Vernalization and Growing Degree-day Requirements for Flowering of *Thalictrum delavayi* 'Hewitt's Double'

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Abstract. Vernalization and growing degree-day (GDD) requirements of *Thalictrum delavayi* Franch. 'Hewitt's Double' were investigated by exposing crowns to cold storage for 0, 3, 6, 9, 12, or 15 weeks at 8 °C, and subsequently planting in a heated greenhouse under long-day conditions. Cumulative vernalization of crowns was complete after 6 weeks of cold storage at 8 °C. The time to flower, including time at 8 °C, was 3338 GDD (base temperature of 0 °C) without vernalization and 2802 GDD after complete vernalization. Commercial recommendations for rapid and predictable flowering of *T. delavayi* 'Hewitt's Double' should include cold storage of crowns for a minimum of 6 weeks at 8 °C as part of the 2802 GDD during vernalization and forcing.

Thalictrum delavayi is a herbaceous perennial native to west China (Durand and Jackson, 1901; Huxley et al., 1992). The storage organ is a crown, which produces slender stems up to 1.2 m in height, with long petiolate leaves comprising two to three terminate or pinnately decompound leaflets (Huxley et al., 1992). In summer the stems terminate in an inflorescence comprising a loose panicle of lilac to white flowers. 'Hewitt's Double' is commonly grown as a garden display plant (Huxley et al., 1992) or as a medicinal plant (Gao et al., 1990).

In recent years 'Hewitt's Double' has been viewed by members of the floriculture industry as a potential new commercial cut flower (I. Ivey, personal communication). As predictable production is required, producers are interested in understanding the flowering requirements of this species and developing production schedules. A common method of scheduling uses the accumulation of heat units or sum of growing degree-days (GDD) to estimate the expected time to flowering (McKay et al., 1981; Whitman et al., 1997).

Production scheduling of some herbaceous perennials must also account for their response

to cold temperature. Some species require a period of cold temperature for flowering for either vernalization or breaking of bud dormancy (Iversen and Weiler, 1994; White et al., 1989; Whitman et al., 1996). Vernalization typically proceeds within the range of –5 to 15 °C, with the most effective range typically 5 to 9 °C (Vince-Prue, 1975; Wiebe, 1990). The cold requirement for flowering may be qualitative or quantitative. If plants remain vegetative without exposure to cold, the vernalization response is qualitative (Iversen and Weiler, 1994; Shedron and Weiler, 1982; White et al., 1989). A quantitative response occurs where exposure to cold hastens flower induction and differentiation. When the response is quantitative, the date of flowering, total number of leaves, and/or flower stalk length may differ with the extent of vernalization (Wiebe, 1990).

The flowering response of *T. delavayi* to cold temperatures has not been previously reported in the literature. However, a qualitative vernalization requirement has been reported in the genus *Aquilegia* (Shedron and Weiler, 1982; White et al., 1989), a close relative of *Thalictrum* (Hoot, 1991). Combinations of temperatures and durations ranging between 0 and 8 °C for between 4 and 10 weeks satisfied the vernalization requirement for various cultivars of *Aquilegia*. Given that *T. delavayi* both originates from a temperate climate and has a high potential market value, the cold requirement of 'Hewitt's Double' was considered worthy of investigation.

The photoperiodic requirement for flowering of *T. delavayi* has not been reported. We forced plants of 'Hewitt's Double' in a long-day environment to approximate the 10.5- to 13.5-h photoperiods that occur during growth and flowering in the parent species' region of origin (Huxley et al., 1992). Forcing in a long-day environment allowed us to focus on investigating the influence of cold treatment on flowering of 'Hewitt's Double' and to determine the GDD requirement for flowering.

Two-year-old crowns of 'Hewitt's Double', lifted in Auckland, N.Z., in late April (fall), were shipped to Palmerston North, N.Z., before treatments were applied. Crowns, covered with moistened bark, were exposed to 8 ± 1 °C in a dark cooler for 0, 3, 6, 9, 12, or 15 weeks at the Plant Growth Unit, Massey Univ., Palmerston North (40°21'S). After cold storage, the crowns were planted in a glasshouse heated to 15 °C and vented at 20 °C. The first planting commenced on 2 May 1994. The glasshouse received a natural photoperiod (11 h increasing to 13 h) plus 4 h of night lighting between 2200 and 0200 HR (incandescent lamps with a mean light intensity of 2.4 µmol·m⁻²·s⁻¹ at the height of the growing medium during the experiment). The crowns were planted individually in black polythene bags (27 × 27 cm, 1.2-L volume, Epic Ltd., Auckland, N.Z.) containing 100% pine bark plus 3.0 kg·m⁻³ each of agricultural lime and dolomite, 0.5 kg·m⁻³ iron sulfate, and 4.0 kg·m⁻³ Osmocote 16N–3.5P–10K. Water was provided by a mixture of continuous capillary and once-weekly overhead applications.

After storage, treated plants were arranged in the greenhouse in a nested unbalanced experimental design with two blocks. One block contained large crowns (>6.9 cm in diameter) with two replicates, while the second block had small crowns (4.2–6.9 cm in diameter) with five replicates. Each replicate consisted of three plants. The experiment comprised six treatments with 126 plants in all. The experiment was blocked for crown size to evaluate any possible influence of size on flower yield and timing (Corr and Widmer, 1991).

Greenhouse air temperatures, measured with a shaded sensor at a height of 1.3 m, were recorded at 30-min intervals during the study with a Squirrel 1200 Digital Meter/Logger (Grant Instruments Ltd., Barrington, Cambridge, U.K.). Daily mean air temperatures in the cooler during vernalization and in the greenhouse during growth were used for the calculation of GDD. Actual air temperatures within the greenhouse rarely exceeded 25 °C over the course of the study, ranging between the set points of 15 and 20 °C.

Flowering was defined by the stage when ≈5% of the buds were open in the upper 45 cm of the primary inflorescence of each plant. The mean time to flower was calculated using both calendar days (CD) and GDD for the first inflorescence harvested. A linear GDD model (Roberts and Summerfield, 1987; Wang, 1960) with a base temperature of 0 °C (Roberts and Summerfield, 1987) was used. Saturation of the vernalization response was judged to have occurred when the cold storage treatment did not further advance GDD to flower, based on total forcing time including duration in cold storage. Stem number per plant and stem length were recorded at flowering. Data were subjected to analysis of variance, and trend analysis using the GLM procedure of SAS (SAS Institute, Cary, N.C.). Mean separation was by Fisher's least significant difference.

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Results

All plants flowered in all treatments. Linear and quadratic trends were significant for all calculations of CD and GDD (i.e., with and without storage duration included) with increasing duration of storage ($P < 0.0001$). Both CD and GDD, including the duration of the cold storage, declined as a result of 3 and 6 weeks of cold storage in a linear trend ($P < 0.0001$) from 196 CD and 3338 GDD to 187 CD and 2848 GDD, respectively (Fig. 1 a and c). After 6 weeks of cold storage, the number of CD necessary for flowering followed a positive linear trend with increasing storage duration up to 215 d ($P < 0.0001$) (Fig. 1a), while GDD remained relatively unchanged ($P > 0.05$). Between 6 and 15 weeks of storage, GDD needed for flowering ranged between 2760 and 2848 (Fig. 1c), with an average of 2802. Excluding cold storage duration, the time to flower decreased linearly with increasing duration of cold storage for both CD and GDD ($P < 0.001$) (Fig. 1 b and d).

Flower stem yield averaged between three and five stems per plant, with stem lengths ranging from 140 to 200 cm (data not presented). Storage duration did not affect flower yield significantly ($P > 0.05$). All stems produced were longer than required to meet current commercial standards. While stem length was reduced to between 141 and 148 cm for plants receiving 6 and 9 weeks of storage, vs. 176–200 cm for all other storage durations ($P < 0.05$), these changes were not considered commercially important.

Discussion

Crowns of 'Hewitt's Double' exhibited a quantitative vernalization requirement. Vernalization reduced the time to flower (Fig. 1 a and c), but exposure to cold temperatures was not an obligate requirement for flowering. After at least 6 weeks of vernalization, the time to flower (including duration of the cold storage) was similar with respect to GDD (Fig. 1c), but increased with respect to CD (Fig. 1a). Thus, the vernalization response became saturated at 6 weeks of cold storage, with longer periods in cold storage merely extending the time in CD to flower. The vernalization response is similar to that previously reported for *Triticum aestivum* L. and *Hordeum vulgare* L., in which the reduction in the time to flower following low-temperature treatment resulted from concurrent accumulation of GDD during that period (Brooking, 1996; Ellis et al., 1989). In the current experiment, sprouting of buds on crowns was detected after 15 weeks of cold storage (data not presented), indicating that growth occurred during cold storage. Therefore, 8 °C is effective for both vernalization and GDD accumulation (i.e., plant development) in this species.

Satisfying the vernalization requirement after 6 weeks in the current experiment is within the 1- to 20-week range reported as optimal for various crops (Iverson and Weiler, 1994; Whitman et al., 1997; Wiebe, 1990), and is similar to that reported for *Aquilegia* (Shedron and Weiler, 1982; White et al., 1989). Depending on cultivar, the vernalization re-

quirement for *Aquilegia* ranged between 4 and 10 weeks at 4.5 °C (Shedron and Weiler, 1982). Similarly, White et al. (1989) reported that *Aquilegia* required up to 6 weeks at temperatures between 0 and 1 °C to satisfy the vernalization requirement.

The most effective temperature range for vernalization for many species is between 5 and 8 °C (Vince-Prue, 1975; Wiebe, 1990). The temperature used for vernalization in this study (8 °C), is higher than the temperatures found to be most effective with other herbaceous perennials (Iverson and Weiler, 1994; Shedron and Weiler, 1982; White et al., 1989; Whitman et al., 1997). Further research is required to determine if 8 °C is the most effective temperature for meeting the vernalization requirement in 'Hewitt's Double'.

Comparison of time to flower using CD and GDD summation illustrated that time to flower for 'Hewitt's Double' was predominantly temperature-dependent, once the vernalization requirement was satisfied (Fig. 1 a and c). This result confirmed the suitability of using GDD for describing the time to flower for this crop, as reported for other herbaceous perennials (McKay et al., 1981; Whitman et al., 1997). For gladiolus, the GDD requirements from planting to flowering, after cold temperature requirements have been met, varied from 1300 to 2300, depending on cultivar (McKay et al., 1981). For *Delphinium* 'Blue Mirror' 1353 GDD were required for flowering after saturation of the vernalization response (Whitman and Heins, personal communication), and Whitman et al. (1997) reported that only 909 GDD were required for flowering of *Campanula carpatica* Jacq. 'Blue Clips'. In the current experiment, the vernalization and forcing phases could not be separated with accuracy. However, if the 336 GDD required to satisfy vernalization (i.e., 6 weeks at 8 °C) were considered to be separate from that for forcing, ≈ 2466 GDD would be required for forcing of 'Hewitt's Double'. A total of 2466 GDD for forcing indicates that this species requires a greater number of GDD for flowering than do the better-known herbaceous perennials noted above.

These results can be used to develop schedules for flowering of commercial plantings of 'Hewitt's Double', with expected improvements in reducing both time to flower and variability in timing between plantings. As an example, if vernalized for 6 weeks at 8 °C and forced at a daily average temperature of 17.5 °C, flowering would occur 141 d after planting (i.e., $2466 \div 17.5 = 141$). This would reduce the time to flower by ≈ 30 d compared with nonvernalized plants.

Recommendations for rapid and predictable timing of flowering of 'Hewitt's Double' for commercial production include using cold storage of crowns for a minimum of 6 weeks at 8 °C as part of the 2802 GDD during vernalization and forcing.

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Fig. 1. Time to flower as calendar days (a and b) and growing degree-days (GDD, base temperature of 0 °C, c and d) of *T. delavayi* 'Hewitt's Double' following different periods of cold storage at 8 °C. Data in (a and c) include and (b and d) exclude the duration of cold storage. Means are an average of data from seven replicates. Vertical bars represent standard errors of means.

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