J. AMER. SOC. HORT. SCI. 127(3):349–354. 2002.

Extension of a Thermal Unit Model to Represent Nonlinearities in Temperature Response of Miniature Rose Development

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ADDITIONAL INDEX WORDS. heat unit, base temperature, degree day, *Rosa* hybrids

ABSTRACT. 'Candy Sunblaze' and 'Red Sunblaze' miniature roses (*Rosa* L. sp.), were grown at several temperatures. The phenological events of budbreak (BB), visible flower bud (VB), and open flower (OF) were recorded daily. Based on these events, phenophases from BB to VB (BB:VB), from VB to OF (VB:OF), and from BB to OF (VB:OF) were defined. Daily rates of development to complete a phenophase increased with temperature between 13.6 and 27 °C. For 'Candy Sunblaze', the rate of increase changed to a smaller slope beyond 25 °C. A piecewise linear regression change point model was fitted to each dataset. The base temperature (T_b) and the temperature at which the nonlinearity (T_i) occurred could then be determined. T_b for the phenophase BB:OF was 9.5 °C for 'Candy Sunblaze' and 8.1 °C for 'Red Sunblaze'. T_i for 'Candy Sunblaze' was 24.9 °C for BB:VB and 25.6 °C for the phenophase BB:OF. The resulting point of change in rate of development prompted a modification of the traditional thermal unit formula. To complete the phenophase BB:OF using the modified formula, 479 degree days (°Cd) were predicted necessary for 'Candy Sunblaze' and 589 °Cd for 'Red Sunblaze'. Predicted time of events was compared with observed values. Subdividing BB:OF into BB:VB and VB:OF and using their respective T_b and thermal units summations (TU) reduced the average prediction error from 1.9 to 1.8 days for 'Candy Sunblaze' and from 2.4 to 1.5 days for 'Red Sunblaze'. In addition to single plant observations, phenological observations and thermal units were determined for pots with four plants to simulate commercial greenhouse crop production. Subdividing BB:OF into BB:VB and VB:OF and using their respective T_b and TU accumulations, reduced OF prediction errors on a crop basis for 'Red Sunblaze', but was ineffective for 'Candy Sunblaze'.

In the first half of the 1700s, René-Antoine Ferchault de Réaumur studied the effects of temperature on plant development (Podolsky, 1984). He recorded the mean daily temperature to study its effects on organisms and found that the sum was almost a fixed quantity for reaching plant developmental stages (Wang, 1960). This concept continues to be used today to predict development of various species of plants (Baker and Gallagher, 1983; Bauer et al., 1984; Gallagher, 1979; Raworth, 1994; Slafer and Rawson, 1994).

Growth refers to irreversible increases in weight, height, or volume of a plant cell, tissue, organ, or whole plant. In contrast, development is the succession of phenological events during a plant's life cycle (Squire, 1990; Wang, 1960). Observing development implies noting when the plants are involved in particular events which signal the start and end of particular periods of time termed phenophase. The rate at which a plant goes through such a phenophase is generally a linear function of temperature above a base temperature (T_b). In some cases, it has also been found that the slope of the relationship changes at some high temperature (T_i) (Grace, 1988; Porter et al., 1987; Summerfield et al., 1991) so that a model that encompasses all this information is

$$R = \begin{cases} 0 & \text{...if } T_j \leq T_b \\ a_0 + b_0 \times T_j & \text{...if } T_b < T_j < T_i \\ a_1 + b_1 \times T_j & \text{...if } T_j > T_i \end{cases} \quad [1]$$

where R is the rate of development calculated as the reciprocal of time from one developmental stage to the next, and T_j is the mean air temperature (Summerfield et al., 1991). The parameters a_0, a_1, b_0, and b_1 are determined empirically and may be specific to a genotype and a given developmental stage (Jamieson et al., 1995; Summerfield et al., 1991). As temperature decreases, the rate of development is reduced until the temperature reaches a value below which further plant development does not occur. However, this temperature limit is only constant for a specific phenophase and changes as development proceeds (Summerfield et al., 1991; Wilson and Barnett, 1983). T_b is given by

$$T_b = -a_0/b_0 \quad [2]$$

By tracking developmental rate in this way, it is assumed that temperature is the dominant environmental factor influencing plant development. Other factors (such as photoperiod) affecting development are generally not accounted for in such a model (Porter et al., 1987).

Thermal units (TU) with units of degree hour (°Ch) or degree day (°Cd) are calculated in successive hours (or days) by subtracting T_b from the mean hourly (or daily) temperature and adding each value to the subtotal accumulation from one phenological event to the next (Montieth, 1984; Summerfield et al., 1991):

$$TU = \sum \max\{(T_j - T_b), 0\}\ \Delta t_j \quad [3]$$

where Δt_j is the length of the period j (hours or days) and T_j stands for the mean (hourly or daily) temperature. The estimated value of accumulated TU is constant for a given phenophase and cultivar (Summerfield et al., 1991). When this value has been reached, a particular phenological event has been attained. However, this association between temperature and the accumulation of TU is

Received for publication 25 Aug. 2001. Accepted for publication 19 Feb. 2002. Salaries and research support provided by state and federal funds appropriated to the Ohio Agricultural Research and Development Center, The Ohio State University. This research was supported in part by a grant from the American Floral Endowment. Institutional manuscript number HCS0034.
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Table 1. Definitions of developmental events of single miniature rose flowering shoots.

Event	Definition of developmental event
Budbreak (BB)	Bud has grown to a length of at least 3 mm and shows signs of continuing growth.
Visible bud (VB)	Flower bud becomes visible to the naked eye (without touching or handling the shoot).
Open flower (OF)	Flower is completely open and the most outer petals extend perpendicular (90°) from the pedicel.

only sustained in environments where the diurnally changing temperatures do not exceed T_i (Summerfield et al., 1991). Temperature accumulation techniques have provided growers of agronomic crops with tools for predicting maturity of a wide range of crops such as wheat (*Ttriticum aestivum* L.), corn (*Zea mays* L.), soybeans (*Glycine max* Merril), and various vegetables (Arnold, 1959; Everaarts, 1999; Yang et al., 1995).

Precise crop timing is one of the most critical aspects of greenhouse production. Timing is essential for crops grown only for specific holidays [e.g., poinsettias (*Euphorbia pulcherrima* Wild. ex Klotzsch)] and it is important for 1) crops grown during the season that have higher demands (and prices) at specific times [e.g., roses (*Rosa* sp.) for Valentines Day and 2) efficient space management, sales and delivery planning, and product marketing for any greenhouse crop. Thus a model modified for the floriculture industry that would allow prediction of crop development under a wide range of temperature conditions could improve production planning. Hence, improving any methodology for crop timing may have the potential to increase profitability. However, limited research has been conducted to adapt the degree-day system for use by the greenhouse floriculture industry.

Pasian and Lieth (1994, 1996) reported use of thermal units to predict flowering in the cut-rose cultivars, Cara Mia, Royalty, and Sonia. A similar methodology was expected applicable to miniature roses grown as a container crop. While cut roses are sold as single flowering stems, three or more flowering plants in a container represents the salable product of miniature roses. Therefore, the objectives of this research were to estimate the TU requirements, develop a model to predict flowering of individual shoots, and adapt the model to a crop of miniature roses.

Materials and Methods

Air temperature recording. Data loggers (On-site Weather Logger; EME Systems, Berkeley, Calif.) were used to measure and log average hourly air temperature ≈50 mm above the plant canopy. The probes were readjusted periodically to maintain this distance. Copper-constantan thermocouples were connected to data loggers and used as temperature probes. Each thermocouple was protected from direct sunlight with an aluminum foil shield.

Modeling development of miniature rose single flowering shoots. Potted 'Candy Sunblaze' and 'Red Sunblaze' miniature rose liners (Yoder Brothers, Inc., Barberton, Ohio) were grown in a glass greenhouse at The Ohio State University, Columbus using standard cultural procedures (Jørgensen, 1992; Pemberton et al., 1997). Plants were grown in 153-mm-diameter (1800-mL) plastic pots using a commercial potting medium (Metro-Mix 360; Scotts-Sierra Hort. Products Co., Marysville, Ohio) containing horticultural vermiculite, Canadian sphagnum peat, processed bark ash, and washed sand. Plants were fertilized at every watering with 20N–4.3P–16.7K (Peters Professional water-soluble fertilizer; Scotts-Sierra Hort. Products Co.) liquid fertilizer at a concentration of 1.0 $g \cdot L^{-1}$. During the winter months (December to February), the concentration of the fertilizer was reduced to 0.75 $g \cdot L^{-1}$. Plants were irrigated by hand as needed.

Six single plants per cultivar were randomly located on one bench in several greenhouse compartments with temperature setpoints of 15, 25, or 30 °C. To achieve low temperature averages, during the winter months, plants were grown in a greenhouse with a 5 °C setpoint. The recorded air temperatures were used in all calculations because actual temperatures varied substantially from setpoints, especially during hot summer months. Plants were under natural light conditions, ranging from 8.3 $mol \cdot m^{-2} \cdot d^{-1}$ during December and 27.3 $mol \cdot m^{-2} \cdot d^{-1}$ during July. Shoots that reached the open flower stage under experimental conditions were harvested leaving two leaves below the point of cut. The part of the stem remaining on the plant was tagged and numbered for identification. Stems originating from the axillary bud of one of the two leaves below the point of cut were observed daily at 1700 HR and their developmental stage was recorded. The developmental stages were defined as in previous studies by Pasian and Lieth (1994, 1996). The phenophases selected for analysis were from budbreak to open flower (BB:OF). Further, BB:OF was divided into budbreak to visible flower bud (BB:VB) and visible flower bud to open flower (VB:OF) (Table 1). This process was conducted three times over a 3-year period (mid-1994 through mid-1997). As a consequence, 124 flowering shoots of 'Candy Sunblaze' and 88 flowering shoots of 'Red Sunblaze' were observed.

Modeling development of a mini-rose crop. Phenological observations of single flowering shoots represent a practical way to determine the base and optimal temperatures of development. Growers of miniature roses, however, deal with crops of multiple plants (containers with four or more plants per container) with development that is not completely synchronized. For this reason, phenological observations were also conducted on crops.

Crop plants were grown using the cultural procedures described previously. Instead of one plant per container, four plants were grown per 100 mm square standard plastic pot (600 mL). About 30 d after transplanting the liners, most plants had 5 mm diameter flower buds (pea size stage) and pots were selected for pinching and separated into three groups of 12 pots. Each group was moved to one greenhouse compartment with the setpoints at 15, 25, or 30 °C. Actual temperatures were within ±2 °C . Nine crops of 'Candy Sunblaze' and 10 crops of 'Red Sunblaze' were observed over 2 years.

It was assumed that T_b and T_i values were the same for both the single flowering shoots or crops. Lack of synchronized development required phenological events and screening procedures to be redefined for the crop study. Each container was considered to have reached a phenological event when three of the four plants were at the defined morphological stage. In turn, the crop was considered to have reached a given phenological event when 75% of the containers had reached such an event. Because some growers sell miniature roses at an earlier than 75% stage, the date when 50% of the containers had reached a phenological event was also recorded.

Estimation of base temperatures. Daily rates of development, (R), were estimated by calculating the reciprocal of the number of days a flowering shoot or a plant required to complete a given phenophase. Rates of development of a given phenophase were correlated to their respective average air temperature T_j using Eq. [1]

and base temperatures were calculated using Eq. [2]. To determine whether each data set presented a nonlinear temperature response (T_i), two linear regression models were fitted simultaneously; a nonlinear piecewise least squares regression with random change point approach. All fittings were done using the S+ statistical package (Stat. Sci., Seattle, Wash.). Because of nonhomogeneity (nonconstant variance), weighted least squares were used with weights inversely proportional to the variances. T_i was calculated using the following formula:

$$T_i = (a_0 - a_1)/(b_1 - b_0) \quad [4]$$

where a_0 and a_1 represent the *y* intercepts and b_1 and b_0 represent the slopes of the two fitted lines. The statistical procedure bootstrap was used to obtain SE values for the estimates and confidence intervals for the temperature limits (Efron and Tibshirani, 1993).

THERMAL UNITS CALCULATION. Use of Eq. [3] assumes a linear relationship between the rate of development and temperature. The traditional thermal unit (TU) formula had to be modified to take into consideration data sets with nonlinearities in temperature response. At temperatures $T_b < T_j < T_i$, the thermal unit calculation can be done using Eq. [3]. A special case of Eq. [3] is when $T_j = T_i$:

$$TU = \sum(T_i - T_b) \quad [5]$$

At $T_j > T_i$, thermal units equal to the sum of thermal units at $T_j = T_i$ (Eq. [5]) plus a fraction of thermal units at T_j:

$$TU = \sum((T_i - T_b) + k\,(T_j - T_i)) \quad [6]$$

where k is the ratio (<1) of the slope of the regression line at $T_j > T_i$ and the slope of the regression line at $T_j < T_i$. If the slope of the regression line at temperatures above T_i is negative (decreasing rates of development with increasing temperatures), the sign of k is also negative. In that case, T_i represents the optimum temperature for development (T_o).

After limiting the model so that no negative thermal units can be accumulated, the final equation is

$$TU = \sum \begin{cases} \max\{T_j - T_b, 0\}\ \Delta t_j & \text{...if } T_j < T_i \\ \max\{T_i - T_b + k \times (T_j - T_i), 0\}\ \Delta t_j & \text{...if } T_j \geq T_i \end{cases} \quad [7]$$

The function for $T_j < T_i$ is the traditional Eq. [3].

Thermal units accumulated during the phenophases BB:VB, VB:OF, and BB:OF of each flowering shoot or crop were calculated using Eq. [7]. An average was then computed for each of these phenophases, yielding the average number of thermal units needed to reach the events VB or OF. Using these averages, the data were re-analyzed to determine the magnitude of the discrepancy (in number of days) between the occurrences of these average thermal unit thresholds and the observed date of the event.

Predictions were tested using 1) average method, where only the T_b and TU summations for the entire phenophase BB:OF were used to predict OF, and 2) additive method, where T_b and TU summations for each of the phases BB:VB and VB:OF were used to predict OF. In the additive method, the predicted dates of VB for the phenophase BB:VB were used instead of the "observed" dates of VB for calculation of OF. The mean error of prediction was calculated by averaging the absolute values of the difference between observed date and predicted date.

Results

MODELING DEVELOPMENT OF MINIATURE ROSE SINGLE FLOWERING SHOOTS. Rate of development increased with mean temperatures for both cultivars (Fig. 1). For 'Candy Sunblaze', variability in the rate of development was larger with increasing temperatures. The rate of development of 'Candy Sunblaze' for the phenophases BB:VB and BB:OF increased up to 25 °C beyond which it increased at a reduced rate. A change in slope was not observed for the phenophase VB:OF or for any phenophase of 'Red Sunblaze'. While some increase in variability with increasing temperatures was also present for this cultivar, it was less than for 'Candy Sunblaze' (Fig. 1).

T_b is represented by the intersection of the regression line for $T_j < T_i$ and the x-axis (Table 2). For both cultivars, the phenophase BB:VB had higher T_b than the phenophase VB:OF while T_b for the phenophase BB:OF was intermediate. For 'Candy Sunblaze', the rate of development increased at a reduced pace at temperatures above 24.9 °C for the phenophase BB:VB and above 25.6 °C for the phenophase BB:OF. For the same cultivar, at $T_j > T_i$ the rate of development was 22% smaller than at $T_j < T_i$ for the phenophase BB:VB and 47% smaller for the phenophase BB:OF (Table 2).

'Candy Sunblaze' accumulated at least 479 ± 42 °Cd as opposed to 589 ± 41 °Cd for the 'Red Sunblaze' (Table 2) to complete the phenophase BB:OF. The TU required to complete the phenophase BB:VB indicate VB occured close to half the development to OF.

Predicted days to OF derived by the average and the additive methods are shown in Table 3. The phenophase BB:OF of 'Candy Sunblaze' was predicted within an error range of ±1.99 d for 60% of all cases using the average method (Table 3). When the additive method was used, the fraction of flowering shoots within ±1.99 d error was increased to 71%. A greater prediction improvement can be seen for 'Red Sunblaze'. The prediction within ±0.99 d improved

Fig. 1. Daily rates of development of single flowering shoots for the phenophases BB:VB, VB:OF and BB:OF of 'Red Sunblaze' and 'Candy Sunblaze' miniature roses as a function of air temperature. Symbols represent observations while lines represent the linear portion of the model for $T_j > T_b$. BB = budbreak; VB = visible flower bud; and OF = open flower.

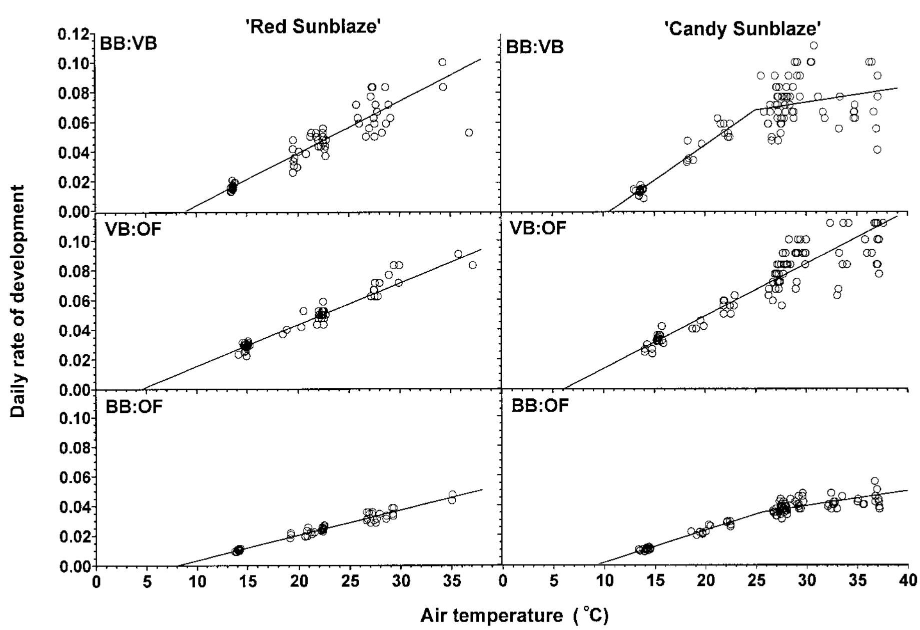

Table 2. Parameters (a_0, b_0, a_1, and b_1) of linear regression models fitted to rates of development as a function of mean air temperature (T_j), base temperature (T_b), temperature at which the nonlinearity occurs (T_i), ratio of slopes (k), and thermal unit accumulations (TU) and their SD for each phenophase of 'Candy Sunblaze' and 'Red Sunblaze' miniature roses. BB = budbreak; VB = visible flower bud; and OF = open flower.

	Estimates for $T_j \le T_i$		Estimates for $T_j > T_i$						
Phenophase	a_0 (d^{-1})	b_0 ($d^{-1}T^{-1}$)	a_1 (d^{-1})	b_1 ($d^{-1}T^{-1}$)	T_b (°C)	T_i (°C)	k	TU (°Cd)	SD (°Cd)
'Candy Sunblaze'									
BB:VB	–0.0496	0.0047	0.0421	0.0011	10.5	24.9	0.22	225	34.3
VB:OF	–0.0221	0.0035	---	---	6.2	---	1	302	33.5
BB:OF	–0.0204	0.0022	0.0085	0.0011	9.5	25.6	0.47	479	42.5
'Red Sunblaze'									
BB:VB	–0.0317	0.0035	---	---	9.0	---	1	304	41.1
VB:OF	–0.0127	0.0028	---	---	4.5	---	1	365	25.3
BB:OF	–0.0137	0.0017	---	---	8.1	---	1	589	40.9

Table 3. Number of predicted flowering shoots for 'Candy Sunblaze' and 'Red Sunblaze' miniature roses within each prediction error category (d) and its percentage. Predicted were calculated using the average and additive methods. The overall average error of prediction (bottom) was calculated using the absolute value of each error of prediction.

	'Candy Sunblaze'				'Red Sunblaze'			
Error	Average method		Additive method		Average method		Additive method	
category (d)	Predicted	Percentage	Predicted	Percentage	Predicted	Percentage	Predicted	Percentage
±0–0.99	35	28.2	42	33.9	25	28.4	41	46.6
±1–1.99	40	32.3	29	23.4	18	20.4	27	30.7
±2–2.99	27	21.8	30	24.2	12	13.7	9	10.2
±3–3.99	12	9.7	17	13.7	17	19.3	7	7.9
±4–4.99	4	3.2	2	1.6	8	9.1	2	2.3
±5–5.99	3	2.4	3	2.4	8	9.1	0	0
±6– 6.99	2	1.6	1	0.8	0	0	2	2.3
±7–7.99	1	0.8	0	0	0	0	0	0
Total	124	100	124	100	88	100	88	100
Overall mean error ± SD	1.9 ± 1.5 d		1.8 ± 1.3 d		2.4 ± 1.65 d		1.5 ± 1.4 d	

from 28.2% with the average method to 33.9% with the additive method. Correspondingly, the overall average error changed from ±1.9 d for the average method to ±1.8 d for the additive method ('Candy Sunblaze') and from ±2.3 d to ±1.5 d ('Red Sunblaze'), respectively (Table 3). The model can be considered unbiased because the prediction error is similar at any time of the year regardless of environmental conditions, i.e., natural light levels, photoperiod, and varying temperature regimes (Fig. 2).

Modeling development of miniature rose crops. Assuming a crop had reached the OF stage when 50% of the plants were at such stage, 482 ± 37 °Cd and 485 ± 41 °Cd had to be accumulated for 'Candy Sunblaze' and 'Red Sunblaze', respectively (Table 4). When the assumption was made that a crop had reached OF when 75% of the plants had reached such stage, 609 ± 74 °Cd and 620 ± 61 °Cd had to be accumulated for 'Candy Sunblaze' and 'Red Sunblaze', respectively (Table 4). Overall, the mean error of OF prediction for crops and for single flowering shoots was similar (Table 3 vs. Table 5). Using the additive method to predict OF at the crop level did not result in any significant reduction in the average error of prediction for

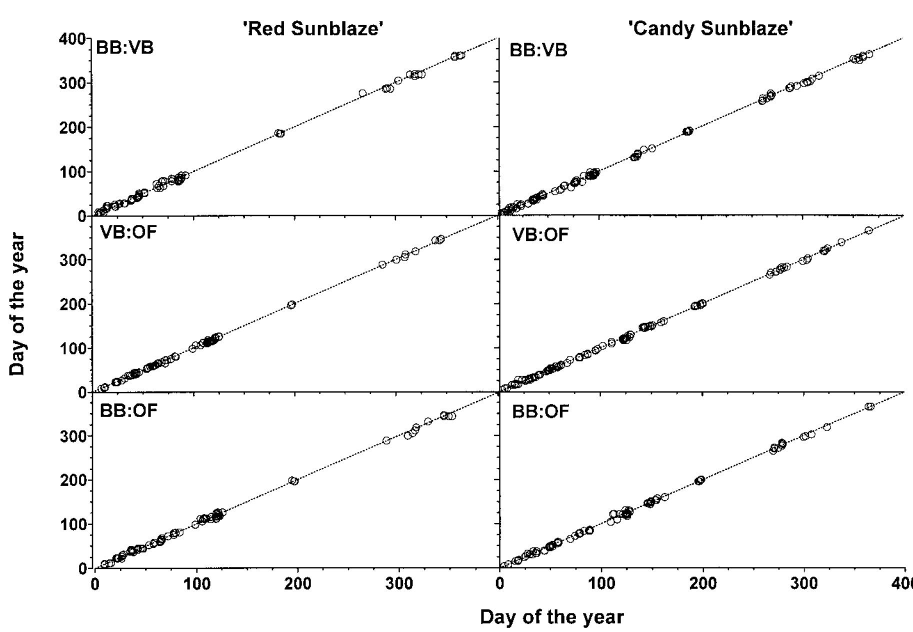

Fig. 2. Predicted versus observed dates of phenophase completion for BB:VB, VB:OF, and BB:OF of 'Red Sunblaze' and 'Candy Sunblaze' miniature roses. The dotted line represents y = x. BB = budbreak; VB = visible flower bud; and OF = open flower.

Table 4. Thermal units summation (°Cd) and their SD for each crop phenophase of two miniature rose cultivars. Subscripts 50% and 75% refer to the percentage of plants in a crop that have reached a given phenological event in order to consider that the whole crop has reached such an event. BB = budbreak; VB = visible flower bud; and OF = open flower.

	'Candy Sunblaze'		'Red Sunblaze'	
Phenophase	°Cd	SD	°Cd	SD
$BB:VB_{50\%}$	241	32.7	246	27.1
$VB:OF_{50\%}$	285	34.0	289	35.7
$BB:OF_{50\%}$	482	37.3	485	41.2
$BB:VB_{75\%}$	330	54.3	340	61.4
$VB:OF_{75\%}$	343	44.2	357	51.9
$BB:OF_{75\%}$	609	74.7	620	61.1

'Candy Sunblaze' (Table 5). However, changes in prediction were noted for 'Red Sunblaze' by using the additive method over the average method. For instance, the crop at the 75% completion changed from ±3.6 d overall mean error to ±2.2 d with the additive method. The predicted versus observed dates of developmental events indicated that the model for whole crops was also unbiased since prediction errors were similar regardless of the time of the year when crops were grown (data not presented).

Discussion

Results presented herein are in agreement with other reports indicating that ambient air temperature has a strong effect on rate of plant development (Baker and Gallagher, 1983; Grace, 1988; Karlsson et al., 1991). In the present investigation, observations were recorded in controlled environments (greenhouses) with different air temperature. By growing plants in greenhouses under quasioptimal conditions, the negative effects of variables other than temperature (e.g., water status, fertility, growing media, etc.) were minimized. Temperature had a strong effect on development of miniature rose flowering shoots when grown under various environmental conditions with observations made during all seasons over a period of 3 years. These procedures were designed to address criticisms voiced by Wang (1960) who believed that limited environmental data had been used in the estimate of thermal time requirements of plants. This, as well as inconsistent recording of developmental events, inevitably led to inadequate estimates of base temperatures, which in turn, resulted in serious errors regarding prediction of crop maturity (Wang, 1960).

Results of the present study support previous research indicating that T_b is dependent on both genotype and phenophase (Angus et al. 1981; Slafer and Rawson, 1995a, 1995b). Several studies (Angus et al., 1981; Del Pozo et al., 1987; Porter et al., 1987; Slafer and Rawson, 1995a; Slafer and Savin, 1991) indicated that for wheat, T_b increased progressively throughout plant development towards anthesis. A change in the increase of developmental rate with increasing temperature was also noted by Slafer and Rawson (1995a) when working with several wheat cultivars.

Based only on the results presented herein, there is no explanation for the increasing variability in rates of development with increasing temperatures. Increasing variability with increasing temperatures was also found by Pasian and Lieth (1994) for the cut flower rose 'Cara Mia'. This model was done using air rather than plant temperature. Perhaps, flowering shoots experience increasing temperature, water and/or mineral nutrient stress with increasing temperature (at the time of the year when radiation is highest) and that the level of stress is different from shoot to shoot, depending on its position on the plant and the orientation of the plant respect to the incoming radiation.

T_b values of various cultivated plants range from –1.9 °C for wheat (Slafer and Rawson, 1995a) to 15.5 °C for cucumber (Cucumis sativus L.) (Perry et al., 1986). The T_b for the phenophase BB:OF of the two miniature rose cultivars studied were 9.5 °C and 8.1 °C respectively, (Table 2) and, therefore, higher than the 5.2 °C T_b for 'Cara Mia' cut flower rose (Pasian and Lieth, 1994). No such increase was evident for the T_b of either miniature rose cultivar studied herein. On the contrary, the base temperatures for the early phenophases for miniature roses were much higher than for the later ones: 10.5 °C vs. 6.2 °C for 'Candy Sunblaze' and 9.0 °C vs. 4.5 °C for 'Red Sunblaze'.

While decreasing rates of development with increasing high temperatures are reported in the literature, very few data showing such plant response are available (Karlsson et al. 1991; Slafer and Rawson, 1995b). The results on development rates as a function of mean air temperature only showed a change of slope for one phase of 'Candy Sunblaze'. Our study did not find nonlinearity in temperature responses for 'Red Sunblaze' even though it was grown at average temperatures as high as 35 °C. Future studies should attempt to grow this cultivar at or beyond temperatures used in this research.

The TU summations allowed estimation of development times

Table 5. Number of crops within each prediction error category and percentage of the total number of shoots of 'Candy Sunblaze' and 'Red Sunblaze' miniature roses. The overall mean error of prediction and SD (bottom) were calculated using the absolute prediction errors. A crop was considered at phenological stage when 50% or 75% of the plants were at such stage (see Materials and Methods for an explanation on how to determine when a plant was considered at a given phenological stage).

	'Candy Sunblaze'				'Red Sunblaze'			
Error	Average method		Additive method		Average method		Additive method	
(d)	50%	75%	50%	75%	50%	75%	50%	75%
±0–0.99	2	2	1	2	3	3	3	3
±1–1.99	4	1	5	3	2	2	1	1
±2–2.99	0	3	1	1	2	1	4	4
±3–3.99	3	1	2	3	1	0	0	0
±4–4.99	---	1	---	---	1	1	1	1
±5–5.99	---	---	---	---	0	1	1	1
±6–6.99	---	---	---	---	0	1	---	---
±7–7.99	---	1	---	---	1	1	---	---
Total	9	9	9	9	10	10	10	10
Overall error ± SD	1.9 ± 1.3	2.4 ± 1.1	1.8 ± 1.1	2.4 ± 1.8	3.0 ± 1.9	3.6 ± 3.47	2.6 ± 2.0	2.2 ± 1.3

for single flowering shoots that were similar to actual observed times over a wide range of dates and environmental conditions (Fig. 2). The same can be said for predictions of developmental events for whole crops. The additive method produced smaller overall mean errors when used to predict OF for individual flowering shoots and whole crops of 'Red Sunblaze'. The same method did not produce changes in prediction for 'Candy Samblaze'. Improvement in prediction obtained with use of the additive method is so small that it has to be weighted against the time and effort required for determination of the extra T_b and temperature summations. From a practical point of view, the average method can produce results that are as good as those obtained with the additive method.

If results herein are validated with a new independent data set, this thermal time model can be used for greenhouse temperature manipulation and timing of miniature rose crops. Using this thermal units model, tools can be produced, not only for growers to keep track of miniature rose crop development but also to determine appropriate temperature changes so that the crop reaches the stage to be sold at the time desired by the grower. However, it is important to remember that the optimum temperature for fast development is not likely the best for plant growth and crop quality.

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