Cooling and Long-day Lighting Influences Growth and Flowering of *Phlox paniculata* L. ‘Ice Cap’ Used for Cut Flowers

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Abstract. In two studies, rooted cuttings of *Phlox paniculata* L. ‘Ice Cap’ (summer phlox) were cooled for 0, 4, 8, 12, or 16 weeks. Plants were forced in a glasshouse averaging 18 °C nights under extended-day and night-interruption lighting from incandescent lamps providing a minimum of 14 $\mu\text{mol}\cdot\text{s}^{-1}\cdot\text{m}^{-2}$ at plant level or continuous lighting from metal halide (HID) lamps providing a minimum of 400 $\mu\text{mol}\cdot\text{s}^{-1}\cdot\text{m}^{-2}$ at plant level. The influence of cooling duration on forcing days to flower, flowering stem counts, and flowering stem length was evaluated. Cooling plants promoted longer stems, higher flowering stem yields, and decreased days to flower when forced under long days provided by incandescent lamps, but when forced under HID lamps, days to flower for cooled plants were similar to those of noncooled plants regardless of cooling duration. Phlox forced in extended daylighting flowered in fewer days, had longer stems, and produced more flowering stems than those forced in night-interruption lighting. With continuous HID lighting, stem lengths and stems harvested per plant increased in a linear manner as cooling increased from zero to 16 weeks. Stem lengths ranged from 63.6 cm for noncooled plants to 96.3 cm for those receiving 16 weeks cooling, and flowering stem yields ranged from seven stems per plant for noncooled plants to 13 for those cooled 16 weeks. Phlox forced under HID lights flowered in substantially fewer days and had longer stems than those forced under incandescent lamps.

Phlox paniculata L., or garden phlox, is an herbaceous perennial in the family Polemoniaceae native to the eastern United States. Flowering stems of phlox are a popular item in cut flower markets because of their wide range of flower colors, large inflorescences, and pleasing fragrance (Armitage and Laushman, 2003). Plants may reach a height of 1.5 m, under favorable conditions, and the 2.5-cm diameter, tubular flowers are borne in dense, terminal cymes up to 20 cm across (Griffiths, 1994). It is a quantitative long-day plant with a critical photoperiod of ≈ 13 h. (Runkle et al., 1998); however, natural flowering occurs in mid- to late summer, well beyond the peak demand period for cut flowers.

Off-season greenhouse forcing of *P. paniculata* can allow growers to produce flowering stems during the most favorable marketing periods, and previous studies with *P. paniculata* showed that long-day photoperiods could induce flowering and cold treatment can accelerate flower development and increase length of the flowering stems (Iversen, 1989; Iversen and Weiler, 1994). The objec-

tive of these investigations was to determine the influence of cooling on the number of greenhouse days to flower, flowering stem length, and yield of cut flower stems of *P. paniculata* forced under incandescent and high-intensity discharge lighting.

Materials and Methods

Expt. 1. On 1 Oct., rooted shoot tip cuttings of *P. paniculata* ‘Ice Cap’ were received at Athens, GA, in plug trays (72 per tray). On 15 Oct., 50 plants were selected for uniformity and 10 plants were randomly apportioned to each of five cooling/lighting treatments in a 2×5 factorial study. Cooling treatments consisted of 0, 4, 8, 12, or 16 weeks at 2 to 4 °C with fluorescent lighting providing $\approx 4 \mu\text{mol}\cdot\text{s}^{-1}\cdot\text{m}^{-2}$ at plant height. Plants that were to receive cooling were placed in refrigeration on 15 Oct. and removed sequentially as the requisite number of cooling weeks was achieved. Plug trays were placed directly on cooler shelves and irrigated with tap water as needed during cooling. On removal from refrigeration, plants were planted in standard (33.2-L) plastic bulb crates in a commercial soilless root substrate (Fafard Mix No. 3-B; Conrad Fafard, Anderson, SC) at a density of 24 plants per meter squared. The crates were placed on benches in a glasshouse with temperature set points of 20 °C days and 18 °C nights. Plants that received zero weeks cooling were planted in

the aforementioned manner at the beginning of the study and placed directly into the forcing house. During the forcing period, all plants received 200 mg-L nitrogen as a constant liquid feed (Peters 15–0–15 Dark Weather Feed; The Scotts Co., Marysville, OH).

Plants from each cooling duration were randomly assigned to two long daylighting regimes for greenhouse forcing. Preliminary work by Garner (unpublished data) and Runkle et al. (1998) suggested that *P. paniculata* flowered poorly or not at all if long days were not provided. Long-day photoperiod was supplied as either night interruption (NI) from 2200 to 0200 HR (56 $\mu\text{mol}\cdot\text{d}^{-1}\cdot\text{m}^{-2}$ cumulative light) or extended day (ED) from 1700 to 2400 HR (98 $\mu\text{mol}\cdot\text{d}^{-1}\cdot\text{m}^{-2}$ cumulative light). Lighting was provided by incandescent lamps providing $\approx 14 \mu\text{mol}\cdot\text{s}^{-1}\cdot\text{m}^{-2}$ at plant height (Sylvania, St. Mary’s, PA). An automatic shade curtain providing $\approx 30\%$ light reduction set to deploy at 1000 $\mu\text{mol}\cdot\text{s}^{-1}\cdot\text{m}^{-2}$ was used throughout the study to control daily irradiance levels (Cravo Corp., Brantford, Ontario, Canada). Ventilation fans and an evaporative cooling system were used to maintain daytime temperatures. A computerized environmental control system (Q-Com, Irvine, CA) was used to regulate and integrate environmental control functions.

Flowering stems were harvested when the first flower in each inflorescence had reached anthesis. Cuts were made ≈ 6 cm above the plant base, generally leaving three or more nodes above the substrate. All flowering stems were harvested, and data collected at harvest were flowering stem length, measured from the base to the apex of the inflorescence, and days to flower from the beginning of greenhouse forcing. Total yield from each plant was calculated for stems harvested from the beginning until the study was ended on 10 June, when daily temperature maxima exceeded the ability of the greenhouse environmental control systems to maintain the desired environmental parameters.

Data were analyzed using analysis of variance and regression analysis (SAS Institute, Cary, NC). Cooling treatments were evaluated to determine linear and quadratic trends within photoperiod treatments.

Expt. 2. In the first experiment, cooled plants were placed in the greenhouse on different dates, depending on cooling duration. A second experiment was conducted in which all plants received the same amount of postcooling time in the greenhouse regardless of cooling duration. In September, shoot tip cuttings of *P. paniculata* ‘Ice Cap’ were rooted in plug trays (72 per tray). One hundred plants were selected for uniformity, and 20 single-plant replicates were randomly apportioned to each of five cooling treatments in a completely randomized design. Cooling treatments consisted of 0, 4, 8, 12, or 16 weeks at 2 to 4 °C with fluorescent lighting providing $\approx 4 \mu\text{mol}\cdot\text{s}^{-1}\cdot\text{m}^{-2}$ at plant height. Plants to receive 16 weeks cooling were placed in refrigeration on 15 Oct. and other

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treatments remained in the greenhouse until placed in the cooler at 4-week intervals thereafter. Plug trays were placed directly on cooler shelves and irrigated with tap water as needed during cooling. After receiving the requisite number of cooling weeks, all treatments were planted on 15 Feb. in standard (33.2-L) plastic bulb crates in a commercial soilless root substrate (Fafard Mix No. 3-B; Conrad Fafard) at a density of 24 plants per meter squared. The crates were placed on benches in a glasshouse with temperature set points of 20 °C days and 18 °C nights. During the forcing period, all plants received 200 mg·L⁻¹ nitrogen as a constant liquid feed (Peters 15–0–15 Dark Weather Feed; The Scotts Co.). Continuous lighting (24 h/d) was provided by 400-W metal halide high-intensity discharge (HID) lamps (MH400/U; Phillips Lighting Co., Somerset, NJ) providing a minimum of 200 μmol·s⁻¹·m⁻² at plant level (17.3 mol·d⁻¹·m⁻² cumulative light). Ventilation fans and an evaporative cooling system were used to maintain day temperatures. A computerized environmental control system (Q-Com) was used to regulate and integrate environmental control functions.

Flowering stems were harvested when three to four flowers in each inflorescence reached anthesis. Cuts were made ≈6 cm above the base, generally leaving three or more nodes above the substrate. All flowering stems were harvested, and data collected at harvest were flowering stem length, measured from the base to the apex of the inflorescence, and days to flower from the start of greenhouse forcing. Total yield from each plant was calculated for stems harvested from the beginning until 15 June, when daily temperature maxima exceeded the ability of the greenhouse environmental control systems to maintain the desired environmental parameters. Data were tested by analysis of variance using the SAS General Linear Model procedure (SAS Institute), and variation among cooling treatments was analyzed by orthogonal contrasts.

Results

Expt. 1

Cooling. Greenhouse days to anthesis decreased in a linear manner as cooling duration increased from zero to 16 weeks regardless of lighting treatment (Table 1). Averaged across lighting treatments, days to flower ranged from 122 for noncooled plants to 80 for plants cooled 16 weeks. Flowering stem length, a critical quality for the cut flower trade, also increased in a linear manner as cooling duration increased from zero to 16 weeks regardless of lighting treatment (Table 1). Averaged across lighting treatments, stems ranged from 38.5 cm for noncooled plants to 57.9 cm for plants cooled 16 weeks. The length of stems from plants cooled less than 12 weeks were considered unacceptably short (less than 50 cm) for cut flower production, although stem length increased for all cooling treatments as additional harvests were cut (data not shown).

Stems harvested per plant also increased in a linear manner with increased cooling duration regardless of lighting treatment (Table 1). Averaged across lighting treatments, stems per plant ranged from 2.5 for noncooled plants to eight for those cooled 16 weeks.

Photoperiod. Plants forced in ED lighting flowered more rapidly and produced longer stems and higher yields than those in NI regardless of cooling duration. Averaged across cooling treatments, plants took 95 d to flower in ED compared with 101 d in NI. In ED, greenhouse days to flower ranged from 118 for noncooled plants to 79 for those cooled 16 weeks. In NI, days to flower ranged from 126 for noncooled plants to 88 for those cooled 16 weeks. Similarly, when averaged across cooling treatments, stems were 49.5 cm long in ED compared with 45.3 cm in NI. In ED, stem lengths ranged from 42.6 for noncooled plants to 59.5 for plants cooled 16 weeks. In NI, stem lengths ranged from 34.4 for noncooled plants to 56.3 for plants cooled 16 weeks. In ED, stems harvested ranged from four per plant with zero weeks cooling to nine per plant with 16 weeks cooling. In NI, stems harvested ranged from two per plant with zero weeks cooling to seven per plant with 16 weeks cooling.

Expt. 2

When forced under continuous HID lighting, greenhouse days to anthesis for cooled plants were similar to those of noncooled plants regardless of cooling duration (Table 2). This contrasts with the results of our previous study that used incandescent lighting and suggests that higher, continuous levels of irradiance substituted for cooling

and promoted rapid flowering in the absence of cooling. Days to flower were substantially reduced with continuous HID lighting compared with results reported for forcing this cultivar under incandescent lamps in Expt. 1. Sixteen weeks cooling and continuous HID lighting resulted in a 39% decrease in greenhouse days to anthesis compared with similar cooling duration under incandescent lighting used in the earlier study (Expt. 1).

In HID lighting, stem lengths also increased in a linear manner as cooling increased from zero to 16 weeks (Table 2), similar to Expt. 1. Stem lengths ranged from 63.6 cm for noncooled plants to 96.3 cm for those cooled 16 weeks. Plants cooled 4 weeks were 38% longer than those from noncooled plants, and with 16 weeks cooling, stems were 51% longer than those from the controls. Stems from cooled plants were considered highly marketable and were substantially longer than those produced under incandescent lamps in our earlier study.

Flowering stems harvested per plant also increased linearly with increasing cooling duration (Table 2). Stems per plant ranged from seven for noncooled plants to 13 for those cooled 16 weeks. Compared with noncooled plants, cooling 4 weeks resulted in a 29% increase in yield and cooling 16 weeks increased yields by 86%.

Discussion

These results suggest that cooling phlox for 8 to 16 weeks before forcing can promote more rapid flowering and increase flowering stem lengths and yields. Extended daylighting with incandescent lamps appears to be more effective than night-interruption lighting in

Table 1. Greenhouse days to anthesis, stem length, and flowering stems harvested per plant for *Phlox paniculata* L. Ice Cap cooled 0, 4, 8, 12, or 16 weeks and forced in extended-day (ED) or night-interruption (NI) incandescent lighting.

Weeks cooling	Greenhouse days to anthesis		Stem length (cm)		Flowering stems harvested per plant	
	Lighting		Lighting		Lighting	
	ED	NI	ED	NI	ED	NI
0	118 ^a	126	42.6	34.4	4	2
4	98	111	44.4	41.4	4	3
8	92	96	47.4	43.7	6	5
12	87	90	53.8	50.7	6	6
16	79	81	59.5	56.3	9	7
Significance	L***	L***	L***	L***	L***	L***

^aED versus NI significant at $P \leq 0.001$ by analysis of variance for each variable. Interactions nonsignificant.

^bL = Linear at (***) $P \leq 0.001$.

Table 2. Greenhouse days to anthesis, stem length, and flowering stems harvested per plant for *Phlox paniculata* L. Ice Cap cooled 0, 4, 8, 12, or 16 weeks and forced under metal halide lamps.

Weeks cooling	Greenhouse days to anthesis		Stem length (cm)		Flowering stems harvested per plant	
0	64		63.6		7	
4	61		87.7		8	
8	59		92.3		10	
12	62		92.8		11	
16	57		96.3		13	
Significance ^a	NS		L***		L***	

^aNS, L = Nonsignificant or linear at (***) $P \leq 0.001$.

promoting growth and flowering of this crop when forcing phlox in greenhouses for off-season production.

The data from Expt. 1 suggest that cooling has a significant influence on the parameters measured. This is similar to other reports with herbaceous perennials in which cooling duration resulted in a linear decrease in flowering time and an increase in stem length on potted crops (Garner and Armitage, 1998; Runkle et al., 1998) and cut flowers (Lewis et al., 1999, 2000). In all of these studies, although the degree of change differed with taxon, the results were similar. Both extended lighting and night break lighting are common methodologies used for long-day distribution in greenhouses, and in this study, the benefits from extended daylighting was likely the result of greater cumulative light and not the method itself. The data also suggest that cooling is not necessary for flowering in *P. paniculata*; however, with the low light levels used in this study, cooling proved highly beneficial in producing this crop as a cut flower.

The second experiment was similar in that it also suggested that stem length and yield increased as cooling duration increased. Also, similarly, cooling was not necessary for flowering. However, the lack of signifi-

cance in flowering time in this experiment suggests that high cumulative light can substitute for cooling. The optimal duration of cooling is dependent on the light provided after cooling.

Together, the experiments suggest that cooling phlox plugs is necessary for longer stems and higher yields when plants are forced in the winter greenhouse. Also, the data suggest that the greater the cumulative light, the less important is cooling duration. In both experiments, cooling duration caused a linear increase in stem length, not seen in work with phlox (Runkle et al., 1998) but common with other perennials we have studied (Lewis et al., 1999, 2000). Cooling duration results in similar trends on stem length and yield regardless if plants are removed from refrigeration at different times (Expt. 1) or if they are removed at the same time.

Although *P. paniculata* does not have an obligate cooling requirement for flowering, these data confirm that cooling *P. paniculata* 'Ice Cap' plugs can increase stem length and flowering stem yields. Use of HID supplemental lighting can accelerate flowering in the absence of cooling and promote longer stems and higher yields when forcing this crop for cut flower production.

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