Chrysanthemum Flowering in a Blue Light-supplemented Long Day Maintained for Biocontrol of Thrips

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Abstract. The application of supplemental blue light in greenhouse chrysanthemum production is part of a biological control strategy to enhance reproduction of *Orius insidiosus* Say, a natural predator of the western flower thrips, *Frankliniella occidentalis* Pergande. Two greenhouse experiments were conducted to determine the influence of a blue light-supplemented long day on flowering and vegetative growth in three cultivars of the short-day plant *Dendranthema ×grandiflora* (Ramat.) Kitamura. In Expt. 1, two cut chrysanthemum cultivars ('Manatee Iceberg' and 'Naples') were exposed to: a) 9-hour ambient light and 15-hour artificial blue-biased (400–500 nm) light at two blue light intensities (3.6 or 7.0 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$); b) 9-hour ambient light and 15-hour artificial broad spectrum light at a broad spectrum intensity of 3.6 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$; c) 9-hour ambient light maintained with black cloth; or d) an ambient short day. Under a continuous photoperiod, flower initiation in both cultivars in the lower intensity blue light was not significantly different from that in short-day regimes. However, in both blue light intensities, flower size and dry mass were significantly less than in the short-day regimes. Increasing the dose of blue light decreased flower dry mass in 'Naples' by 60% and in 'Manatee Iceberg' by 72%. Plants were shorter with less vegetative mass in the short-day regimes. In Expt. 2, 'Naples' and the pot chrysanthemum 'Boaldi' were exposed to a) 9-hour ambient light and 6-hour artificial blue-biased (400–500 nm) light at four blue light intensities (0.4, 0.7, 1.6, or 3.5 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$); b) 9-h ambient light maintained with black cloth; or c) an ambient long day. For both cultivars, in all blue light regimes, neither flower dry mass nor vegetative dry mass differed significantly from those in the short-day regime. The results indicate that exposing *D. grandiflora* to a blue light-supplemented long day at blue light intensities $<3.5 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ does not adversely affect flower initiation and development.

Dendranthema grandiflora is a quantitative short-day plant. Flowers fail to develop to anthesis or develop crown buds in long days (Cockshull, 1976; Cockshull and Kofranek, 1985; Post, 1948). Flower initiation is earlier and more predictable and flower development is more uniform if plants are exposed to a

critical number of short days (Kofranek and Halevy, 1974; Seeley and Weise, 1965). Unless specialized interrupted lighting techniques are used to manipulate flower size, inflorescence shape, or other aspects of flower quality, chrysanthemum is grown in short days, the duration of which depends on cultivar traits (Mastalerz, 1977).

Most commercial cultivars of *D. grandiflora* with 8- to 10-week response periods have a critical photoperiod of <14.5 h for flower initiation and <13.5 h for flower development (Furuta, 1954; Post, 1948). Red light (600–660 nm) is most effective and blue light (400–500 nm) least effective for flower initiation in both long-day and short-day plants (Borthwick et al., 1948; Parker et al., 1946). In short days, an interruption of the dark period with red light induces flowering in long-day plants and prevents flowering in short-day plants. Intensities need only to exceed a low level (1–10 $\mu\text{W}\cdot\text{cm}^{-2}\cdot\text{s}^{-1}$) within the critical spectral region over a variable length of time to effect a response (Salisbury, 1963).

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Flower development is also influenced by photosynthetic photon flux (PPF) and daily quantum integrals ($\text{PPF} \times \text{light duration}$) (Karlsson et al., 1989; Warrington and Norton, 1991). The influence of blue light on morphogenesis has been examined in some plant species (Thomas, 1981; Warrington and Mitchell, 1976), but, to our knowledge, the effects of blue light on chrysanthemum flower initiation and development have not been reported.

The photic environment influences the reproductive and developmental physiology of a predaceous insect, *Orius insidiosus* Say (Hemiptera: Anthoridae). This insect is used to control a serious insect pest, *Frankliniella occidentalis* Pergande (Thysanoptera: Thripidae), the western flower thrips, in greenhouse ornamental and vegetable production systems in the United States, Canada, and Europe (Parrella, 1995; Stack and Drummond, 1997). *F. occidentalis* causes economic loss by polyphagy and by vectoring lethal tospoviruses (Stack et al., 1997). Inundative releases of *O. insidiosus* have suppressed *F. occidentalis* infestations on chrysanthemum (Fransen and Tolsma, 1992). However, *O. insidiosus* undergoes a facultative reproductive diapause if the photoperiod is shorter than ≈ 13 h (Ruberson et al., 1991). As a result, this potentially effective biological control agent has not been recommended for release on north temperate fall- and winter-grown greenhouse crops, including chrysanthemum.

Various methods are used to manipulate photoperiod in order to enhance flowering in short-day plants and to prevent diapause in long-day insects. Black shade cloth is used to shorten daylength to promote flowering (Post, 1934). Diapause may be averted in arthropods used as biological control agents in greenhouses by extending daylength with broad spectrum artificial light (Gilkeson and Hill, 1986) or by identifying strains, clinal variants, or geographic races that have a shorter than normal critical photoperiod for diapause induction (Taylor and Spalding, 1986). Manipulating light quality has largely been ignored in applied efforts to prevent diapause. Stack and Drummond (1997) found that a blue light-supplemented long day of 9-h broad spectrum light and 6-h low-intensity ($\approx 0.98 \text{ W}\cdot\text{m}^{-2}$) blue-biased (400–500 nm) light prevented reproductive diapause induction in *O. insidiosus*. If a similar blue light regime does not adversely affect flowering in chrysanthemum, then an important deterrent to a year-round biological control strategy of certain pests on short-day greenhouse crops may be removed. The objective of this research was to determine the effect of blue light on flower initiation and development and on vegetative growth in *D. grandiflora*.

Materials and Methods

Experiment 1. We assessed the effect of a continuous photoperiod and supplemental blue light at two intensities on chrysanthemum flowering and vegetative growth. One hundred rooted cuttings each of 'Manatee Iceberg' and 'Naples', cut flower chrysanthemum

mums with 10- and 8-week responses, respectively, were obtained from a commercial propagator (Yoder Brothers, Barberton, Ohio) on 16 Dec. 1994. Plants were grown in a soilless medium (Fafard 3B; Conrad Fafard, Agawam, Mass.), one per 10.16-cm-diameter standard pot. Osmocote 14N-14P-14K (Scotts-Sierra, Marysville, Ohio) at $7 \text{ kg} \cdot \text{m}^{-3}$ was incorporated into the medium. Plants were exposed to 8- to 9-h ambient light (PPF ranged from 200 to $450 \mu\text{mol} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$) supplemented with 8-h artificial light ($PPF \approx 450 \mu\text{mol} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$) from 400-W high-pressure sodium lamps (P&L Lighting Systems, Quebec, Canada) for 21 d to promote vegetative growth. On 7 Jan., 45 uniform plants of each cultivar were selected for the experiment. Each plant's main shoot was pinched back to seven nodes to promote axillary shoots, thereby increasing flower number.

Fifteen enclosure frames, each $0.75 \times 0.75 \times 1.2 \text{ m}$, were constructed from schedule 40 polyvinyl chloride (PVC) to isolate groups of plants for the designated light regimes. All frames, except for the artificial short-day regime frames, were equipped with lamp receptacles into which 9-W lamp holders (ballast base G23; Osram, Montgomery, N.Y.) were inserted. The lamps were suspended 80 to 90 cm above the plants during the experiment. A common time clock provided identical exposures of supplemental light. Black cloth was pulled over each frame at 1700 HR and removed at 0800 HR each day of the experimental period.

Temperature and humidity were monitored daily inside and outside the enclosures. Temperature ranged from 15 to 27°C , with a daily mean of 21.5°C . Radiational warming and cooling inside the frames were negligible ($\pm 1^\circ\text{C}$) compared with the temperature outside the frames. Relative humidity ranged from 40% to 90%. Plants were fertilized weekly with 15N-16P-17K (Scotts-Sierra, Marysville, Ohio) at $250 \text{ mg} \cdot \text{L}^{-1} \text{ N}$, beginning 22 d after potting and ending at the penultimate week of the response period for each cultivar.

The experimental design was a split-plot randomized complete block with five light regimes (main plots), two cultivars (split plots), and three replicate blocks. Six plants, three of each cultivar, were randomly placed within each frame. Three of the photoperiod regimes were continuous and were partially established in the PVC frames. These consisted of 9-h ambient light and 15-h broad spectrum (Fig. 1A) fluorescent light (9-W lamp F9TT/27K Dulux S; Osram) at an average intensity of $3.6 \mu\text{mol} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$, and 9-h ambient light and 15-h blue-biased (Fig. 1B) fluorescent light (9-W lamp F9TT/Blue Dulux S; Osram) at two different average intensities (3.6 and $7.0 \mu\text{mol} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$). The fourth and fifth regimes were a 9-h ambient light short day maintained by black cloth, and an ambient short day. Lamp intensities, measured as photosynthetic photon flux (PPF) with a LI-190SA quantum sensor (LI-COR, Lincoln, Nebr.), were determined at plant canopy on 7 Jan. and 4 Feb. and these values were averaged. The range of ambient PPF during the experimental period was measured. The spectral photon flux of the

Fig. 1. Spectral energy distributions for: (A) the 9-W broad spectrum fluorescent lamp; (B) the 9-W blue-biased fluorescent lamp; and (C) the 9-W blue-biased fluorescent lamp with one, two, or three blue cinemoid filter overlays. Scales on the Y-axis differ due to the particular total energy output from the various wavebands in the three experimental lamps.

Table 1. Plant responses reported for each of the light regimes in Expt. 1 for the cut flower chrysanthemums 'Manatee Iceberg' and 'Naples' and in Expt. 2 for the cut flower chrysanthemum 'Naples' and the pot flower chrysanthemum 'Boaldi', and the week in the flowering response period when data were recorded.

Photomorphogenic response	Cultivar	Week
Axillary branches with flower buds ^z	Manatee Iceberg	4
	Naples	4
Total flower number ^y	Manatee Iceberg	10
	Naples	8
Terminal flower diameter ^x	Boaldi	8
	Manatee Iceberg	10
Plant height ^w	Naples	8
	Boaldi	8
	Manatee Iceberg	4
	Naples	4
Dry mass ^v	Boaldi	4
	Manatee Iceberg	10
	Naples	8
	Boaldi	8

^zNumber from a maximum of seven nodes was counted. Axillary flowering branches were not counted in Expt. 2, as all plants in the short-day regime initiated flowers.

^yAll flower buds $> 5 \text{ mm}$ in diameter were counted.

^xTerminal flower diameter was measured on the three distal branches.

^wHeight was measured from the basal leaf node to the plant apex.

^vDry mass was recorded for flowers, leaves, and stems.

lamps was determined from 300 to 850 nm in 1-nm steps with a LI-1800 spectroradiometer (LI-COR).

Light regimes were initiated on 7 Jan. when daylength in Orono, Maine, was ≈ 9 h. Expt. 1 ended for 'Naples' on 3 Mar. when daylength was ≈ 11 h 10 min and for 'Manatee Iceberg' on 17 Mar. when daylength was ≈ 12 h. These ambient daylengths promote flower initiation and development in chrysanthemum. The photomorphogenic responses measured for each cultivar are summarized in Table 1.

Experiment 2. We assessed whether shortening photoperiod, reducing light intensity, and filtering out long spectral wavelengths of the experimental lamps improved chrysanthemum flower development. Cultivar selection was based on treatment responses observed in Expt. 1. We chose the cut flower cultivar yielding greater flower production, as well as a pot flower cultivar.

Fifty rooted cuttings each of 'Naples' and 'Boaldi', an 8-week pot flower chrysanthemum, were obtained from the same source as in Expt. 1. Pot size, medium, planting method, and fertilizer regimes were as described for Expt. 1. Plants were exposed to 10-h ambient light (PPF ranged from 300 to $650 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$) supplemented with 6-h artificial light ($PPF \approx 450 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$) from 400-W high-pressure sodium lamps (P&L Lighting Systems, Quebec, Canada) for 21 d.

On 16 Apr. 1995, 36 uniform plants of each cultivar were selected for the experiment. Each plant's main shoot was pinched back to seven nodes. Eighteen PVC frames (see Expt. 1) were used to isolate groups of plants for the designated light regimes. The lamps were suspended 80–90 cm above the plants during the experiment. A common time clock provided identical exposures of supplemental blue light. Black cloth was pulled over each frame at 1700 HR and removed at 0800 HR each day of the experimental period.

Temperature and humidity were recorded daily inside and outside the enclosures. Temperature ranged from 16 to 29°C , with a daily mean of 22°C . Radiational warming and cooling inside the frames were negligible. Relative humidity ranged from 35% to 85%. Fertilizer was applied as in Expt. 1, starting on day 22 and ending at week 7.

The experimental design was a split-plot randomized complete block with six light regimes (main plots), two cultivars (split plots), and three replicate blocks. Four plants, two of each cultivar, each in a separate pot, were randomly placed within each PVC frame. The four light regimes were a 15-h photoperiod of 9-h ambient light and 6-h blue-biased (Fig. 1B) fluorescent light (9-W lamp F9TT/Blue Dulux S; Osram), at one of four different average intensities (0.4, 0.7, 1.6, and $3.5 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$). Intensities were altered and red spectral wavelengths were reduced (Fig. 1C) by overlaying one, two, or three cinemoid filters (Roscolux "Night Blue"; Rosco, Port Chester, N.Y.) on the blue lamp. The other two light regimes were a 9-h ambient light short day maintained by black cloth and an ambient long day of at least 13.75 h. Lamp intensities

Fig. 2. Effect of several light regimes on morphogenesis in 'Manatee Iceberg' and 'Naples' chrysanthemum (Expt. 1). Light regimes consisted of a long-day (LD) of 9-h ambient light and 15-h blue-biased fluorescent light at 1) $3.6 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ or 2) $7.0 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$; 3) a LD of 9-h ambient light and 15-h broad spectrum fluorescent light at $3.5 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$; 4) a short-day (SD) of 9-h ambient light and 15-h of black cloth; and 5) a SD of varying photoperiods of ambient light. Morphogenic responses measured were (A) number of axillary flowering shoots from a maximum of seven nodes; (B) total number of flowers >5 mm in diameter; (C) diameter of terminal flowers on the three distal branches; (D) total flower dry mass; (E) total stem dry mass; (F) total leaf dry mass; and (G) plant height from the basal leaf node to the apex. Separation of means within cultivars for interactive effects are by SNK at $P \leq 0.05$. Separation of means of simple treatment effects are by SNK at $P \leq 0.05$. Data are averaged over cultivar whenever the cultivar effect was nonsignificant.

were determined as in Expt. 1 at plant canopy on 16 Apr. and 14 May and these values were averaged. The range of ambient PPF and the spectral photon flux were determined as in Expt. 1.

Light regimes were initiated on 16 Apr. when daylength in Orono, Maine, was ≈ 13 h 45 min. Expt. 2 ended on 11 June when daylength was ≈ 15 h 30 min. The beginning daylength was less than the 14.5-h critical photoperiod for chrysanthemum flower initiation, and all experimental photoperiods, with the exception of the black cloth-maintained 9-h light regime, were greater than the 13.5-h

critical photoperiod for chrysanthemum flower development. The photomorphogenic responses measured for each cultivar are summarized in Table 1.

Statistical analysis. Data for both experiments were analyzed with univariate analysis of variance (Abacus Concepts, 1989). Means within cultivars that differed by a significant F-ratio were separated with the Student-Newman-Keuls (SNK) test ($P \leq 0.05$). Where no significant interactions occurred, but simple treatment effects were observed, the treatment means for each cultivar were pooled and then separated with SNK ($P \leq 0.05$).

Results

Experiment 1

Number of axillary shoots with flower buds. Visual inspection for macroscopic flower buds during week 4 indicated that flowers were produced in all light regimes with the exception of the broad spectrum long day. In this light regime, 'Naples' had an average of 2.9 shoots with terminal crown buds (Fig. 2A). There was a significant light regime $\times$ cultivar interaction ($F_{(4,10)} = 7.53$, $P = 0.005$). In the lower intensity blue light, both cultivars had a similar number of flowering shoots as in the ambient and black cloth short-day regimes. 'Naples' produced the same number of flowering shoots in the higher intensity blue light regime as in the short-day regimes, whereas 'Manatee Iceberg' had fewer flowering shoots in the higher intensity blue light than in the short-day regimes.

Total number of flowers. Again, light regime $\times$ cultivar interaction was significant ($F_{(4,10)} = 12.85$, $P = 0.001$) (Fig. 2B). In 'Manatee Iceberg', the greatest number of flowers per plant developed in ambient short days, with no differences between the lower intensity blue light regime and the black cloth short-day regime. In contrast, no differences were observed between the lower intensity blue light regime and either of the short-day regimes in 'Naples'. 'Naples' produced more flowers than 'Manatee Iceberg' in higher intensity blue light; however, both cultivars yielded fewer flowers in this regime than in lower intensity blue light or in either of the short-day regimes.

Flower diameter. Light regime by cultivar interaction was nonsignificant for flower diameter ($F_{(4,8)} = 2.16$, $P = 0.15$), but there was a significant light regime effect ($F_{(4,8)} = 52.32$, $P = 0.0001$) (Fig. 2C). Mean flower diameter was greatest in plants in short-day ambient light. The black cloth short-day yielded larger flowers than the supplemental blue light regimes, which did not differ from each other. Doubling the intensity of blue light did not reduce flower size.

Dry mass. Light regime $\times$ cultivar interaction was evident in flower dry mass ($F_{(4,10)} = 6.51$, $P = 0.008$) (Fig. 2D) and stem dry mass ($F_{(4,10)} = 4.07$, $P = 0.04$) (Fig. 2E). The ambient and black cloth short-day plants had the greatest flower dry mass in both cultivars. 'Naples' flower dry mass was greater in the lower than in the higher intensity blue light. No difference was observed between the blue light regimes in 'Manatee Iceberg'. More variation was observed among plants exposed to the short-day light regimes and the supplemental blue light regimes in 'Manatee Iceberg' than in 'Naples'. For both cultivars, stem dry mass was inversely proportional to flower dry mass (Fig. 2D and E). 'Manatee Iceberg' had similar stem dry mass in the broad spectrum and blue light regimes, whereas values were lower in the two short-day regimes. A similar trend was observed in 'Naples', except that plants in the lower intensity blue light had stem dry masses intermediate between those in the broad spec-

Fig. 3. Effect of several light regimes on morphogenesis in 'Manatee Iceberg' and 'Naples' chrysanthemum (Expt. 2). Light regimes consisted of a long-day (LD) of 9-h ambient light and 6-h blue-biased fluorescent light at 1) 3.5, 2) 1.6, 3) 0.7, or 4) 0.4 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$; 5) a short-day (SD) of 9-h ambient light and 15-h of black cloth; and 6) a LD of varying photoperiods of ambient light. Morphogenic responses measured were (A) total number of flowers > 5 mm in diameter; (B) diameter of terminal flowers on the three distal branches; (C) total flower dry mass; (D) total stem dry mass; (E) total leaf dry mass; and (F) plant height from the basal leaf node to the apex. Separation of means within cultivars for interactive effects are by SNK at $P \leq 0.05$. Separation of means of simple treatment effects are by SNK at $P \leq 0.05$. Data are averaged over cultivar whenever the cultivar effect was nonsignificant.

trum and short-day regimes. Leaf dry mass was greatest in plants in the broad spectrum and higher intensity blue light regimes ($F_{(4,8)} = 12.81$, $P = 0.001$) (Fig. 2F). Leaf dry mass was not affected by intensity of blue light but was less in the lower intensity blue light than in the broad spectrum regime. Plants in the short-day regimes had the least leaf dry masses.

Height. Prior to flower initiation, all plants were of equal height. The vegetative plants in the broad spectrum regime were taller at the

end of the response period than those in the other light regimes (Fig. 2G). No light regime $\times$ cultivar interaction was observed ($F_{(4,8)} = 1.19$, $P = 0.37$). Plants in the blue light regimes were similar in height, as were plants in the short-day regimes, but the former were taller.

Experiment 2

Total number of flowers. Flower buds were initiated in the cut flower 'Naples' and the pot

flower 'Boaldi' in all regimes, with the exception of long-day ambient light. Light regime $\times$ cultivar interaction was evident in number of flowers ($F_{(5,12)} = 7.63$, $P = 0.002$) (Fig. 3A). 'Naples' had the same number of flowers in all light regimes that resulted in flower initiation; however, 'Boaldi' produced more flowers in the lowest intensity blue light ($0.4 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$), whereas differences among other blue light regimes and the short-day regime were non-significant. The ambient long day resulted in no flowering in either cultivar. 'Boaldi' produced more flowers than 'Naples' whenever flowering occurred.

Flower diameter. No light regime $\times$ cultivar interaction was observed affecting flower size ($F_{(5,12)} = 2.63$, $P = 0.08$) (Fig. 3B), but there was a significant light regime effect ($F_{(5,12)} = 560.5$, $P = 0.0001$). Plants in the lowest intensity blue and short-day light regimes produced the largest flowers, while the highest intensity ($1.6 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$) and the intermediate intensity ($0.7 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$) filtered blue light regimes yielded mean flower diameters similar to those in the short-day light regime. 'Boaldi' produced larger flowers than 'Naples' in all flower-producing light regimes ($F_{(1,12)} = 15.77$, $P = 0.001$).

Dry mass. No light regime $\times$ cultivar interaction was observed for either flower ($F_{(5,12)} = 2.25$, $P = 0.12$) (Fig. 3C) or stem dry mass ($F_{(5,12)} = 1.96$, $P = 0.18$) (Fig. 3D). The significant light regime effect for flower dry mass ($F_{(5,12)} = 87.2$, $P = 0.0001$) resulted from the absence of flowering in the long-day regime. Flower dry masses in all other light regimes were similar. Flower dry mass was greater in 'Boaldi' than in 'Naples' across all flower-producing treatments ($F_{(5,12)} = 35.7$, $P = 0.0001$). The vegetative plants in the ambient long-day regime produced the greatest stem dry mass ($F_{(5,12)} = 84.3$, $P = 0.0001$), while no differences were observed for stem mass in any of the other light regimes. In 'Naples', no differences between any blue light regime and the short-day regime were significant for leaf dry mass, whereas in 'Boaldi' leaf dry mass was greater in the lowest than in the highest intensity blue light ($F_{(5,12)} = 131.7$, $P = 0.0001$) (Fig. 3E). No difference was observed between any filtered blue light regime and the short-day regime. The ambient long day resulted in the greatest leaf dry mass in both cultivars.

Height. Prior to flower initiation, all plants were of equal height. Light regime $\times$ cultivar interaction was again significant ($F_{(5,12)} = 6.73$, $P = 0.003$) (Fig. 3F). 'Naples' was shorter in all blue light regimes than in the short-day regime, and plants in the blue light regimes were similar in height. Under short days, 'Boaldi' plants were similar in height to plants in all blue light regimes. The long-day ambient regime resulted in the tallest plants in both cultivars.

Discussion

In a 24-h photoperiod under broad spectrum light (Expt. 1), crown buds were initiated in 'Naples', but no flowers developed in either

cut flower cultivar. These results are similar to those of previous studies in which chrysanthemum was exposed to continuous irradiance (Cockshull, 1976; Cockshull and Kofranek, 1985; Stefanis and Langhans, 1983; Warrington and Norton, 1991). All blue light and short-day regimes induced flowering but flower development varied considerably. Supplemental blue light at an intensity of $\approx 3.6 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ was not limiting for 'Manatee Iceberg' or 'Naples' in comparison with the black cloth short-day regime (Fig. 2 A and B). However, at a blue light intensity of $\approx 7.0 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$, 'Manatee Iceberg' produced fewer flowering shoots and flowers than in the short-day regimes. This reduction in flower initiation in 'Manatee Iceberg' and in flower number in 'Naples' in the higher intensity light regime, suggests a total light energy (energy $\times$ time) effect (Salisbury, 1963), with accumulated light energy having a negative effect on flower initiation at the spectral wavelengths designated in Fig. 1B. This effect may be due to contaminating red light emission from the blue-biased lamp or to the effect of intensity saturation from two lamps. However, 'Naples' appeared to be less sensitive to these conditions than 'Manatee Iceberg'.

Flower size and dry mass can be used as indicators for flower development and as measures of plant quality and marketability. Although flower initiation in plants exposed to the lower intensity supplemental blue light regime in Expt. 1 was similar to that in the black cloth short-day regime, the same trend for flower size and dry mass was not observed (Fig. 2 C and D). Flower development was negatively affected by increasing light intensity. Both blue light regimes reduced flower dry mass in comparison with the short-day regimes.

There was a negative relationship between flower production and vegetative mass and height (Fig. 2D–G). Subsequent to flower initiation, energy in the plant is directed into reproductive tissue while vegetative organs are secondary sinks for assimilates (Cockshull and Hughes, 1971). Height differences were greater in the broad spectrum long-day regime than in all other regimes (Fig. 2G). Plants exposed to either intensity of supplemental blue light were taller than those in the short-day regimes. A so-called "high irradiance reaction" (HIR) to long exposures of low-intensity blue light reportedly inhibits stem elongation (Thomas, 1981). Our results do not appear to confirm this blue light response, although our experimental light intensities were extremely low.

In Expt. 1, neither supplemental blue light regime produced a finished crop equal to those in the short-day regimes. Flower initiation and development data indicated that chrysanthemum flowering responses were sensitive to varying wavelengths and intensities of blue light. There was a differential cultivar response to supplemental blue light in a continuous photoperiod (Fig. 2 A, B, D, and E). In Expt. 2, reducing intensity by overlaying blue filters on blue lamps at blue light intensities

$\leq 1.6 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ had an effect on flowering equal to or better than that of the black cloth short-day regime (Fig. 3 A, B, and C). The cinemoid filters decreased total light energy and effectively eliminated the emission of red light from the blue-biased lamp (Fig. 1C). Flower size and dry mass of 'Naples' and 'Boaldi' were similar in the blue light regimes (Fig. 3 B and C). A significant light regime $\times$ cultivar interaction occurred for flower number, leaf dry mass, and plant height. Other studies have reported differential cultivar responses to changes in the photic environment (Langton, 1977; McMahon et al., 1991).

For 'Naples' in the black cloth short-day regime, an average of 48% more flowers and 39% greater dry mass were observed in Expt. 2 than in Expt. 1. The difference in flowering responses in the two experiments could be due to the different ranges in ambient PPF over the experimental period (200 to $550 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ in Expt. 1; 300 to $750 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ in Expt. 2). The number and size of flower buds and the rate of flower development in chrysanthemum and other plants increase with either PPF or daily quantum integral (Warrington and Norton, 1991). Under higher PPF in Expt. 2, plants produced more and larger flowers. The greater flower diameter and dry mass in 'Naples' in black cloth short-day light regimes in Expt. 1 suggest an influence of different PPF levels. Our analyses show trends and relative comparisons of treated plants at the morphological growth stages observed, but we have not attempted to explain the physiological basis of these results.

In Expt. 2, plants in all blue light regimes were as short or shorter than plants in the black cloth short-day regime (Fig. 3E). Whether or not this was a blue light response is unknown, as our data do not allow us to draw definite conclusions. However, if supplemental blue light reduces plant height, it would be a desirable response in the production of many pot chrysanthemum cultivars (Erwin and Heins, 1995).

The effects of light quality, intensity, and total radiant energy in the photic environment have important implications for the application of supplemental lighting to chrysanthemum in a short-day greenhouse production system and to a biological control strategy recommended for controlling western flower thrips (Stack and Drummond, 1997). Our data indicate that chrysanthemum exposed to 6-h blue-biased light (Fig. 1 B and C) in a 15-h photoperiod at intensities $< 3.5 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$, at tested PPF levels, flower as well and are of the same quality as plants grown in conventional short-day production conditions. However, the results also suggest that higher doses of blue light may reduce flower size and dry mass. The blue-biased fluorescent lamps tested are readily available, powered with 120-V AC, and can be easily incorporated into existing greenhouse lighting systems. Based only on the two cut flower and one pot flower chrysanthemum cultivars tested, results indicate the need for screening specific cultivars for their adaptability to this supplemental blue light system.

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