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Photoperiod, Irradiance, and Temperature Affect *Echinopsis* 'Rose Quartz' Flowering

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Abstract. **Photoperiod, irradiance, cool temperature (5 °C), and benzyladenine (BA) application effects on *Echinopsis* 'Rose Quartz' flowering were examined. Plants were placed in a 5 °C greenhouse under natural daylight (DL) for 0, 4, 8, or 12 weeks, then moved to a 22/18 °C (day/night temperature) greenhouse under short days (SD, 8-hour DL) plus 0, 25, 45, or 75 μmol·m^{-2}·s^{-1} supplemental lighting (0800–1600 HR; 8-hour photoperiod), long days (LD) delivered with DL plus night-interruption lighting (NI) (2200–0200 HR), or DL plus 25, 45, or 75 μmol·m^{-2}·s^{-1} supplemental lighting (0800–0200 HR) for 6 weeks (8-hour photoperiod). Plants were then grown under DL only. Percent flowering plants increased as irradiance increased from 0 to +75 μmol·m^{-2}·s^{-1} on uncooled plants, from 0% to 100% as 5 °C exposure increased from 0 to 8 weeks under subsequent SD and from 25% to 100% as 5 °C exposure increased from 0 to 4 weeks under subsequent LD. As 5 °C exposure duration increased from 0 to 12 weeks (SD-grown) and from 0 to 8 weeks (LD-grown), flower number increased from 0 to 11 and from 5 to 21 flowers per plant across irradiance treatments, respectively. Total production time ranged from 123 to 147 days on plants cooled from 8 to 12 weeks (SD-grown) and from 52 to 94 days on plants cooled for 0–4 weeks to 119–153 days on plants cooled for 8–12 weeks (LD-grown). Flower life varied from 1 to 3 days. BA spray application (10–40 mg·L^{-1}) once or twice after a 12-week 5 °C exposure reduced flower number. Flower development was not photoperiodic. High flower number (17–21 flowers/plant) and short production time (including cooling time, 120–122 days) occurred when plants were grown at 5 °C for 8 weeks, then grown under LD + 45–75 μmol·m^{-2}·s^{-1} for 6 weeks (16 hours; 10.9–12.8 mol·m^{-2}·d^{-1}) at a 22/18 °C day/night temperature. Taken together, *Echinopsis* 'Rose Quartz' exhibited a facultative cool temperature and facultative LD requirement for flowering.**

Cacti have potential as new floriculture and landscape crops. Cacti can have ornamental spines, unique forms, and occasionally showy flowers and can often survive dry conditions. The epiphytic cacti *Schlumbergera*, *Hatoria*, and *Rhipsalidopsis* have been commercialized as flowering potted plants (Boyle, 1990, 1991; Meier, 1995; O'Leary and Boyle, 1999, 2000). Subsequent work on *Schlumbergera* and *Hatoria* showed BA spray application during flower initiation increased flower number (Boyle, 1995; Heins et al., 1981; Ho et al., 1985). In other work, Japanese and Korean scientists facilitated the development of a grafted cactus industry (primarily *Gymnocalycium* and *Echinopsis* grafted on *Hylocereus*) where plants are grown for colorful and/or uniquely shaped scions as potted plants (Kim and Kim, 2006). Erwin (1996) subsequently researched temperature and photoperiod effects on grafted cacti growth to decrease scion losses.

Little recent work has focused on desert cacti flowering physiology. Work by Runger on temperature and photoperiod effects on *Mammillaria zeilmanniana* (Runger, 1967), *Mammillaria longicoma* (Runger, 1968a), *Notocactus tabularis* (Runger, 1971), *Rebutia marsoneri* (Runger, 1968b), and *Rebutia violaciflora* flowering (Runger, 1973) showed cool temperature (5–17 °C) and photoperiod interacted to affect flowering, and species varied in temperature and photoperiod requirements for flower induction and development. Research here examined irradiance, photoperiod, and cool-temperature effects on flowering of the desert cactus hybrid *Echinopsis* 'Rose Quartz'.

'Rose Quartz' is cross between *Echinopsis silvestrii* and another *Echinopsis* species (parent not reported, R. O'Connell) that is asexually propagated. *Echinopsis silvestrii* is indigenous to the Tucuman and Salta regions of northern Argentina where it is often solitary, with white, nonfragrant, 2–5 cm long flowers (Anderson, 2001; Hunt et al., 2006). Other *Echinopsis* species are indigenous to northern Argentina, northeastern Chile, and northwestern Brazil, and Bolivia, and have large white, yellow, red, or orange flowers that can be fragrant (Anderson, 2001; Hunt et al., 2006). 'Rose Quartz' has large red flowers, blooms repeatedly, is large stemmed, and branches readily (personal observation). The habit and prolific flowering of this cultivar make it a potential new ornamental crop. Research objectives here were to 1) determine whether photoperiod, irradiance, and/or a 5 °C exposure affected *Echinopsis* 'Rose Quartz' flowering, and 2) determine whether BA spray application affected *Echinopsis* 'Rose Quartz' flowering.

Materials and Methods

Two hundred 3-year-old multistemmed *Echinopsis* 'Rose Quartz' plants in 10-cm diameter plastic pots were received from Altman Plants, Inc., on Sept. 1 (Vista, CA) and were grown in a greenhouse under natural DL (7–16 mol·m^{-2}·d^{-1}) with a decreasing photoperiod (13:15–9:06 h) under 26/18 ± 2 °C day/night temperatures.

Expt. 1: Flowering responses to environment. One hundred twenty-eight plants were selected for uniformity (based on size and branch number) and placed in a cool greenhouse (5 ± 2 °C; DL) on Nov. 28. After a 0-, 4-, 8-, or 12-week 5 °C exposure, plants were moved to a lighting treatment greenhouse (22/18 °C day/night temperature) for 6 weeks. A 5 °C cooling treatment temperature is in the optimal range (4–6 °C) for vernalization and overcoming dormancy, and 12 weeks is the maximum time many species require to complete vernalization or overcome dormancy (Lang, 1959; Padhye et al., 2006). Six weeks was selected as a lighting treatment length because previous research on a number of herbaceous species showed that 3–5 weeks was required for complete flower induction at 20–25 °C (Mattson and Erwin, 2005). Lighting treatments were SD (8-h DL; +0 μmol·m^{-2}·s^{-1}), +25 μmol·m^{-2}·s^{-1}, +45 μmol·m^{-2}·s^{-1}, or +75 μmol·m^{-2}·s^{-1} supplemental high-pressure sodium lighting (0800–1600 HR; LucoLux LU400, General Electric, Cleveland, OH), or LD treatments [DL plus NI (2200–0200 HR; 2 μmol·m^{-2}·s^{-1} from incandescent lamps)], +25 μmol·m^{-2}·s^{-1}, + 45 μmol·m^{-2}·s^{-1}, or + 75 μmol·m^{-2}·s^{-1} supplemental lighting from high-pressure sodium lamps (0800–0200 HR; 18-h photoperiod; 0800–0200 HR). SD was achieved by pulling an opaque cloth over plants from 1600 to 0800 HR. After lighting treatments, plants were placed in a 22/18 ± 1 °C day/night temperature greenhouse (DL only) and data were collected for 85 d.

Mean daily light integral (DLI) in the 5 °C greenhouse was 4.0 ± 2.0 mol·m^{-2}·d^{-1} (12 weeks). Mean DLI on plants grown under

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SD, SD + 25, SD + 45, and SD + 75 µmol·m^{-2}·s^{-1} (after a 12-week 5 °C exposure) were 8.2 ± 4.6, 8.9 ± 4.6, 9.5 ± 4.6, and 10.4 ± 4.6 mol·m^{-2}·d^{-1}, respectively. Mean DLI on plants grown under NI, LD + 25, LD + 45, and LD + 75 µmol·m^{-2}·s^{-1} environments (after a 12-week 5 °C exposure) were 8.3 ± 4.6, 9.5 ± 4.6, 10.9 ± 4.6, and 12.8 ± 4.6 mol·m^{-2}·d^{-1}, respectively.

In the 5 °C greenhouse, plants were watered lightly every other week. Thereafter, plants were fertilized weekly with 14.3 mM N, 0.72 mM P, 6.5 mM K, 1.67 mM Ca, and 1.1 mM Mg, plus micronutrients in the irrigation water (Miracle-Gro 15N–2.2P–12.5K Cal–Mg, The Scotts Co., Marysville, OH). The date each flower opened, how many flowers bloomed per plant, and how long each of the first three flowers per plant stayed open were collected. The experiment was organized in a completely randomized statistical design in a factorial arrangement. Main factors were photoperiod, irradiance, and 5 °C exposure duration. Analysis of variance (ANOVA) (P = 0.05) and mean separation [Tukey's honestly significant difference (HSD) (α = 0.05)] were conducted. Percent data were arcsine transformed before ANOVA.

Expt. 2: BA effects on flower number. Thirty-two plants were selected for uniformity and grown as in Expt. 1, except plants were grown at 5 °C for 12 weeks then under LD (DL ± 45 µmol·m^{-2}·s^{-1}; 22/18 °C) for 12 weeks. Plants were sprayed with a solution containing 0 (distilled water only), 10, 20, or 40 mg·L^{-1} BA (wet, but not dripping; Sigma-Aldrich Inc., St. Louis, MO) 1 week after

Table 1. Effect of 5 °C exposure, photoperiod, and irradiance on percent *Echinopsis* 'Rose Quartz' percent flowering (PF), days to first open flower (DTF) from the end of cooling, flower number per plant (FN), and total production time (PT; cooling time + DTF). Plants were placed in a 5 °C greenhouse under natural daylight (DL) for 0, 4, 8, or 12 weeks, and were then moved to a 22/18 °C (day/night temperature) greenhouse under short days (SD, 8-h DL) plus 0, 25, 45, or 75 µmol·m^{-2}·s^{-1} supplemental lighting, or long days (LD) provided as DL plus night-interruption lighting (NI; 2200–0200 HR), or DL plus 25, 45, or 75 µmol·m^{-2}·s^{-1} supplemental lighting (0800–0200 HR; 18 h) for 6 weeks after which plants were grown under DL only. Percent data were arcsine transformed before analysis of variance. Lowercase letters represent mean separation (Tukey's HSD$_{(0.05)}$) across cooling time. Uppercase letters represent mean separation across light treatments.

	5 °C exposure (weeks)			
Lighting treatment	0	4	8	12
		Short day		
DL only				
PF	0 aA	0 aA	100 bA	100 bA
DTF	- aA	- aA	70 cAB	61 bAB
FN	0 aA	0 bA	5 ab	8 bA
PT	- aA	- aA	136 bA	145 bA
DL + 25 µmol·m^{-2}·s^{-1}				
PF	0 aA	0 aA	100 bA	100 bA
DTF	- aA	- aA	75 cB	60 bA
FN	0 aA	0 aA	7 aA	9 aA
PT	- aA	- aA	131 bA	144 bA
DL + 45 µmol·m^{-2}·s^{-1}				
PF	0 aA	0 aA	100 bA	100 bA
DTF	- aA	- aA	68 bA	63 bAB
FN	0 aA	0 aA	6 aA	9 aA
PT	- aA	- aA	124 bA	147 bA
DL + 75 µmol·m^{-2}·s^{-1}				
PF	0 aA	0 aA	100 bA	100 bA
DTF	- aA	- aA	67 bA	60 bA
FN	0 aA	0 aA	9 aA	11 aA
PT	- aA	- aA	123 bA	144 bA
		Long day		
NI (2 µmol·m^{-2}·s^{-1}; 2200–0200 HR; incandescent lamps)				
PF	50 aB	100 bB	100 bA	100 bA
DTF	52 aB	66 bB	68 bA	69 bB
FN	8 aA	14 aB	12 aAB	12 aA
PT	52 aB	94 bB	124 bcA	153 cA
DL + 25 µmol·m^{-2}·s^{-1}				
PF	25 aB	100 bB	100 bA	100 bA
DTF	52 aB	64 bB	64 bA	66 bAB
FN	5 aA	12 bAB	17 cB	12 bAB
PT	52 aB	92 bB	120 cA	150 dA
DL + 50 µmol·m^{-2} s^{-1}				
PF	25 aB	100 bB	100 bA	100 bA
DTF	63 aC	62 aB	66 aA	63 aA
FN	5 aA	14 bB	19 cB	18 bcB
PT	63 aB	90 bB	122 cA	147 dA
DL + 75 µmol·m^{-2}·s^{-1}				
PF	100 aC	100 aB	100 aA	100 aA
DTF	58 aBC	64 aB	63 aA	56 a
FN	9 aA	10 aAB	21 bB	15 abAB
PT	58 aB	88 abB	119 bA	140 cA
	PF	DTF	FN	PT
Cooling	***[z]	***	***	***
Photoperiod	**	**	***	**
Irradiance	NS	NS	*	NS
Cooling × photoperiod	***	***	NS	***
Cooling × irradiance	**	**	NS	**
Photoperiod × irradiance	***	***	NS	***
Cooling × photoperiod × irradiance	*	*	NS	*

HSD = honestly significant difference; NS = nonsignificant.
"-" denotes no flowering.
[z]Denotes significance at the α < 0.05 (*), < 0.01 (**), and < 0.001 (***) levels.

removal from 5 °C. Half of plants received a second application (same concentration) 1 week later. Application timing and concentrations were based on effective timing and rates identified on epiphytic cacti (Boyle, 1995; Heins et al., 1981; Ho et al., 1985). Data collection and analysis were as in Expt. 1. The experiment was organized in a completely randomized statistical design.

Expt 3: LD effects on early flower development. Sixteen plants were selected for uniformity and grown as in Expt. 1, except plants were grown at 5 °C for 12 weeks and then 22/18 °C under LD (DL ± 45 $\mu mol \cdot m^{-2} \cdot s^{-1}$; 0800–0200 HR) for 0, 2, 4, 6, or 8 weeks. Plants were then moved to SD (DL ± 45 $\mu mol \cdot m^{-2} \cdot s^{-1}$; 0800–1600 HR) for 12 weeks. Data were collected as in Expt 1. The experiment was organized in a completely randomized statistical design.

Results

Expt 1. SD-grown plants cooled for 0 or 4 weeks did not flower, but all SD-grown plants flowered when cooled for 8–12 weeks (Table 1). In contrast, 25% to 100% of uncooled LD-grown plants flowered, and all cooled (>4 weeks) LD-grown plants flowered (Table 1). Percent uncooled LD-grown plants that flowered increased from 25% to 50% to 100% as supplemental irradiance increased from 0 to 75 $\mu mol \cdot m^{-2} \cdot s^{-1}$ (Table 1).

Days to first flower (DTF) from the end of cooling decreased when plants were cooled for 12 vs. 8 weeks on SD-grown plants under 0 and SD + 25 $\mu mol \cdot m^{-2} \cdot s^{-1}$ lighting treatments (Table 1). DTF of LD-grown plants (0 and LD+25 $\mu mol \cdot m^{-2} \cdot s^{-1}$) increased from 52 to 64 to 66 d as 5 °C duration increased from 0 to 4 weeks (Table 1). DTF was greatest on SD + 25 $\mu mol \cdot m^{-2} \cdot s^{-1}$ (75 d), and least (56–64 d across cooling treatments) when grown under the LD + 45 to 75 $\mu mol \cdot m^{-2} \cdot s^{-1}$ lighting treatments (Table 1).

As 5 °C exposure duration increased from 0 to 12 weeks, flower number increased from 0 to 11 flowers per plant on SD-grown plants across irradiance treatments (Table 1). In contrast, as 5 °C duration increased from 0 to 8 weeks on LD-grown plants, flower number per plant increased from 5 to 21 flowers per plant across irradiance treatments (Table 1).

Total production time among SD-grown plants that flowered ranged from 123 to 147 d across irradiance treatments. Among LD-grown plants, production time ranged from 52 to 94 d on plants cooled for 0–4 weeks, to 119–153 d on plants cooled for 8–12 weeks (Table 1). We note that those differences were more related to cooling time, rather than forcing time, as the DTF was unchanged in most treatments (Table 1). Flower life varied from 1 to 3 d across all treatments (data not presented).

Expts. 2 and 3. BA concentration interacted with application number (*; P = 0.05) to affect flower number. One BA application (across concentrations) decreased flower number from 16 (water only) to 15 flowers per plant. There were 11 flowers on plants that received two BA applications.

Moving plants from LD to SD after a 12-week 5 °C exposure, affected DTF (*; P = 0.05), but not flower number per plant (P = nonsignificant.). DTF were 61 (b), 59 (ab), 54 (a), 58 (ab), and 61 (b) d for plants moved from LD to SD after 0, 2, 4, 6, or 8 weeks, respectively (letters in parenthesis denote mean separation using Tukey's HSD). Plants moved from LD to SD after 4 weeks had a lower DTF than plants moved after 0 or 8 weeks (see Tukey's mean separation above).

Discussion

Classification of flowering response groups involves comparison of node number below the first flower on plants grown under different environments (Thomas and Vince-Prue, 1997). Node counting is difficult on cacti as they have areoles (specialized axillary or lateral buds) often arranged in whorls (Mauseth, 1983). Because node number is not easily quantified, DTF and flower number per plant were considered. Of these, we focused on flower number as it quantifies the earliness and "degree" of induction to classify plants into photoperiodic/cool-temperature response groups here.

'Rose Quartz' can be classified as a facultative LD plant with a facultative cool-temperature requirement for flowering. Determination of whether the cool-temperature requirement resulted from vernalization or overcoming flower bud dormancy would require areole dissection before cooling to determine whether flower buds were present.

Our results are consistent with conclusions that can be drawn from previous work on desert cacti flowering (personal interpretation of data). Runger's (1967) data suggested *M. zeilmanniana* had a facultative cool-temperature and facultative SD requirement for flowering. Similarly, *N. tabularis* flowering data suggested this species had a facultative cool-temperature and facultative irradiance requirement for flowering (Runger, 1971). In contrast, *R. marsoneri* (Runger, 1968b) and *R. violaciflora* (Runger, 1973) data suggested plants had a facultative cool-temperature and facultative SD requirement for flowering.

Data here suggested 'Rose Quartz' had an optimal cooling duration of 8 weeks (56 d) for maximum flowering. Runger (1968a, 1968b, 1971, 1973) suggested that optimal cooling duration for cacti he studied was 60–70 d. However, cacti in Runger's work were cooled at 10–15 °C rather than at 5 °C as here. Runger acknowledged cooling at 5–10 °C vs. 10–15 °C reduced the duration of cooling required for full induction (1967, 1968a, 1968b, 1971).

Both cool temperature and LD promoted 'Rose Quartz' flowering (Table 1). Similar cool temperature and LD promotion of flowering occurs with Easter lily (*Lilium longiflorum*; Waters and Wilkins, 1967) and other herbaceous perennials (Padhye et al., 2006). Runger (1967) showed that *M. zeilmanniana* flowering was promoted by 5–7 °C and photoperiod was irrelevant during cooling; however, photoperiod was increasingly important as temperature increased from 5 to 17 °C. In contrast, *N. tabularis* flowering was promoted by a 5–15 °C exposure and photoperiod was irrelevant (Runger, 1971).

BA application after a 5 °C exposure did not increase 'Rose Quartz' flower number. In fact, BA application decreased 'Rose Quartz' flower number. Increased flower number resulting from a spray application of 20–40 $mg \cdot L^{-1}$ BA to *Schlumbergera* and *Hatoria* required synchronization of that application with flower induction (Boyle, 1995; Heins et al., 1981; Ho et al., 1985). We do not know when desert cacti initiate flowers. Therefore, the lack of response (increased flower number) to a BA spray application may be a result of inappropriate spray timing.

Flower development on 'Rose Quartz' was photoperiod independent. Photoperiod independence of cacti flower development may be species specific as Runger (1967) reported an LD requirement for flower development with *M. zeilmanniana*, but not *N. tabularis* (Runger, 1971).

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