, 2001). Runkle and Heins (2003) were successful in promoting flowering of viola by adding FR radiation inside an FR-deficient environment throughout the photoperiod, or for 4 h, at the end of the photoperiod or during the middle of the 15-h night. However, treatments that promoted flowering also promoted extension growth. More experimentation is required to determine the usefulness of including FR radiation in SR on plant growth and development, perhaps with higher FR intensities or alteration of the timing at which it is delivered.

When the ambient solar DLI is low (e.g., <8 mol·m$^{-2}$·d$^{-1}$), SR can be used in greenhouses to increase DLI and thus quality parameters of seedlings (Pramuk and Runkle, 2005). The DLI under the HPS$_{10}$ treatment was $\approx$3–4 mol·m$^{-2}$·d$^{-1}$ lower than under the 90 mol·m$^{-2}$·s$^{-1}$ SR treatments, whereas the photoperiod was the same (16 h). In previous SR experiments that increased DLI during the seedling phase, growth (as measured by dry mass accumulation), stem caliper, and leaf area increased (Hernandez and Kubota, 2014; Randall and Lopez, 2015). For example, Hernandez and Kubota (2014) grew cucumber plants in a greenhouse with and without SR at a $PPFD$ of 54 mol·m$^{-2}$·s$^{-1}$ from LEDs at three different R and B radiation ratios at two ambient DLIs, 5.2 and 16.2 mol·m$^{-2}$·d$^{-1}$. At both DLIs, the

| Supplmental lighting treatment | HPS$_{90}$ | $B_{12}R_{50}$ | $B_{12}G_{30}R_{68}$ + FR | $B_{12}G_{30}R_{68}$ + FR | $B_{45}R_{55}$ |
|------------------------------|------------|---------------|--------------------------|--------------------------|--------------|
| Days to flower after transplant | 66 | 66 | 66 | 66 | 66 |
| Plant height at first flower (cm) | 20 | 20 | 20 | 20 | 20 |
| Total flower or inflorescence number | 10 | 10 | 10 | 10 | 10 |

Fig. 5. Days to flower after transplant, plant height at first flower, and total flower or inflorescence number of three seedling crops grown under ambient greenhouse radiation and supplemental radiation from two high-pressure sodium (HPS) or four light-emitting diode treatments delivering different percentages of blue (B; 400–500 nm), green (G; 500–600 nm), red (R; 600–700 nm), and far red (FR; 700–800 nm) radiation. For petunia, the $y$-axis values for flower number are divided by three, as noted. See caption for Fig. 2 for treatment and statistical information.
seedlings grown with SR had a greater dry and fresh weight, leaf number, leaf area, and stem diameter. Similarly, in our experiment, seedlings of each species had a greater dry shoot weight when grown under the 90 μmol·m⁻²·s⁻¹ SR treatments. Root dry weight, leaf area, and leaf number were also greater for three of five species grown under SR.

Plants can exhibit shade-avoidance responses, such as increases in extension growth, in response to decreases in the R:FR ratio, the PPFD, or both (Ballaré et al., 1991; Smith, 1982). However, in a separate study, stem length of petunia and snapdragon decreased as DLI increased, whereas the opposite occurred in impatiens and salvia decreased as DLI increased (Pramuk and Runkle, 2005). We attribute the shorter seedlings in our study to radiation or transplant growth and morphology. Growers can use this knowledge to improve plant height control, depending on the DLI conditions. The inclusion of FR radiation with SR also showed inconsistent responses, but it did accelerate flowering of snapdragon and may have a similar effect on other long-day crops when the natural photoperiod is short.

Therefore, we postulated that time to flower would be reduced by providing SR during the transplant and finishing phases. Faust et al. (2005) reported that increasing DLI from 5 to 19 mol·m⁻²·d⁻¹ during the transplant phase decreased days to flower for marigold, petunia, salvia, and zinnia. In our experiment, all species tested flowered earlier under the high-intensity SR treatments. Similarly, Sams et al. (2016) noted an increase in the inflorescence number on marigold grown under SR that added 8.6 mol·m⁻²·d⁻¹ (from HPS lamps or LEDs) to a solar DLI of 11.5 mol·m⁻²·d⁻¹ compared with those grown without SR. We observed an increase in the inflorescence number in geranium under four SR treatments compared with those grown under HPS00, whereas flower and inflorescence numbers in petunia and snapdragon showed inconsistent responses to DLI. However, more radiation does not necessarily increase the flower number at first flowering. Although an increased DLI decreased time to flower, there was also a decrease in the total flower number at first flowering (Pramuk and Runkle, 2005). Plants that take longer to flower have a longer vegetative phase and therefore have more time to harvest radiation and accumulate carbohydrates for flower production. A similar response in flower production occurred when plants were grown at lower temperatures; time to flower and the flower number at first flowered generally increased as the average daily temperature decreased (Vaid et al., 2014).

Even with an increased percentage of B radiation in our SR treatments, we were not able to elicit consistent responses in seedling or transplant growth and morphology. Growing geraniums for their complete life cycle under Br3R55 SR (with a higher percentage of B radiation) as a tool for height control, depending on the DLI conditions. The inclusion of FR radiation with SR also showed inconsistent responses, but it did accelerate flowering of snapdragon and may have a similar effect on other long-day crops when the natural photoperiod is short. Research with SR treatments with more extreme spectral differences in B and FR radiation or a range of ambient solar DLIs, and perhaps other wavebands, is needed to further explore the potential of how SR can be used to achieve more compact growth and early flowering of ornamental crops.

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