Modeling the Effect of Temperature on the Flower Development Rate of Hybrid Impatiens

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ADDITIONAL INDEX WORDS. flower bud meter, flower bud width, *Impatiens* × *hybrida*, SunPatiens, time to flower

SUMMARY. The effect of average daily temperature (ADT) on flower bud development and subsequent time to flower was investigated on hybrid impatiens (*Impatiens* × *hybrida*) cultivars Compact Electric Orange, Compact Hot Coral, and Compact Orchid Blush. Plants with a visible flower bud measuring 2 mm in width were placed in one of the four greenhouses with temperature setpoints ranging from 16 to 28 °C. Flower bud width was measured every 3 days in each ADT treatment until flowering. The subsequent days to flower (DTF) from the onset of a visible bud decreased from 36 to 27 days as the ADT increased from 17 to 28 °C. The DTF from visible bud varied by <3 days among the three cultivars across all temperatures; therefore, cultivar data were pooled to create a stronger prediction model. A logistic formula was used to predict the remaining DTF as a function of flower bud width and ADT. The model accurately described the effect of bud width and ADT on flowering time within ±3 days for 87% of the actual DTF across all three cultivars. The resulting flower development model provides greenhouse growers with a guide for manipulating temperature to produce flowering plants for specific market dates based on flower bud width measurements.

Specific market weeks govern the production of greenhouse-grown ornamental plants; therefore, predictability of flowering dates is essential for commercial growers. To predict flowering, the crop's current developmental status and its future rate of development must be identified accurately. The time necessary for the completion of a developmental stage, such as leaf unfolding or floral development, is converted to a rate by calculating the reciprocal of the number of DTF, e.g.,

1/DTF. Mathematical functions are used to relate the plant development rate to environmental factors such as temperature (Erwin and Heins, 1990; Faust and Heins, 1993; Fisher et al., 1996). These models can then be used as decision-support tools that allow growers to manipulate greenhouse temperatures to improve their ability to accurately schedule crops for the planned market dates.

The rate of progress toward a developmental event, such as flowering, is largely a function of ADT (White and Warrington, 1984). The rate of plant development in response to ADT increases from zero to a maximum value between the base temperature and optimum temperature (Adams et al., 1997; Karlsson et al., 1988; Tollenaar et al., 1979). Developmental rates decrease as temperatures exceed the optimum temperature. Models that

describe flower development rates as a function of ADT have been developed for many species. These prediction models allow the user to determine the current stage of flower development and then predict the remaining DTF based on the anticipated temperatures (Faust and Heins, 1994; Larsen and Persson, 1999; Pramuk and Runkle, 2005).

The genus *Impatiens* comprises several popular ornamental species valued in the floriculture industry for their highly decorative flowers and long blooming season. For several decades, the most popular commercial species was the bedding plant impatiens (*Impatiens walleriana*); however, the wholesale value dropped from \$133 million in 2009 to \$91 million in 2014 (USDA, 2014) due to a new race of impatiens downy mildew (*Plasmopara obducens*) that causes rapid defoliation in the landscape (Wegulo et al., 2004). New guinea impatiens (*Impatiens hawkeri*) were first introduced into the United States in the 1970s and have grown in popularity over many decades. New guinea impatiens are resistant to impatiens downy mildew as are the hybrid impatiens marketed under the trademark name SunPatiens (Sakata Seed Corp., Yokohama, Japan), which resemble new guinea impatiens in appearance but are more tolerant of high light conditions. SunPatiens accounted for nearly 50% of all new guinea-type impatiens sold in North America in 2019 and have a wholesale market value of ≈\$95 million (M. Seguin, personal communication).

Our hypothesis was that flower bud expansion is closely related to ADT such that measurements of flower bud width and ADT could be used to predict the open flower date. Therefore, the objectives of this study were to investigate the effect of ADT on bud expansion from visible bud to open flower for three hybrid impa-

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Units

To convert U.S. to SI, multiply by	U.S. unit	SI unit	To convert SI to U.S., multiply by
0.3048	ft	m	3.2808
3.7854	gal	L	0.2642
2.54	inch(es)	cm	0.3937
25.4	inch(es)	mm	0.0394
16.3871	inch ³	cm ³	0.0610
1	ppm	mg·L ⁻¹	1
10.7639	W/ft ²	W·m ⁻²	0.0929
(°F - 32) ÷ 1.8	°F	°C	(°C × 1.8) + 32

tiens cultivars and develop a model to predict the time to flower.

Materials and methods

GENERAL PROCEDURES. A total of 105 shoot-tip cuttings were taken from stock plants of each of the three hybrid impatiens cultivars (Compact Electric Orange, Compact Orchid Blush, and Compact Hot Coral) bred by Sakata Ornamentals and propagated in 105-cell, loose-fill trays (21 cm³/cell) placed on benches in a propagation greenhouse located in Clemson, SC (Lat. 34.7°N). A propagation substrate (Propagation Mix; Sun Gro, Anderson, SC) containing fine sphagnum peatmoss, fine perlite, and vermiculite was used. Intermittent mist was provided during the photoperiod at a 6- to 10-min frequency and a 6-s duration per mist event. Bottom heat was provided to maintain the propagation substrate temperature at ≈25 °C. Photosynthetic photon flux density (PPFD) was altered with a retractable shade curtain that engaged when outdoor solar radiation exceeded 500 W·m⁻². Relative humidity averaged 78% over the experimental times. No rooting hormone was used. The commercial propagation substrate had a starter charge of plant nutrients, and no additional fertilization was applied during propagation. After propagation, 40 uniform plants from each cultivar were selected and transplanted into 6-inch-diameter (1.33 L) containers using a commercial peat-based growing substrate (Fafard 3B; Sun Gro, Anderson, SC) that contained Canadian sphagnum peatmoss, vermiculite, bark, and perlite. The plants were grown on 5 ft × 24 ft expanded metal benches. A constant liquid fertigation program provided 50 ppm N using 15N-2.2P-12.5K-5Ca-2Mg (Peter's Excel Cal-Mag Special; Scotts-Sierra, Marysville, OH) with each irrigation event.

Two replications of the experiment were conducted. The cuttings for the first replication were stuck in propagation on 2 Dec. and transplanted on 19 Dec. A total of 24 plants (6 plants/treatment) per cultivar were selected for uniform bud development on 3 Jan. and placed in the temperature treatments at this time. The cuttings for the second replication were stuck in propagation on 30 Jan. and transplanted on 17 Feb. A total of 24 plants (6 plants/

treatment) per cultivar were selected for uniform bud size on 3 Mar. and placed in the temperature treatments.

TEMPERATURE TREATMENTS. To achieve the ADT treatments, four greenhouse compartments were individually controlled with an environmental control system (Argus Control Systems, Surrey, BC, Canada) that was programed to target each of the four temperature setpoints (16, 20, 24, or 28 °C) and to record temperature data at the height of the plant canopy. Six plants per cultivar were placed in each of the four greenhouses. The mean ADTs (±1 SD) over the course of the experiment were 16.6 ± 1.6, 18.9 ± 2.4, 23.6 ± 1.3, and 27.4 ± 1.0 °C for replication 1 and 17.9 ± 2.7, 21.6 ± 1.8, 23.7 ± 0.8, and 28.1 ± 0.7 °C for replication 2. Metal halide lamps provided supplemental lighting of 175 ± 25.0 μmol·m⁻²·s⁻¹ between 800 and 1700 HR in addition to the ambient lighting in each greenhouse. Line quantum sensors (SQ-316-SS; Apogee Instruments, Logan, UT) were placed immediately above the plant canopy in each of the temperature environments to measure PPFD every 10 s while recording 15-min averages with a data logger (CR206X; Campbell Scientific, Logan, UT). The daily light integral (±1 SD), which included sunlight and supplemental lighting, averaged 10.4 ± 3.0 mol·m⁻²·d⁻¹ for replication 1 and 12.6 ± 2.8 mol·m⁻²·d⁻¹ for replication 2.

DATA COLLECTION. At the start of the temperature treatments, one flower bud per plant measuring the width of 2 mm was chosen for data collection, and the subtending leaf was tagged to identify the location for future measurements. The bud width of a selected flower bud on each plant was measured every 3 d using digital calipers (Mitutoyo Corp., Aurora, IL). Impatiens flowers are bilaterally symmetrical, so the bud width measurement was made across the widest portion of the horizontal axis. Buds began to open after they were 10- to 12-mm width, so data collection ceased once the buds were 10-mm width. A flower was considered to be open when each of the five flower petals unfurled from the bud to create a planar surface.

EXPERIMENTAL DESIGN AND DATA ANALYSIS. Data analysis was performed using JMP Pro (version 13.2.0; SAS Institute Inc, Cary, NC). The

experiment was a split-plot design with four levels of ADT and three levels of cultivar within each ADT treatment. Analysis of variance (ANOVA) was used to determine treatment effects for time to flower, and regression analysis was performed to construct prediction models. The DTF from visible bud averaged 29 d for Compact Hot Coral, 30 d for Compact Electric Orange, and 31 d for Compact Orchid Blush. In the ANOVA (Table 1), cultivar was significant; however, since the difference was <3 d among the three cultivars and ADT was dominant variable, as indicated by the F-ratio, the cultivar data were pooled to create a stronger and more useful prediction model.

Results and discussion

Time to flower was influenced by the interaction of ADT and cultivar (Table 1). As ADT increased from 17 to 28 °C, DTF decreased from 36 to 27 d from a 2-mm-wide bud. A four-parameter logistic model generated in JMP Pro (version 13.2.0). Eq. [1] was fitted to the pooled cultivar data for DTF as a function of flower bud width:

$$DTF = c + \frac{(d - c)}{(1 + \text{Exp}(-a \times (\text{Bud width} - b)))} \quad [1]$$

where a is the growth rate (the slope of the curve at b), b is the inflection point (bud width measured in mm), c is the lower asymptote (minimum DTF), and d is the upper asymptote (maximum DTF). Parameter estimates for Eq. [1] were analyzed to determine whether any relationship existed between individual parameters and ADT. Only the upper asymptote parameter (d) was significantly affected by ADT; therefore, the upper asymptote was modeled as a function of ADT using the Michaelis-Menten equation in JMP.

$$d = \frac{(d_0 \times \text{ADT})}{(d_1 + \text{ADT})} \quad [2]$$

Parameter estimates are shown in Table 2. Combining Eqs. [1] and [2] results in a model to predict DTF based on bud width and ADT, noting that ADT is measured in °C (Fig. 1). The model demonstrates how DTF decreases as ADT increases from 17 to 28 °C and as bud width increases from 2 to 10 mm. Figure 2 displays

Table 1. Analysis of variance for the effect of average daily temperature (ADT) on hybrid impatiens cultivars (Compact Electric Orange, Compact Orchid Blush, and Compact Hot Coral) and their interaction on time to flower from visible bud (2-mm width) to open flower.

Response	Factor	F-ratio	P value
Time to flower	ADT	169.74	<0.0001
	Cultivar	8.60	0.0003
	ADT × Cultivar	5.64	<0.0001

, *Significant at $P < 0.01$ or 0.001 , respectively.

the predicted DTF values for all three cultivars vs. the actual DTF for each temperature × bud-width combination, and 87% of the predicted values were within ± 3 d of the actual DTF.

This model does not predict when a bud will be present in the leaf axil, so the use of the model begins when a 2-mm-wide bud is present. Hence, this is a flower bud development model and does not predict flower initiation. Hybrid impatiens are vegetatively propagated, so they do not go through a juvenile period when the plants are not sufficiently mature to initiate flowers. Hybrid impatiens are a day-neutral species with respect to photoperiod, so flower initiation is generally considered to be a function of DLI, that is, flowers initiate once sufficient energy is available. Hybrid impatiens have a relatively low DLI requirement for flowering, thus, they often flower continuously in

normal greenhouse environments. Therefore, the value of this model is to aid in the prediction of the first open flower of a rooted cutting coming out of propagation so that the grower can anticipate the future market date, since open flowers are necessary for plants to be shipped to retailers.

Predicting the production time of crops can be achieved through quantitative models that are created by fitting a mathematical function to data through regression analysis. Crop prediction models have aided the production of several important floriculture crops, such as poinsettia (Liu and Heins, 1997), easier lily (Erwin and Heins, 1990), and chrysanthemum (Larsen and Persson, 1999). ADT is the most common measure of temperature used to regulate a number of plant developmental responses, such as flowering or leaf unfolding (Roberts and Summerfield, 1987). Through the manipulation of temperature, crop timing can be altered to appropriately hit specific market windows (Heins et al., 1998). The amount of time necessary for a specific plant developmental response is most often presented as a function of ADT, and events can be expressed as the number of days to reach a particular stage of plant development.

Studies investigating the effect of temperature on flowering time report a decrease in time to flower as ADT increases for petunia (*Petunia × hybrida*) (Adams et al., 1999), evening primrose (*Oenothera fruticosa*) (Clough et al., 2001), cosmos (*Cosmos atrosanguineus*) (Kanellos and Pearson, 2000), angelonia (*Angelonia angustifolia*) (Miller and Armitage, 2002), french marigold (*Tagetes patula*) (Moccaldi and Runkle, 2007), pansy (*Viola × wittrockiana*) (Niu et al., 2000), campanula (*Campanula carpatica*) (Niu et al., 2001), impatiens (Pramuk and Runkle, 2005), vinca (*Catheranthus roseus*) (Pietsch

et al., 1995), and geranium (White and Warrington, 1988).

Bud development has previously been modeled using measurements of bud length or width as the bud expands while comparing the pattern and rate of expansion at different temperatures. Healy and Wilkins (1984) were the first to develop the bud meter concept in which a mathematical model was incorporated into a measuring device. Time to flower was estimated by holding the bud meter up to the bud, where the tip of the budlines up with the number of DTF at given temperatures. Fisher et al. (1996) modified the original Healy–Wilkins model of easter lily bud expansion by using an exponential rather than linear model, which provided a better fit for the data along with using fewer model parameters. Wang et al. (1998) also found an exponential equation was the best fit for modeling bud expansion of *Hibiscus moscheutos*. Bud development models are helpful to growers when their crop will flower based on the bud size and species. Faust and Lewis (2005) reported for new guinea impatiens that time to flower was 31, 43, and 72 d from visible bud at 25, 20, and 15 °C, respectively, and bud width increased linearly from 1 to 9 mm. The new guinea impatiens were slightly slower than hybrid impatiens examined in the present study, and bud expansion of the hybrid impatiens was curvilinear from 2 to 10 mm.

Flower development models, such as the one presented here, have inherent limitations that are worth noting. Supra-optimal temperatures are not taken into consideration and can lead to inaccurate predictions. For example, 28 °C is the maximum temperature provided in this study and is likely near the optimum temperature. Temperatures above the optimum typically result in a rapid decrease in flower development rates (Cave et al., 2013; Blanchard et al., 2011; Brøndum and Heins, 1993), so if ADTs exceed 28 °C, the model prediction is invalidated. Also, this model assumes that adequate DLIs are being provided, since 10–12 mol·m⁻²·d⁻¹ were provided in this study. Low DLI can limit plant development (Faust and Heins, 1994). Since impatiens are rather tolerant of low DLI conditions, we expect the model would yield valid results as long as DLIs were ≥ 4 mol·m⁻²·d⁻¹ (Faust

Table 2. Parameter estimates for a flower development model for hybrid impatiens that predicts the number of days to flower (DTF) based on bud width measurements (in mm) and average daily temperature (ADT) measurements (in °C) using Eqs. [1] and [2] and presented in Fig. 1. In Eq. [1], the parameter a is the growth rate at b , b is the inflection point (bud width measured in mm), c is the lower asymptote (minimum DTF), and d is the upper asymptote (maximum DTF). The upper asymptote parameter (d) was significantly affected by ADT; therefore, it was modeled as a function of ADT using the Michaelis–Menten equation, which has two parameter estimates denoted d_0 and d_1 (Eq. [2]).

Parameter	Estimate
a	−0.6535
b	5.257
c	3.588
d_0	20.58
d_1	−8.315

Fig. 1. Time to flower (d) for hybrid impatiens as a function of average daily temperature (ADT) and bud width for hybrid impatiens. The response surface graph represents the time to flower model predictions from Eqs. [1] and [2] using the parameter estimates presented in Table 2. The model can be used once a 2-mm-wide flower bud is present in the leaf axil, and the model does not predict when the bud will be present.

and Logan, 2018). Cultivars can vary in developmental responses; however, the three cultivars examined in this study were sufficiently similar that they could be combined into one model. Data

collection would be required to justify the use of the model on other cultivars, particularly hybrid impatiens that are not in the SunPatiens series. It is important to note that the model requires

Fig. 2. The predicted time to flower (open circles) for hybrid impatiens using Eqs. [1] and [2] compared with the actual time to flower. Each data point represents the mean predicted value for each temperature $\times$ bud-width combination measured across all three cultivars. $R^2 = 0.95$.

that the input variables be in the correct units, for example, ADT in $^{\circ}\text{C}$ and bud width in millimeters. Finally, temperature management decisions have a greater potential to affect the final market date if the decision is made while the flower buds are relatively small and the DTF can be maximally altered. For example, when the buds are 2-mm wide, DTF differs by 9 d between 17 and 28°C , whereas 6-mm-wide buds differ in DTF by only 4 d across the same temperature range. Thus, one's ability to manipulate market dates is greatly reduced if decisions are not made while the buds are relatively small.

Conclusions

The model presented in this study provides a guide for manipulating greenhouse ADTs to predict a target market date based on bud-width measurements made periodically during crop production. For example, if a crop's average bud width is 3 mm and current average greenhouse temperature is 18°C , then the crop will reach first open flower in ≈ 32 d. If the plants are to be sold earlier than that, the model estimates that first open flower could be expected in 24 d if ADT is increased to 28°C . This decision-making process can be used to potentially save energy if crops are ahead of schedule or to allow the crop to "catch up" by accelerating the rate of flower development if there is potential to miss a market date. Decision-support tools such as this can take the guesswork out of growing crops for specific market dates.

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