Lamp Type and Irradiance Level for Daylength Extensions Influence Flowering of *Campanula carpatica* ‘Blue Clips’, *Coreopsis grandiflora* ‘Early Sunrise’, and *Coreopsis verticillata* ‘Moonbeam’

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ABSTRACT. The effectiveness of cool-white fluorescent, high-pressure sodium, incandescent, and metal halide lamps for inducing flowering through daylength extensions in *Campanula carpatica* Jacq. ‘Blue Clips’, *Coreopsis grandiflora* Hogg ex Sweet ‘Early Sunrise’, and *Coreopsis verticillata* L. ‘Moonbeam’ was compared. Lighting was delivered as a 7-hour day extension with photosynthetic photon flux (PPF) ranging from 0.05 to 2.0 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ following a 9-hour natural daylength. Threshold irradiance values for flowering ranged from <0.05 to 0.4 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$, depending on species. Saturation irradiance values for *Campanula carpatica* ‘Blue Clips’ and *C. grandiflora* ‘Early Sunrise’ were between 0.2 $\pm$ 0.2 and 0.7 $\pm$ 0.5 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$, and did not differ between lamps. An irradiance of 1.0 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ from any lamp was adequate for flowering in *Coreopsis verticillata* ‘Moonbeam’. Time to flower at irradiances above the saturation points did not differ significantly between lamp types for all species tested. *Campanula carpatica* ‘Blue Clips’ and *Coreopsis grandiflora* ‘Early Sunrise’ plants had significantly longer stems under incandescent lamps than in any other treatment. *Coreopsis verticillata* ‘Moonbeam’ plants grown under cool-white fluorescent lamps had stems $\approx$ 10% longer than those grown under high-pressure sodium or incandescent lamps.

The popularity of herbaceous perennials has increased recently. Combined wholesale, retail, and landscape sales in 1994 were estimated by the Perennial Plant Association at \$396 million, with 86% of respondents reporting increases over 1993 levels (Rhodus, 1995). A plant in bloom has much greater sales appeal than a nonflowering plant, however in North America, perennials traditionally have been produced outdoors, and many are not in flower in the spring when the majority of garden plants are sold (Schwarze, 1993). Consequently, producers of herbaceous perennials are interested in production methods that will allow them to produce flowering plants anytime.

Several popular species of herbaceous perennials are long-day plants (LDP), so photoperiods exceeding a certain minimum length are needed to induce or hasten flowering (Beattie and German, 1985; Iversen and Weiler, 1994). Long days can be provided by extending the daylength to 14 to 16 hours, or by providing a 4-hour night break (Armitage, 1994; Vince-Prue and Canham, 1983).

Traditional photoperiodic lighting involves the use of incandescent lamps (INC) (Vince-Prue and Canham, 1983). Incandescent lights are effective, inexpensive, and simple to install; however, their output in the 400- to 700-nm waveband is only 57 to 69 $\text{mW}\cdot\text{W}^{-1}$ ($\approx$ 6%) of input power compared to over 200 mW ($>$ 20%) for cool-white fluorescent (CWF), high-pressure sodium (HPS), and metal halide (MH) lamps (Thimijan and Heins, 1983). Replacing INC with one of these light sources can reduce photoperiodic lighting energy costs.

The spectral quality of photoperiodic lighting is an important

consideration. In LDP, light in the red (600 to 700 nm) and far-red (700 to 800 nm) portions of the spectrum is important for flower induction (Thomas, 1993; Thomas and Vince-Prue, 1995). Red light is most effective during brief night interruptions. In contrast, mixtures of red and far-red light are often more effective for long night interruptions or day extensions (DE) (Thomas, 1993). A combination of red and far-red light, when delivered as DE following 8 h of natural daylight, more effectively hastened the flowering of *Dianthus caryophyllus* L. ‘Puritan’, *Lactuca sativa* L. ‘Cheshunt Vb’ (Vince et al., 1964), and *Lolium temulentum* L. (Vince, 1965) than either light source alone. The action spectrum for floral development, quantified as apex elongation, in light-grown *Triticum aestivum* L. under 16-h DE showed two maxima, one at 660 nm and one at 716 nm (Carr-Smith et al., 1989).

Incandescent lamps emit a mixture of red and far-red light which is very effective for photoperiodic lighting. The output is rich in far-red light, the ratio of red (600 to 700 nm) to far-red (700 to 800 nm) being <1 (Lane et al., 1965). Far-red light has several horticulturally undesirable effects on plant morphology including promotion of stem elongation and suppression of lateral branching (Downs et al., 1958; Moe and Heins, 1990; Vince-Prue and Canham, 1983). Several other lamp types such as CWF, HPS, and MH, deliver proportionately less far-red than red light compared to INC lamps (deGraaf-van der Zande and Blacquire, 1992; Thimijan and Heins, 1983). Using lamps other than INC offers the potential for flower induction with less stem elongation, while reducing photoperiodic lighting energy costs.

Cool-white fluorescent lamps emit very little far-red light, and their ability to induce flowering has been compared with that of several other lamps. Flowering delays of 10 to 44 d have been reported in *Anethum graveolens* L., *Triticum compactum* Host var. Little Club, *Hordeum vulgare* L. var. Colless I (Downs et al., 1958); *Hyoscyamus niger* L., *Beta vulgaris* L., *A. graveolens* L., *Petunia hybrida* Vilm. (Lane et al., 1965); and *P. hybrida* ‘Pink Cascade’ (Cathey and Campbell, 1975) plants treated with CWF compared to those under other light sources with lower ratios of red

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to far-red light. CWF lamps did not induce flowering in *Gypsophila paniculata* L., but were effective when combined with INC lamps (Shillo and Halevy, 1982). However, *Callistephus chinensis* 'Kometa pink' displayed similar flowering responses under INC, CWF, low-pressure sodium, or compact discharge lamps (deGraaf-van der Zande and Blacquière, 1992). The flowering response in *Campanula isophylla* Moretti was similar under either INC or CWF lamps (Moe and Heins, 1990).

Lighting used to extend the photoperiod must be of adequate intensity (Summerfield and Roberts, 1987; Vince-Prue, 1975). Summerfield and Roberts (1987) proposed that each LDP has a threshold irradiance below which flowering is not induced or hastened by light treatment. As plants are exposed to higher light levels, flowering is hastened until a saturation irradiance is reached, above which the time to flower becomes constant. At light levels between threshold and saturation, the rate of progress to flowering (inverse of time to flower) for an LDP often is related linearly to the log of the irradiance level (Summerfield and Roberts, 1987). For incandescent lighting, the threshold irradiance for floral induction in many species of LDP lies between 0.02 and 1.0 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ (Vince-Prue, 1975). Horticulturally, a knowledge of threshold and saturation irradiance levels is important in order to induce rapid and uniform flowering most economically, and to avoid inadvertent induction in nearby greenhouse sections.

In this study, experiments were conducted to compare the effectiveness of four lamp types on flower induction in LDP by establishing threshold and saturation light intensities, and to determine the effect of lamp type on plant height.

Materials and Methods

PLANT CULTURE. Seedlings of *Campanula carpatica* 'Blue Clips' and *C. grandiflora* 'Early Sunrise' were acquired from a commercial plug producer ≈ 4 weeks after sowing. Cuttings of *Coreopsis verticillata* 'Moonbeam' were propagated on 28 June 1994 for use in Expt. 1, and plants in 72-cell trays (50-mL cell volume) were acquired from a commercial producer for use in Expt. 2. Characteristics of the plant material are presented in Table 1. Seedlings subsequently were transplanted into 10-cm pots (0.47 L), using a commercial soilless medium containing composted pine bark, horticultural vermiculite, Canadian sphagnum peat moss, processed bark ash, and washed sand (MetroMix 510, Scotts-Sierra Horticultural Products Co., Marysville, Ohio). Plants were top-watered as necessary with 7 mM N, 0.7 mM P, and 2 mM K from a 20N-4.4P-16.6K all-purpose water-soluble fertilizer

(Peter's professional Peat-lite special; Grace-Sierra Horticultural Products Co., Milpitas, Calif.). Before long-day treatments, plants were maintained under a 9-h photoperiod (SD) provided by pulling black cloth from 1700 to 0800 HR daily. Supplemental lighting (high-pressure sodium providing $\approx 50 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ at plant level) was provided when ambient PPF outside the greenhouse dropped below 200 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ between 0800 and 1700 HR, and terminated when PPF exceeded 400 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$.

LIGHT SOURCES AND TREATMENTS. Four lamps were tested: cool-white fluorescent (F48T12, 60 W; Philips, Somerset, N.J.), high-pressure sodium (Lucolox LU70/MED, 70 W; General Electric, Fairfield, Conn.), incandescent (100 W, Philips), and metal halide (MH70, 70 W; Philips). One lamp was installed at one end of each of four benches, 75 to 90 cm above the bench, so that an irradiance gradient from 0.05 to 2.0 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ (400 to 700 nm) was established as measured by a quantum sensor (model LI-189; LI-COR, Lincoln, Neb.) oriented horizontally at plant height. Irradiance was measured at the beginning of each of the experiments and midway through the first experiment.

The spectrum of each light source was determined at the 1.0 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ bench position using a portable spectroradiometer (LI-1800; LI-COR) with the remote sensor pointed directly toward the lamp, oriented 45° from the horizontal position. Calculations of red to far-red ratio used band widths of 600 to 700 nm for red radiation and 700 to 800 nm for far-red radiation, and represent the average of three scans. Ratios of R to FR were 8.8, 5.9, 0.7, and 3.3 for CWF, HPS, INC, and MH lamps, respectively. Photon flux in the 600- to 700-nm waveband at the 1.0 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ level was 0.25, 0.40, 0.58, and 0.27 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ for CWF, HPS, INC, and MH lamps, respectively.

Fifteen plants of each species were arranged along the length of each of the four benches, and 15 plants remained in SD. Black cloth was pulled at 1700 HR and opened at 0800 HR on all benches. Treatment lamps were turned on at 1700 HR and remained on until 2400 HR, providing a 7-h DE.

The experiment was replicated in time with Expts. 1, 2, and 3 starting on 16 Sept. 1994, 15 Dec. 1994, and 15 Mar. 1995, respectively. *Campanula carpatica* 'Blue Clips' and *Coreopsis grandiflora* 'Early Sunrise' were included in all three experiments, and *Coreopsis verticillata* 'Moonbeam' was included in Expts. 1 and 2. Date of the first visible flower bud and date of opening of the first flower were recorded for each plant, and days to visible bud and flowering were calculated. At flowering, total plant height (soil surface to tallest point), number of visible flower buds, and number of leaves on the main stem were determined.

Table 1. Characteristics of plant material. Expts. 1, 2, and 3 started on 16 Sept. 1994, 15 Dec. 1994, and 15 Mar. 1995, respectively.

Species	Sowing date	Start of experiment	
		Age (wks)	Leaves (avg no.)
Expt. 1			
<i>Campanula carpatica</i> Blue Clips	7 June 1994	14	16.3
<i>Coreopsis grandiflora</i> Early Sunrise	7 June 1994	14	24.5
<i>Coreopsis verticillata</i> Moonbeam	Cuttings propagated 28 June 1994	11	NR ²
Expt. 2			
<i>Campanula carpatica</i> Blue Clips	8 Sept. 1994	14	11.4
<i>Coreopsis grandiflora</i> Early Sunrise	8 Sept. 1994	14	16.7
<i>Coreopsis verticillata</i> Moonbeam	NR	NR	NR
Expt. 3			
<i>Campanula carpatica</i> Blue Clips	7 Dec. 1994	14	8.6
<i>Coreopsis grandiflora</i> Early Sunrise	7 Dec. 1994	14	13.6

²NR = not recorded.

Fig. 1. Effect of light source and intensity on rate of progress to flowering in *Campanula carpatica* 'Blue Clips'. Each symbol (●) represents one plant from each of three experiments. Plants that did not flower were not included in the saturation irradiance (I_{sat}) analysis. The solid line represents the predicted rate of progress to flowering based on Eqs. [2] and [3]. The I_{sat} is the quantum flux at the point of intersection between the two lines. Statistical analysis is presented in Table 2.

TEMPERATURE CONTROL. Air temperatures on each bench were monitored with two 36-gauge (0.127 mm) thermocouples connected to a CR10 datalogger (Campbell Scientific, Logan, Utah). The datalogger collected temperature data every 10 s and recorded the hourly average. Nighttime air temperatures under black cloth on solid benches can be up to 3.5 °C cooler than greenhouse air temperatures because of radiant heat loss to the greenhouse glazing material (Heins and Faust, 1994). Air temperature on individual benches is also influenced by their position in the greenhouse. To provide uniform temperatures, the datalogger controlled a 1500-W electric heater under each bench, which provided supplemental heat as needed throughout the night. Actual daily air mean was 20.6 °C for all three experiments. The maximum difference in actual daily air mean between any two benches within each experiment was 0.8, 0.6, and 0.2 °C for Expts. 1, 2, and 3, respectively.

DATA ANALYSIS. In the system proposed by Summerfield and Roberts (1987), as irradiance increases above a threshold value, flowering of an LDP is hastened and the rate

of progress to flowering (inverse of time to flower) often is related linearly to the log of the irradiance. As irradiance increases above a saturation value, the rate of progress to flower becomes constant. One linear equation can be used to describe the response below saturation irradiance, and another to describe the response above saturation irradiance. In this system, the intersection of these two lines would give the minimum saturation irradiance.

To determine saturation irradiance levels in these experiments, days to flower was converted to rate of progress to flowering by taking the reciprocal (1/no. days to flower). Log irradiance was calculated using $1 + \text{measured } \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ so that all values would be positive. The relationship between log irradiance and rate of progress to flowering was developed using a multiphase function with two linear components, as proposed by Argo and Biernbaum (1996). Initial estimates for the parameters were obtained from graphs of the observed data. The functions used were

$$I_{\text{saturation}} = b_2 - b_0/b_1 - b_3 \quad [1]$$

$$\text{if } I < I_{\text{saturation}} \text{ then } R_1 = b_0 + b_1 I \quad [2]$$

$$\text{if } I > I_{\text{saturation}} \text{ then } R_2 = b_2 + b_3 I \quad [3]$$

Fig. 2. Effect of light source and intensity on rate of progress to flowering in *Coreopsis grandiflora* 'Early Sunrise'. Each symbol (●) represents one plant from each of three experiments. Plants that did not flower were not included in the saturation irradiance (I_{sat}) analysis. The solid line represents the predicted rate of progress to flowering based on Eqs. [2] and [3]. The I_{sat} is the quantum flux at the point of intersection between the two lines. Statistical analysis is presented in Table 2.

Table 2. Parameters of nonlinear and linear regression analysis relating rate of progress to flowering to quantum flux (400 to 700 nm). b_1 and b_3 are slopes and b_0 and b_2 are intercepts. For nonlinear regression, b_0 , b_1 , b_2 , and b_3 represent values for Eqs. [2] and [3]. $I_{\text{saturation}}$ is the irradiance at the intersection point of the two lines (in $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$) and is calculated using Eq. [1]. For linear regression, b_2 and b_3 are intercepts and slopes, respectively. Values $\pm$ SE.

Species	Lamp ^x	b_0	b_1	b_2	b_3	$I_{\text{saturation}}$	$I_{\text{saturation}}$	No. ^y	R^{2x}
		1/DTF	(1/DTF)/ log (1 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$)	1/DTF	(1/DTF)/ log (1 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$)	log (1 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$)	$\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$		
<i>Campanula carpatica</i>									
Blue Clips	CWF	0.015 $\pm$ 0.002	0.027 $\pm$ 0.026	0.019 $\pm$ 0.004	0.001 $\pm$ 0.013	0.159 $\pm$ 0.169	0.44 $\pm$ 0.47	40	0.30
	HPS	0.013 $\pm$ 0.003	0.047 $\pm$ 0.047	0.019 $\pm$ 0.000	0 ^w	0.137 $\pm$ 0.102	0.37 $\pm$ 0.26	33	0.46
	INC	0.012 $\pm$ 0.004	0.076 $\pm$ 0.067	0.019 $\pm$ 0.003	0.002 $\pm$ 0.009	0.097 $\pm$ 0.078	0.25 $\pm$ 0.20	38	0.39
	MH	0.014 $\pm$ 0.002	0.026 $\pm$ 0.002	0.020 $\pm$ 0.001	0 ^w	0.225 $\pm$ 0.164	0.68 $\pm$ 0.46	33	0.47
<i>Coreopsis grandiflora</i>									
Early Sunrise	CWF	0.012 $\pm$ 0.003	0.056 $\pm$ 0.058	0.017 $\pm$ 0.002	0.002 $\pm$ 0.01	0.086 $\pm$ 0.089	0.22 $\pm$ 0.23	35	0.36
	HPS	0.013 $\pm$ 0.003	0.041 $\pm$ 0.055	0.017 $\pm$ 0.001	0 ^w	0.097 $\pm$ 0.109	0.25 $\pm$ 0.28	35	0.22
	INC	0.013 $\pm$ 0.002	0.039 $\pm$ 0.027	0.019 $\pm$ 0.001	0 ^w	0.155 $\pm$ 0.174	0.43 $\pm$ 0.49	34	0.43
	MH	0.013 $\pm$ 0.002	0.020 $\pm$ 0.024	0.017 $\pm$ 0.002	0 ^w	0.176 $\pm$ 0.148	0.50 $\pm$ 0.41	29	0.26
<i>Coreopsis verticillata</i>									
Moonbeam, Expt. 1	CWF	---	---	0.017 $\pm$ 0.001	0 ^w	---	---	15	0.13 ^{vns}
	HPS	---	---	0.017 $\pm$ 0.001	0.002 $\pm$ 0.004	---	---	14	0.01 ^{vns}
	INC	0.014 $\pm$ 0.004	0.042 $\pm$ 0.061	0.019 $\pm$ 0.002	0 ^w	0.104 $\pm$ 0.142	0.27 $\pm$ 0.39	11	0.52
	MH	0.009 $\pm$ 0.005	0.123 $\pm$ 0.115	0.018 $\pm$ 0.000	0 ^w	0.0755 $\pm$ 0.051	0.19 $\pm$ 0.12	15	0.62
<i>Coreopsis verticillata</i>									
Moonbeam, Expt. 2	CWF	---	---	0.014 $\pm$ 0.001	0.008 $\pm$ 0.003	---	---	9	0.49 ^{ns}
	HPS	---	---	0.015 $\pm$ 0.000	0.005 $\pm$ 0.001	---	---	7	0.75 ^{ns}
	INC	---	---	0.014 $\pm$ 0.001	0.005 $\pm$ 0.005	---	---	6	0.17 ^{vns}
	MH	---	---	0.015 $\pm$ 0.001	0 ^w	---	---	9	0.001 ^{vns}

¹CWF = cool-white fluorescent, HPS = high-pressure sodium, INC = incandescent, MH = metal halide.

²Number of observations in the data set.

^xThe R^2 value was calculated as $1 - \text{SS}_{\text{residual}} / \text{SS}_{\text{corrected total}}$.

^w b_3 was defined as zero to avoid a negative slope.

^{NS} P^2 .

^{NS, *, **}Nonsignificant or significant at $P < 0.05$ or 0.01 , respectively.

where the I value is log irradiance and R is the rate of progress to flowering. $I_{\text{saturation}}$ is the intersection point of the two lines where R_1 and R_2 are equal and is calculated using Eq. [1]; b_1 and b_3 are the slopes, and b_0 and b_2 are the y-intercepts of Eqs. [2] and [3], respectively. Values for b_0 , b_1 , b_2 , and b_3 , based on irradiance, were obtained simultaneously using SAS's nonlinear regression procedure (NLIN) (SAS Institute, Cary, NC). In cases where b_3 was <0 , data were reanalyzed with b_3 set at 0. Standard error of the estimated saturation point was calculated using a Taylor's series approach. In cases where Eqs. [2] and [3] could not be simultaneously fit to the data, linear regression (GLM) (SAS Institute, Cary, N.C.) was used to estimate the relationship between irradiance and rate of progress to flowering.

Results

***Campanula carpatica* 'BLUE CLIPS' AND *Coreopsis grandiflora* 'EARLY SUNRISE'**. No plants flowered under SD. Some plants treated with DE of 0.05 to $0.1 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ flowered under all light sources, indicating

that the threshold irradiance for flowering in these species is below $0.1 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ (Figs. 1 and 2). Flowering was hastened as irradiance increased, with the response becoming saturated ($I_{\text{saturation}}$) at irradiances between 0.2 and $0.7 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ for *Campanula carpatica* 'Blue Clips', and 0.2 to $0.5 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ for *Coreopsis grandiflora* 'Early Sunrise' (Table 2). Saturation irradiances for each species were not statistically different between lamps. Time to flower at irradiances above the saturation point for each lamp averaged 51 and 60 d in *Campanula carpatica* 'Blue Clips' and *Coreopsis grandiflora* 'Early Sunrise' respectively, and did not differ significantly between lamp types. Time from visible bud to flower was not significantly affected by irradiance, or by lamp type. Days from visible bud to flower for *Campanula carpatica* 'Blue Clips' and *Coreopsis grandiflora* 'Early Sunrise' averaged 21 and 23, respectively. *Campanula carpatica* 'Blue Clips' and *Coreopsis grandiflora* 'Early Sunrise' plants in INC light treatments were significantly taller than those under CWF, HPS, or MH lamps (Table 3).

***Coreopsis verticillata* 'MOONBEAM'**. No plants flowered under SD. Flowering response differed somewhat between the two

Table 3. Influence of light source used for daylength extensions on mean plant height at the time of flowering, for all plants that flowered.

Lamp	<i>Campanula carpatica</i> Blue Clips	<i>Coreopsis grandiflora</i> Early Sunrise	<i>Coreopsis verticillata</i> Moonbeam
	(cm)	(cm)	(cm)
Cool-white fluorescent	13.6 b ²	26.0 b	41.1 a
High-pressure sodium	13.3 b	25.1 b	37.7 b
Incandescent	16.2 a	31.9 a	37.5 b
Metal halide	12.5 b	23.7 b	39.9 ab

²Mean separation in columns by Duncan's multiple range test, $P \leq 0.05$.

Fig. 3. Effect of light source and intensity on rate of progress to flowering in *Coreopsis verticillata* 'Moonbeam' for Expt. 1. Each symbol (●) represents one plant. Plants that did not flower were not included in the saturation irradiance (I_{sat}) or linear regression analysis. For A and B, the solid line represents the predicted rate of progress to flowering based on linear regression. For C and D, the solid line represents the predicted rate of progress to flowering based on Eqs. [2] and [3]. The I_{sat} is the quantum flux at the point of intersection between the two lines. Statistical analysis is presented in Table 2.

replications, so the data were analyzed separately. In Expt. 1 (Fig. 3), all plants under CWF and HPS treatments flowered at approximately the same time, with a saturation irradiance apparently $\leq 0.05 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$. Under INC and MH lamps, some plants flowered at 0.05 to 0.1 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$, and as irradiance increased, flowering was hastened until the response became saturated at 0.3 and 0.2 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$, respectively (Table 2). Saturation irradiances did not differ significantly between lamps. Time to flower at irradiances above the saturation point for each lamp averaged 57 d and did not differ significantly between lamp types.

In Expt. 2, threshold irradiances were between 0.2 and 0.4 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ for all lamps (Fig. 4). Under CWF and HPS lamps, rate of progress to flowering increased linearly as light levels increased, indicating that a saturation irradiance was not reached within the experimental irradiance range. Under INC lamps, rate of progress to flowering increased as light levels increased, but not significantly (Table 2). Plants under INC and MH lamps exposed to irradiances above threshold levels all flowered at approximately the same time, indicating that saturation irradiance was very

close to threshold irradiance. At irradiances above the saturation points for INC and MH, time to flower averaged 66 d and did not differ significantly between the treatments.

In both experiments, time from visible bud to flower in *Coreopsis verticillata* 'Moonbeam' was not significantly affected by irradiance, or by lamp type, and averaged 30 d. Overall, plants treated with CWF lamps were ≈ 3.6 cm taller than those grown under HPS or INC (Table 3).

Discussion

Under the conditions of this experiment, all tested lamps induced flowering in these species of LDP. When saturation irradiances could be determined for a species, they did not differ between lamps due to variation among data points. Days to flower at irradiances above the saturation points did not differ significantly between lamps in any species tested. Horticulturally, all the lamps tested are adequate for floral induction in these crops.

Mixtures of red and far-red light are effective for flower induction in LDP (Thomas and Vince-Pruc, 1995; Vince, 1965; Vince et al., 1964). Previous research with other species

often has shown that lamps with a high red to far-red ratio, such as CWF, are less effective for flower induction in LDP than lamps

Fig. 4. Effect of light source and intensity on rate of progress to flowering in *Coreopsis verticillata* 'Moonbeam' for Expt. 2. Each symbol (●) represents one plant. Plants that did not flower were not included in the linear regression analysis. The solid line represents the predicted rate of progress to flowering based on linear regression. Statistical analysis is presented in Table 2.

with a low red to far-red ratio, such as INC (Cathey and Campbell, 1975; Downs et al., 1958; Lane et al., 1965; Shillo and Halevy, 1982). In our experiments, CWF lamps were as effective as the other lamps tested. All lamps included in this work emit some radiation in the red and far-red wavebands, which apparently was sufficient for floral induction in these species. These findings are comparable to results reported by deGraaf-van der Zande and Blacquire (1992) and Moe and Heins (1990).

Time to visible bud in these species decreased as irradiance increased, and reached a saturation point, analogous to the response for time to flower. In contrast, time from visible bud to flower for each species was similar for all individuals that flowered, regardless of light source or irradiance. We conclude that irradiance influenced floral development prior to the visible-bud stage.

Threshold irradiance values in this experiment (<0.05 to $0.4 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$) are similar to values published for other LDP. For example, the threshold irradiance of incandescent lighting for floral induction in *Callistephus chinensis* was reported as $0.02 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ (Withrow and Benedict, 1936). In *Cicer arietinum* L., threshold irradiance values under incandescent lamps were 0.02 to $0.04 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ (Summerfield and Roberts, 1987), while in *Lens culinaris* L. the values were 1.2 to $1.4 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ (Summerfield et al., 1984). The sensitivity of these species to low light levels indicates that growers of herbaceous perennials should consider the potential impact of light pollution, which may promote flowering at times when vegetative growth is desired. In the Netherlands, light levels up to $0.1 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ were measured in greenhouses adjacent to those using supplemental lighting during the night (Bakker and Blacquire, 1992).

Saturation irradiance values in this experiment were between 0.2 to $0.7 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ for all lamps for *Campanula carpatica* 'Blue Clips' and *Coreopsis grandiflora* 'Early Sunrise'. These values are similar to those reported for *Cicer arietinum* (Summerfield and Roberts, 1987) and *G. paniculata* (Shillo and Halevy, 1982). A light level of $2.0 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ is commonly used for photoperiodic control of crops such as poinsettias and chrysanthemums (Ball, 1991; Ecke and Hartley, 1991). Producers who currently use photoperiodic lighting for poinsettias and chrysanthemums also can use their equipment for these species of herbaceous perennials.

Far-red light strongly enhances stem elongation and suppresses lateral branching (Moe and Heins, 1990). INC lamps have the lowest red to far-red ratio of the lamps that we tested, and *Campanula carpatica* 'Blue Clips' and *Coreopsis grandiflora* 'Early Sunrise' were significantly taller when exposed to INC lamps compared to all other lamps. *Coreopsis verticillata* 'Moonbeam' grown under HPS and INC were shorter than those treated with CWF and MH, a response that did not correspond with the red to far-red ratios of the lamps. For at least some crops, use of lamps with a high red to far-red ratio can reduce final plant height compared to lamps with a low red to far-red ratio.

Use of CWF, HPS, or MH lamps in place of INC lighting offers benefits in energy savings as well. For example, using values presented by Cathey and Campbell (1980) to provide $1 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$, the electrical input that must be provided per square meter of growing space is 2.4, 1.5, or 2.4 W for CWF, HPS, or MH lamps, respectively, compared to 7.0 W for INC.

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