Using Flowering and Heat-Loss Models for Improving Greenhouse Energy-Use Efficiency in Annual Bedding Plant Production

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Abstract

In temperate climates, annual bedding plant crops are typically produced in heated greenhouses from late winter through early summer. Temperature, photoperiod, light intensity, and transplant date are commonly manipulated during commercial production so that plants are in flower for predetermined market dates. We used nine flowering models that predict the effect of mean daily temperature on time from transplant until first flowering, which can be used to identify the combinations of transplant dates and growing temperatures necessary for flowering to occur on chosen market dates. The computer program Virtual Grower was also used to estimate greenhouse heating costs based on user-defined inputs such as building material, construction style, temperature set point, heating system, and typical weather at the selected locations. Using the flowering models and Virtual Grower, the temperatures and transplant dates that consumed the least amount of energy for heating, on a per-crop basis, were estimated for two market dates and three U.S. locations. For flowering on March 15, the estimated energy consumption for heating per crop decreased in Michigan as the greenhouse setpoint increased from 15 to 24°C for all species. In contrast, the temperature that elicited the lowest heating cost per crop in North Carolina for a March 15 finish date varied among species. This kind of analysis allows the determination of the most energy-efficient production schedule for greenhouse- and crop-specific situations.

INTRODUCTION

Annual bedding plants is the largest segment of floriculture crop production in the United States, with wholesale sales exceeding \$1.9 billion in the 15 states surveyed in 2010 (USDA, 2011). The vast majority of these crops are produced in heated greenhouses for spring sales, especially in northern (e.g., >35 °N) latitudes. Buyers demand that plants are in flower for pre-determined market dates, which requires growers to accurately schedule crops. Most wholesale growers negotiate sale periods and prices with merchandisers in advance, requiring growers to limit their production inputs to ensure profitability.

Energy for greenhouse heating has traditionally been the second largest indirect production cost for growers in temperate climates behind labor (Bartok, 2001). Although the price of some fuels has recently decreased in the U.S., such as that for natural gas, growers strive to conserve energy for economic and sustainability reasons. When natural gas was more expensive, some growers intuitively lowered their production temperatures so that less energy was consumed on a daily basis. Generally, fuel consumption for greenhouse heating is reduced by 5% for each 1°C decrease in the night temperature

(Bartok, 2001). However, many growers did not consider that a decrease in temperature also has an effect on plant development and thus, crop time.

The length of production time for bedding plants varies by species and cultivar and can depend on the maturity and conditions in which plants were propagated (Pramuk and Runkle, 2005b; Fisher et al., 2006), application of plant growth regulating chemicals, desired finish size, mean daily temperature (MDT) (Blanchard and Runkle, 2011a), photosynthetic daily light integral (DLI) (Blanchard, 2009; Pramuk and Runkle, 2005a), and photoperiod (Erwin and Warner, 2002). Assuming plants are grown under an inductive photoperiod and with a sufficient DLI, temperature is the primary environmental factor that regulates flowering time. Scientists have generated data and then developed linear, quadratic, cubic, and exponential functions to describe the relationship between the rate of plant development (the inverse of days to flower) and MDT. These equations can be useful to predict the effect of temperature on flowering time, potentially serving as a resource to help growers manage their crops.

The DLI available to greenhouse-grown plants depends on a number of factors, including location, time of year, seasonal weather patterns, glazing material, overhead structures, presence of hanging baskets, supplemental lighting, and strategies to mitigate heat stress (e.g., shade curtains and whitewash). Flowering of crops is progressively delayed as the DLI decreases below some species-specific value (e.g., <8 $mol{\cdot}m^{-2}{\cdot}d^{-1}$), especially for shade-avoiding plants (Blanchard, 2009). The saturating DLI with respect to flowering time has been estimated as <4 $mol{\cdot}m^{-2}{\cdot}d^{-1}$ in shade-tolerant *Impatiens walleriana* to 20 $mol{\cdot}m^{-2}{\cdot}d^{-1}$ in high-light crops such as *Gazania rigens*. In the U.S., the mean outdoor DLI is as low as 5-10 $mol{\cdot}m^{-2}{\cdot}d^{-1}$ in January in the Pacific Northwest to as high as 55-60 $mol{\cdot}m^{-2}{\cdot}d^{-1}$ in summer in the desert Southwest (Korczynski et al., 2002). Without supplemental lighting, mean DLIs inside a greenhouse of <10 $mol{\cdot}m^{-2}{\cdot}d^{-1}$ are common until March in the northern U.S., assuming that 50-60% of the outdoor DLI is available to crops. Therefore, a low DLI can delay flowering of high-light crops during late winter and early spring production.

A computer program called Virtual Grower (www.virtualgrower.net) can estimate greenhouse heating costs in the U.S. based on user-defined inputs (Frantz et al., 2010). Users build a virtual greenhouse with the same characteristics as their existing greenhouse, including location, greenhouse dimensions, glazing material, heating system characteristics, temperature setpoints, characteristics that influence air infiltration, etc. The software calculates the estimated amount of energy consumed for each scenario to maintain the desired temperature. Here, we estimate crop production schedules based on recently developed flowering models, then predict the relative heating costs for those different production situations using Virtual Grower. Results from the two models can be used to estimate heating costs for growing plants at different times of the year, in different locations, at different temperature setpoints.

MATERIALS AND METHODS

A nonlinear model relating flowering rate to mean daily air temperature (MDT) and DLI was used for nine bedding plant species. The model was in the form of:

$$1/\text{days to flower} = (-1 \times T_{min} \times b_1 + b_1 \times \text{MDT}) \times [1 - \exp(-e \times \text{DLI})] \qquad (1)$$

where T_{min} is the base temperature (°C) at which flowering rate is zero, b_1 is a species-specific temperature constant that is the slope, MDT (°C) is from transplant to flowering, e is a species-specific light constant that determines the skew of the curve, and greenhouse DLI ($mol{\cdot}m^{-2}{\cdot}d^{-1}$) is the mean from transplant to flowering. Models of this type have been used to describe the rate of flower development in *Chrysanthemum ×grandiflorum* (Hiden and Larsen, 1994; Larsen and Persson, 1999) and *Pericallis × hybrida* (Larsen, 1989). Parameter estimates were previously determined using 155 to 200 observations (individual plants) for each species (Table 1; Blanchard, 2009). The models also assume a crop-specific maturity and growing environment for the propagules and a long-day photoperiod.

Flowering time of the nine bedding plants was estimated using the flowering models at four greenhouse MDTs (15, 18, 21, and 24°C) and with the outdoor DLI values used in Virtual Grower 3.0 (Table 2). The greenhouse DLI was calculated as 60% of the outdoor values, which is typical of a double-polyethylene greenhouse. Market dates of March 15 and May 1 were subjectively chosen to represent a relatively early crop and peak season crop, respectively. Three locations in the U.S. (Grand Rapids, MI; New York, NY, and Charlotte, NC) were subjectively selected based on their climate differences (Table 2) and the large number of bedding plants produced in their vicinities. Transplant dates were determined by subtracting days to flower from each market date given each temperature and greenhouse DLI scenario for each location.

Virtual Grower 3.0 was used to estimate the heating costs from each date of transplant until the marketing date. The greenhouse characteristics were held constant for each estimation and location. The virtual greenhouse consisted of four connected spans each 31.25×8 m (total of 1,000 m^2), 3 m side height, 4 m peak height, and a single arched peak per span. The glazing consisted of an inflated double layer of polyethylene, no energy curtain was present, and the end and side walls were of polycarbonate bi-wall. The air infiltration rate was set in the program at once per hour. Unit heaters with powered ventilation and forced air above benches burned natural gas, which yielded a predicted heating system efficiency of 45%. These inputs are considered representative of bedding plant producers in the U.S. The MDT consisted of a day temperature that was 2°C warmer than the night and each was 12 h long.

RESULTS AND DISCUSSION

Predicted flowering time decreased as temperature increased from 15 to 24°C (Table 3). Cropping time was longest in *Browallia* and shortest in *Petunia* ‘Fantasy Blue’ at all temperature simulations. However, the relative effect of temperature on flowering time was greatest in crops with the highest estimated T_{min} values. For example, a decrease in greenhouse temperature from a mean of 21 to 15°C delayed flowering by 167% in *Catharanthus* (T_{min} = 11.4°C) and 118% in *Angelonia* (T_{min} = 9.9°C), whereas the delay in flowering time was only 46% in *Antirrhinum* (T_{min} = 2.0°C) and 50% in *Petunia* ‘Fantasy Blue’ (T_{min} = 3.0°C).

The flowering model predictions among locations showed that the photosynthetic DLI had little or no effect on flowering time. Based on our assumptions and “typical” weather conditions for each location studied, the greater DLI (by 3-4 $mol{\cdot}m^{-2}{\cdot}d^{-1}$) in North Carolina compared to Michigan for the March 15 finish date accelerated flowering by ≤1 day in *Angelonia*, *Antirrhinum*, *Begonia*, *Dianthus*, and *Petunia* ‘Easy Wave Coral Reef’; by ≤2 days in *Petunia* ‘Fantasy Blue’; by ≤3 days in *Browallia*; and by ≤4 days in *Pelargonium* (data not shown). DLI had less of an effect on flowering time for the May 1 market date, when the greenhouse DLI in all locations was ≥14.2 $mol{\cdot}m^{-2}{\cdot}d^{-1}$. It is important to note that the models do not predict quality characteristics; it is expected that an increase in DLI would result in an increase in plant quality.

The amount of energy required to heat a greenhouse for each production situation (9 crops, 4 temperatures, 3 locations, and 2 market dates) was determined using Virtual Grower. The situation with the greatest amount of heating per crop was for *Browallia* at a 15/13°C day/night setpoint in Michigan for first flowering on March 15 (9.55 therms·$m^{-2}{\cdot}crop^{-1}$). The heating inputs for all of the other situations are presented relative to that required for *Browallia* (Fig. 1). As expected, heating inputs were always greater for the March 15 finish date compared with May 1, since the outdoor temperatures and light intensities increase as spring progresses into summer. In addition, heating costs were always greatest in Michigan and lowest in North Carolina. Averaged across all species and temperature combination simulations, energy costs were 33.4% higher in Michigan than New York for the March 15 market date, and 27.8% higher for the May 1 market date. The greenhouse in New York consumed 59.1 and 91.5% more energy to maintain temperature setpoints than the greenhouse in North Carolina for the March 15 and May 1 market dates, respectively.

The production temperature that consumed the least amount of energy, on a per-crop basis, often depended on the species, market date, and location. However, some trends were apparent. For flowering on March 15, energy consumption per crop decreased in Michigan as the greenhouse setpoint increased from 15 to 24°C for all crops. Therefore, although more energy is required to heat a greenhouse to a higher temperature on a daily basis, the shorter production time at the higher temperature meant that crops had to be heated fewer days (Fig. 2). In contrast, the temperature that elicited the lowest heating cost per crop in North Carolina for a March 15 finish date varied by species. Heating cost per crop was lowest at 24°C for crops with high T_{min} values (*Browallia*, *Catharanthus*, and *Angelonia*), but was similar among the temperatures compared in other crops, such as *Pelargonium*, *Dianthus*, and *Begonia*. Heating predictions in Michigan for a May 1 flowering date were somewhat similar to those in North Carolina for March 15; less heating was consumed per crop at the higher temperatures only for plants with a high T_{min}. In New York and especially North Carolina, less heating was required by growing *Dianthus*, *Begonia*, *Antirrhinum*, and the two *Petunia* crops at the lower temperature setpoints for May 1.

These outcomes have several assumptions, most notably that the greenhouses would not otherwise be heated when not used for production. In fact, many growers provide minimal heating to their empty greenhouses so that they stay above freezing. Greenhouse growers would also have to consider other factors when choosing a temperature setpoint, including the effects on crop quality, the opportunity cost of growing fewer successive crops at lower temperatures, and labor availability. In addition, the temperature simulations included setpoints where the day was 2°C higher than the night. Blanchard and Runkle (2011b) showed that a greater day than night temperature consumes even less energy, although stem extension was also promoted. Heating inputs could be further minimized by integrating the daily temperature to maximize solar gain during the day, or to increase the night temperature when energy curtains are closed (Körner et al., 2004).

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Tables

Table 1. Parameter estimates for a nonlinear model[1] relating flowering rate to mean daily air temperature (MDT, °C) and daily light integral (DLI, $mol \cdot m^{-2} \cdot d^{-1}$).

Species	T_{min} (°C)[2]	b_1 ($\times 10^{-3}$)[3]	e ($\times 10^{-1}$)[3]
Angelonia angustifolia 'Serena Purple'	9.9	2.31	5.60
Antirrhinum majus 'Montego Burgundy'	2.0	2.12	2.54
Begonia semperflorens-cultorum 'Sprint Blush'	6.1	2.07	4.41
Browallia speciosa 'Bells Marine'	8.9	1.81	2.84
Catharanthus roseus 'Viper Grape'	11.4	3.08	9.63
Dianthus chinensis 'Super Parfait Raspberry'	3.9	1.33	4.71
Pelargonium ×hortorum 'Florever Violet'	5.0	1.21	2.59
Petunia ×hybrida 'Fantasy Blue'	3.0	3.55	1.83
Petunia ×hybrida 'Easy Wave Coral Reef'	7.3	2.96	3.20

[1] 1/days to flower = $(-1 \times T_{min} \times b_1 + b_1 \times MDT) \times [1 - \exp(-e \times DLI)]$ (Blanchard, 2009).
[2] T_{min} = Estimated base temperature at which flower development rate is zero.
[3] b_1 and e are species-specific constants.

Table 2. The outdoor photosynthetic daily light integral (DLI)[1], temperature[2], and latitude for three U.S. cities. Values are representative for each month and location and are those used in Virtual Grower 3.0.

Location (latitude)	Parameter	January	February	March	April
Grand Rapids, MI	DLI	11.0	17.5	25.5	33.3
(43 °N)		(5.8/18.0)	(10.2/28.0)	(13.6/38.7)	(11.5/48.7)
	Temp.	-10.5/-2.1	-8.8/-1.3	-3.9/6.2	2.9/14.8
New York, NY	DLI	11.7	18.5	26.2	32.2
(41 °N)		(3.6/22.2)	(6.0/29.2)	(7.9/43.8)	(11.9/49.5)
	Temp.	-2.8/4.8	-4.1/3.3	2.4/9.2	7.3/15.0
Charlotte, NC	DLI	17.2	21.8	31.6	39.9
(35 °N)		(6.3/26.6)	(7.1/36.5)	(12.9/45.0)	(18.2/54.8)
	Temp.	-1.0/9.1	2.6/13.8	4.7/16.3	9.7/22.8

[1]Mean (minimum/maximum) in $mol \cdot m^{-2} \cdot d^{-1}$.

[2]Mean minimum/maximum outdoor temperature (temp., °C).

Table 3. Predicted days to first flowering from transplant of nine bedding plant crops produced at four mean temperatures and daily light integrals typical of that in a double-polyethylene greenhouse in Grand Rapids, MI using flowering models in Table 1.

Species	Mean temperature (°C)				Delay at
	15	18	21	24	15 vs. 21°C
Angelonia angustifolia ‘Serena Purple’	85	54	39	31	118%
Antirrhinum majus ‘Montego Burgundy’	39	32	27	23	46%
Begonia semperflorens-cultorum ‘Sprint Blush’	55	41	33	27	67%
Browallia speciosa ‘Bells Marine’	96	64	48	39	98%
Catharanthus roseus ‘Viper Grape’	90	49	34	26	167%
Dianthus chinensis ‘Super Parfait Raspberry’	68	54	44	38	54%
Pelargonium ×hortorum ‘Florever Violet’	89	68	56	47	60%
Petunia ×hybrida ‘Fantasy Blue’	28	22	19	16	50%
Petunia ×hybrida ‘Easy Wave Coral Reef’	46	33	26	21	78%

Figures

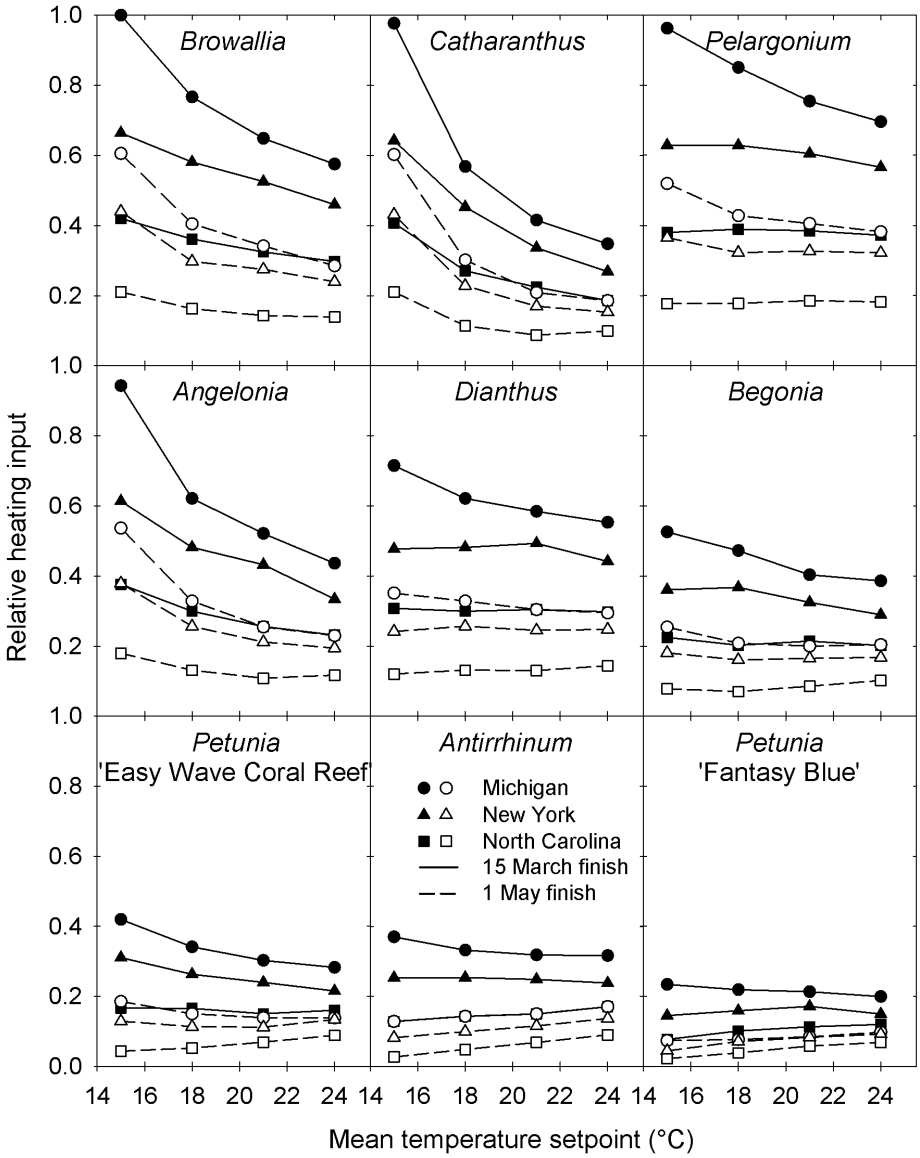

Fig. 1. The relative amount of energy required to heat a 1,000 m^2 double-polyethylene greenhouse to produce nine bedding plant crops at four mean temperatures (12-h day was 2 °C greater than the night), for two finish dates, in Grand Rapids, MI, New York, NY, and Charlotte, NC. Legend in *Antirrhinum* applies to all graphs. Simulations performed with Virtual Grower 3.0 using the flowering models presented in Table 1.

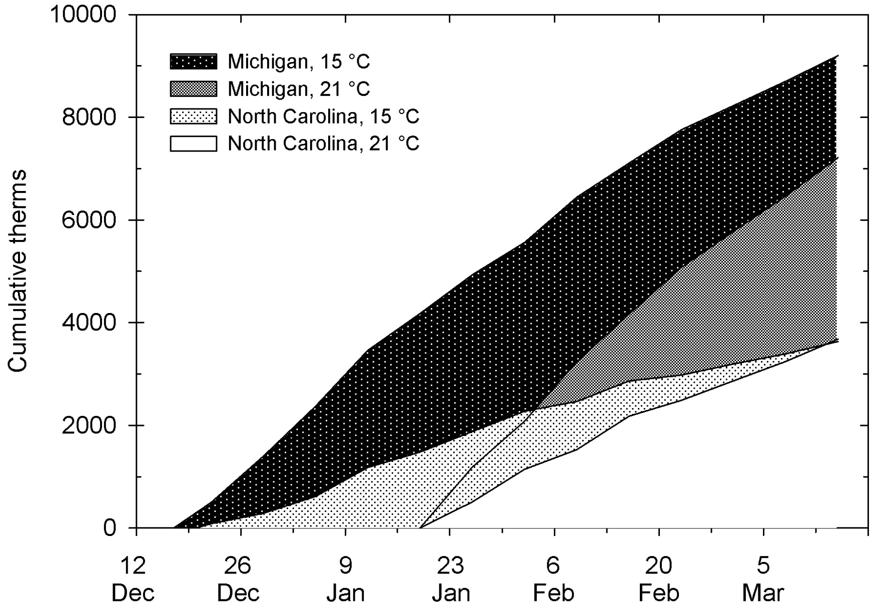

Fig. 2. The cumulative amount of energy required to heat a 1,000 m^2 double-polyethylene greenhouse in Grand Rapids, MI or Charlotte, NC to produce a crop of *Pelargonium* at 15 or 21°C for a 15 March finish. Production time determined using equation in Table 1; heating predictions from Virtual Grower 3.0.