Cold Treatments, Photoperiod, and Forcing Temperature Influence Flowering of *Lavandula angustifolia*

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Abstract. The influence of cold treatments and photoperiod on flowering of 8- to 11-node and 18- to 23-node *Lavandula angustifolia* Mill. 'Munstead' plants from 128-cell (10-mL cell volume; P1) and 50-cell (85-mL cell volume; P2) trays, respectively, was determined. Plants were stored at 5 °C for 0, 5, 10, or 15 weeks, then forced under a 9-h photoperiod (SD), or under a 4-h night-interruption (NI) (2200 to 0200 HR) photoperiod at 20 °C. Percentage of plants flowering, time to flower, and plant appearance were evaluated. Increasing duration of cold treatment was associated with an increase in flowering percentage in plants from both cell sizes. More plants flowered under NI than SD except in P2 cooled for 15 weeks, where all plants flowered. Average time to visible bud (VB) and to opening of the first flower (FLW) generally decreased with increasing duration of cold treatment. Inflorescence count in P2 plants increased with increasing duration of cold treatment. To determine the relationship between forcing temperature and time to flower in *L. angustifolia* 'Munstead', three sizes of plants were exposed to 5 °C for 13 weeks and then forced under a 4-h NI (2200 to 0200 HR) at 15, 18, 21, 24, or 27 °C. Plants generally flowered more quickly at higher temperatures, time to FLW decreasing from 77, 71, and 60 days at ≈15.6 °C to 46, 40, and 36 days at ≈26 °C for P1, P2, and 5.5-cm (190-mL pot volume) (P3) plants, respectively. Generally, P1 plants flowered 5 to 10 days later than P2, and P2 flowered 5 to 10 days later than P3.

Lavandula angustifolia is native to the Mediterranean region and is cultivated for its aromatic oil, which is used in perfumery, and as an ornamental for its purple flowers and attractive grey-green foliage (Liberty Hyde Bailey Hortorium, 1976). It is hardy in USDA zones 5 to 9 (Ball, 1991). Botanically, *L. angustifolia* is considered a shrub (Liberty Hyde Bailey Hortorium, 1976), but is commonly produced and marketed as a herbaceous perennial (Ball, 1991). Like most herbaceous perennials in North America, *L. angustifolia* is traditionally produced outdoors and is not in bloom in the spring when the majority of garden plants are sold. Since consumers prefer to purchase plants in flower, producers are interested in understanding the flowering requirements of this species.

Exposure to a period of low temperature modifies plant development and flowering in many species (Roberts and Summerfield, 1987). Some species of herbaceous perennials

require a cold treatment for subsequent flowering, while in others, low temperature hastens or improves uniformity of flowering (Iversen and Weiler, 1994). We have been unable to find information in the literature on the response of *L. angustifolia* to cold treatments. In preliminary experiments, we found that *L. angustifolia* seedlings required low-temperature exposure for subsequent flowering in the greenhouse, and that older seedlings were more sensitive to cold treatment (unpublished data).

A requirement for a period of low temperature frequently is coupled with a photoperiodic requirement, generally for long days, so photoperiods exceeding a certain minimum length either are required for flowering or hasten flowering (Roberts and Summerfield, 1987). In preliminary experiments, cooled *L. angustifolia* plants exhibited a facultative response to long days (unpublished data).

Production time for any crop is related to temperature provided during forcing. Most biological processes, such as flowering, proceed more quickly as temperature rises until a species-specific optimum is reached. At temperatures above optimum, development is delayed or ceases. Temperatures that produce most-rapid flowering may not result in the most attractive plants. We were unable to find any recommended temperatures for production of *L. angustifolia* as a flowering plant, but for greenhouse production as an herb, 15 to 18 °C has been suggested, although experimental evidence was not presented (Laskey, 1991).

The objectives of our study were to deter-

mine the influence of plant size, cold treatment, and photoperiod on flowering and to determine the effect of forcing temperature on time to flower. Percentage of plants flowering, time to flower, and plant appearance were evaluated.

Materials and Methods

General. Plants were grown in a commercial soilless medium containing composted pine bark, horticultural vermiculite, Canadian sphagnum peat, 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 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.). Supplemental lighting (high-pressure sodium providing ≈50 μmol·m⁻²·s⁻¹ at plant level) was initiated at 200 μmol·m⁻²·s⁻¹ ambient photosynthetic photon flux (PPF) and terminated when PPF exceeded 400 μmol·m⁻²·s⁻¹.

Plants were exposed to cold treatments in a 5 ± 0.5 °C cooler illuminated for 9 h·day⁻¹ with cool-white fluorescent lamps (VHO96T12; Philips, Bloomfield, N.J.) at ≈10 μmol·m⁻²·s⁻¹, and were watered with well water (340 mg CaCO₃/L) acidified (93% H₂SO₄) to a titratable alkalinity of 100 mg CaCO₃/L.

Cold treatments and photoperiod (Expt. 1). Two plug sizes were tested. Seedlings with 8 to 11 nodes growing in 128-cell trays (10-mL cell volume; P1) and seedlings with 18 to 23 nodes in 50-cell trays (85-mL cell volume; P2) were received from a commercial producer on 27 Oct. 1994. Twenty plants of each size were removed from the plug tray, thinned to a single plant per cell (singulated), and transplanted. The seedlings in P1 were transplanted into 10 × 9-cm containers (470-mL) and those from P2 into 16 × 16-cm (2.2-L) containers. Plants were placed in the greenhouse at 20 °C. Ten plants of each size group were placed under a 9-h photoperiod (SD) and 10 under a 9-h photoperiod with a 4-h night interruption (NI) from 2200 to 0200 HR. The NI was supplied by 60-W incandescent lamps at 3 to 5 μmol·m⁻²·s⁻¹ as measured at plant height by a LI-COR quantum sensor model LI-189 (LI-COR, Lincoln, Neb.). Black cloth was pulled at 1700 HR and opened at 0800 HR on all benches. Remaining plugs were placed in the cooler. Twenty plugs of each size group were removed from the cooler at 5-week intervals and treated as described above. Dates of the first visible bud (VB) (when the inflorescence was ≈2 mm long) and of first open flower (FLW) were recorded for each plant, and days from transplant to VB and FLW were calculated. At flowering, total plant height, number of visible inflorescences, and number of nodes on the main stem were determined.

Air temperatures on each bench were monitored every 10 s with two 36-gauge (0.127 mm in diameter) thermocouples connected to a CR10 datalogger (Campbell Scientific, Logan, Utah). Nighttime air under black cloth on solid aluminum benches can be 3.5 °C cooler

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than greenhouse air temperatures because of radiant heat loss to the greenhouse glazing material (Heins and Faust, 1994). To provide uniform temperature conditions, the datalogger controlled a 1500-W electric heater under each bench, which provided supplemental heat as needed throughout the night. The actual daily air mean throughout the course of the experiment was 20.4 °C. The maximum difference in actual daily air mean between any two treatments throughout the experiment was 0.7 °C.

Forcing temperature (Expt. 2). Three plant sizes were tested. Seven- to nine-node seedlings in P1 and 19 to 23 node seedlings in P2 were received from a commercial producer 27 Oct. 1994. They were placed in a 5 °C cooler for 13 weeks until 21 Jan. 1995, when they were singulated and transplanted. Plants from P1 were transplanted into 10 × 9-cm containers (470-mL), and those from P2 into 13-cm square containers (1.1-L). Ten plants of each size were placed in each of five greenhouses set to 15, 18, 21, 24, or 27 °C. Plants growing in 5.5 × 9-cm pots (190-mL volume; P3) were received on 17 Jan. 1995, transplanted into 16 × 16-cm (2.2-L) containers, and 10 were placed in each of the treatment zones on 4 Feb. 1995. Plants received natural daylengths with a 4-h NI from 2200 to 0200 HR, provided by high-pressure sodium lamps that delivered $\approx 90 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$. Data were recorded as described for Expt. 1.

Temperatures in each greenhouse were controlled with a Priva environmental computer (model CD750; Priva, De Lier, Hol-

land). Actual air temperatures were recorded every 15 min by a CR-10 datalogger. Actual average daily air temperatures were determined and used in all calculations.

Results

Cold treatments and photoperiod. Percentage of plants from P1 that flowered did not reach 100 in any treatment (Fig. 1). Increasing durations of cold treatment were associated with an increase in flowering percentage in P1 and P2 plants. The percentage of plants flowering for both plant sizes tested was higher under NI than SD, except in P2 cooled for 15 weeks, where all plants flowered.

Plants cooled for 5 weeks reached VB and FLW ≈ 30 days more rapidly than noncooled plants (Fig. 1). Cold treatments of 10 or 15 weeks further reduced mean time to VB and FLW by ≈ 10 days.

Plants of P1 that flowered produced one to two inflorescences in all treatments (Fig. 2). The average number of inflorescences on P2 plants increased with increasing durations of cold treatment.

The final node count and height in P1 under NI were similar whether plants were cooled for 10 or 15 weeks (Fig. 2). Final node count and height in P2 were not affected by cold treatments.

Forcing temperature. All plants flowered at all temperatures, except for those from P1 at ≈ 26 °C (40% flowered) and 23 °C (70% flowered). Time to FLW decreased as forcing

temperature increased from ≈ 16 °C to ≈ 21 °C, but further increases had little effect (Fig. 3). Time to FLW at ≈ 16 °C averaged 69 days, and at ≈ 26 °C, 41 days. Under all forcing temperatures, P1 plants flowered 5 to 10 days later than P2, and P2 flowered 5 to 10 days later than P3.

Larger initial plant size resulted in a higher average inflorescence count per plant (Fig. 4). Increasing forcing temperature had little effect on inflorescence count on P1 and P2 plants, but was associated with a decreasing number of inflorescences for P3 plants. Plants from P1, P2, and P3 grew 5, 6, and 12 cm taller, respectively, when plants were forced at ≈ 15 °C than at ≈ 26 °C. The P3 plants were pruned before shipment, resulting in a final plant height below that of P2 plants.

Discussion

Many biennials and perennials must attain a certain size before they are capable of floral induction. Juvenility is defined as an early developmental phase during which a plant is insensitive to conditions that later promote flower initiation (Bernier et al., 1981). A juvenile phase has been described in several herbaceous perennials including some cultivars of *Aquilegia × hybrida* Sims. (Shedron and Weiler, 1982), and *Heuchera sanguinea* Engelm. (Yuan, 1995). A juvenile phase appears to exist in *L. angustifolia* 'Munstead', but its duration could not be determined from these experiments. What these experiments did show is that plant size influences the flowering response of *L. angustifolia* 'Munstead'. Plants with 8 to 11 nodes required a longer cold treatment to induce flowering than those with 18 to 23 nodes. Because 100% of 18- to 23-node P2 plants flowered in Expt. 2, and because flowering for P1 plants in Expt. 1 did not reach 100% in any treatment, but 100% of P1 plants flowered in some treatments in Expt. 2 (Figs. 1 and 3), the juvenile phase in *L. angustifolia* 'Munstead' appears to end after plants have about 8 to 11 nodes.

Low temperatures are required for flowering of many herbaceous perennials. The requirement for cold differs among species, and can often be categorized by the relationship between exposure to cold and time of floral initiation. Some species of herbaceous perennials require a cold treatment for 1) further development of existing dormant flower buds; 2) in others, floral bud initiation occurs during exposure to low temperatures; and 3) in some cases, low temperatures hasten or are required for subsequent initiation and development of floral primordia. For species in the third category, floral primordia are not initiated until after the return of warmer temperatures, and in many species initiation will not occur until photoperiodic requirements are met as well (Chouard, 1960). Our experiments show that exposure to a period of low temperatures is the primary factor promoting flowering in *L. angustifolia* 'Munstead'. Increasing durations at 5 °C were associated with an increase in flowering percentage and number of inflorescences, and a decrease in time to flower (Figs. 1 and 2). Vegetative growth emerged from the

Fig. 1. Influence of cold treatments on flowering of *L. angustifolia* 'Munstead' forced in a 20 °C greenhouse under either a 9-h photoperiod (SD), or a 9-h photoperiod with a 4-h night-interruption (NI) (2200 to 0200 HR) photoperiod. (A) and (B) show flowering percentage for plants from 128-cell trays (8 to 11 nodes, P1) and from 50-cell trays (18 to 23 nodes, P2), respectively, within the 120-day duration of the experiment. (C) and (D) show time to visible bud and flower for P1 and P2, respectively. Error bars in (C) and (D) represent 95% confidence intervals.

Fig. 2. Influence of cold treatments on flowering of *L. angustifolia* 'Munstead' forced in a 20 °C greenhouse under either a 9-h photoperiod (SD), or a 9-h photoperiod with a 4-h night-interruption (NI) (2200 to 0200 hr) photoperiod. (A) and (B) represent number of inflorescences visible per plant at the time of first flower opening for plants from 128-cell trays (8 to 11 nodes, P1) and from 50-cell trays (18 to 23 nodes, P2), respectively. (C) and (D) show number of nodes present on the main stem at flowering for P1 and P2, respectively. (E) and (F) are total plant height at flowering for P1 and P2, respectively. Error bars represent 95% confidence intervals.

apical meristem, but flowering was absent on *L. angustifolia* 'Munstead' plants that were not exposed to low temperatures. Since this plant has a terminal inflorescence, it is unlikely that flower buds were present before cold treatments. While low temperatures clearly promote flower induction of *L. angustifolia* 'Munstead', we did not determine in these experiments whether initiation occurs during or after cold treatments.

When P2 plants were cooled for 10 or 15 weeks, most flowered when forced under SD. Extended exposure to 5 °C apparently eliminated any subsequent photoperiodic requirement for flowering of *L. angustifolia* 'Munstead'. A similar response has been found in some other herbaceous perennials (Buxton and Mohr, 1969; Iversen, 1989; Lopes and Weiler, 1977; Shedron, 1980).

Forcing temperatures have a significant effect on rates of development in all plants. Optimum temperature ranges vary within and between species and are related to climatic origin (Roberts and Summerfield, 1987). Fewer *L. angustifolia* 'Munstead' flowered when forced at 23 and 26 °C than when forced at lower temperatures, suggesting that 23 °C is near the optimum for this species. Alternatively, temperatures ≥ 23 °C may have devernalized the plants. Inflorescences were similar in appearance at all temperatures tested.

Initial plant size influenced time to VB and FLW at all forcing temperatures. The P3 plants were pruned before shipment, yet flowered 5 to 10 days before P2. The P2 plants flowered 5 to 10 days before P1 plants. The larger plants apparently were at a more advanced physiological stage at the start of forcing. Also, fewer P1 plants flowered at ≥ 23 °C than at lower temperatures, but all P2 and P3 plants flowered at all temperatures tested.

Regrowth of the pruned P3 plants used in this experiment was compact, uniform, and attractive. P1 and P2 plants were not pruned, and were sometimes weak and uneven in appearance. Although not specifically tested in this work, our observations suggest that prun-

Fig. 3. Influence of forcing temperature on flowering of *L. angustifolia* 'Munstead' plants from 128-cell trays (P1), 50-cell trays (P2), and 5.5-cm pots (P3). Each symbol (▲, ●, or ■) represents the mean of 10 plants except for P1 at 23 °C (seven flowered) and ≈ 26 °C (four flowered). Vertical bars represent least significant differences (LSD) between plug sizes at each forcing temperature.

Fig. 4. Influence of forcing temperature on (A) number of inflorescences and (B) total plant height in *L. angustifolia* 'Munstead' plants from 128-cell trays (P1), 50-cell trays (P2), and 5.5-cm pots (P3). Each symbol (▲, ●, or ■) represents the mean of 10 plants, except for P1 at 23 °C and ≈26 °C where the symbols represent the mean of seven and four plants, respectively. Error bars represent 95% confidence intervals.

ing or pinching prior to cooling and forcing may be beneficial when forcing other sizes of *L. angustifolia* 'Munstead' as flowering plants.

In conclusion, recommendations for bringing *L. angustifolia* 'Munstead' to flower for commercial production include using initial plant material with more than 11 nodes, and providing a minimum of 10 weeks of 5 °C. Flower count may be increased slightly if the plants subsequently are forced under a 4-h NI. Cooled plants with 18 to 23 nodes forced under NI will flower in ≈7 weeks at 20 °C.

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