

Effect of Two-week High-temperature Treatment on Flower Quality and Abscission of *Rosa* L. ‘Belinda’s Dream’ and ‘RADrazz’ (KnockOut®) under Controlled Growing Environments

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Additional index words. flower size, heat stress, phenotyping, rose breeding

Abstract. The decline in sales of garden roses can, in part, be attributed to the lack of well-adapted cultivars. Successful selection for any trait requires an accurate phenotyping protocol. Apart from field screening, a protocol for phenotyping high-temperature tolerance in garden roses is yet to be established. An experiment was conducted to determine the stage of development when flowers were most sensitive to high-temperature stress. Liners of *Rosa* L. ‘Belinda’s Dream (BD) and the Knock Out® rose ‘RADrazz’ (KO) were planted in a soilless medium and grown in a greenhouse. Established plants were pruned retaining several nodes with leaves on two main shoots and treatments started. The experiment was conducted in growth chambers held at either 24/17 °C (control) or 36/28 °C (stress) day/night temperatures. Six time and duration temperature treatments included 8 weeks of continuous control conditions, 8 weeks of continuous stress conditions, and four sequential 2-week high-temperature shock treatments. Continuously stressed plants flowered in the least amount of days but did not differ from the continuous control-treated plants based on nonlinear thermal unit accumulation until flowering. Both cultivars had a 70% reduction in flower dry weight under continuous stress conditions. Flowers were most sensitive to high-temperature stress at the visible bud stage, which corresponds to Weeks 5 to 6 and Weeks 7 to 8 for BD and Weeks 3 to 4 and Weeks 5 to 6 for KO, respectively. KO was more resistant to flower abscission than BD when treated at the visible bud stage, but no difference in flower dry weight reduction between BD and KO was found. The number of vegetative nodes to the flower was unaffected by treatment and differed between the cultivars.

A decrease in the sale of garden roses in the United States has been observed in the past 20 years (Byrne et al., 2010), which can,

in part, be attributed to the lack of well-adapted cultivars (Hutton, 2012). One of the major limiting factors for growing crops worldwide, especially in subtropical climates like Texas, is high-temperature stress, which can cause irreversible damage to plant growth and development. An approach to manage this issue is the development of plants with greater high-temperature tolerance. High temperature-

tolerant plants would be able to produce an economically viable yield under high-temperature conditions (Wahid et al., 2007); so then would garden roses with greater tolerance be expected to perpetually flower during the warm season while maintaining a positive landscape appearance.

The effect of high-temperature stress on rose growth and development is complex. Excessively high or low growing temperatures negatively impact the longevity and quality of cut roses (Marissen, 2001; Moe, 1975; Wahid et al., 2007). Several models describing rose shoot growth and development using ambient temperature and thermal unit accumulation have been developed for greenhouse rose production (Mattson and Lieth, 2007; Pasian and Lieth, 1994; Steininger et al., 2002). Growers can use software tools to model and schedule rose crops. An upper threshold where development is impaired is commonly included when calculating growing degree-days for agronomic crops such as maize (*Zea mays* L.) and wheat (*Triticum aestivum* L.) (McMaster and Wilhelm, 1997). Although not included by Pasian and Lieth (1994), such a threshold for potted miniature rose ‘Candy Sunblaze®’ was presented by Steininger et al. (2002) as 25.6 °C for development from budbreak until flowers open.

Evidence suggests that rose flower size and quality are most sensitive to high-temperature stress at or after the visible bud stage of development. Rising temperature before the visible bud stage did not affect the size of ‘Kardinal’ roses. Flower size quadratically decreased with increasing growing temperature after the visible bud stage (Shin et al., 2001). Loss of rose flower quality by way of anthocyanin reduction was most severe when ‘Jaguar’ seedlings were subjected to a 3-d 39/18 °C day/night high-temperature stress at the stage right before flower buds started showing color (Dela et al., 2003).

Rose plant architecture is influenced by the growing temperature. Grossi et al. (2004) reported a reduction in the number of vegetative nodes when potted miniature roses (cultivar Meijikatar) were produced under summer-like conditions when compared with plants grown under winter-like conditions. Kawamura et al. (2011) reported a strong positive correlation ($r = 0.66$) between the number of vegetative nodes and the days to flower on a diploid rose population.

Field observations show that garden roses suffer from loss of flower quality and yield due to high temperatures. These observations also point to a wide range of variation in garden rose accessions with regard to performance under high-temperature conditions. To our knowledge, this variation has yet to be quantified. The first step to quantify and ultimately breed for any trait of interest is an accurate and repeatable method of phenotyping.

The objectives of this study were to: 1) identify the stage of shoot development where garden rose flower size and abscission are most sensitive to high temperature stress; and 2) evaluate how the number of vegetative nodes and time to flowering are affected by

Received for publication 18 Nov. 2013. Accepted for publication 7 Apr. 2014.

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high-temperature stress on two garden rose cultivars.

Materials and Methods

Plant material. Liners of *Rosa* L. cultivars BD and KO were planted in 0.72-L pots in LC-1 soilless medium (SunGro Horticulture, Bellevue, WA) and grown in greenhouse conditions at the Texas A&M AgriLife Research and Extension Center in Overton, TX. The plants were irrigated until run-through as required with a 200 mg·L⁻¹ 15N–5.4P–14.1K liquid fertilizer adjusted for nitrogen (N). After the plants were established, the plants were pruned to synchronize flowering. Plants were pruned on the morning the experiment was initiated at each location. Pruning was similar to what was described by Grossi et al. (2004) with the modification of leaving two main shoots for buds to develop from instead of just one and more than three leaves on each remaining shoot.

Experimental setup. A factorial design was used with two cultivars × six treatments × seven replications (individual plants). The plants were arranged in a randomized complete block design. The experiment was repeated at two locations. The whole experiment was conducted in growth chambers (Conviroon Model E-15, Winnipeg, Manitoba, Canada). The plants were subjected to six time and duration temperature treatments, which included 8 weeks of continuous control conditions, 8 weeks of continuous stress conditions, and four sequential 2-week high-temperature shock treatments whereby plants were exposed to stress conditions during Weeks 1 to 2, Weeks 3 to 4, Weeks 5 to 6, or Weeks 7 to 8 with the balance of the 8 weeks under control conditions.

The day/night temperatures for the control and stress conditions were maintained at 24/17 and 36/28 °C with 70% relative humidity. Thermometers included in the growth chambers were monitored periodically to ensure that growth chambers were running at set point.

The experiment was ended on Day 70. The experiment was conducted at the Texas A&M AgriLife Research and Extension Center at Overton and repeated at the Borlaug Center on the College Station campus of Texas A&M University. The experiment in the Borlaug Center was initiated 4 d after initiation in Overton.

A 14-h photoperiod was maintained at a photosynthetic photon flux density of 570

μmol·m⁻²·s⁻¹ (LI-191 Line Quantum Sensor; LI-COR®, Lincoln, NE). The plants were irrigated until run through as required with a 200 mg·L⁻¹ 15N–5.4P–14.1K liquid fertilizer adjusted for N.

Flower developmental stages were not quantified. A note was made during which the flower buds became macroscopically visible without manipulating leaves, from here on referred to as the visible bud stage. Data were recorded for each plant on the day the first flower fully opened. Number of days to flower from pruning, the number of vegetative nodes to flower, and flower dry weight were recorded for the first flowering shoot on each plant. Flowers were harvested by cutting at the base of the hypanthium. Flower abscission was evaluated on a whole plant level and scored on a binomial scale; abscission was scored if two or more shoots on a plant had abscised flowers. Plants that did not flower by the end of the experiment were scored as abscised. Although no blind shoots or abscission was detected on these plants, they maintained vegetative growth. According to the number of nodes, flower formation should have occurred and undetected abscission was assumed. If plants flowered before or within 3 d of the high-temperature treatment they were scheduled to receive, data were collected and the plants were considered as control-treated plants during analysis. Proportionate dry weight was calculated by taking the mean flower dry weights of plants grown continuously under control conditions and expressing each observation as a proportion of the mean flower dry weight of the control observations for each cultivar at each location.

The amount of thermal units (TUs), in hours, accumulated until flowering was calculated for each plant based on two equations:

$$TU1 = \sum_{j=1}^r \max[(T_j - T_{b1}), 0] \Delta t_j \quad [1]$$

$$TU2 = \sum_{j=1}^r \max[T_i - T_{b2} + k(T_j - T_i), 0] \Delta t_j \quad [2]$$

where r = the number of days to flower, T_j is the average air temperature (°C) over a period j, Δt_j is the length of time period j (24 h), and T_b is the base temperature (Thornley and Johnson, 1990). TU calculations were performed based on growth chamber set points.

The base temperature (T_{b1}) used in Eq. [1] was reported by Pasion and Lieth (1994) as 5.2 °C for ‘Cara Mia’ hybrid tea roses. In Eq. [2], T_i refers to the temperature where TUs are not linearly accumulated (Steininger et al., 2002) and was reported by Steininger et al. (2002) to be 25.6 °C for miniature rose ‘Candy Sunblaze®’; T_{b2} was reported as 9.5 °C for ‘Candy Sunblaze®’. The term k is the ratio of the slope for the regression line at T_j > T_i and T_j < T_i and was reported as 0.47 for ‘Candy Sunblaze®’ by Steininger et al. (2002). The TUs accumulated were calculated by summing the TUs until flowering.

Statistical analysis. All statistical analysis was performed using JMP software, Version 9.0 (SAS Institute Inc., Cary, NC, 1989–2010). Analysis of variance was performed by fitting a standard least squares model, where the replication effect was considered as a random effect. Variance components were estimated using an all random model and inferences were made on the mixed models. Tests of equal variance between locations were performed before performing analyses combined over locations. Differences between means were tested using Tukey’s honestly significant difference test. Significant interaction effects were further investigated by way of linear contrasts. Nominal regression was used to analyze flower abscission and differences between treatments were evaluated based on odds ratios.

Results

Flower dry weight. BD has heavier flowers than KO. For better comparison between the cultivars, flower dry weight was analyzed as the proportionate flower weight. Based on Levene’s equal variance test, there was no evidence of unequal variance (P = 0.389), and data from both locations were combined. KO did not have any plants flowering in treatment Weeks 7 to 8, and the cultivar × treatment term was not considered. Thus, each cultivar was analyzed separately over both locations. Only the main effects of location and treatment were significant for both cultivars (Table 1). Plants of both cultivars, BD and KO, produced larger flowers (23% and 12%, respectively) in Overton as compared with the College Station trial experiment.

Plants grown in continuous high-temperature conditions produced the smallest flowers, whereas plants grown in continuous control

Table 1. Analysis of variance F-ratio results for different traits analyzed separately for ‘Belinda’s Dream’ (BD) and ‘RADrazz’ (KO) after plants were subjected to high-temperature stress during different stages of development.

Source of variance	P flower wt ²		Days to flower		TU1 ^y		TU2	
	BD	KO	BD	KO	BD	KO	BD	KO
Location	12.91 ^{x**}	4.80*	10.10*	19.02 ^{***}	12.98 ^{**}	15.47 ^{**}	11.31*	17.92 ^{**}
Treatment	18.43 ^{***}	46.71 ^{***}	9.00 ^{***}	17.11 ^{***}	9.02 ^{***}	50.00 ^{***}	3.49*	7.29 ^{***}
Location × treatment	2.64 NS	2.45 NS	0.97 NS	5.46 ^{***}	1.04 NS	4.59*	0.98 NS	5.19 ^{**}

²Flower dry weight proportionate to the mean control treatment dry weight.

^yTU1 and TU2 refers to thermal unit accumulated in hours calculated based on following equations: $TU1 = \sum_{j=1}^r \max[(T_j - T_{b1}), 0] \Delta t_j$ and $TU2 = \sum_{j=1}^r \max[T_i - T_{b2} + k(T_j - T_i), 0] \Delta t_j$ where r = number of days to flower, T_j is the average air temperature (°C) over period j, Δt_j is the length of time period j (24 h), T_{b1} and T_{b2} is the base temperature (5.2 and 9.5 °C), T_i is the temperature where thermal units are not linearly accumulated (25.6 °C), and k is the ratio of the slope for the regression line at T_j > T_i and T_j < T_i (0.47) (Pasion and Lieth, 1994; Steininger et al., 2002).

^xNS, *, **, *** Nonsignificant or significant at P ≤ 0.05, 0.01, or 0.001, respectively.

conditions resulted in the largest flowers in both BD and KO (Table 2). Flower dry weight of both BD and KO produced under continuous high temperatures were reduced to $\approx 30\%$ of the weight of flowers grown under continuous control conditions. The greatest effect of high temperatures on flower dry weight on both cultivars was during the visible bud stage. Because the cultivars flowered differently, the visible bud stage corresponded to stress during Weeks 5 to 6 and Weeks 7 to 8 for BD (46% reduction in size) and Weeks 3 to 4 and Weeks 5 to 6 for KO (38% reduction in size). Pooling the proportionate flower weights of BD for Weeks 5 to 6 and Weeks 7 to 8 and for KO during Weeks 3 to 4 and Weeks 5 to 6 resulted in the proportionate flower weight not being different between cultivars.

Flower abscission. Separate χ^2 analyses for location, cultivar, and treatment indicated a nonsignificant location effect ($P = 0.834$) and highly significant cultivar and treatment effects ($P < 0.001$). The majority of the cultivar differences observed was the result of BD, because only two KO plants showed flower abscission. Because KO showed little flower abscission (Fig. 1), BD and KO were analyzed separately.

The nominal logistic model for KO flower abscission was not significant ($P = 0.518$). The nominal logistic model for BD was significant ($P = 0.022$) with no evidence for lack of fit ($P = 0.680$). The treatment effect was significant ($P = 0.008$), whereas the location and the location \times treatment interaction effects were not. Four of 15 BD control plants did not flower within 70 d and were classified as having abscised flowers. Treatments Weeks 5 to 6 and Weeks 7 to 8 had the highest rate of flower abscission (Fig. 1; Table 3). The odds of BD plants from treatment Weeks 5 to 6 having more than two shoots with abscised flowers was greater than those of plants under continuous control conditions, Weeks 1 to 2, and continuous stress-treated plants. The odds of a plant from treatment Weeks 7 to 8 having more than two shoots with abscised flowers were significantly greater than Weeks 1 to 2 and the continuous stress treatments (Fig. 1; Table 3).

Interestingly, the odds of a continuously stressed plant having two or more abscised flowers was significantly lower than the odds of plants from treatments Weeks 3 to 4, Weeks 5 to 6, and Weeks 7 to 8. BD flowers were more susceptible to flower abscission from a high-temperature shock after reaching the visible bud stage (Fig. 1).

Time to flower. Based on Levene's test for equal variance, there was evidence for unequal variance in the days to flower between the two locations ($P = 0.023$). College Station had greater variance in the number of days to flower. Days to flower had a sd of 6.9 in College Station and 4.9 in Overton. Data were combined across locations regardless of unequal variance. For the same reasons, the two cultivars were analyzed separately. Only the main effects of location and treatment were significant for BD, and all effects were significant for KO (Table 1).

Plants from BD flowered 5 d earlier in Overton than in College Station. Plants of both BD and KO grown under continuous stress temperatures flowered in the least amount of days (Fig. 2). BD plants from treatment Weeks 7 to 8 took the longest to flower, whereas plants from treatment Weeks 5 to 6 flowered in the same amount of time as plants subjected to continuous stress (Fig. 2A). KO plants from treatment Weeks 1 to 2 took the longest to flower but not significantly longer than control-treated plants. Excluding continuous stress-treated plants, KO plants from treatments Weeks 3 to 4 and Weeks 5 to 6 flowered in the least amount of days. Week 5 to 6 plants were not different from the control (Fig. 2B).

For days to flower, the significant location \times treatment interaction in KO explained nearly 10% of the variation, whereas the location and treatment effects explained 40% and 43% of the variation, respectively. Apart from the control and Week 3 to 4 treatment, respectively, flowering 7.3 and 3.1 d earlier in Overton, KO showed no difference in the number of days to flower between locations for the remaining treatments. KO control-treated plants in College Station all flowered between 39 and 44 d, whereas in Overton, the plants flowered between 29 and 37 d. The trend was

similar for treatment Weeks 3 to 4 where plants in College Station flowered between 32 and 43 d and plants from Overton flowered between 27 and 36 d.

Because there was no evidence for unequal variance for thermal units accumulated up to flowering (TU1 and TU2), the data were combined over the two locations. For BD, the main effects of location and treatment but not the interaction was significant based on both equations (Table 1). All model effects were found to be significant for TUs accumulated for KO based on both equations (Table 1). The significant location \times treatment interaction found for KO resulted from control and Week 3 to 4-treated plants in College Station accumulating more TUs than the same treatment in Overton. The interaction term accounted for 6% with TU1 as a response variable and 14% with TU2 as a response variable. It has to be taken into account that the model for TU2 had a lower coefficient of determination (adjusted $R^2 = 0.80$ vs. 0.59) than the model for TU1.

Based on TUs accumulated from Eq. [1], plants subjected to continuous stress accumulated more hours than plants under control conditions for both cultivars. For both cultivars, TU1 under stress conditions grouped in the group accumulating the most TUs (Table 4).

Table 2. Proportionate flower dry weight (± 1 SE of the mean) over different treatments for 'Belinda's Dream' (BD) and 'RADrazz' (KO).

Treatment	BD	KO
Control	0.987 \pm 0.067 a ^z	1.002 \pm 0.034 a
Week 1–2	0.893 \pm 0.059 a	0.988 \pm 0.047 a
Week 3–4	0.861 \pm 0.07 a	0.613 \pm 0.047 b
Week 5–6	0.536 \pm 0.117 b	0.623 \pm 0.074 b
Week 7–8	0.543 \pm 0.103 b	—
Stress	0.333 \pm 0.052 b	0.323 \pm 0.049 c

^zLevels within a column not connected by the same letters are significantly different at $\alpha \leq 0.05$ with Tukey's adjustment.

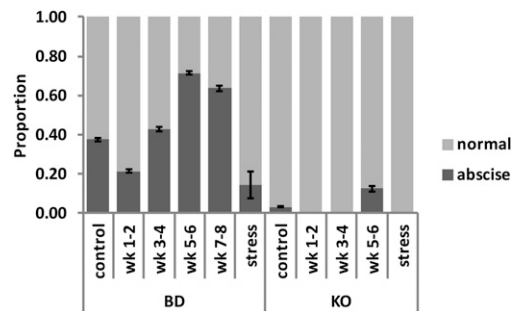


Fig. 1. Proportion of plants with more than two shoots abscising flowers over treatment for 'Belinda's Dream' (BD) and 'RADrazz' (KO). "Abscise" indicates having more than two shoots per plant with abscised flowers; "normal" indicates having less than two or no shoots with abscised flowers per plant. Error bars represent 1 SEM probability.

Table 3. Significance of odds ratios for plants of 'Belinda's Dream' (BD) having more than two shoots with abscised flowers across all treatment combinations.

	Control	Week 1–2	Week 3–4	Week 5–6	Week 7–8	Stress
Control	—	NS ^z	NS	+	NS	NS
Week 1–2		—	NS	**	*	NS
Week 3–4			—	NS	NS	+
Week 5–6				—	NS	**
Week 7–8					—	**
Stress						—

^zNS, +, *, ** Nonsignificant or significant at $P \leq 0.1, 0.05, \text{ or } 0.01$, respectively.

No differences in TU1 were seen among 2-week treatments for BD. Two-week treatments of KO plants had Weeks 1 to 2 accumulate the greatest TUs followed by Weeks 3 to 4 and then Weeks 5 to 6.

The nonlinear TU accumulation based on Eq. [2] resulted in no difference in TU2 between control and continuous stress-treated plants for both BD and KO (Table 4). BD plants from treatment Weeks 7 to 8 had the greatest TU2, whereas none of the other treatments were significantly different from each other. KO plants from treatment Weeks 1 to 2 had the greatest TU2, whereas none of the remaining treatments were significantly different from each other.

Number of nodes to flower. Data from both locations were combined as the variances were similar. A combined analysis revealed only the cultivar effect to be significant with KO (9.1 nodes) having fewer vegetative nodes before the flower than did BD (10.7 nodes).

The heat stress treatments did not affect the number of vegetative nodes produced.

Discussion

Flower dry weight and flower abscission were most affected at the visible bud stage, which corresponds to stress treatments during Weeks 5 to 6 and 7 to 8 for BD and Weeks 3 to 4 and 5 to 6 for KO. The proportionate reduction in flower dry weight between BD and KO was the same when plants were subjected to continuous stress. Fading of flower color was observed but not recorded when plants were stressed at the visible bud stage for both cultivars.

'Madelon' roses subjected to drought stress was most affected at the stamen formation stage before the carpel formation stage of development (Chimonidou-Pavlidou, 2004), thus slightly earlier than the visible bud stage. 'Jaguar' rose seedlings were most susceptible

to reduction in anthocyanin preceding pigmentation of flower buds (Dela et al., 2003), thus later than the visible bud stage. Rose flowers were more sensitive to high growing temperatures after the visible bud stage and flower size was reduced in a quadratic fashion with increasing growing temperatures (Shin et al., 2001). Literature suggests that flower weight and quality are most affected by abiotic stress factors after the visible bud stage of development, and the results of the current study for flower dry weight and abscission are in agreement with others. Different from Shin et al. (2001) who subjected plants to different constant growing temperature after specific developmental stages have been reached, predetermined time periods for treatments were used. Dela et al. (2003) subjected plants to short 1- to 3-d heat shock treatments. Close tracking of flower developmental stages and short heat shock treatments would provide a good comparison of short heat shock treatments at sensitive stages of development on flower weight and abscission.

Both BD and KO flower weights were reduced by 70% when grown under continuous high-temperature stress. The low amount of flower abscission for BD plants grown under continuous stress is evidence of BD's ability to adapt to growing under high temperatures. The flower abscission response when stressed at the visible bud stage was probably the result of the shock of being moved from the control environment into the stress environment at that critical time. Plants adapt to their environment. For example, *Nerium oleander* plants grown at 45/32 °C (day/night) had a different membrane lipid composition than those grown at 20/15 °C (Raison et al., 1982). The membranes of plants grown under high temperature were less fluid providing integrity under elevated temperatures. Thus, although the flowers of BD plants under continuous high stress conditions were subjected to the high temperatures during the visible bud stage, the plants had time to respond to growing under elevated temperatures.

The 8% difference in flower weight reduction between BD and KO when stressed at the critical time was not different from each other. A larger sample size would be required to investigate whether flower weight reduction when stressed at the visible bud stage is different between BD and KO. Both BD and KO are well adapted to the south-central United States and carry the Earth-Kind® designation, which means that they perform well in the landscape under a wide range of conditions (Texas A&M University System, 2013). Differences in flower weight reduction between well-adapted and not so well-adapted cultivars might prove to be greater than we observed between these two adapted cultivars.

Larger flowers are associated with cooler growing conditions. Shin et al. (2001) reports that flowers of 'Kardinal' produced at 15 °C were 3 g compared with less than 2 g for temperatures above 24 °C. The increase in flower weight between the control and continuous stress plants in our study could in part

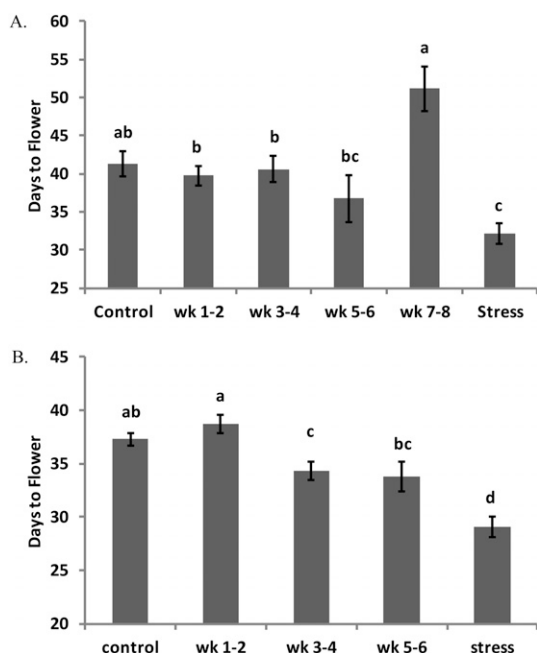


Fig. 2. Number of days to flower for 'Belinda's Dream' (BD) (A) and 'RADrazz' (KO) (B) at each treatment combined over both locations. Error bars represent the SEM. Treatments not connected by the same letter are significantly different, $\alpha = 0.05$, with Tukey's adjustment.

Table 4. Thermal units accumulated (± 1 SE of the mean) for 'Belinda's Dream' (BD) and 'RADrazz' (KO) across both locations for each treatment.

Treatment	BD		KO	
	TU1 ^z	TU2	TU1	TU2
Control	649 \pm 29 c ^y	649 \pm 27 b	590 \pm 10 c	587 \pm 9 b
Week 1-2	789 \pm 24 ab	681 \pm 22 ab	773 \pm 15 a	664 \pm 13 a
Week 3-4	802 \pm 31 ab	694 \pm 29 ab	702 \pm 15 b	595 \pm 13 b
Week 5-6	674 \pm 55 bc	610 \pm 51 b	602 \pm 22 c	555 \pm 20 b
Week 7-8	899 \pm 52 ab	836 \pm 47 a	—	—
Stress	883 \pm 24 a	643 \pm 22 b	799 \pm 15 a	573 \pm 14 b

^zTU1 and TU2 refers to thermal unit accumulated in hours calculated based on following equations:

$$TU1 = \sum_{j=1}^r \max[(T_j - T_{b1}), 0] \Delta t_j \text{ and } TU2 = \sum_{j=1}^r \max[T_i - T_{b2} + k(T_j - T_i), 0] \Delta t_j \text{ where } r \text{ is the number}$$

of days to flower, T_j is the average air temperature (°C) over period j , Δt_j is the length of time period j (24 h), T_{b1} and T_{b2} is the base temperature (5.2 and 9.5 °C), T_i is the temperature where thermal units are not linearly accumulated (25.6 °C), and k is the ratio of the slope for the regression line at $T_j > T_i$ and $T_j < T_i$ (0.47) (Pasian and Lieth, 1994; Steininger et al., 2002).

^yLevels within a column not connected by the same letters are significantly different at $\alpha \leq 0.05$ with Tukey's adjustment. Comparisons are made among treatments within cultivar.

be attributed to the increased number of days to flower for control plants in combination with reduced photosynthesis at the higher temperature. Jiao and Grodzinski (1998) reported a significant reduction in photosynthesis and carbohydrate export at 40 °C compared with 15 °C in ‘Samantha’ roses.

Both cultivars flowered in the least amount of time under continuous stress conditions. Developmental rates of rose shoots are heavily influenced by air temperature. Pasian and Lieth (1994) report a positive linear relationship between the rate of development and air temperature for all stages of shoot development with the exception of budbreak after pruning. A reduction in the number of days to flower compared with the control treatment would be expected for both cultivars.

It is expected that the number of TUs accumulated to reach a certain stage of development remains fairly constant within a cultivar. The differences in TU1 between control and continuous stressed plants for both BD and KO indicated that a linear accumulation of TUs for the temperatures used was not appropriate. No differences in TU2 were seen between control and continuous stressed plants for either cultivar suggesting that a nonlinear accumulation of TUs occurs for both BD and KO. Pasian and Lieth (1994) reported that TU accumulation could not reliably predict the period from pruning until budbreak; not taking the time to budbreak into account in this experiment likely added to the variation. The linear model for TU accumulation used by Pasian and Lieth (1994) remains valid within the temperatures experienced during their experiment where the maximum temperature was 29.8 °C. Steininger et al. (2002) reports that TU accumulation is cultivar-dependent because they found no non-linearity for miniature rose ‘Red Sunblaze’[®] although it was grown at 35 °C.

An increase in the days to flower and TUs accumulated for BD plants from treatment Weeks 7 to 8 is contradictory to what was expected. Time to flower decreased in cut roses and miniature potted roses with increased temperature applied after the visible bud stage (Pasian and Lieth, 1994; Shin et al., 2001; Steininger et al., 2002). It is possible that early flower abscission was not detected and plants continued to grow vegetatively for a longer period of time until they reached flowering. This is unlikely to have been the cause for the delayed flowering because an increase in the number of vegetative nodes would be expected under such conditions. An increase in the time to flower for plants of chrysanthemum ‘Bright Golden Age’ (*Dendranthema grandiflora*) was reported by Karlsson et al. (1989) when plants at the visible bud stage of development were moved from cooler growing conditions to 30 °C conditions; however, this is yet to be reported in roses.

The only difference in the number of nodes to flower was the cultivar difference. KO flowered in less time and produced less vegetative nodes to flower than did BD (9.1 vs. 10.3). Marcellis-van Acker (1995) concludes that the number of vegetative nodes on rose

shoots is determined during the formation of the axillary buds; thus, the temperature regime the parent shoots are exposed to could affect the number of vegetative nodes. All the plants from our experiment were grown under the same conditions before the onset of the experiment and the axillary buds were presumably formed under the same conditions. Not observing node number differences within a cultivar due to treatment is consistent with node number before flowering being predetermined in the axillary buds.

Conclusions

Flower quality and abscission are most sensitive to high-temperature stress after flowering shoots have reached the visible bud stage. Lower flower abscission rates for BD under continuous stress conditions provided evidence of BD’s ability to acclimate to high-temperature conditions and that the increased rates in flower abscission were probably due to a high-temperature shock. Based on near zero flower abscission, KO may be ranked as more tolerant to a high-temperature shock. Evaluating garden rose flowering response after a high-temperature shock could be used in screening roses for high-temperature tolerance.

Plants flowered faster under continuous stress conditions compared with the control conditions. No differences in TU2 accumulated between control and continuous stressed plants of either cultivar suggest that there is a nonlinear accumulation of TUs and that the stress treatment was severe enough to exceed optimum temperatures of development for both cultivars. Results presented also suggest that a nonlinear TU accumulation model is more appropriate than a linear TU accumulation model. None of the treatments had any effect on the number of vegetative nodes to flowering for either BD or KO. Selecting rose cultivars and seedlings with a high minimum T_i could prove useful in breeding toward roses with better performance under high-temperature conditions.

Although the differences in flower dry weight reduction between BD and KO shoots subjected to a high-temperature shock at the critical stage were not significant, differences in dry weight reduction between cultivars could be a useful indicator of a cultivar’s ability to maintain flower quality during periods of high-temperature stress. Plants showing major reductions in flower dry weight would be likely more heat-susceptible.

Evaluating rose plants in the field is costly and ties up land and resources for several years because it takes a number of years to properly evaluate a new seedling. Subjecting plants to a high-temperature shock with flower buds at the visible bud stage of development could be the first step in selecting against the most high temperature-susceptible roses. Propensity toward flower abscission and reduction in flower dry weight in combination with measurements evaluating the maximum temperature where plant development starts to decline could be used to quantify garden rose high-temperature

susceptibility and add to breeding progress for better adapted garden roses.

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