Research Reports

End-of-Day Lighting Effects on Herbaceous Perennials Grown Under Night Interrupted Lighting Outdoors in the Southern United States[1]

Gary J. Keever[2], J. Raymond Kessler, Jr.[2] and James C. Stephenson[3]
Department of Horticulture
Auburn University, AL 36849

Abstract

A study was conducted in 2004 to determine if end-of-day lighting (EOD) alone or in combination with night-interrupted lighting (NIL) could be used to suppress stem elongation of 'Goldsturm' coneflower (*Rudbeckia fulgida* Aiton 'Goldsturm'), 'Moonbeam' coreopsis (*Coreopsis verticillata* L. 'Moonbeam') and 'Early Sunrise' coreopsis (*Coreopsis grandiflora* Hogg ex Sweet. 'Early Sunrise') when grown outdoors under nursery conditions in the southern U.S. without negating the benefits of earlier flowering from NIL. End-of-day lighting, NIL, and the combination of the two treatments accelerated time to flowering of all three cultivars compared to that of plants under a natural photoperiod (NP); however, rudbeckia flowered quicker when exposed to NIL or NIL + EOD than when grown under EOD only. Height of rudbeckia grown under EOD or NIL was greater than that of plants grown under NP, whereas 'Moonbeam' coreopsis exposed to EOD, NIL or EOD + NIL were similar in height and taller than plants grown under NP. Height of 'Early Sunrise' coreopsis was minimally affected by treatments, except that plants under EOD were shorter than those under EOD + NIL. Growth index, flower number, shoot length and quality rating were similar in almost all cases for plants of the three cultivars when grown under EOD lighting, NIL, or EOD + NIL. These results indicate EOD was ineffective in suppressing height growth and provided no benefit, either alone or in combination with NIL, over NIL alone in the accelerated production of these cultivars outdoors under nursery conditions.

Index words: flower induction, forcing, height control, long-day plant, container production, nursery production.

Species used in this study: 'Goldsturm' coneflower (*Rudbeckia fulgida* Aiton 'Goldsturm'); 'Moonbeam' coreopsis (*Coreopsis verticillata* L. 'Moonbeam'); 'Early Sunrise' coreopsis (*Coreopsis grandiflora* Hogg ex Sweet. 'Early Sunrise').

Significance to the Nursery Industry

Long-day herbaceous perennials like 'Goldsturm' coneflower (*Rudbeckia fulgida* 'Goldsturm'), 'Moonbeam' coreopsis (*Coreopsis verticillata* ('Moonbeam') and 'Early Sunrise' coreopsis (*Coreopsis grandiflora* 'Early Sunrise') can be forced to flower out-of-season under greenhouse conditions by manipulating temperature and photoperiod. Growers in the southern United States have a similar opportunity for early forcing without adversely affecting flower and flower bud counts by exposing plants to night-interrupted lighting (NIL) outdoors from 10 pm to 2 am. However, NIL using incandescent lamps can promote excessive shoot

[1]Received for publication October 17, 2012; in revised form November 21, 2012.

[2]Professors. keevegj@auburn.edu and kessljr@auburn.edu.

[3]Associate Director, Ornamental Horticulture Research Center, Mobile, AL. stephjc@auburn.edu.

The *Journal of Environmental Horticulture* (ISSN 0738-2898) is published quarterly in March, June, September, and December by the Horticultural Research Institute, 1200 G Street NW, Suite 800, Washington, DC 20005. Subscription rate is $75.00 per year for scientists, educators and ANLA members; $120.00 per year for libraries and all others; add $25.00 for international (including Canada and Mexico) orders. Periodical postage paid at Washington, DC, and at additional mailing offices. POSTMASTER: Send address changes to Journal of Environmental Horticulture, 1200 G Street NW, Suite 800, Washington, DC 20005.

elongation. End-of-day light extension (EOD) using a light source with a high red to far-red ratio (R:FR ratio), such as high-pressure sodium lamps, has been effective in suppressing shoot elongation of numerous greenhouse crops. However, in the nursery production of several herbaceous perennials outdoors under natural and night-interrupted lighting conditions, EOD failed to suppress height growth and provided no added benefit in growth or flowering to that provided by NIL.

Introduction

Flowering is controlled by internal and external factors, including exposure to low temperatures (vernalization) and photoperiod (3, 24, 26). Vernalization promotes flowering at subsequent higher temperatures (25), and even when vernalization is not required for flowering, many herbaceous perennials benefit from cold exposure by earlier or heavier flowering (1, 2, 5). Photoperiod is a reliable environmental signal for flower induction that has been artificially manipulated by greenhouse growers to keep plants vegetative or induce flowering. Under natural short days (SDs), night-interrupted lighting (NIL) from 10:00 pm to 2:00 am generally is recommended to induce flowering of long-day plants (LDPs) (1, 2, 5), including the qualitative LDPs, 'Moonbeam' coreopsis (*Coreopsis verticillata* 'Moonbeam') (9), 'Early Sunrise' coreopsis (*Coreopsis grandiflora* 'Early Sunrise') (28), and 'Goldsturm' coneflower (*Rudbeckia fulgida* 'Goldsturm') (29). In quantitative LDPs, long days are not required to induce flowering, but are beneficial in either hastening the rate of flowering or increasing the number of flowers (1, 2). Incandescent lamps are most commonly used to create long days because they are inexpensive and easy to install. However, incandescent lamps are rich in far-red light, the part of the spectrum that promotes stem elongation (11).

While the above cited photoperiod research was conducted in greenhouses or in growth chambers under climate controlled conditions, similar responses were reported in LDPs grown outdoors under nursery conditions in the southeastern United States where environment control was lacking (13, 16). Coastal states in the South, primarily in USDA hardiness zone 8, experience cool nights and mild days in late winter that provide ideal conditions for growing many herbaceous perennials. When NIL was initiated outdoors at different times in late winter and continued until visible floral development, flowering of 'Goldsturm' coneflower was accelerated by 26 to 46 days in 1999 and by 51 to 75 days in 2000 when compared to plants grown under a natural photoperiod (NP) (13). Night-interrupted lighting accelerated time to flower and increased flower counts of 'Moonbeam' coreopsis by 7 to 36 days and 20 to 244%, and of 'Early Sunrise' coreopsis by 3 to 20 days and 26 to 64%, respectively (16). However, 'Goldsturm' coneflower grown under NIL was 18 to 23% (1999) and 48 to 52% (2000) taller than plants under natural photoperiods (NP) at anthesis, and plant quality rating was lower in both years because of excessive plant height. Similarly, 'Moonbeam' and 'Early Sunrise' coreopsis under NIL were up to 155 and 46%, respectively, taller than plants under NP. Multiple applications of the plant growth retardants (PGRs) B-Nine (daminozide) at 5000 or 7500 ppm mixed with Cycocel (chlormequat chloride) at 1500 ppm, or single applications of 40 or 60 ppm Sumagic (uniconazole) were most effective in suppressing height growth of 'Moonbeam' coreopsis and 'Goldsturm' rudbeckia grown outdoors under NIL when timed to periods of rapid shoot elongation (14). However, the use of PGRs during the production of potted crops is an environmental concern (17).

Limited inductive photoperiod (LIP), a method of giving plants the minimum number of inductive cycles to initiate flowering before transferring them back to non-inductive conditions, has promoted flowering in LD plants, but inhibited bolting-related stem elongation upon transfer back to short-day photoperiods. *Rudbeckia hirta* 'Marmalade' that received only enough LDs for floral initiation were half as tall as plants held under LDs until anthesis (20). Similarly, LIP effectively controlled height of 'Sunray' and 'Early Sunrise' coreopsis by inhibiting stem elongation without affecting scape length or axillary floral bud number, although flowering was delayed compared to plants grown in continuous LDs (6, 7). LIP effects on height of 'Moonbeam' and 'Early Sunrise' coreopsis and 'Goldsturm' coneflower' grown outdoors under nursery conditions in the southern U.S. were mixed, although at least one duration of LIP resulted in earlier flowering of the three cultivars, and plants were similar to or shorter than plants under NP (15).

Manipulation of light quality may also be a viable option for controlling plant height. Plants absorb photons in the red (R) and far-red (FR) regions of the spectrum by a photoreversible receptor called phytochrome. Action of phytochrome is dependent on the relative amounts of the active (P_{FR}) and inactive (P_R) forms established in the tissues and positively correlates with the R/FR ratios in a wide range of light conditions (22). Low R/FR ratios induce several responses in plants including a promotion of internode, petiole, and leaf elongation; a strengthening of apical dominance; and a reduction in branching (23). In contrast, high R/FR ratios suppress internode elongation and promote branching (21).

A decrease in the R:FR ratio at the end of the day occurs naturally during twilight, from about 1.2 during daylight to 0.7 during twilight (12). This change has been shown to increase stem elongation in several species comparable to end-of-day far-red (EOD-FR) treatments (4). Conversely, eliminating twilight using blackout curtains resulted in a 10 to 25% decrease in height of Easter lilies compared to ambient (4). Similarly, low irradiance given at the EOD from a light source with a higher R:FR ratio suppressed height of *Chrysantheumum ×morifolium* 'Coral Charm' (17) and tomato transplants (8) when compared to plants exposed to EOD-FR light or ambient. The objective of this study was to determine if EOD-lighting from a source with a high R:FR ratio would suppress shoot elongation of LD-herbaceous perennials forced outdoors without negating the accelerated flowering of NIL.

Materials and Methods

Unbranched rooted cuttings of 'Moonbeam' coreopsis (*Coreopsis verticillata* 'Moonbeam')' and 'Goldsturm' coneflower (*Rudbeckia fulgida* 'Goldsturm') from 72-cell flats (Green Leaf Perennials, Lancaster, PA) were transplanted on December 17, 2003, into 2.8 liter (#1 trade) pots containing a milled pine bark:peat (3:1, by vol) substrate. The growth medium was amended per m^3 (yd^3) with 8.3 kg (14 lb) 17N-3P-10K (Osmocote 17-7-12, The Scotts Company, Marysville, OH/Everris NA, Dublin, OH, since 2011), 3.6 kg (6 lb) dolomitic limestone, 1.2 kg (2 lb) gypsum, and 0.9 kg (1.5 lb) Micromax (The Scotts Company/Everris NA, Dublin, OH). 'Moonbeam' coreopsis plants were 1 cm (0.4 in) tall and 3 cm (1.2 in) wide and rudbeckia plants were 1 cm (0.4 in) tall and 5 cm (2.0 in) wide when transplanted. 'Early Sunrise' coreopsis (*Coreopsis grandiflora* 'Early Sunrise') in 72-cell flats (Green Leaf Perennials) were held in an unheated greenhouse for 3 weeks to promote growth before being transplanted on January 24, 2004, into the same substrate and containers; at that time they were 4 cm (1.6 in) tall and 15 cm (6.0 in) wide. Plants were grown pot-to-pot outdoors in full sun through the winter under NPs at the Ornamental Horticulture Research Center, Mobile, AL (USDA cold hardiness zone 8b; 30.7° north latitude, 88.2° west longitude), and were watered as needed from overhead impact sprinklers. Pots were respaced as plants grew so that plant canopies did not overlap. Plants were covered with white polyethylene from December 21–23, 2003, due to predicted temperatures below –6.7C (20F). Low-temperature protection was not necessary at any other time during the study.

A night-interrupted lighting (NIL) block was established outdoors in the nursery area to provide a minimum of 10 foot-candles of light from 10:00 pm to 2:00 am. Sixty watt incandescent lamps were spaced 1.3 m (4 ft) on center within rows and 1.5 m (5 ft) between rows. Incandescent (INC) lamps emit a mixture of R and FR light that is very effective for photoperiod lighting. The output is rich in FR light with a R:FR ratio of about 0.52 (10). Photosynthetically active radiation at plant height, as measured with a LI-COR LI-6400 steady-state porometer (LI-COR Biosciences, Lincoln, NE), averaged 1.5 $\mu mol \cdot m^{-2} \cdot s^{-1}$ over the NIL area. An adjacent growing area was constructed similarly using 100 W high pressure sodium (HPS) lamps. These lamps delivered proportionately less FR than R light compared to INC, having a R:FR ratio of about 1.7 (10). HPS lighting was begun one hour before sunset and was continued for 4 hours [end-of-day lighting (EOD)]. A third lighting block was constructed that included both INC NIL and HPS EOD lighting. Space limitations prevented the replication of the lighting set-ups. On February 1, 2004, 40 plants of each cultivar were selected for uniformity and 10 plants of each cultivar were moved to each of the three lighting treatments (NIL, EOD, NIL + EOD), and 10 plants of each cultivar remained as unlighted controls. Black plastic curtains 1.8 m (6 ft) tall separated plants in the four treatments, and were far enough from all plants to provide no shading. Plant cultivars were treated as separate experiments, and all treatments included 10 single plants.

The dates of the first visible floral bud and first fully-opened flower (inflorescence) were recorded; first flower was considered as when ray flowers on the first inflorescence were fully reflexed. At first flower, flower and flower bud counts (except on 'Moonbeam' coreopsis), plant height from the substrate surface to the uppermost plant part, plant widths (widest and perpendicular to the widest), lengths of the three longest shoots, and quality rating were determined. Rather than actual flower and flower bud counts, flowering of 'Moonbeam' coreopsis was rated on the following scale: 1 = 0, 2 = 1 to 50, 3 = 51 to 100, 4 = 101 to 150, or 5 = >150 flowers and flower buds per plant. Quality rating varied slightly among the three cultivars but in general was as follows: 1 = dead; 2 = chlorotic foliage, excessive stem elongation or small plant, minimal flowers; 3 = light green foliage, excessive stem elongation or small plant, reduced flower count as compared to '4'; 4 = medium green foliage, less stem elongation and a larger plant than those rated '3', adequate flowers and flower buds; and 5 = dark green foliage, compact, full plant with more flowers and flower buds than plants with lower ratings. The quality rating scale, while subjective, was the consensus of four individuals and represented an effort to quantify and rank in one rating several factors that impacted overall plant quality: compactness, fullness, foliar color and flowering. All ratings were assigned by one person.

The homogeneity of variance assumption was tested for all responses using Levene's test and the ABS option in PROC GLM in SAS version 9.2 (SAS Institute, Cary, NC). An analysis of variance was then performed on data using PROC GLIMMIX and a completely randomized design model. Appropriate corrections for heterogeneity of variance were applied where Levene's test was significant with the GROUP option on the RANDOM statement in PROC GLIMMIX. Tukey's test was used to determine difference among least squares means. Flower number scale for 'Moonbeam' coreopsis and all quality ratings were analyzed using the multinomial probability distribution and a cumulative logit link; values presented in tables are medians for each treatment. All significances were at $\alpha = 0.05$.

Results and Discussion

Over the February to June 2004 duration of this study, average monthly temperatures in Mobile, AL, ranged from 2.4C (4.4F) below normal in February to 1.1C (1.9F) above normal in March (Table 1). Natural photoperiods at the initiation and termination of lighting treatments on February 1 and May 19, 2004, were 10 hr 44 min and 13 hr 48 min, respectively. Photoperiods for the first day of each month of February–June 2004 are provided in Table 1.

'Goldsturm' coneflower. Compared to NP, NIL and NIL + EOD lighting accelerated times to visible flower bud and first flower of 'Goldsturm' rudbeckia by 53 and 55 days, respectively (Table 2, Fig. 1), which is consistent with the earlier flowering of the same cultivar in other studies conducted outdoors under NIL (13, 14, 15, 16). Plants receiving only EOD lighting flowered 48 days before those under NP, but 7 days after plants that received NIL or NIL + EOD lighting. The 7-day delay, compared to plants exposed to NIL, may have been due to plants not receiving LDs until later than those under NIL. 'Goldsturm' rudbeckia is an obligate LD-plant with a critical photoperiod of ≥13 hr following vernalization and ≥14 hr in the absence of vernalization (29). The amount of chilling plants received prior to the initiation of treatments in this study is not known. Also, there is no

Table 1. Average monthly temperatures and departures from normal for Mobile, AL and photoperiod on the first day of each month from February through June 2004.

Month	Temperature[z] [C (F)]	Departure[y] [C (F)]	Photoperiod
February	9.4 (48.9)	–2.4 (–4.4)	10 h 44 min
March	16.6 (61.9)	1.1 (1.9)	11 h 33 min
April	18.1 (64.5)	–0.6 (–1.0)	12 h 31 min
May	23.1 (73.5)	0.1 (0.2)	13 h 23 min
June	26.2 (79.1)	0.0 (0.0)	14 h 1 min

[z]Temperatures measured 1.5 m (5 ft) above ground.

[y]Departures from normal (30-year average); temperature data provided by the NOAA, National Climatic Data Center.

Table 2. The effect of night-interrupted and end of day lighting on growth and flowering of coreopsis and rudbeckia.

Lighting treatments[z]	Days to visible bud	Days to first flower	Plant height (cm)	Growth index[y]	Flower number[x]	Shoot length (cm)[w]
			Rudbeckia fulgida 'Goldsturm'			
Natural daylength	124a[v]	153a	47.0b	46.1b	19c	9.5b
End of day	78b	105b	52.6a	48.1ab	28a	16.2a
Night-interrupted	71c	98c	49.5ab	44.8b	24ab	14.5a
Night-interrupted + End of day	71c	98c	53.4a	51.0a	21bc	15.1a
			Coreopsis verticillata 'Moonbeam'			
Natural daylength	77a	92a	22.2b	24.6b	1.5ns	5.2b
End of day	55b	80b	44.2a	46.3a	2.5	8.2a
Night-interrupted	54b	78b	45.4a	49.4a	2.5	8.2a
Night-interrupted + End of day	52b	77b	48.0a	49.7a	2.5	8.1a
			Coreopsis grandiflora 'Early Sunrise'			
Natural daylength	57a	85a	26.7ab	34.2ns	35ns	15.3b
End of day	46b	70b	25.7b	32.9	29	16.2ab
Night-interrupted	44b	68b	27.8ab	34.8	37	19.5a
Night-interrupted + End of day	44b	61c	29.6a	34.3	30	17.3ab

[z]Lighting treatments were begun February 1, 2004. End of day lighting provided for four hours by high pressure sodium lamps beginning one hour before sunset. Night-interrupted lighting provided by incandescent lamps from 10:00 PM to 2:00 AM.

[y]Growth index = (shoot height + widest width + width perpendicular to first width) / 3.

[x]Actual inflorescence counts made on "Goldsturm' and 'Early Sunrise'; 'Moonbeam' inflorescence counts were estimated using the scale: 1 = 0, 2 = 1–50, 3 = 51–100, 4 = 101–150, or 5 = >150. Data on 'Moonbeam' are medians. ns = not significant.

[w]The three longest shoots per plant were measured.

[v]Least square mean separation for variables within columns using Tukey's test at $\alpha = 0.05$.

direct comparison of chilling hours in a controlled environment and accrued chilling under fluctuating temperatures in an uncontrolled outdoor environment. In early February plants in the EOD treatment received <14 hr of light (NP on February 1 of 10 hr 44 min + 4 hr of EOD lighting begun 1 hr before sunset), although by February 11 the NP was 11 hr. Alternately, NIL may simply have been more effective than EOD lighting at inducing flowering of 'Goldsturm' rudbeckia, as it was with *Campanula isophylla* (19). Flower counts of plants exposed to EOD lighting were similar to those of plants exposed to NIL only and higher than those of plants given NIL + EOD lighting or of plants under NP. EOD exposure to a light source high in red light promoted increased flowering of roses (18) and tomato transplants (8), but it is unclear why the NIL + EOD treatment would not have also promoted increased flowering compared to the NP. NIL outdoors increased flowering of 'Goldsturm' rudbeckia in 2002 (14), but had no effect on flower counts in 1999, 2000 (except when NIL was begun February 1) (13) or 2003 (14), indicating the inconsistent effects of NIL outdoors on flower counts of this cultivar.

Plants exposed to EOD and NIL + EOD lighting were similar in height to those grown under NIL, but 12 and 14% taller, respectively, than plants grown under NP. The promotion of height growth in response to EOD lighting was unexpected and contrast with the suppression in height growth reported in other studies from a light source with a high R:FR ratio (17, 21). Similar heights of 'Goldsturm' rudbeckia exposed to NIL and NP is consistent with previous results in 2000 and 2003 with the same cultivar, but contrast with results from 1999 and 2002 when NIL stimulated height growth (13, 14). Growth index was similar for plants under NP and for those exposed to EOD lighting and NIL, but lower than that of plants exposed to EOD + NIL. The lengths of the three longest shoots per plant were similar for plants exposed to the three light treatments and greater than those on plants under NP. Again, there was no benefit from EOD lighting, either alone or in combination with NIL. Quality rating was similarly high for plants in all treatments, and all plants were considered marketable (data not shown).

'Moonbeam' coreopsis. Days to visible floral buds and full flower were accelerated similarly by NIL, EOD lighting and the combination of the two, an average of 23 and 14 days, respectively (Table 2, Fig. 1). The effectiveness of NIL in promoting earlier flowering of 'Moonbeam' coreopsis outdoors under nursery conditions is consistent with previous studies (13, 14, 15, 16). The similar response of plants under the three light treatments contrast with the response of 'Goldsturm' rudbeckia in which flowering was delayed by EOD only lighting, possibly because 'Moonbeam' coreopsis does not have a juvenile stage or because its critical photoperiod for flowering, 12 hr when chilled, is shorter than that of 'Goldsturm' rudbeckia (9). The EOD photoperiod at the beginning of treatments on February 1 was about 13 hr 44 min (Table 1). Like time to flower, plant height, growth index and shoot length were similar for plants exposed to the three light treatments and averaged 107, 97 and 57%, respectively, greater than the same attributes of plants grown under NP. Quality rating was similar for plants in all treatments, and all plants were considered marketable (data not shown). Consistent with 'Goldsturm' rudbeckia, 'Moonbeam' coreopsis did not benefit from EOD lighting alone or in combination with NIL.

'Early Sunrise' coreopsis. As with 'Moonbeam' coreopsis, days to visible floral buds of 'Early Sunrise' coreopsis was accelerated similarly by NIL, EOD lighting and the com-

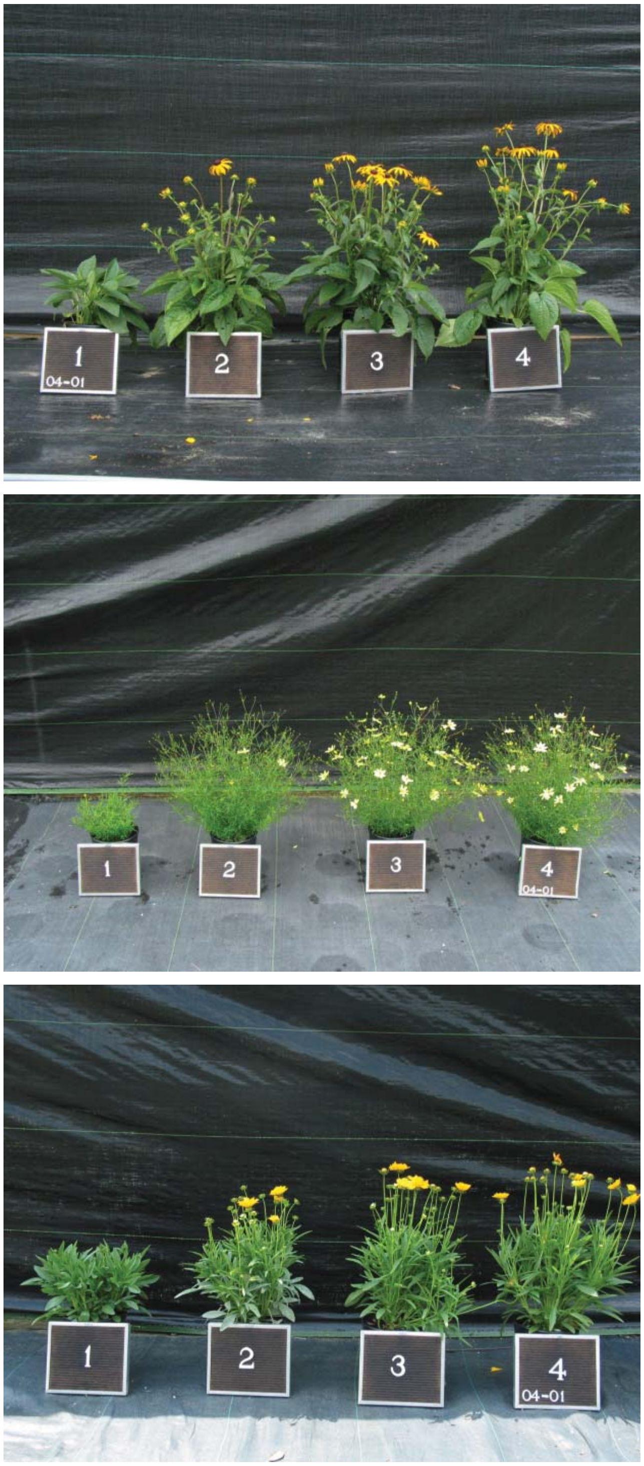

Fig. 1. ‘Goldsturm’ rudbeckia, ‘Moonbeam’ coreopsis, and ‘Early Sunrise’ coreopsis (top to bottom) 15, 13, and 10 weeks, respectively, after exposure to natural photoperiod (1), 4-hour, end-of-day photoperiod extension (EOD) from high pressure sodium lamps begun one hour before sunset (2), night-interrupted incandescent lighting (NIL) from 10 pm–2 am (3), and EOD + NIL (4) begun February 1, 2004.

bination of the two, an average of 12 days (Table 2, Fig. 1). Plants also reached first flower 16 to 24 days before those grown under NP; however, plants exposed to NIL + EOD lighting reached first flower 8 days before those exposed to EOD lighting or NIL only. ‘Early Sunrise’ coreopsis does not have a cold requirement for flowering (28) and has a relatively short juvenile stage, with plants having nine to 21 expanded leaves at the beginning of LDs flowering most rapidly (6). Plants in our test had more than nine expanded leaves at the start of LDs. ‘Early Sunrise’ coreopsis flowers most rapidly following the juvenile stage when exposed to photoperiods ≥14 hr (28), which is slightly longer than the photoperiod plants in the EOD were exposed to on February 1, but long enough to promote flowering as rapidly as NIL. There were only minor differences in plant height and shoot length among treatments. Plant height was similar for ‘Early Sunrise’ coreopsis exposed to NP, EOD lighting and NIL; only plants exposed to EOD + NIL were taller than those grown under EOD only lighting. The only difference among treatments for shoot length was longer shoots on plants exposed to NIL compared to NP. Flower counts ranged from 33 to 35 but were not affected by treatments. Similarly, median quality ratings ranged from 4.0 to 4.7 but were similar among all treatments (data not shown).

Results of this study indicate ‘Goldsturm’ coneflower, ‘Moonbeam’ coreopsis and ‘Early Sunrise’ coreopsis grown under naturally short days outdoors can be forced into flower earlier by 4-hr NIL from INC lamps, 4-hr EOD lighting from HPS lamps, or by a combination of the two, with only minor differences in response. However, EOD lighting with HPS lamps, a source high in R to FR light, was not effective in suppressing height growth of any of these cultivars when provided alone or in combination with NIL. These results were unexpected considering the extensive research showing the suppression of shoot elongation by EOD lighting with a source rich in red light (17, 18, 19, 21, 23), but consistent among the cultivars and consistent with the similar heights of ‘Moonbeam’ coreopsis exposed to 7-hr EOD lighting from HPS and INC lamps (27). The authors in this study evaluated several species and concluded that for at least some crops, use of lamps with a high R:FR ratio can reduce final plant height compared to lamps with a low R:FR. Based on our research, EOD lighting or EOD + NIL offered no benefit in flowering or compactness over NIL alone and a slight delay in flowering of ‘Goldsturm’ rudbeckia from EOD lighting compared to NIL alone. Previous studies evaluating the acceleration of flowering of herbaceous perennials outdoors under nursery conditions indicate excess shoot elongation promoted by NIL using an INC light source are best controlled using plant growth retardants (14), and to a lesser extent by using limited inductive photoperiods (15).

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