Energy-Efficient Greenhouse Production of *Petunia* and *Tagetes* by Manipulation of Temperature and Photosynthetic Daily Light Integral

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Abstract

The cost of fuel is an increasingly significant production expense for greenhouse growers in temperate climates. High heating costs have motivated growers to improve the efficiency of crop production to minimize energy inputs. We performed greenhouse experiments with *Petunia ×hybrida* 'Dreams Neon Rose' and *Tagetes patula* 'Janie Flame' to understand how mean daily temperature (MDT) and photosynthetic daily light integral (DLI) influence plant development. This information was then used to determine how the production environment and crop timing influence greenhouse energy consumption for heating on a per-crop basis. Seedlings of each species were grown in an environmental growth chamber at an MDT of 20.4°C with a DLI of 10 mol m^{-2} d^{-1} and under a 16-h photoperiod. After 19 to 32 d from seed sow, seedlings were transplanted into 10-cm pots and grown in glass-glazed greenhouses at constant air temperature set points of 14, 17, 20, 23, or 26°C and under a 16-h photoperiod provided by high-pressure sodium (HPS) lamps. At each temperature, plants were grown under two DLI treatments provided by the use of a shade curtain and different intensities of supplemental lighting from HPS lamps. Time to flower in *Petunia* decreased from 43 to 17 d as MDT and DLI increased from 14°C and 4 mol m^{-2} d^{-1} to 26°C and 16 mol·m^{-2} d^{-1}. In *Tagetes*, time to flower ranged from 17 to 38 d. A decision-support software (Virtual Grower) was used to estimate energy consumption at different locations in the United States based on the predicted crop production durations at different MDTs and DLIs. For example, the predicted energy cost for greenhouse heating to produce a *Petunia* crop in Grand Rapids, Michigan, USA for a 1 April finish date was 8% lower when grown at an MDT of 20°C compared to that at 14°C. This information can be used by greenhouse growers to determine how to minimize heating input costs in the production of their crops.

INTRODUCTION

The cost of fuel for greenhouse heating is one of the largest production expenses for growers in temperate climates (Bartok, 2001). In The Netherlands, greenhouses account for 79% of the energy used by the agricultural sector and 7% of the country's total energy consumption (Lansink and Ondersteijn, 2006). The greenhouse industry in The Netherlands agreed with the government in 1995 to improve energy efficiency from 1980 to 2010 by 65% (Lansink and Ondersteijn, 2006). In the US, the mean commercial price of natural gas has increased by 125% during the past 10 years (EIA, 2009). In a January 2009 survey of greenhouse growers in the US, 74% of respondents identified energy costs as one the biggest challenges that limited the opportunity for their business to increase profitability (Onofrey, 2009). The high cost of energy for heating has motivated growers to improve greenhouse production efficiency so that less energy inputs are required to grow a crop.

There are several strategies greenhouse growers can use to reduce energy

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consumption, such as the purchase and installation of retractable energy curtains (Dieleman and Kempkes, 2006), improvements in greenhouse environmental controls (Körner et al., 2004; Lund et al., 2006), or investments in alternative fuels (García et al., 1998). Under a non-inductive photoperiod, growers can provide artificial lighting or truncate the photoperiod to create inductive photoperiods, which can reduce the total crop production time. Another strategy to decrease energy inputs for heating is to optimize greenhouse temperature and photosynthetic daily light integral (DLI) so that crops are more efficiently scheduled and less energy is consumed on a per-crop basis.

Mathematical models have been developed to predict the influence of mean daily temperature (MDT) and DLI on time to flower in several ornamental annuals such as *Impatiens walleriana* Hook.f. (Pramuk and Runkle, 2005), *Viola ×wittrockiana* Gams. (Adams et al., 1997), and *Pelargonium ×hortorum* Bailey (White and Warrington, 1988). These models can be used to predict time to flower under different environmental conditions. However, to evaluate energy-efficient production regimens, crop models that predict flowering need to be integrated with models that estimate greenhouse energy consumption.

The objectives of this study were (1) to quantify the influence of MDT and DLI on flowering during the finish stage of two popular ornamental annual crops, *Petunia ×hybrida* Vilm.-Andr. and *Tagetes patula* L., (2) to develop crop models that predict the effects of changing MDT and DLI on flowering time and plant quality, and (3) to predict energy costs for greenhouse heating for different crop finish dates and at different locations in the United States.

MATERIALS AND METHODS

Seeds of *Petunia ×hybrida* ‘Dreams Neon Rose’ and *Tagetes patula* ‘Janie Flame’ were sown in plug trays (288-cell size (6-ml volume)) by a commercial greenhouse (C. Raker & Sons, Litchfield, Michigan, USA). After germination, plugs were received at Michigan State University and were grown in a controlled environmental growth chamber at a mean daily air temperature (MDT) of 20.4°C and under 180 µmol m^{-2} s^{-1} provided by cool-white fluorescent (F96T12CWVHO; Philips, Somerset, New Jersey, USA) and incandescent lamps with a 16-h photoperiod. Plants were irrigated as necessary with acidified well water (containing 95, 34, and 29 mg L^{-1} Ca, Mg, and S, respectively) supplemented with a water-soluble fertilizer providing (mg L^{-1}): 62 N, 6 P, 62 K, 7 Ca, 0.5 Fe, 0.3 Cu, Mn, and Zn, 0.1 B and Mo (MSU Well Water Special; GreenCare Fertilizers, Inc., Kankakee, Illinois, USA).

Greenhouse Environment

After 19 to 32 d from seed sow, 6-leaf (*Petunia*) or 6- or 8-leaf (*Tagetes*) seedlings were transplanted into 10-cm round plastic containers (480-ml volume) filled with a commercial soilless peat-based medium (Suremix; Michigan Grower Products, Inc., Galesburg, Michigan, USA). Plants were randomly assigned to treatments and grown in glass-glazed greenhouses at constant air temperature set points of 14, 17, 20, 23, or 26°C and under a 16-h photoperiod that consisted of natural photoperiods (43°N lat.) with day-extension lighting from 0600 to 2200 h provided by high-pressure sodium (HPS) lamps. At each temperature, plants were grown under two DLI treatments provided by the use of a shade curtain and different intensities (25 to 150 µmol m^{-2} s^{-1}) of supplemental lighting from HPS lamps. Ten plants of each species were randomly assigned to each temperature and DLI combination. The experiment was performed twice and mean DLIs from transplant to flowering ranged from 4 to 20 mol m^{-2} d^{-1}.

Temperature in each greenhouse compartment was controlled by an environmental computer that controlled steam heating, passive and active ventilation, and fan-and-pad evaporative cooling when needed. Air temperature was independently measured in each greenhouse by an aspirated, shielded thermocouple and the photosynthetic photon flux was measured by a line quantum sensor (Apogee Instruments, Inc., Logan, Utah, USA) under six DLI and temperature combinations. Environmental measurements were collected every 10 s and hourly averages were recorded by a data logger (CR10; Campbell Scientific, Logan, Utah, USA). A vapor-pressure deficit of 1.2 kPa was maintained during the night by the injection of steam into the air. Horizontal airflow fans positioned 1.4 m above the growing surface operated continuously and provided air movement at ≈0.1 m s^{-1}. Plants were irrigated as necessary with reverse osmosis water supplemented with a water-soluble fertilizer providing (mg L^{-1}): 125 N, 12 P, 100 K, 65 Ca, 12 Mg, 1.0 Fe and Cu, 0.5 Mn and Zn, 0.3 B, and 0.1 Mo (MSU RO Water Special; GreenCare Fertilizers, Inc.).

Data Collection and Analysis

The date of first open flower or inflorescence was recorded and time to flower was calculated for each plant. Plants were considered flowering when *Petunia* had one flower with a fully open corolla and when *Tagetes* had an inflorescence with at least 50% of the ray petals fully reflexed. When each plant flowered, plant height, and the number of flowers and flower buds (*Petunia*) or inflorescences (*Tagetes*) were recorded. Plant height was measured from the soil surface to the base of the first open flower (*Petunia*) or to the uppermost node on the flowering shoot (*Tagetes*).

Flowering data were used to develop mathematical models to predict time to flower and flower bud or inflorescence number under different temperature and DLI conditions. Data were analyzed using the calculated MDT and DLI for each plant from transplant to the date of flowering. Flowering time data were converted to developmental rates by calculating the reciprocal of days to flowering (1/d to flower). The rate of development towards flowering was fitted to the following model:

$$1/\text{d to flower} = (-1 \times \text{Tmin} \times b_1 + b_1 \times \text{MDT}) \times (1 - \text{EXP}(-e \times \text{DLI})) \quad (1)$$

where Tmin = base temperature (°C), b_1 is a species-specific temperature constant, MDT is the mean daily temperature (°C), e is a species-specific light constant, and DLI is the mean daily light integral (mol m^{-2} d^{-1}) from transplant to flowering. Estimates for model coefficients b_1 and e were determined by using the nonlinear regression procedure (NLIN) of SAS (SAS Institute, Cary, North Carolina, USA). Tmin for *Petunia* 'Dreams Neon Rose' and *Tagetes* 'Janie Flame' was assumed to be 2.8 and 1.1°C, respectively (Blanchard, 2009).

Data for the number of flower buds or inflorescences and plant height at first flowering were analyzed using the regression procedure (REG) of SAS to determine the influence of MDT and DLI. The flower bud or inflorescence and plant height response surface equations are in the form:

$$y = y_0 + a\text{MDT} + b\text{MDT}^2 + c\text{DLI} + d\text{DLI}^2 + g\text{MDT}\times\text{DLI} \quad (2)$$

where y_0 = y-axis intercept, MDT = mean daily temperature (°C), DLI = mean daily light integral (mol m^{-2} d^{-1}) from transplant to flowering, and a, b, c, d, and g are species-specific constants. The terms of the equation were only included if they were significant at $P \leq 0.05$.

Models were validated by growing 15 plants of each species in glass-glazed greenhouses at constant temperature set points of 17, 20, or 23°C and under a 16-h photoperiod and a DLI of 10 to 15 mol m^{-2} d^{-1}. The photoperiod, DLI, other experimental conditions, and plant culture were as previously described.

Heating Cost Estimation

The cost to heat a 1991 m^2 greenhouse to produce a flowering crop for 1 April or 15 May was estimated for seven locations in the US using the Virtual Grower 2.51 software (Frantz et al., 2007; USDA-ARS, 2009). The crop models developed for *Petunia* and *Tagetes* were used to predict time to flower at five MDTs and under 10 mol m^{-2} d^{-1}. The greenhouse characteristics used to estimate heating costs included: 8 spans each

34.1×7.3 m, arched 3.7-m roof, 2.7-m gutter, polyethylene double layer roof with no infrared barrier, polycarbonate bi-wall ends and sides, forced air unit heaters burning natural gas at US\$ 0.36 m^3, 50% heater efficiency, no energy curtain, an air infiltration rate of 1.0 h^{-1}, and constant temperature set points. Cities were chosen from each of the seven leading garden plant-producing states in the United States (USDA, 2009).

RESULTS

In both species, time to flower decreased as MDT and DLI increased. For example, as temperature increased from 14 to 26°C, mean time to flower of *Petunia* grown under a DLI of 12 mol m^{-2} d^{-1} decreased from 36 to 17 d (Fig. 1A). Under the same conditions, mean time to flower of *Tagetes* decreased from 33 to 17 d (Fig. 1B). The rate of progress to flowering was linear for both species within the measured MDT ranges of 14 to 26°C (Fig. 1C and D).

As DLI increased from 4 to 8 mol m^{-2} d^{-1}, time to flower in both species grown at an MDT of 20°C decreased by 3 or 4 d. The saturation DLI (within 99% of maximum development rate) above which there was no acceleration in flowering time was 10.6 and 8.6 mol m^{-2} d^{-1} for *Petunia* and *Tagetes*, respectively. For example, *Petunia* grown at 17°C and under 11 mol m^{-2} d^{-1} was predicted to flower at the same time as plants grown at the same temperature, but under 18 mol m^{-2} d^{-1}.

The flowering models developed for *Petunia* and *Tagetes* were validated using an independent data set consisting of 45 data observations for each species. When the models were applied to the validation data, *Petunia* and *Tagetes* were predicted to flower within 5 d for 89 and 91% of the actual data, respectively.

In both species, the number of flower buds or inflorescences at first flowering decreased as temperature increased and DLI decreased. For example, the predicted flower bud number in *Petunia* grown at an MDT of 20°C increased by 10 as DLI increased from 4 to 18 mol m^{-2} d^{-1} (Fig. 1E). In *Tagetes,* the predicted inflorescence number in plants grown under a DLI of 12 mol m^{-2} d^{-1} decreased from 13 to 9 as temperature increased from 14 to 26°C (Fig. 1F).

Plant height of *Petunia* at flower was influenced by DLI, but not temperature; as DLI increased from 4 to 18 mol m^{-2} d^{-1}, the predicted plant height decreased by 6.3 cm (data not presented). In *Tagetes*, there was an interactive effect of temperature and DLI on plant height; DLI had a larger effect at an MDT of 14 than at 26°C. For example, *Tagetes* grown at 14°C and under 4 mol m^{-2} d^{-1} were 1.8 cm shorter than those grown at the same MDT, but under 18 mol m^{-2} d^{-1}.

To achieve flowering on 1 April, our models indicate that *Petunia* plugs would have to be transplanted on 23 February, 3, 8, 11, or 14 March if grown at an MDT of 14, 17, 20, 23, or 26°C, respectively. To achieve flowering on 15 May, *Tagetes* would have to be transplanted on 11, 17, 22, 25, or 27 April if grown at an MDT of 14, 17, 20, 23, or 26°C, respectively. Using the Virtual Grower software, the predicted energy cost to heat a *Petunia* crop in a greenhouse from transplant to flowering, located in San Francisco, California, Tallahassee, Florida, Charlotte, North Carolina, or Fort Worth, Texas, for 1 April flowering was 32 to 547% lower when grown at an MDT of 14 versus 23°C (Table 1). In contrast, for the same finish date, the predicted energy cost for a *Petunia* crop grown in the same greenhouse but in Grand Rapids, Michigan and Cleveland, Ohio was 3 to 5% greater at an MDT of 14°C compared with that at 23°C.

For a finish date of 15 May, a *Petunia* crop grown at an MDT of 14 or 17°C had the lowest predicted energy costs for heating at all locations. In *Tagetes*, an MDT of 14°C had the lowest predicted energy cost for both finish dates at all locations.

DISCUSSION

In response to increased energy costs, some greenhouse growers have lowered the night temperature to reduce energy inputs for heating. Although the energy required to maintain a lower greenhouse temperature decreases on a daily basis, this attempt at saving energy creates a lower MDT, which increases time to flower. At some greenhouse locations, the longer production duration at a low MDT could require more energy inputs per crop than a shorter production time at a higher MDT. For example, according to our model, *Petunia* grown in Grand Rapids, Michigan under 10 mol m^{-2} d^{-1} and at an MDT of 14°C would flower 12 d later and consume 8% more energy for heating than plants grown at 20°C.

The MDT that had the lowest estimated heating cost to produce flowering *Petunia* and *Tagetes* varied among greenhouse locations and between finish dates. The amount of energy lost from a greenhouse is influenced by many different factors, particularly the climate in which the greenhouse is located and the time of year (Bartok, 2001). For example, our model estimated that a *Petunia* crop grown for 1 April at 20°C and under 10 mol m^{-2} d^{-1} would require 208% more energy for heating if grown in Cleveland, Ohio (outside mean monthly low temperature during February and March is -6.1 to -1.7°C) versus Fort Worth, Texas (-3.7 to 8.0°C) (NOAA, 2009). The estimated heating cost to produce *Petunia* and *Tagetes* was 21 to 92% lower at all locations when grown for a finish date of 15 May versus 1 April. Different locations would also have different amounts of radiant energy from the sun to offset the need for supplemental heating during the day.

In both species, time to flower and the number of flower buds or inflorescences at first flowering decreased as the MDT increased from 14 to 26°C. This response is similar to *Impatiens*; under a DLI of 10 mol m^{-2} d^{-1}, as MDT increased from 15 to 25°C, days to flower and the number of flower buds decreased by 14 and 45, respectively (Pramuk and Runkle, 2005). These results indicate that there is a trade-off between a short production duration and higher plant quality. Crops grown at lower temperatures have more time to harvest photosynthetic light and accumulate dry matter before flowering. White and Warrington (1988) reported that in *Pelargonium* grown under 17 mol·m^{-2}·d^{-1}, as MDT decreased from 22.5 to 13.5°C, time to flower and the sugar and starch percentage at flowering increased by 33 d and 1.4 to 4.7%, respectively.

The models developed can be used to evaluate the benefits of increasing the DLI on flowering time and plant quality during different production seasons. For example, if the DLI from natural sunlight is 4 mol m^{-2} d^{-1}, the addition of 4 mol·m^{-2} d^{-1} from supplemental lighting is predicted to accelerate flowering of *Petunia* grown at an MDT of 17°C by 5 d and increase the number of flower buds by 3. At the same MDT, the model predicts that increasing the DLI from 15 to 19 mol m^{-2} d^{-1} has no effect on time to flower, but plants would have 3 more flower buds at flowering.

This information can be used by greenhouse growers to help identify the most energy-efficient production strategy for their location and crop. The cost of energy for heating is just one of the many production expenses for greenhouse crops. Other factors, such as the number of crop production cycles and overhead costs, should also be considered when choosing growing temperature set points.

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Tables

Table 1. Estimated heating costs using Virtual Grower software (USDA-ARS, 2009) from time of transplant of 6-leaf *Petunia* and 6- or 8-leaf *Tagetes* to first flowering on 1 April or 15 May. Time to flower was calculated using models in Figure 1 and is for plants grown at different constant temperatures in different locations under a 16-h photoperiod and a mean photosynthetic daily light integral of 10 mol m^{-2} d^{-1}. See Materials and Methods for greenhouse and heating parameter inputs.

	Estimated heating cost (US$ m^{-2} $crop^{-1}$)									
	1 April					15 May				
	Mean daily temperature (°C)									
Location	14	17	20	23	26	14	17	20	23	26
Petunia 'Dreams Neon Rose'										
San Francisco, CA	0.75	1.07	1.23	1.41	1.57	0.51	0.81	0.97	1.10	1.21
Tallahassee, FL	0.56	0.69	0.78	0.97	1.04	0.09	0.11	0.16	0.30	0.43
Grand Rapids, MI	2.78	2.64	2.56	2.70	2.75	1.12	1.11	1.14	1.22	1.30
New York, NY	1.96	1.92	1.94	2.06	2.03	0.48	0.63	0.70	0.83	0.88
Charlotte, NC	0.95	1.15	1.24	1.40	1.44	0.29	0.40	0.41	0.54	0.72
Cleveland, OH	2.52	2.34	2.31	2.40	2.52	0.96	0.98	1.19	1.26	1.33
Fort Worth, TX	0.55	0.70	0.75	0.93	1.07	0.06	0.12	0.25	0.42	0.60
Tagetes 'Janie Flame'										
San Francisco, CA	0.69	1.03	1.18	1.34	1.57	0.46	0.79	0.92	1.03	1.21
Tallahassee, FL	0.48	0.65	0.76	0.91	1.04	0.07	0.09	0.16	0.28	0.43
Grand Rapids, MI	2.46	2.51	2.50	2.61	2.75	0.98	1.05	1.07	1.15	1.30
New York, NY	1.79	1.85	1.86	1.92	2.03	0.43	0.61	0.65	0.77	0.88
Charlotte, NC	0.84	1.11	1.21	1.29	1.44	0.28	0.35	0.37	0.51	0.72
Cleveland, OH	2.22	2.30	2.18	2.32	2.52	0.80	0.94	1.14	1.17	1.33
Fort Worth, TX	0.48	0.67	0.71	0.88	1.07	0.04	0.12	0.25	0.39	0.60

<u>**Figures**</u>

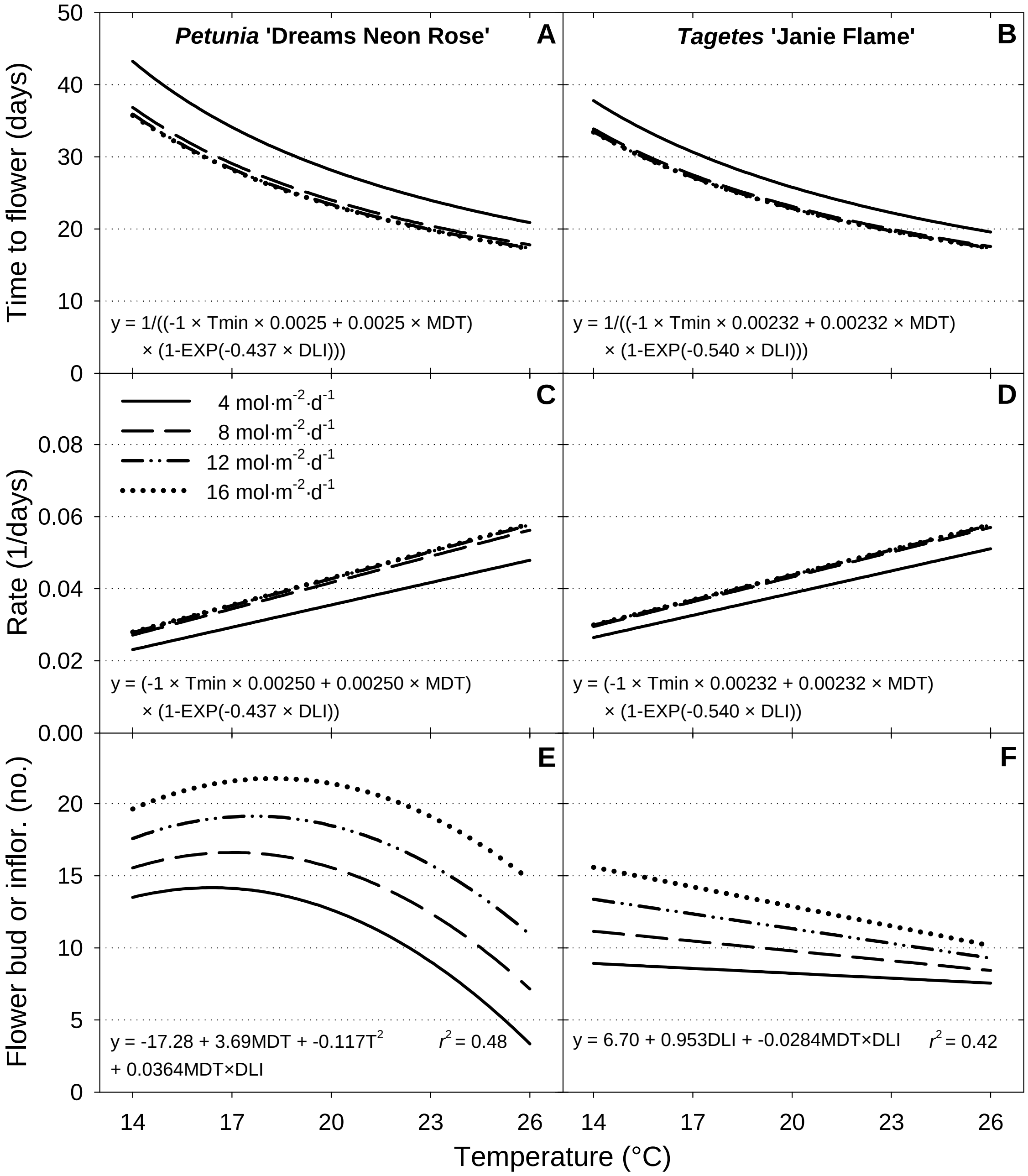

Fig. 1. The effect of mean daily temperature (MDT) and photosynthetic daily light integral (DLI) on the predicted time to flower (A and B), rate of progress to flower (C and D), and number of flower buds or inflorescences at first flowering (E and F) in *Petunia* and *Tagetes* grown under a 16-h photoperiod. Legend in panel C applies to all panels. Time to flower is from transplant of 6-leaf (*Petunia*) or 6- or 8-leaf (*Tagetes*) seedlings that had been grown at an MDT of 20.4°C and under a 16-h photoperiod and a DLI of 10 mol m^{-2} d^{-1}. The base temperature (Tmin) for *Petunia* 'Dreams Neon Rose' and *Tagetes* 'Janie Flame' was assumed to be 2.8 and 1.1°C, respectively (Blanchard, 2009).