Morphology and Flowering Responses of Four Bedding Plant Species to a Range of Red to Far Red Ratios

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Abstract. In greenhouse ornamental crop production, bedding plants grown below high densities of hanging baskets (HBs) tend to be of lower quality. Hanging basket crops can decrease the red to far red ratio (R:FR) of the growing environment below; however, the extent to which decreased R:FR affects plant morphology and flowering of the lower-level crops is unknown. The present study examined effects of R:FR on morphology and flowering of marigold ‘Antigua Orange’ (Tagetes erecta), petunia ‘Duvet Red’ (Petunia ×hybrida), calibrachoa ‘Kabloom Deep Blue’ (Calibrachoa ×hybrida), and geranium ‘Pinto Premium Salmon’ (Pelargonium ×hortorum). Five R:FR light treatments were provided ranging from R:FR 1.1 (representing unfiltered sunlight) to R:FR 0.7 (representing shaded conditions under HBs) using light-emitting diodes (LEDs) in growth chambers, each with identical photosynthetically active radiation (PAR) (400–700 nm) and FR added to achieve the target R:FR ratio. Two experiments using the same R:FR treatments were conducted with day/night temperature regimes of 20 °C/18 °C and 25 °C/21 °C, respectively. In the second experiment, a fluorescent light treatment was included. The results of the second experiment were more dramatic than the first, where reducing R:FR from 1.1 to 0.7 increased height by 11%, 22%, and 32% in marigold, petunia, and calibrachoa, respectively, and increased petiole length in geranium by 10%. Compared with R:FR 1.1, the R:FR 0.7 shortened the time to the appearance of first flower bud by 2 days in marigold, whereas flowering was minimally affected in other species. Compared with pooled data from the LED treatments, fluorescent light increased relative chlorophyll content for all species, reduced height in marigold, petunia, and calibrachoa, and geranium by 26%, 67%, 60%, and 48%, and reduced stem dry weight by 28%, 39%, 21%, and 31%, respectively. The differences in morphology observed under fluorescent light compared with LED R:FR treatments indicate that light quality manipulation is a potential alternative to chemical growth regulators in controlled environments such as greenhouses and growth chambers.

In greenhouse production, it has been observed that bedding plants tend to be of lower quality when grown below a dense canopy of HBs, characterized by elongated stems and reduced branching (Hamrick, 2003). Although it has been demonstrated that HBs alter both light quantity and quality (Faust et al., 2014; Llewellyn et al., 2013), the extent to which altered light quality beneath HBs contributes to changes in plant morphology is unknown. Research into the factors of the light environment which contribute to ‘leggy’ plants may also provide insight toward the use of light as a nonchemical plant growth regulator, which has been of growing interest in ornamental horticulture (Folla and Childers, 2008).

Bedding plants, especially flowering annuals, are produced in high quantities in the winter and early spring in preparation for the gardening season in North America (Brown, 2014; Kessler, 2004). To maximize production space, some growers install rows of HBs above bench- or floor-level crops. Our group (Llewellyn et al., 2013) surveyed the light environment in some Southern Ontario greenhouses to quantify reductions in light intensity and characterize alterations to the red (R, 600–700 nm) to far red (FR, 700–800 nm) photon flux ratio (R:FR) at lower crop level because of the presence and growth of HBs. The photosynthetic photon flux (PPF, μmol m⁻² s⁻¹) between 400 and 700 nm), measured inside the greenhouses just above the HB level, were reduced by 40% to 53% relative to outdoors. The PPF was reduced by an additional 15% to 55% at lower crop levels, relative to measurements above HBs, with greater reductions as HB plants grew larger. These results were corroborated by Faust et al. (2014) in North Carolina, who found that the greenhouse structures intercepted 48% of outdoor PPF, and HBs intercepted up to 45% of the transmitted light, with greatest PPF interception resulting from the highest density of HBs, darkest pot color, and presence of plants. The reductions in PPF at the lower crop level because of high density HB production may result in a daily light integral (DLI) at or below the minimum requirement for ‘good quality’ bedding plants, which is considered to be 10–12 mol·m⁻²·d⁻¹ for greenhouse ornamental crops including Pelargonium hortorum, Tagetes ssp., and Petunia ssp. (Faust, 2003; Llewellyn et al., 2013).

Llewellyn et al. (2013) also reported reductions in R:FR under HBs. Reductions in R:FR are commonly observed below foliage canopies, as green leaves absorb light strongly within the range of PAR (400–700 nm), including R, whereas higher proportions of wavelengths longer than 700 nm are either reflected or transmitted to the surrounding environment (Gates et al., 1965; Holmes and Smith, 1977a). Accordingly, Llewellyn et al. (2013) reported a decrease in R:FR over the season (April to mid-May) as the light reaching the lower crop passed through an increasingly large canopy of HB foliage. At the lower crop level, the lowest R:FR measurement was 0.86, whereas the average R:FR above HB level was 1.11. The average R:FR above HBs was similar to other reported values for unfiltered sunlight, generally ranging between 1.0 and 1.3 (Holmes and Smith, 1977b; Kittas et al., 1999). However, care should be taken when comparing values using other methods for calculating R:FR, which sometimes include the common narrow-band R:FR (R:FRunarrow, 660 ± 5 nm : 730 ± 5 nm) (Holmes and Smith, 1977b; Meng and Runkle, 2014). The R:FR of sunlight at the Earth’s surface is generally stable throughout the day when the solar elevation is greater than 15° (Holmes and Smith, 1977b), although R:FR is known to vary with geographic location (Goldberg and Klein, 1977).

Plant responses to R:FR have been extensively documented (Casal and Smith, 1989; Chen and Chory, 2011; Demotes-Mainard et al., 2016). Plants respond to R:FR via phytochrome, a class of pigments which interconvert between red-absorbing and far-red-absorbing forms (P₉₅ and P₇₃₀, respectively) based on the proportion of R and FR photons illuminating the plant (Smith and Holmes, 1977). The proportion of these two forms within the plant, represented by the phytochrome photoequilibrium (P₉₅/P₇₃₀), initiates a cascade of metabolic events ultimately influencing germination, flowering, and morphology (Blom et al., 1995; Chory et al., 1996). The R:FR is a reliable signal for plants indicating competition for light from nearby or overhead vegetation (Gates et al., 1965; Holmes and Smith, 1975). In many plant species, reduced R:FR contributes to ‘shade avoidance’ responses such as stem elongation and apical dominance as means to compete for available light (Casal, 2012; Casal and Smith, 1989; Chen and Chory, 2011; Smith and Whitteland, 1997). The ultimate phenotypic expression to low R:FR is species-specific and is codependent on other interacting factors,
including temperature (Qaderi et al., 2015; Xiong et al., 2002) and absolute intensity of R and FR (Lund et al., 2007). There are limited studies of R:FR effects on bedding plants, including petunia (Petunia sp.), impatiens (Impatiens sp.), and marigold (Tagetes sp.) (Bachman and McMahon, 2006; Craig and Runkle, 2012; Fletcher et al., 2005). However, these studies vary widely in the range of R:FR investigated, as well as intensities and timing of R:FR treatment applications. The objective of the present study was to quantify the effects of R:FR ranging from 0.7 to 1.1 on bedding plant morphology and flowering. This range captures the R:FR measured above and below HBS as measured by Llewellyn et al. (2013).

Materials and Methods

Two experiments (Expts. 1 and 2) were conducted sequentially in walk-in growth chambers at the University of Guelph, ON, Canada, from 2 May to 22 Sept. 2016. Environmental conditions were consistent across the two experiments except for temperature and relative humidity.

Seedling propagation. Seeds of petunia ‘Duet Red’ (Petunia ×hybrida) (Ball Horticultural Co., West Chicago, IL), marigold ‘Antigua Orange’ (T. erecta) (Syngenta Flowers, Gilroy, CA), geranium ‘Pinto Premium Salmon’ (Pelargonium zonatum) (Express Seed Company, Oberlin, OH) and calibrachoa ‘Kabloom Deep Blue’ (Calibrachoa ×hybrida) (PanAmerican Seed Co., West Chicago, IL) were sowed in 288-cell (10 mL) plug trays containing a commercial media (Sunshine Mix #1; Sun Gro Horticulture Distribution, Agawam, MA). Plug trays were placed in a walk-in growth chamber (floor area: 29.2 m²) under a panel of Sylvania 4200K cool-white fluorescent lamps (F96T12/CW/HO; LEDVANCE, Wilmington, MA). The light panel height was adjusted weekly to maintain a constant canopy-level PPF of 200 μmol·m⁻²·s⁻¹, measured with a LI-190 quantum sensor (LI-COR, Inc., Lincoln, NE) calibrated to a spectrometer. The chamber photoperiod was set to 16-h. Air temperature and relative humidity were set at constant 20°C and 60%, respectively, for Expt. 1 and day/night temperatures were set at 25°C/22°C for Expt. 2. The CO₂ concentration for both experiments was ≈440 ppm.

Seedlings were top-irrigated as needed with tap water until cotyledons were visible on 50% of the plugs. Thereafter, groundwater supplemented with water-soluble fertilizer (20N–3.4P–16.6K All Purpose High Nitratre; Master Plant-Prod, Inc., Brampton, ON, Canada) was used for irrigation, providing (in mg·L⁻¹): 250 N, 42 P, 207 K, 1.8 Mg, 1.2 Fe, 0.62 Mn, Zn, and Cu, 0.25 B, and 0.18 Mo. Two separate fertilizer solution tanks were adjusted to pH 5.5 (for petunia and calibrachoa) and pH 6.0 (for geranium and marigold) using aqueous phosphoric acid. Uniform-sized seedlings were transplanted into 8.89-cm-tall black plastic pots (458 mL) containing an all-purpose soilless substrate (Sunshine Mix #1; Sun Gro Horticulture Distribution) when the roots could hold the shape of the substrate when gently pulled (22–42 d for Expt. 1, 17–28 d for Expt. 2). The growth chamber was divided into six treatment zones, separated by white vinyl curtains to prevent light contamination between treatments while allowing sufficient air flow to maintain air temperature and relative humidity. Each treatment area, or plot, was divided into four subplots (2 × 2 grid). Each species was randomly assigned to one subplot and five uniformly sized plants of a chosen species were placed in its respective subplot. Border plants were placed around the outer edges of the plot. Over time, plants were spread further apart to prevent mutual shading, while keeping sample plants within the characterized light treatment plot area. Plants were rearranged within the subplots or the subplots were rotated within the plot at least every 3 d to reduce effects of nonuniform light distribution.

Plants were top-irrigated as needed by hand until minimal drainage was observed. Tap water was used for the first two irrigations after transplant. Thereafter, fertilizer solutions of either pH 6.0 or 5.5 were used as previously described for seedlings before transplanting.

The day/night air temperatures (mean ± SD), excluding 30 min after each day/night transition, were 20.4 ± 0.6°C/18.3 ± 0.5°C in Expt. 1 and 25.1 ± 0.9°C/21.4 ± 0.3°C (excluding fluorescent light treatment) in Expt. 2. When the lights were on, the fluorescent treatment plot was 1.5°C higher than the average temperature of the LED treatment plots, but when the lights were off, all treatment plots had homogeneous temperatures. Average RH was 75% ± 7% in Expt. 1 and 69% ± 7% in Expt. 2.

Light treatments. In five of the six treatment zones, pairs of programmable LED lights (LX602C; Heliospectra AB, Gothenburg, Sweden) were suspended side by side (centers 38 cm apart), 60 cm above pot level. Each fixture had a rectangular array of 240 LEDs (27.6 cm × 16.8 cm) comprised of blue (450 nm), white (5700 K), red (660 nm), and far red (735 nm) LEDs, as described by the manufacturer. In the second experiment, the fluorescent light panels used for plug development provided a sixth light treatment.

LED lamps were programmed using System Assistant Version 1.3.0 software (Heliospectra AB). The photoperiod was 16-h from 0900 to 0100 hr. The red and white LEDs provided the same pot-level PPF and spectral distribution in all LED treatments. The blue channel was not used as the white LEDs provided sufficient blue light to give a B:R ratio of almost 2:5. Far red settings were adjusted to target R:FR of 0.70, 0.80, 0.90, and 1.10 for the treatments. The light treatments were rerandomized among the five LED plots for the second experiment. The fluorescent lights in Expt. 2 were programmed to the same photoperiod, and panel height was adjusted to provide the same canopy-level PPF as the LED treatments.

Light spectra were measured with a USB2000 + spectrometer equipped with a 1.5-m long, 3900-μm diameter ultraviolet-VIS optical fiber with a CC-3 cosine corrector (OceanOptics, Dunedin, FL). The spectrometer was calibrated for absolute irradiance on 16 Mar. 2016 between 300 and 1050 nm using an LS-1 calibrating light source (OceanOptics). The average spectral distribution under each treatment was obtained from 25 points, measured at pot height on an equally spaced 5-by-5 square grid covering a 56 cm × 56 cm plot.

The peak wavelengths of the LED colors (mean ± SD), averaged from all 25 points under each treatment, were 445.7 ± 1.1 nm (blue peak of white channel), 659.5 ± 0.7 nm (red), and 736.2 ± 0.5 nm (far red) with full width at half maxima of 21 ± 2.2 nm, 17 ± 0.5 nm, and 22 ± 0.5 nm, respectively, at treatment intensities.

The spectral irradiance data were converted from μW·cm⁻²·nm⁻¹ to μmol·m⁻²·s⁻¹·nm⁻¹, then multiplied by corresponding spectrometer pixel wave bands and summed over the following ranges to calculate photon flux of blue (B, 400–500 nm), green (G, 500–600 nm), R, and PAR, with B:G:R presented as percent of total PAR in Table 1. The R:FR photon flux ratio of each treatment was measured and described using wide (R: FR) and narrow (R:FRnarrow) wavebands, and PPF was estimated for each treatment following Sager et al. (1988) and Sager and McFarlane (1997), also presented in Table 1. The wide-bandwidth R:FR was preferred over R:FRnarrow for analysis because a slight shift in LED peak wavelength could lead to a large percentage of the peak being truncated in a R:FRnarrow calculation. This may skew the R:FRnarrow data substantially without a corresponding physiological response.

Because the fluorescent panel was initially positioned higher than the LED panels, over time, the canopy-level PPF under LEDs increased at a faster rate as plants grew. The relationship between height and average PPF under LED treatments was determined before transplant with spectrometer measurements at five heights. After treatments commenced, average canopy-level PPF under the LED treatments was calculated from canopy height measurements and the fluorescent panel height was adjusted weekly using a LI-190 quantum sensor calibrated to the spectrometer to match the canopy-level PPF under LED treatments.

Mean PPF at pot level was 210.7 μmol·m⁻²·s⁻¹ (Expts. 1 and 2), corresponding to a DLI of 12.1 mol·m⁻²·d⁻¹. As the plants grew closer to the light fixtures, canopy-level PPF increased to 266 μmol·m⁻²·s⁻¹ (calculated based on canopy height), corresponding to a DLI of 15.3 mol·m⁻²·d⁻¹ at harvest.

Data collection. Harvest dates were determined based on the development of reproductive structures, with one harvest date for each species. The harvest dates were chosen to be late enough to provide data relevant to generative tissue development whereas early enough to avoid excessive
Table 1. Summary of light treatments in Expts. 1 and 2.  

| Light treatment | R:FR | R:FR_{mature} | Estimated P_{FR}/P | Max | Avg | Min | B:G:R (%)^a |
|-----------------|------|---------------|-------------------|-----|-----|-----|-------------|
| Expt. 1         |      |               |                   |     |     |     |             |
| LED R:FR 0.7    | 0.71 ± 0.04 | 0.73 ± 0.07  | 0.63              | 239.9 | 206.8 ± 19.3 | 174.5 | 19:31:50    |
| LED R:FR 0.8    | 0.79 ± 0.04 | 0.78 ± 0.06  | 0.65              | 251.3 | 213.1 ± 22.4 | 171.4 | 19:31:50    |
| LED R:FR 0.9    | 0.90 ± 0.04 | 0.91 ± 0.06  | 0.67              | 243.0 | 209.5 ± 20.2 | 167.6 | 19:30:51    |
| LED R:FR 1.0    | 1.00 ± 0.05 | 1.00 ± 0.07  | 0.69              | 252.3 | 213.2 ± 22.7 | 174.5 | 19:31:50    |
| LED R:FR 1.1    | 1.09 ± 0.05 | 1.04 ± 0.06  | 0.70              | 246.3 | 209.9 ± 21.4 | 168.9 | 19:31:50    |
| Expt. 2         |      |               |                   |     |     |     |             |
| LED R:FR 0.7    | 0.79 ± 0.03 | 0.78 ± 0.02  | 0.62              | 243.6 | 210.6 ± 20.2 | 168.3 | 19:30:51    |
| LED R:FR 0.8    | 0.80 ± 0.04 | 0.80 ± 0.03  | 0.65              | 247.0 | 210.3 ± 22.5 | 164.9 | 19:31:50    |
| LED R:FR 0.9    | 0.89 ± 0.04 | 0.87 ± 0.02  | 0.67              | 252.6 | 213.5 ± 23.2 | 171.2 | 19:31:50    |
| LED R:FR 1.0    | 1.00 ± 0.05 | 0.98 ± 0.10  | 0.69              | 238.7 | 205.9 ± 19.2 | 173.5 | 19:31:50    |
| LED R:FR 1.1    | 1.09 ± 0.05 | 1.08 ± 0.06  | 0.70              | 253.3 | 212.8 ± 22.4 | 174.7 | 19:31:50    |

*Measurements were taken at 25 locations per treatment at pot height. All LED treatments used the same lamp settings for white, blue, and red channels with the far red channel adjusted to produce the target R:FR.

zThe R:FR (600–700 nm : 700–800 nm), R:FR_{mature} (655–665 nm : 725–735 nm), estimated P_{FR}/P, and average PPF (400–700 nm) are reported as mean ± SD (n = 25) with all calculations based on photon flux (PF, μmol·m⁻²·s⁻¹).

Photon flux ratios of blue (B, 400–500 nm), green (G, 500–600 nm), and red (R, 600–700) are reported as percentage of total PPF.

wWhite fluorescent lamps (WFL) had PF for ultraviolet-A (320–400 nm) and ultraviolet-B (300–320 nm).

## Results

### Expt. 1

There were no treatment effects on final height or dry weight (Table 2) for all four species.

**Calibrachoa.** There were no treatment effects for any variable measured.

Petunia. Low R:FR resulted in greater number of nodes and earlier appearance of first bud (comprised with higher R:FR) although there was no subsequent difference in days to first flower.

*Geranium.* Decreasing R:FR was associated with fewer leaves and reduced bud count.

**Marigold.** Stem diameter, leaf area, and SLA responded to R:FR quadratically. Stem diameter followed a positive parabolic function, with minimum at R:FR of 0.94, whereas leaf area and SLA followed negative parabolic functions with maxima at R:FR of 0.89 and 0.91, respectively.

During the experiment, an interesting observation was made. A few excess plants were kept in the unused chamber zone under fluorescent lights (initially used to produce the seedlings). These plants had noticeably darker green leaves and markedly shorter stems and internodes than the plants under any of the LED treatments. Hence, a fluorescent treatment was included in Expt. 2 to compare morphology between plants grown under fluorescent and LED treatments.

### Expt. 2

A greater number of treatment effects were observed in Expt. 2 compared with Expt. 1. Some measures of height were affected in all species, as decreased R:FR increased the height (primary stem length) of marigold, petunia, and calibrachoa, and increased petiole length in geranium (Table 2).

*Marigold.* Plants treated with R:FR 0.7 had 11% greater height than those treated with R:FR 1.1 (i.e., 17.0 cm vs. 15.3 cm). Lower R:FR (0.7) was also associated with earlier date of first flower bud by ≥2 d, longer terminal flower bud stems, and greater stem and total dry weight than higher R:FR (1.1).

Petunia. Plants treated with R:FR 0.7 had 22% greater height than those treated with R:FR 1.1 (i.e., 12.5 cm vs. 10.2 cm). Petunia leaf area and leaf dry weight both followed positive quadratic trends, whereas overall means (pooled data from all LED treatments) were presented when there were no treatment effects for descriptive purposes. Packages used were “dplyr” (Wickham and François, 2016) for summary statistics and “agricolae” (de Mendiburu, 2016) for Tukey’s honestly significant difference post hoc test to check for differences between the fluorescent and pooled LED treatment data.
Fluorescent versus LED treatments in Expt. 2
Compared with the means of pooled data for LED treatments, all species under fluorescent light had reduced height, reduced stem dry weight, and increased relative chlorophyll content (SPAD) (Table 3). Overall, plants grown under fluorescent lights were visually more compact.

Height, dry weight, petiole length, and stem diameter. Under fluorescent light, marigolds, petunias, calibrachoa, and geraniums were 26%, 67%, 60%, and 48% shorter, and had 28%, 39%, 21%, and 31% lower stem dry weights, respectively.

Under fluorescent light, marigold leaf dry weight was reduced by 8%, and total dry weight was reduced in all species except for calibrachoa. For geraniums, the length of the longest petiole under fluorescent light was 46% shorter than under the LED treatments. Although reduction in dry weight primarily occurred in the stems, stem diameter was unaffected in all species. It follows that the reductions in dry weight could be primarily accounted for by shorter stems, and also shorter petioles in geraniums.

Leaf color and relative chlorophyll content. The relative chlorophyll content (SPAD) for all species was higher under fluorescent light (Table 3), where leaves were also observably darker green in color when viewed under a common light environment. Geranium leaves also had starker
Table 3. Growth and flowering of marigold, petunia, geranium, and calibrachoa under fluorescent light and LEDs* in Expt. 2.

| Measurement               | Fluorescent | LED |
|---------------------------|-------------|-----|
| **Marigold**              |             |     |
| Height (cm)               | 11.9 ± 0.4 b| 16.1 ± 0.3 a |
| Flower stem length (cm)   | 2.6 ± 0.3 a | 2.7 ± 0.2 a |
| Nodes (No.)               | 10.6 ± 0.4 b| 11.6 ± 0.2 a |
| Stem diameter (mm)        | 9.5 ± 0.3 a | 9.4 ± 0.1 a |
| Leaf area (cm²)           | 1,147 ± 30 b| 1,312 ± 12 a |
| Leaf dry weight (g)       | 3.87 ± 0.10 b| 4.19 ± 0.04 a |
| Stem dry weight (g)       | 2.85 ± 0.14 b| 3.84 ± 0.07 a |
| Total dry weight (g)      | 6.72 ± 0.22 b| 8.02 ± 0.08 a |
| **Petunia**               |             |     |
| Height (cm)               | 4.9 ± 0.2 b | 9.5 ± 0.2 a |
| Nodes (No.)               | 4.0 ± 0.0 b | 5.1 ± 0.1 a |
| Stem diameter (mm)        | 4.7 ± 0.1 a | 4.4 ± 0.1 a |
| Branches (No.)            | 10.2 ± 0.2 a| 10.4 ± 0.2 a |
| Leaf area (cm²)           | 524 ± 47 a  | 551 ± 8 a |
| Leaf dry weight (g)       | 1.19 ± 0.08 a| 1.24 ± 0.02 a |
| Stem dry weight (g)       | 0.82 ± 0.04 b| 1.34 ± 0.03 a |
| Total dry weight (g)      | 2.01 ± 0.09 b| 2.58 ± 0.04 a |
| **Geranium**              |             |     |
| Height (cm)               | 4.9 ± 0.2 b | 9.5 ± 0.2 a |
| Longest petiole (cm)      | 5.6 ± 0.0 b | 10.3 ± 0.1 a |
| Leaves (No.)              | 11.6 ± 0.2 a| 10.4 ± 0.1 b |
| Stem diameter (mm)        | 8.6 ± 0.3 a | 8.9 ± 0.1 a |
| Leaf area (cm²)           | 476 ± 21 a  | 526 ± 11 a |
| Leaf dry weight (g)       | 2.19 ± 0.15 a| 2.46 ± 0.07 a |
| Stem dry weight (g)       | 0.56 ± 0.03 b| 0.81 ± 0.02 a |
| Total dry weight (g)      | 2.74 ± 0.18 b| 3.27 ± 0.08 a |
| **Calibrachoa**           |             |     |
| Height (cm)               | 14.2 ± 1.6 b| 35.9 ± 1.4 a |
| Nodes (No.)               | 24.8 ± 1.0 a| 25.4 ± 0.5 a |
| Stem diameter (mm)        | 2.8 ± 0.1 a | 3.0 ± 0.1 a |
| Branches (No.)            | 25.4 ± 2.0 a| 21.5 ± 0.8 a |
| Leaf area (cm²)           | 459 ± 36 a  | 498 ± 23 a |
| Leaf dry weight (g)       | 1.57 ± 0.12 a| 1.38 ± 0.06 a |
| Stem dry weight (g)       | 1.19 ± 0.11 b| 1.51 ± 0.06 a |
| Total dry weight (g)      | 2.76 ± 0.20 a| 2.89 ± 0.12 a |

*Data for all LED treatments were pooled (mean ± SE; n = 25) and compared with the cool-white fluorescent (mean ± SE; n = 5) treatment using Tukey’s honestly significant difference test. Data in the same row with different letters are significantly different (P < 0.05).

Discussion

Effects of R:FR on growth and morphology of bedding plants. Plant growth and morphology were affected over the R:FR range of 0.7–1.1, which corresponds to the range measured under HBs in greenhouses in Southern Ontario, Canada, during early spring. Some metrics responded differently between experiments such as height, petiole length, and dry weight only showed treatment effects in Expt. 2, whereas numbers of nodes and leaves, stem diameter, and SLA only showed treatment effects in Expt. 1.

The response trends across the four species were more consistent in Expt. 2, where lower R:FR produced longer stems in marigold, calibrachoa, and petunia and longer petioles in geranium (typical shade avoidance responses). These results are consistent with other studies which reported greater stem elongation or petiole elongation in response to lower R:FR during the day or at the end-of-day in Petunia hybrida (Bachman and McMahon, 2006; Ilias and Rajapakse, 2005), zinnia, chrysanthemum, cosmos (Cerny et al., 2003), impatiens (Fletcher et al., 2005), squash rootstock (Yang et al., 2012), Cucurbita pepo, Chenopodium album (Holmes and Smith, 1977c), soybean (Kasperbauer, 1987), tobacco (Kasperbauer and Peaslee, 1973), and other dicotyledonous species (Demotes-Mainard et al., 2016). The different responses to R:FR between Expts. 1 and 2 might be related to temperature differences, as several studies have reported interactions between R:FR and day/night temperature differential (DIF) (Blom and Kerec, 2003; Kubota et al. 2000; Moe et al., 1991; Xiong et al., 2011) or with absolute temperature (higher or lower with the same DIF) (Qaderi et al., 2015) on the stem length of various species, where low R:FR combined with positive DIF or higher absolute temperatures result in longer stem length.

Reductions in PAR have also been implicated as an influential factor promoting stem elongation under HBs, as the DLI may fall below minimum requirements for “good quality” plants in greenhouse production (Faust, 2003; Llewellyn et al., 2013). However, interaction between R:FR and irradiance was not investigated and cannot be ruled out, as evidence suggests that phytochrome B (phyB), which is considered to be the main photoreceptor for shade-avoidance responses, has an integrated response to R:FR and irradiance on the subcellular level (Trupkin et al., 2014). More specifically, lowering irradiance (from 200 to 25 μmol·m⁻²·s⁻¹) in addition to lower R:FR (from 4.3 to 0.8) had compounding effects on the number and size of phyB nuclear bodies within Arabidopsis thaliana petiole cells (phyB in the nucleus is related to phytochrome activity, as phyB migrates from the cytosol to the cell nucleus only in the ‘active’ P₆₅ form).

Effects of R:FR on flowering. The R:FR had limited effects on flower development. For petunia in Expt. 1, lower R:FR was associated with earlier date of first bud, but there was subsequently no difference in the date of first flower. For geraniums, lower R:FR was associated with reduced bud count, which in this case may be interpreted as a delay in flowering; because plants had 0 or 1 bud, treatments with lower average bud numbers had a higher proportion of plants with no buds at the time of harvest. In Expt. 2, lower R:FR stimulated flowering in marigold, with R:FR 0.7 producing an earlier date of first bud by ≈2 d and longer terminal flower stems than R:FR 1.1. Although the effects on flowering were subtle, results for marigold and petunia agree with other studies which reported that a reduced R:FR can accelerate flower development (Ilias and Rajapakse, 2005), or conversely that an FR-deficient environment (increased R:FR) can delay flower initiation (Cerny et al., 2003; Runkle and Heins, 2001), especially in long-day plants.
86% of higher intensities of green light (51% and 24% of PPF) was associated with increased dry weight in lettuce. Other studies have reported reduced chlorophyll content in response to low R:FR in a variety of species (Heract-Bron et al., 1999; Smith and Whiteham, 1997; Tucker, 1981). The presence of ultraviolet, which has been associated with elevated anthocyanin pigments in lettuce (Tsormpatisidis et al., 2008), baby leaf lettuce (Li and Kubota, 2009), and turpin hypocotyls (Zhou et al., 2007), may have also contributed to the increased leaf variegation in lettuce grown under fluorescent lights, as anthocyanins have been found to be abundant in zonal dark rings of Pelargonium xhortorum leaves (Lakopoulos and Spanorogias, 2012).

In summary, although the specific causes of morphological difference in the fluorescent treatment are uncertain, the results show the potential for light spectrum manipulations to induce changes to morphology and flowering. There were three noteworthy differences between the growth chamber experiments and realistic greenhouse conditions which could affect the transferability of the results. Although the LED treatments provided wavelengths in blue, green, and red wavebands, solar spectral ratios were not replicated. The LED treatments had a B:G:R of 19:31:50 whereas solar radiation was measured to be 28:37:35 (measured on a mostly clear day on 8 Feb. 2017 at lat. 42°N, data not shown). In addition, the PPF in the growth chamber was constant throughout the photo-period, whereas PPF in a greenhouse follows a variable, diurnal pattern with instantaneous PPF being highly influenced by outdoor weather. Differences in temperature may also interact with R:FR to influence transferability of results to commercial production.

**Conclusion**

This study investigated the effects of R:FR on morphology and flowering of marigold, petunia, calibrachoa, and geranium under the range of R:FR (0.7–1.1) found in commercial greenhouse production scenarios where a canopy of HBs is grown above the bench level. Although light treatment effects were found, the crop responses were generally not considered commercially relevant because of similar appearances between plants grown under different treatments. In terms of the potential of using light as a growth regulator, the fluorescent treatment provided evidence that spectral manipulation could be used to control growth, as plants grown under fluorescent lights showed noticeable differences in qualitative factors such as leaf coloration and stem elongation. Any of the distinct spectral parameters in fluorescent lights are candidates for further investigation toward using light as a growth regulator in a greenhouse setting, including increased R:FR, presence of ultraviolet-A or ultraviolet-B, or increased B:R. Further research is needed to determine whether spectral manipulation can be used to create commercially relevant outcomes.

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