Energy-Efficient Annuals

Perfecting Temps & Light

In part one of a 12-part series, researchers from Michigan State University, the University of Florida and the University of Minnesota present research-based information for scheduling annuals in a more energy-efficient and predictive manner.

by ***MATTHEW BLANCHARD, ERIK RUNKLE, PAUL FISHER*** and ***JOHN ERWIN***

BEDDING and garden plants are the largest category of floriculture crops in the United States with a wholesale value of $1.76 billion in 2007. Scheduling these crops in flower for specific market dates, at different times of the year, can be a challenge. In addition, most bedding plants are produced when energy for heating a greenhouse is a large production cost, particularly in northern climates. To optimize the greenhouse environment and produce crops as energy efficiently as possible, more information is needed on how bedding plants respond to temperature and light.

During the past several years, we have performed greenhouse experiments at Michigan State University to study the effects of temperature and light on crop timing and plant quality of many popular seed-propagated annuals. In this 12-part series, we will present research-based information so that these crops can be scheduled in a more energy-efficient, predictive manner. We will also use computer software (Virtual Grower) to predict how different scheduling options influence greenhouse energy consumption. This first article reviews how temperature and light influence crop timing and plant quality.

Average Daily Temperature

The rate of plant development (time to flower) is controlled by the 24-hour average daily temperature (ADT). Many greenhouse crops develop a certain number of leaves before flowering. Therefore, how fast or slow a crop develops can be controlled by raising or lowering the ADT. For example, petunia 'Dreams Red' grown at 79°F (26°C) flowered 19 days earlier than plants grown at 59°F (15°C) (**Figure 1**). Some growers have lowered the night temperature in an attempt to lower energy costs for greenhouse heating. However, this practice delays development and increases production time unless the day temperature is increased so that the ADT is the same. The net result can be that plants grown at cool temperatures can use the same or more heating fuel (spread out over more time) and fewer crop turns are possible.

The rate of plant development stops when the ADT is near the base temperature and increases linearly as temperature increases until some optimum temperature is reached (**Figure 2**). With further increases in temperature, the rate of plant development begins to decrease and thus delay flowering. The base and optimum temperature vary among species, and until now, little information on bedding plants has been available. In our greenhouse experiments, plants

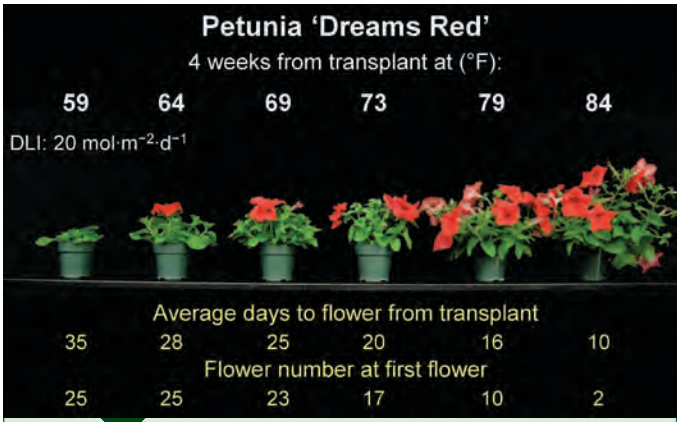

Figure 1. The effects of average daily temperature on time to flower and number of flower buds in petunia. Plants were grown under a 16-hour photoperiod and an average daily light integral of 20 mol·m–2·d–1. The photograph was taken four weeks after transplant from a 288-cell plug tray.

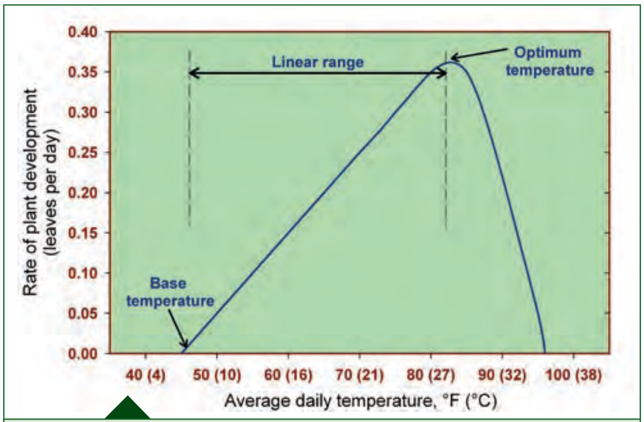

Figure 2. Conceptual diagram of the rate of plant development (such as leaf unfolding) in relation to the average daily temperature. The shape of the curve varies from crop to crop.

were grown at four or five different ADTs between 57 and 79°F (14 and 26°C) and flowering time was recorded.

Plants grown at cooler temperatures often have more flowers at first flowering than plants grown at warmer temperatures. For example, petunia 'Dreams Red' grown at 59 or 64°F had 15 more flower buds at flower than plants grown at 79°F (Figure 1). This is especially a concern under light-limiting conditions. Higher plant quality at a cooler temperature can occur because plants are in the greenhouse longer and have more time to harvest light for photosynthesis. Therefore, there can be a trade-off between producing a high-quality crop and short crop timing. We will present our research information on how individual crops respond to temperature and light, and the impacts on energy consumption, in future articles of this series.

Daily Light Integral

Flowering time and plant quality can also be influenced by the total amount of photosynthetic light (daily light integral, or DLI) that a plant receives. DLI is the cumulative amount of light received during a 24-hour period and is expressed as moles per square meter per day ($mol \cdot m^{-2} \cdot d^{-1}$). In the north (above 35°N latitude) and during the winter, the DLI inside a greenhouse without supplemental lighting can be less than 5 $mol \cdot m^{-2} \cdot d^{-1}$. In late spring, the greenhouse DLI can reach 25 to 30 $mol \cdot m^{-2} \cdot d^{-1}$ before shading is used to prevent unwanted high temperatures.

Many crops grown under a high DLI flower faster than those grown under a low DLI. For example, marigold 'Moonstruck Orange' grown at 63°F and under 12 $mol \cdot m^{-2} \cdot d^{-1}$ flowered 8 days earlier than plants grown at the same temperature, but under 5 $mol \cdot m^{-2} \cdot d^{-1}$ (**Figure 3**). The acceleration of flowering under a high DLI can be related to various factors, including: 1) greater photosynthesis; 2) formation of fewer leaves before flower initiation; and 3) warmer plant temperature. Species that produce fewer leaves before flowering when grown under a high DLI are described as having a facultative irradiance response. As with temperature, there is a saturation value at which any further increase in DLI has little or no effect on flowering time.

A higher DLI can also improve crop quality. Plants grown under a high DLI typically have smaller and thicker leaves, thicker stems, shorter internodes, increased rooting and more lateral branches and flowers. This is why plants finished in late spring are generally of higher quality than those produced earlier. Plants in our experiments were grown under DLIs ranging from 4 to 20 mol·m^{-2}·d^{-1} to determine the influence of DLI on flowering. DLI responses for different annual crops will be discussed in future articles.

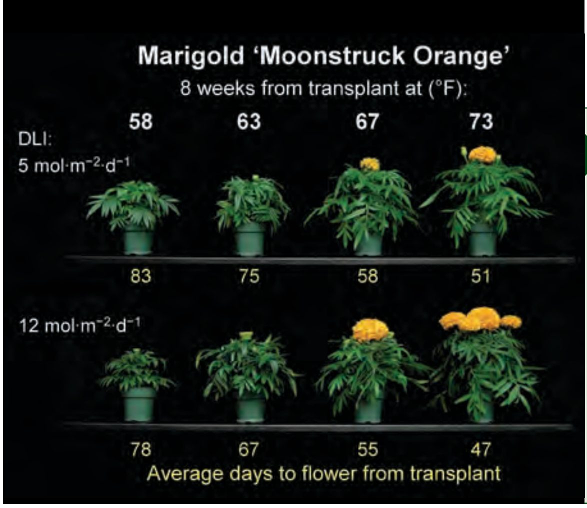

Figure 3. Effects of average daily temperature and daily light integral (DLI) on time to flower in marigold 'Moonstruck Orange.' Plants were grown under a 16-hour photoperiod. Photograph was taken eight weeks after transplant from a 288-cell plug tray.

Photoperiod (day length) can also influence crop timing because many plants flower in response to short days (for example, poinsettia) or long days (for example, petunia). Other plants are day neutral (not affected by photoperiod). For energy-efficient greenhouse production, photoperiod-sensitive plants should be grown under a photoperiod that promotes flowering. In our greenhouse experiments, most of the annuals studied were all long-day crops, so plants were grown under a 16-hour photoperiod. **GG**

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Energy-Efficient Annuals

Scheduling Bedding Plants

In part two of a 12-part series, researchers from Michigan State University and USDA present research-based information for scheduling annuals in a more energy-efficient and predictive manner.

by ***ERIK RUNKLE, JONATHAN FRANTZ*** and ***MATTHEW BLANCHARD***

DESIRABLE scheduling of garden plants includes producing a marketable crop for a specific date with the least amount of inputs as possible. A large contribution to input costs for greenhouse production are overhead expenses (often calculated on a cents-per-square-foot basis). During winter and early spring production, heating can be a large component of overhead costs, especially for growers in the North. As a result, some growers have lowered their growing temperature in an attempt to save on fuel costs.

When greenhouse temperature is lowered, plants develop more slowly, so production time increases. The effect of temperature on crop timing depends on several factors, most notably on the crop grown. In this series of articles, we are presenting research-based information on the effect of temperature on crop timing of a variety of popular bedding plants. We then can estimate the cost to heat a greenhouse given the temperature, cropping time, and greenhouse characteristics.

Signing On To Software

Estimating heating costs for different greenhouse production scenarios was nearly impossible several years ago. That has changed. Virtual Grower is a free, user-friendly computer program that enables anyone to virtually create their greenhouse and then predict the effect of changing different parameters on heating costs. Using temperature and crop timing data, we can use Virtual Grower to estimate heating costs throughout the bedding plant season and beyond. This ultimately allows us to project the most energy-efficient growing temperature.

Some of the parameters that one can enter in Virtual Grower are location, scheduling time, greenhouse characteristics (glazing, side wall composition, size, roof type, etc.), fuel type and cost, "leakiness" of a greenhouse and utilization of an energy curtain (**Figure 1**). To obtain a free copy of Virtual Grower, and for more information on the program, visit **www.VirtualGrower.net**.

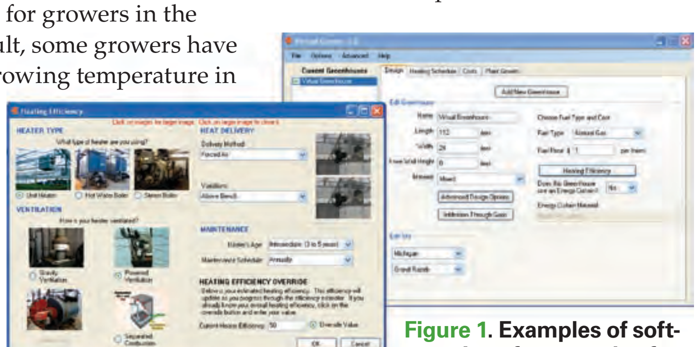

Figure 1. Examples of software interface panels of Virtual Grower. This program can be downloaded free at VirtualGrower.net and can be used to estimate greenhouse energy costs throughout the United States.

Let's illustrate the utility of Virtual Grower and our crop timing information with petunia 'Easy Wave Coral Reef.' We grew 288-cell plugs under a 16-hour long day until they were ready for transplant. Plugs were transplanted into 4-inch pots and grown at a range of constant day/night temperatures, all with a 16-hour photoperiod using high-pressure sodium lighting. We also grew plants at different daily light integrals, but we'll discuss that in future articles. As expected, petunia developed progressively faster as temperature increased. Time from transplant of a completely vegetative 288-cell plug to first flowering took 62 days at 58°F (14°C), 42 days at 63°F (17°C), 30 days at 68°F (20°C), and 26 days at 73°F (23°C).

Date of transplant of 288-cell plugs for desired market dates							
April 1				May 15			
58°F	63°F	68°F	73°F	58°F	63°F	68°F	73°F
Jan. 29	Feb. 18	Mar. 2	Mar. 6	Mar 14	Apr. 3	Apr. 15	Apr. 19

Table 1. Date of transplant of 288-cell plug trays of petunia 'Easy Wave Coral Reef' to achieve first flowering when grown at different temperatures for two market dates. Plugs were grown under a 16-hour long day and were completely vegetative at transplant. A 16-hour long day and an average daily light integral of 10 mol·m^{-2}·d^{-1} were provided during the finish stage.

Using this information, we can then identify the date that plugs need to be transplanted for two different finish dates: April 1 and May 15. For example, if we want first flowering of this petunia on April 1 and we want to grow at an average daily temperature of 63°F, then plugs should be transplanted on Feb. 18 (**Table 1**). Or, we can grow at 68°F and delay transplanting until March 2.

Location	Estimated heating cost (U.S. dollars per square foot per crop)							
	April 1				May 15			
	58°F	63°F	68°F	73°F	58°F	63°F	68°F	73°F
San Francisco, Calif.	0.13	0.14	0.15	0.16	0.10	0.11	0.11	0.13
Tallahassee, Fla.	0.14	0.11	0.10	0.11	0.04	0.03	0.02	0.03
Grand Rapids, Mich.	0.56	0.40	0.31	0.30	0.26	0.18	0.15	0.15
New York, N.Y.	0.38	0.29	0.24	0.24	0.15	0.11	0.10	0.11
Charlotte, N.C.	0.24	0.15	0.15	0.16	0.08	0.07	0.07	0.07
Cleveland, Ohio	0.49	0.36	0.28	0.29	0.22	0.16	0.13	0.15
Fort Worth, Texas	0.15	0.12	0.10	0.11	0.03	0.02	0.03	0.04

Table 2. Estimated heating costs to produce flowering petunia 'Easy Wave Coral Reef' (from a 288-cell plug; see Table 1) at different temperatures and locations for first flowering on April 1 or May 15. Cities were chosen from each of the seven leading garden plant-producing states. Calculations performed with Virtual Grower 2.0 software with constant temperatures. Greenhouse characteristics include: eight spans each 112 by 24 feet, arched 12-foot roof, 9-foot gutter, polyethylene double-layer roof, polycarbonate bi-wall ends and sides, forced air unit heaters burning natural gas at $1 per therm ($10.24 MCF), 50 percent heater efficiency, no energy curtain and an hourly air infiltration rate of 1.0.

Estimating Heating Costs

Finally, we can use Virtual Grower to estimate the energy cost for heating a greenhouse given the different crop schedules. We calculated this cost for a variety of locations throughout the United States (**Table 2**). Data is expressed as the heating cost per square foot of production area per crop (not per week). For example, the heating cost to produce a petunia crop in Grand Rapids, Mich., for a desired finish date of April 1 was 56 cents per square foot when transplanted on Jan. 29 and grown at 58°F, and 31 cents when transplanted on March 2 and grown at 68°F.

Using more locations, we quantified the heating cost to produce this petunia at different locations for an April 1 finish date. Figure 2 provides the change in heating cost (per square foot per crop) to produce petunia at 58°F compared to 68°F. Except for the two locations in California, less energy was consumed by growing the crop warm (68°F) compared to growing it 10°F cooler because of the substantial increase in production time. Thus, an earlier transplant date is required for a cooler production temperature, and

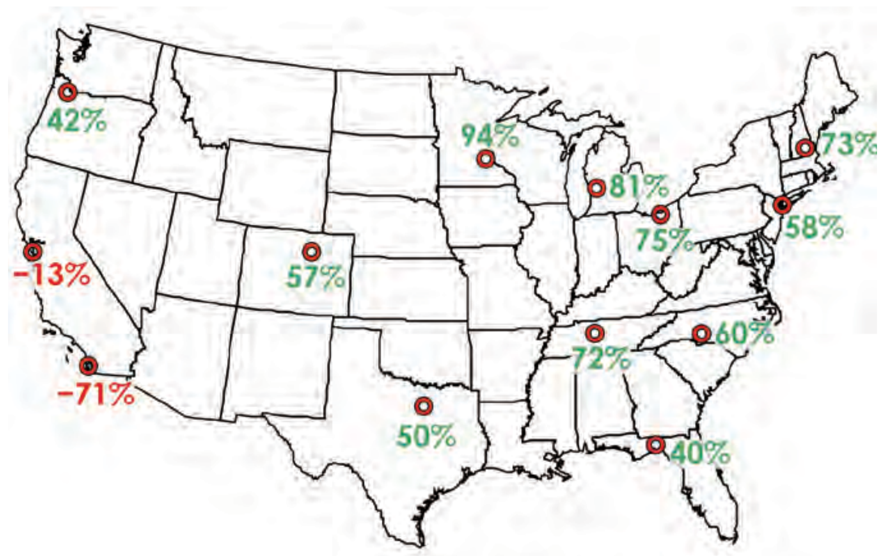

Figure 2. The estimated increase (in green) or decrease (in red) in heating costs by growing petunia 'Easy Wave Coral Reef' at 58°F instead of 68°F for first flowering on April 1 given our virtual greenhouse characteristics. In this example, the increase in energy consumption is because crop timing is extended by 32 days when grown at 58°F compared to 68°F. See Table 2 for calculations on energy consumption using Virtual Grower.

greenhouse heating costs are (in many locations) higher earlier in the year. As Table 2 indicates, heating costs are lower later in the spring.

An important consideration we will not address in this series is the opportunity cost when growing a crop slowly and at a cool temperature. Because crop timing is longer when grown cool, fewer crop turns are possible, and there is a greater likelihood of other problems occurring (such as a pathogen outbreak). This means overhead costs must be allocated to fewer crops at low production temperatures. An advantage of growing cooler is when light conditions are limiting, crop quality is often higher. These calculations reflect the most rapid development rate. A decision must be made between optimum energy use and crop quality.

Starting next month, we will present crop timing data and will use Virtual Grower to estimate heating costs in different locations. Of course, fuel costs depend on numerous factors. To make comparisons, we will use the same virtual greenhouse throughout this series. See Table 2 for some of our virtual greenhouse parameters. **GG**

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Energy-Efficient Annuals

Timing Marigolds

In part three of a 12-part series, researchers from Michigan State University present research-based information for scheduling annuals in a more energy-efficient and predictive manner.

by ***MATTHEW BLANCHARD*** *and* ***ERIK RUNKLE***

IN the first article of this scheduling annuals series, we introduced the concepts of temperature and daily light integral (DLI) and how these factors influence crop timing and plant quality. In the second article, Virtual Grower software was presented as a tool to predict energy costs for greenhouse heating. In this article, we present crop timing data for two species of marigolds, then estimate greenhouse heating costs to produce marigolds at different temperatures and in different locations.

Marigolds are among the top 10 bedding plants produced in the United States. In 2007, the 15 largest floriculture-producing states collectively sold 3.7 million flats at a total wholesale value of $31.7 million. Four species of marigolds are commonly grown commercially and include African or American marigold (*Tagetes erecta*), French marigold (*T. patula*), sweet-scented marigold (*T. lucida*), and signet marigold (*T. tenuifolia*). Our crop scheduling research focused on African and French marigolds.

Materials and Methods

Seeds of African marigold 'Antigua Primrose' and 'Moonstruck Orange' and French marigold 'Janie Flame' and 'Bonanza Yellow' were sown in 288-cell plug trays by C. Raker & Sons, then grown in controlled environmental growth chambers at Michigan State University at 68°F (20°C). The photoperiod was 16 hours and the DLI was 9 to 11 mol·m^{-2}·d^{-1}.

When plugs were ready for transplant (two to four weeks after seed sow, depending on variety), they were transplanted into 4-inch pots and grown in greenhouses with constant temperature set points of 57, 63, 68, 73 and 79°F (14, 17, 20, 23 and 26°C). At each temperature, plants were grown under a 16-hour photoperiod with two different DLIs provided by a combination of shade curtains and different light intensities from high-pressure sodium lamps.

The experiment was performed twice to obtain average DLIs that ranged from 3.5 to 21 mol·m^{-2}·d^{-1}. The flowering date was recorded for each plant when an inflorescence with at least 50 percent of the ray petals were fully reflexed. When each plant flowered, plant height, number of leaves and number of flowers and flower buds were recorded.

Crop timing data was used to develop mathematical models to predict

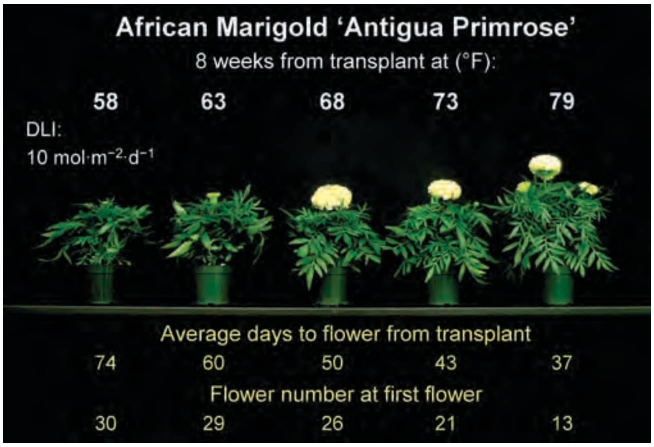

Figure 1. The effects of average daily temperature on time to flower and number of flower buds (at first flowering) in African marigold. Plants were grown under a 16-hour photoperiod and an average daily light integral of 10 mol·m^{-2}·d^{-1}. Photograph was taken eight weeks after transplant from a 288-cell plug tray.

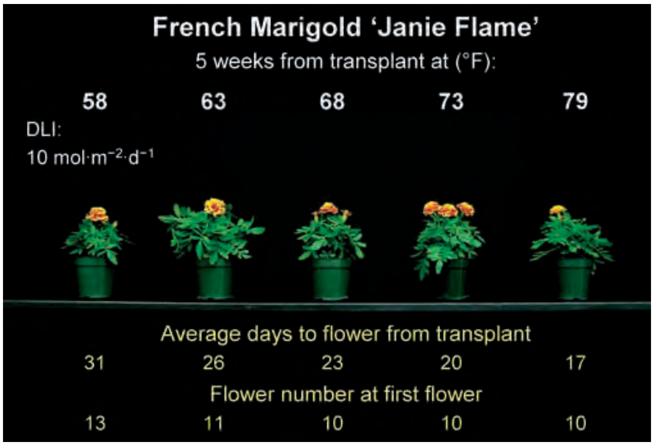

Figure 2. The effects of average daily temperature on time to flower and number of flower buds (at first flowering) in French marigold. Plants were grown under a 16-hour photoperiod and an average daily light integral of 10 mol·m^{-2}·d^{-1}. Photograph was taken five weeks after transplant from a 288-cell plug tray.

flowering time and plant quality under different temperature and DLI conditions. The scheduling models were validated by growing marigolds at three different constant temperatures to compare predicted flowering times with actual times. Temperature responses were similar between cultivars of African and French marigolds, so one crop timing model was used for each species. The Virtual Grower software (free at **www.virtualgrower.net**) was used to estimate the cost to heat a 21,504 square foot greenhouse (about half an acre) to produce a marigold crop for different finish dates and at different locations in the U.S.

Table 1. Date of transplant of 288-cell plug trays of African marigold 'Antigua Primrose' and French marigold 'Janie Flame' to achieve first flowering when grown at different temperatures for two market dates. Time to flower is presented in Figures 1 and 2. Plugs were grown at 68°F and under a 16-hour long day. A 16-hour long day and an average daily light integral of 10 mol·m^{-2}·d^{-1} were provided during the finish stage.

Market Date	Average Temperature	Date Of Transplant Of 288-Cell Plugs For Desired Market Dates	
		African Marigold	French Marigold
April 1	58°F	January 16	March 1
	63°F	January 31	March 5
	68°F	February 9	March 9
	73°F	February 16	March 12
May 15	58°F	March 1	April 14
	63°F	March 16	April 18
	68°F	March 25	April 22
	73°F	April 1	April 25

Table 2. Estimated heating costs to produce flowering African marigold 'Antigua Primrose' and French marigold 'Janie Flame' (from a 288-cell plug; see Table 1) at different temperatures and locations for first flowering on April 1 or May 15. Cities were chosen from each of the seven leading garden plant-producing states. Calculations performed with Virtual Grower 2.01 software with constant temperatures. Greenhouse characteristics include: eight spans each at 112 by 24 feet, arched 12-foot roof, 9-foot gutter, polyethylene double layer roof, polycarbonate bi-wall ends and sides, forced air unit heaters burning natural gas at $1 per therm ($10.24 MCF), 50 percent heater efficiency, no energy curtain and an hourly air infiltration rate of 1.0. (The lowest predicted energy cost is highlighted in green for each location and market date.)

Location	Estimated Heating Cost (U.S. Dollars Per Square Foot Per Crop)							
	April 1				May 15			
	58°F	63°F	68°F	73°F	58°F	63°F	68°F	73°F
	African Marigold							
San Francisco, Calif.	0.18	0.20	0.24	0.27	0.13	0.16	0.19	0.22
Tallahassee, Fla.	0.19	0.19	0.22	0.23	0.06	0.05	0.07	0.10
Grand Rapids, Mich.	0.69	0.65	0.60	0.58	0.36	0.32	0.30	0.31
New York, N.Y.	0.52	0.46	0.46	0.46	0.22	0.20	0.20	0.22
Charlotte, N.C.	0.32	0.31	0.29	0.28	0.12	0.12	0.13	0.16
Cleveland, Ohio	0.61	0.56	0.57	0.55	0.30	0.28	0.30	0.27
Fort Worth, Texas	0.19	0.20	0.22	0.23	0.05	0.06	0.07	0.10
	French Marigold							
San Francisco, Calif.	0.07	0.09	0.11	0.13	0.05	0.07	0.09	0.10
Tallahassee, Fla.	0.04	0.06	0.07	0.09	0.00	0.01	0.01	0.03
Grand Rapids, Mich.	0.22	0.22	0.23	0.24	0.09	0.09	0.10	0.11
New York, N.Y.	0.15	0.17	0.17	0.18	0.04	0.06	0.06	0.07
Charlotte, N.C.	0.08	0.10	0.12	0.12	0.03	0.03	0.03	0.05
Cleveland, Ohio	0.19	0.22	0.20	0.22	0.07	0.09	0.11	0.11
Fort Worth, Texas	0.04	0.06	0.07	0.08	0.00	0.01	0.02	0.04

Results

In both African and French marigolds, time to flower decreased as temperature and DLI increased. For example, under an average DLI of 10 mol·m^{-2}·d^{-1}, time to flower of African marigold decreased by 24 days as temperature increased from 58 to 68°F (**Figure 1**). French marigold grown under the same DLI flowered eight days earlier at 68°F compared to 58°F (**Figure 2**). This information can be used to determine the date 288-cell plugs need to be transplanted for two different market dates when grown at different temperatures (**Table 1**).

As the DLI increased from 4 to 16 mol·m^{-2}·d^{-1}, time to flower in African and French marigold grown at 63°F decreased by 10 and four days, respectively. The saturation DLI for the shortest time to flower was 12 mol·m^{-2}·d^{-1}. In other words, increasing the DLI above 12 mol·m^{-2}·d^{-1} did not shorten crop time.

In both species, the number of inflorescences decreased as temperature increased and as DLI decreased. For example, in African marigold grown under an average DLI of 10 mol·m^{-2}·d^{-1}, the number of flowers decreased by nine as temperature increased from 58 to 73°F.

Therefore, there is a trade-off between fast cropping and plant quality. African and French marigolds grown at the warmest temperature (79°F) and under the lowest DLI (4 mol·m^{-2}·d^{-1}) in our study were of poorest quality (e.g., few flowers and branches), whereas plants grown at 58°F and under 16 mol·m^{-2}·d^{-1} were of highest quality.

Heating Costs

The growing temperature that had the lowest predicted heating cost to produce a crop of African marigolds varied among locations and market dates (**Table 2**). For example, to produce a finish crop for April 1, a greenhouse located in San Francisco, Calif., would save 9 cents per square foot per crop in heating costs by growing at 58°F compared to 73°F.

In contrast, heating costs per square foot were 4 to 11 cents cheaper at four of seven locations when the crop was grown at 73°F versus 58°F. In other words, less energy was consumed by transplanting the African marigold crop later and growing warm compared to transplanting earlier and growing cool.

For French marigold, a production temperature of 58°F had the lowest predicted energy cost for both market dates at all locations. In every simulation, the heating cost to produce a crop of French marigolds was at least 50 percent cheaper than the heating costs for African marigolds because crop timing was so much shorter. The different responses of African and French marigold to temperature indicate that at many locations, it would be more energy efficient to grow these crops at different temperature set points.

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 turns and overhead costs, should also be considered when choosing the most economical growing temperature. **GG**

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Energy-Efficient Annuals

Dianthus & Snapdragon

In part four of a 12-part series, researchers from Michigan State University present research-based information for scheduling annuals in a more energy-efficient manner.

by ***MATTHEW BLANCHARD*** and ***ERIK RUNKLE***

ENERGY-efficient greenhouse production requires information on how crops respond to average daily temperature and daily light integral (DLI) so they can be more precisely scheduled. At Michigan State University (MSU), we have performed experiments with many seed-propagated annuals to quantify the effects of temperature and DLI on flowering and the impacts of different cropping strategies on energy consumption. In this article, we present information on dianthus and snapdragon, and then use crop timing data to estimate greenhouse heating costs at different locations, temperatures and finish dates.

Materials and Methods

Seeds of dianthus (*Dianthus chinensis* 'Super Parfait Raspberry') and snapdragon (*Antirrhinum majus* 'Montego Burgundy Bicolor') were sown in 288-cell plug trays by C. Raker & Sons (Litchfield, Mich.). Plugs were then grown in controlled environmental growth chambers at MSU at 68°F (20°C). The photoperiod was 16 hours and the DLI was 10 to 11 mol·m^{-2}·d^{-1}.

When plugs were considered marketable (38 days after seed sow for dianthus and 27 days for snapdragon), they were transplanted into 4-inch pots and grown in greenhouses with constant temperature set points of 57, 63, 68, and 73°F (14, 17, 20 and 23°C). At each temperature, plants were grown under a 16-hour photoperiod with two different DLIs provided by a combination of shade curtains and different light intensities from high-pressure sodium lamps. Many varieties of dianthus and snapdragon do not require long days for flowering, but varieties flower faster when long days are provided. Therefore, both crops can be considered facultative long-day plants.

The flowering date was recorded for each plant when dianthus had an inflorescence with the ray petals fully reflexed and snapdragon had an inflorescence with two opened flowers. When each plant flowered, plant height, number of leaves on the flowering shoot, branch number, and number of flowers and flower buds were recorded.

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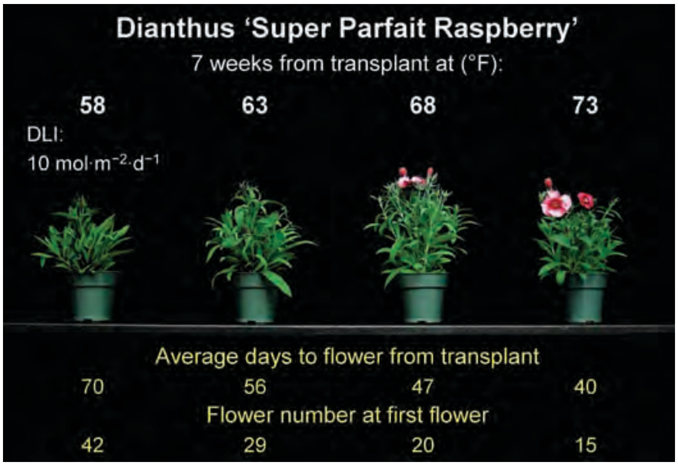

Figure 1. The effects of average daily temperature on time to flower and number of flower buds (at first flowering) in dianthus. Plants were grown under a 16-hour photoperiod and an average daily light integral of 10 mol·m^{-2}·d^{-1}. Photograph was taken seven weeks after transplant from a 288-cell plug tray.

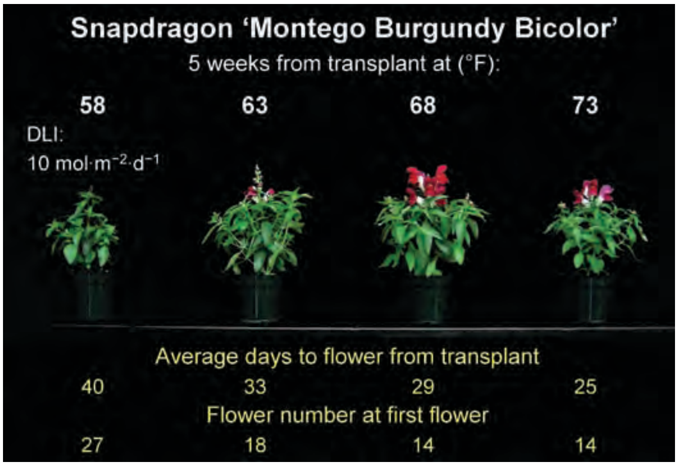

Figure 2. The effects of average daily temperature on time to flower and number of flower buds (at first flowering) in snapdragon. Plants were grown under a 16-hour photoperiod and an average daily light integral of 10 mol·m^{-2}·d^{-1}. Photograph was taken five weeks after transplant from a 288-cell plug tray.

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The experiment was performed twice to obtain average DLIs that ranged from 4 to 19 mol·m^{-2}·d^{-1}.

To give perspective, growers in the North may receive 4 mol·m^{-2}·d^{-1} of light during the winter on a cloudy day, and 19 mol·m^{-2}·d^{-1} of light on a sunny day in early spring. To identify how much light you receive on a typical day outdoors, view the DLI maps created by Jim Faust online at **http://hrt.msu.edu/floraoe/productioninfo.htm**. Then, take those values and multiply them by the light transmission percentage of your greenhouse (a typical value is 50 to 60 percent).

Crop timing data was used to develop mathematical models to predict flowering time and plant quality under different temperature and DLI conditions. The scheduling models were validated by growing dianthus and snapdragon at three different constant temperatures to compare predicted flowering times with actual times. The Virtual Grower software (available free at **www.virtualgrower.net**) was used to estimate the cost to heat a 21,504-square-foot greenhouse (about half an acre) to produce each crop for different finish dates and at different locations in the United States.

Results

In both dianthus and snapdragon, time to flower decreased as average daily temperature and DLI increased. For example, under an average DLI of 10 mol·m^{-2}·d^{-1}, time to flower of dianthus decreased from 70 to 40 days as temperature increased from 58 to 73°F (Figure 1).

Under the same conditions, time to flower of snapdragon decreased from 40 to 25 days (Figure 2). As DLI increased from 4 to 18 mol·m^{-2}·d^{-1}, time to flower in dianthus and snapdragon grown at 63°F decreased by 10 and 17 days, respectively. We can use this crop timing data to determine the date that 288-cell plugs need to be transplanted for two different market dates when grown at different temperatures (Table 1).

The number of flower buds at first flowering increased as temperature decreased and as DLI increased. For example, dianthus grown under 10 mol·m^{-2}·d^{-1} and at 58°F had 27 more flower buds than plants grown under the same DLI, but at 73°F (Figure 1). Snapdragon grown under the same DLI had almost twice the number of flower buds at 58°F compared with plants grown at 68 or 73°F (Figure 2).

Plants grown at 73°F and under 4 mol·m^{-2}·d^{-1} had the fewest flowers and were the poorest quality. Therefore, if these crops are grown at a warm temperature, the DLI should be greater than 4 mol·m^{-2}·d^{-1} to improve plant quality. The number of lateral branches also increased as temperature decreased from 73 to 58°F. Therefore, as with many floriculture crops, there is a trade-off with quick crop timing and high plant quality, especially when the DLI is low.

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Market Date	Average Temperature	Dianthus	Snapdragon
April 1	58°F	January 21	February 20
	63°F	February 4	February 27
	68°F	February 13	March 3
	73°F	February 20	March 7
May 15	58°F	March 6	April 5
	63°F	March 20	April 12
	68°F	March 29	April 16
	73°F	April 5	April 20

Table 1. Predicted date of transplant of 288-cell plug trays of dianthus 'Super Parfait Raspberry' and snapdragon 'Montego Burgundy Bicolor' to achieve first flowering when grown at different temperatures for two market dates. Time to flower is presented in Figures 1 and 2. Plugs were grown at 68°F and under a 16-hour long day. Transplant dates are with a 16-hour long day and an average daily light integral of 10 mol·m^{-2}·d^{-1} during the finish stage.

Location	Estimated Heating Cost (U.S. Dollars Per Square Foot Per Crop)							
	April 1				May 15			
	58°F	63°F	68°F	73°F	58°F	63°F	68°F	73°F
Dianthus								
San Francisco, Calif.	0.16	0.19	0.22	0.25	0.12	0.15	0.18	0.20
Tallahassee, Fla.	0.16	0.18	0.18	0.20	0.05	0.05	0.07	0.09
Grand Rapids, Mich.	0.64	0.60	0.53	0.51	0.31	0.28	0.27	0.27
New York, N.Y.	0.46	0.43	0.43	0.41	0.19	0.18	0.18	0.19
Charlotte, N.C.	0.30	0.26	0.25	0.26	0.11	0.10	0.12	0.14
Cleveland, Ohio	0.58	0.53	0.51	0.47	0.28	0.26	0.24	0.26
Fort Worth, Texas	0.18	0.18	0.20	0.21	0.04	0.05	0.06	0.08
Snapdragon								
San Francisco, Calif.	0.08	0.11	0.14	0.16	0.06	0.08	0.11	0.13
Tallahassee, Fla.	0.07	0.08	0.09	0.11	0.01	0.01	0.02	0.03
Grand Rapids, Mich.	0.31	0.28	0.30	0.29	0.12	0.13	0.14	0.15
New York, N.Y.	0.22	0.22	0.23	0.23	0.06	0.07	0.09	0.10
Charlotte, N.C.	0.10	0.12	0.15	0.16	0.03	0.05	0.06	0.07
Cleveland, Ohio	0.27	0.26	0.27	0.28	0.11	0.11	0.13	0.15
Fort Worth, Texas	0.07	0.08	0.10	0.11	0.01	0.01	0.03	0.04

Table 2. Estimated heating costs to produce flowering dianthus 'Super Parfait Raspberry' and snapdragon 'Montego Burgundy Bicolor' (from a 288-cell plug; see Table 1) at different temperatures and locations for first flowering on April 1 or May 15. Cities were chosen from each of the seven leading garden plant-producing states. Calculations performed with Virtual Grower 2.01 software with constant temperatures. Greenhouse characteristics include: eight spans each 112 by 24 feet, arched 12-foot roof, 9-foot gutter, polyethylene double-layer roof, polycarbonate bi-wall ends and sides, forced air unit heaters burning natural gas at $1 per therm ($10.24 MCF), 50 percent heater efficiency, no energy curtain and an hourly air infiltration rate of 1.0. The lowest predicted energy cost is highlighted in green for each location and market date.

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Heating Costs

The production temperature that had the lowest estimated heating costs to produce a flowering crop of dianthus and snapdragon varied among locations and market dates. For example, to produce a finish crop of dianthus for April 1, a greenhouse located in Grand Rapids, Mich., New York, N.Y., or Cleveland, Ohio, would save 11 to 20 percent on heat per square foot if the crop was transplanted on February 20 and grown at 73°F, compared to the same crop transplanted earlier and grown at 58°F (Table 2).

In other words, a shorter crop time at a warm temperature required less heat on a per-crop basis than a longer crop time at a cool temperature. However, for a greenhouse located in San Francisco, Calif., Tallahassee, Fla., or Fort Worth, Texas, heating costs would increase 17 to 56 percent if dianthus were grown for April 1 at 73°F instead of 58°F.

For market dates later in the spring, outside temperatures are warmer and the greenhouse heating demand is less. Therefore, the most energy-efficient growing temperature can be different depending on the crop and finish date. For example, dianthus grown for April 1 in a greenhouse located in New York, N.Y., would save 2 cents on heating costs per crop per square foot at 73°F versus 63°F, whereas the same crop grown for May 15 would require 1 cent more heat per square foot at 73°F versus 63°F. For snapdragon, a growing temperature of 58 or 63°F consumed the least heat per crop at all locations and for both market dates.

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 turns and overhead costs, should also be considered when choosing the most economical growing temperature for each floriculture crop producer. **GG**

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To see the first four articles in this series go to GreenhouseGrower.com.

Energy-Efficient Annuals: Ageratum & Cosmos

Researchers from Michigan State University present research-based information for scheduling annuals in a more energy-efficient and predictive manner.

by **MATTHEW BLANCHARD** and **ERIK RUNKLE**

SCHEDULING annual bedding plants in flower for specific market dates is of increasing importance to many greenhouse growers. During the past several years at Michigan State University (MSU), we have performed experiments with many seed propagated annuals to quantify how temperature and daily light integral (DLI) influence flowering time and plant quality. In the fifth article of this series, we present information on ageratum and cosmos and then use crop timing data to estimate greenhouse heating costs at different locations, growing temperatures and finish dates.

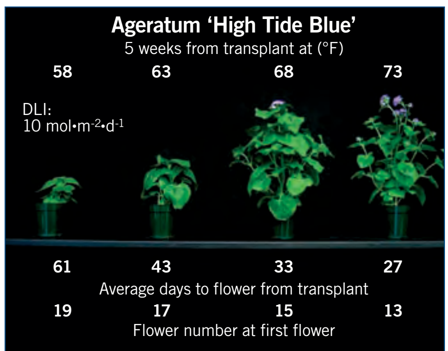

Figure 1. **The effects of average daily temperature on time to flower and number of flower buds (at first flowering) in ageratum. Plants were grown under a 16-hour photoperiod and an average daily light integral of 10 $mol·m^{-2}·d^{-1}$. The photograph was taken five weeks after transplant from a 288-cell plug tray.**

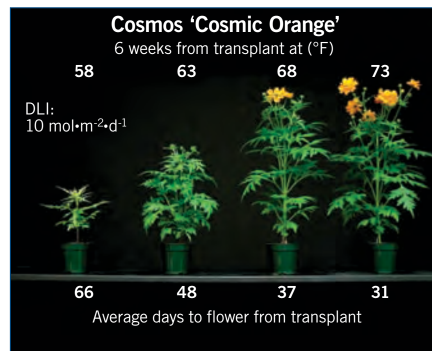

Figure 2. **The effects of average daily temperature on time to flower and number of flower buds (at first flowering) in cosmos. Plants were grown under a 16-hour photoperiod and an average daily light integral of 10 $mol·m^{-2}·d^{-1}$. The photograph was taken six weeks after transplant from a 288-cell plug tray.**

Market Date	Average Temp.	Date Of Transplant Of 288-Cell Plugs For Desired Market Dates	
		Ageratum	Cosmos
April 1	58°F	January 30	January 25
	63°F	February 17	February 12
	68°F	February 27	February 23
	73°F	March 5	March 1
May 15	58°F	March 15	March 10
	63°F	April 2	March 28
	68°F	April 12	April 8
	73°F	April 18	April 14

Table 1. **Date of transplant of 288-cell plug trays of ageratum 'High Tide Blue' and cosmos 'Cosmic Orange' to achieve first flowering when grown at different temperatures for two market dates. Time to flower is presented in Figures 1 and 2. Plugs were grown at 68°F and under a 16-hour long day. Transplant dates assume a 16-hour long day and an average daily light integral of 10 $mol·m^{-2}·d^{-1}$ during the finish stage.**

Materials and Methods

Seeds of ageratum (*Ageratum houstonianum* 'High Tide Blue') and cosmos (*Cosmos sulphureus* 'Cosmic Orange') were sown in 288-cell plug trays by C. Raker & Sons, and then grown in controlled environmental growth chambers at MSU at 68°F (20°C). Inside the chambers, the photoperiod was 16 hours and the DLI was 9 to 11 $mol·m^{-2}·d^{-1}$.

When plugs were ready for transplant (27 days after seed sow for ageratum and 16 days for cosmos), they were transplanted into 4-inch pots and grown in greenhouses with constant temperature set points of 57, 63, 68 and 73°F (14, 17, 20 and 23°C). At each temperature, plants were grown under a 16-hour photoperiod with two different DLIs provided by a combination of shade curtains and different light intensities from high-pressure sodium lamps.

Ageratum does not require long days for flowering, but plants flower faster if long days are provided. Cosmos 'Cosmic Orange' is a day-neutral plant and flowers in the same time if provided with short or long daylengths. However, some cosmos varieties flower faster when grown under short days.

The experiment was performed twice to obtain average DLIs that ranged from 3 to 19 $mol \cdot m^{-2} \cdot d^{-1}$. To give perspective, a DLI of 3 $mol \cdot m^{-2} \cdot d^{-1}$ is received in a northern greenhouse on a cloudy day in the winter. A DLI of 19 $mol \cdot m^{-2} \cdot d^{-1}$ is typical for a mid- to late spring day. The flowering date was recorded for each plant when ageratum had two open flowers and petals of cosmos were fully reflexed. When each plant flowered, plant height, number of leaves and branches and number of flowers and flower buds were recorded.

Crop timing data was used to develop mathematical models to predict flowering time and plant quality under different temperature and DLI conditions. The scheduling models were validated by growing ageratum and cosmos at three different constant temperatures to compare predicted flowering times with actual times. The Virtual Grower software (available free at **www.virtualgrower.net**) was used to es-

Location	Estimated Heating Cost (U.S. Dollars Per Square Foot Per Crop)							
	April 1				May 15			
	58°F	63°F	68°F	73°F	58°F	63°F	68°F	73°F
Ageratum								
San Francisco, Calif.	0.13	0.15	0.16	0.17	0.10	0.11	0.12	0.14
Tallahassee, Fla.	0.13	0.12	0.11	0.12	0.03	0.03	0.03	0.04
Grand Rapids, Mich.	0.55	0.41	0.34	0.32	0.25	0.19	0.17	0.16
New York, N.Y.	0.38	0.30	0.27	0.25	0.14	0.11	0.11	0.11
Charlotte, N.C.	0.23	0.16	0.17	0.17	0.08	0.07	0.08	0.08
Cleveland, Ohio	0.47	0.38	0.31	0.31	0.22	0.16	0.15	0.16
Fort Worth, Texas	0.14	0.12	0.11	0.12	0.03	0.03	0.03	0.04
Cosmos								
San Francisco, Calif.	0.14	0.16	0.18	0.20	0.11	0.12	0.14	0.16
Tallahassee, Fla.	0.15	0.14	0.13	0.14	0.05	0.04	0.04	0.05
Grand Rapids, Mich.	0.60	0.46	0.40	0.37	0.29	0.22	0.20	0.19
New York, N.Y.	0.41	0.36	0.31	0.30	0.17	0.13	0.13	0.14
Charlotte, N.C.	0.27	0.20	0.19	0.20	0.10	0.08	0.09	0.10
Cleveland, Ohio	0.54	0.44	0.37	0.34	0.24	0.20	0.18	0.18
Fort Worth, Texas	0.17	0.14	0.14	0.15	0.03	0.04	0.04	0.05

Table 2. Estimated heating costs to produce flowering ageratum 'High Tide Blue' and cosmos 'Cosmic Orange' (from a 288-cell plug; see Table 1) at different temperatures and locations for first flowering on April 1 or May 15. Cities were chosen from each of the seven leading garden plant-producing states. Calculations were performed with Virtual Grower 2.01 software with constant temperatures. Greenhouse characteristics include: eight spans each 112 × 24 feet, arched 12-foot roof, 9-foot gutter, polyethylene double-layer roof, polycarbonate bi-wall ends and sides, forced air unit heaters burning natural gas at $1 per therm ($10.24 MCF), 50 percent heater efficiency, no energy curtain and an hourly air infiltration rate of 1.0.

timate the cost to heat a 21,504 square foot greenhouse (about half an acre) to produce each crop for different finish dates and at different locations in the United States.

Results

In both ageratum and cosmos, time to flower decreased as average daily temperature increased and DLI increased. For example, time to flower in ageratum 'High Tide Blue' grown under a DLI of 10 $mol \cdot m^{-2} \cdot d^{-1}$ decreased from 61 days at 58°F to 27 days at 73°F (Figure 1). We were a bit surprised by the substantial flowering delay when ageratum was grown cool because many consider it a cool-growing (cold-tolerant) crop. Flowering time of cosmos 'Cosmic Orange' was similar: It decreased from 66 to 31 days as temperature increased from 58 to 73°F (Figure 2).

In both crops, higher light levels accelerated flowering more when plants were grown cool than at warmer temperatures. For example, as DLI increased from 3 to 8 $mol \cdot m^{-2} \cdot d^{-1}$, time to flower in ageratum grown at 58°F and 73°F decreased by 15 days and seven days, respectively. There was no acceleration in flowering when the DLI exceeded 10 $mol \cdot m^{-2} \cdot d^{-1}$ for ageratum and 7 $mol \cdot m^{-2} \cdot d^{-1}$ for cosmos.

Using this crop timing data, we identified dates that 288-cell plugs need to be transplanted for two different market dates when grown at different temperatures (Table 1).

Temperature and DLI had different effects on the number of flower buds at first flowering in cosmos and ageratum. In ageratum, flower bud number was primarily influenced by temperature, whereas in cosmos, flower bud number was primarily influenced by DLI. For example, ageratum had six more flower buds when grown at 58°F versus 73°F (Figure 1). In cosmos, plants grown at 63°F and under a DLI of 15 $mol \cdot m^{-2} \cdot d^{-1}$ had 15 more flower buds than plants grown at the same temperature, but under 5 $mol \cdot m^{-2} \cdot d^{-1}$.

In both crops, as the DLI increased from 3 to 19 $mol \cdot m^{-2} \cdot d^{-1}$, the number of lateral branches at flower increased by two to four. Therefore, although plants did not flower faster as DLI increased above 10 $mol \cdot m^{-2} \cdot d^{-1}$, plant quality improved because plants had more flowers. Plant height at flower increased as constant temperatures increased from 58 to 73°F. Under a DLI of 10 $mol \cdot m^{-2} \cdot d^{-1}$, ageratum and cosmos were 2.6 inches and 5 inches taller, respectively, at a constant temperature of 73°F versus 58°F.

Heating Costs

We can use this crop timing information with Virtual Grower to determine if it is more energy efficient to transplant a crop earlier and grow cool versus transplanting later and growing warm. For example, to produce an ageratum or cosmos crop for April 1 in Grand Rapids, Mich., New York, N.Y., or Cleveland, Ohio, heating costs per square foot would be 27 to 42 percent lower at 73°F versus 58°F (Table 2).

In contrast, to produce these crops for the same market date in Charlotte, N.C., and Fort Worth, Texas, a production temperature of 63 or 68°F would consume the least energy for heating. San Francisco was the only location tested that had lower predicted fuel consumption when crops were transplanted early and grown at 58°F for a market date of April 1.

At some locations, the production temperature that had the lowest heating costs per square foot per crop varied between market dates. For example, ageratum grown for April 1 in New York had the lowest predicted heating costs when grown at 73°F. In contrast, for a market date of May 15, estimated fuel costs were lowest if grown at 63, 68, or 73°F. In this example, because there is no difference in heating costs to produce ageratum for May 15 in New York at 63 to 73°F, other factors such as plant quality, availability of labor, overhead costs and opportunity costs could be considered when selecting a growing temperature. **GG**

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Energy-Efficient Annuals: Petunias

Researchers from Michigan State University present research-based information for scheduling annuals in a more energy-efficient and predictive manner.

by **MATTHEW BLANCHARD** and **ERIK RUNKLE**

ESCALATING fuel costs have made it important for greenhouse growers to improve production efficiency and schedule crops more efficiently. At Michigan State University (MSU), we have performed experiments with many seed-propagated annuals to quantify how temperature and daily light integral (DLI) influence flowering time and plant quality. In the sixth article of this series, we present crop timing data on petunias and then use this information to estimate greenhouse heating costs at different locations, growing temperatures and finish dates.

Petunias are among the top 10 bedding plants produced in the United States. In 2008, the 15 largest floriculture-producing states collectively sold 34.5 million flats, pots and hanging baskets at a total wholesale value of $120 million. Among the different species and hybrids of petunias available, our studies have included grandiflora petunia 'Dreams Neon Rose,' milliflora petunia 'Fantasy Blue,' and spreading petunias 'Easy Wave Coral Reef' and 'Wave Purple.'

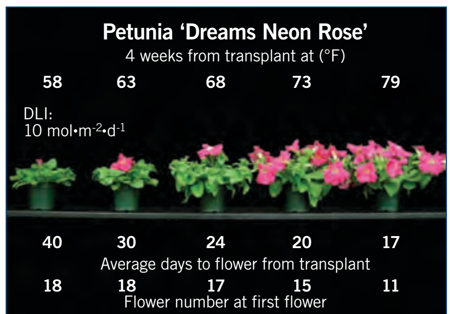

Figure 1. The effects of average daily temperature on time to flower and number of flower buds (at first flowering) in petunia 'Dreams Neon Rose.' Plants were grown under a 16-hour photoperiod and an average daily light integral (DLI) of 10 $mol \cdot m^{-2} \cdot d^{-1}$. Photograph was taken four weeks after transplant from a 288-cell plug tray that was grown under long days.

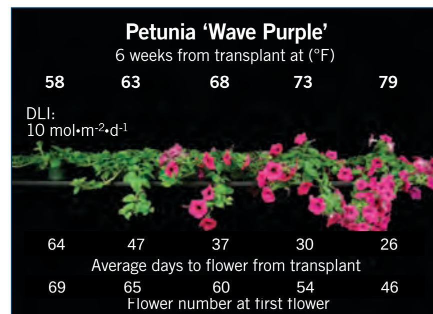

Figure 2. The effects of average daily temperature on time to flower and number of flower buds (at first flowering) in petunia 'Wave Purple.' Plants were grown under a 16-hour photoperiod and an average daily light integral (DLI) of 10 $mol \cdot m^{-2} \cdot d^{-1}$. Photograph was taken six weeks after transplant from a 288-cell plug tray that was grown under long days.

Market Date	Average Temp.	Date Of Transplant Of 288-Cell Plugs For Desired Market Dates	
		Dreams Neon Rose	Wave Purple
April 1	58°F	February 20	January 26
	63°F	March 2	February 13
	68°F	March 8	February 23
	73°F	March 12	March 1
May 15	58°F	April 5	March 11
	63°F	April 15	March 29
	68°F	April 21	April 8
	73°F	April 25	April 14

Table 1. Date of transplant of 288-cell plug trays of petunia 'Dreams Neon Rose' and 'Wave Purple' to achieve first flowering when grown at different temperatures for two market dates. Time to flower is presented in Figures 1 and 2. Plugs were grown at 68°F and under a 16-hour long day. Transplant dates assume a 16-hour long day and an average daily light integral of 10 $mol \cdot m^{-2} \cdot d^{-1}$ during the finish stage.

Materials and Methods

Seeds of each petunia variety were sown in 288-cell plug trays by C. Raker & Sons, then grown in controlled environmental growth chambers at MSU at 68°F (20°C). Inside the chambers, the photoperiod was 16 hours (an inductive long day) and the DLI was 9 to 11 $mol \cdot m^{-2} \cdot d^{-1}$.

When plugs were ready for transplant (27 to 35 days after seed sow), they were thinned to one seedling per plug and transplanted into 4-inch pots and grown in greenhouses with constant temperature set points of 57, 63, 68, 73 and 79°F (14, 17, 20, 23 and 26°C). At each temperature, plants were grown under a 16-hour photoperiod with two different DLIs provided by a combination of shade curtains and different supplemental lighting intensities from high-pressure sodium lamps.

Some petunia varieties such as 'Dreams Neon Rose' do not require long days for flowering, but flower faster if grown under long days. Other petunia varieties such as 'Wave Purple' are obligate long-day plants and must be grown under long days for flowering. Therefore, when producing petunias under naturally short day lengths (less than 13 to 14 hours), photoperiodic lighting will accelerate flowering and shorten cropping time.

Our experiments were performed twice to obtain average DLIs that ranged from 4 to 20 $mol{\cdot}m^{-2}{\cdot}d^{-1}$. To give perspective, a DLI of 4 $mol{\cdot}m^{-2}{\cdot}d^{-1}$ is representative of light conditions received by a northern greenhouse on a cloudy day in the winter; a DLI of 20 $mol{\cdot}m^{-2}{\cdot}d^{-1}$ is typical for a mid- to late spring day. The flowering date was recorded for each plant when the first flower opened, and at that time, plant height, number of leaves and number of flowers and flower buds were recorded.

Crop timing data were used to develop mathematical models to predict flowering time and plant quality under different temperature and DLI conditions. The scheduling models were validated by growing petunias at three different constant temperatures to compare predicted flowering times with actual times. The Virtual Grower software (available free at **VirtualGrower.net**) was used to estimate the cost to heat a 21,504-square-foot greenhouse (about half an acre) to produce each crop for different finish dates and at different locations in the United States.

Results

In all petunia varieties, time to flower decreased as average daily temperature increased. For example, in 'Dreams Neon Rose' grown under a DLI of 10 $mol{\cdot}m^{-2}{\cdot}d^{-1}$, time to flower from a 288-cell plug decreased from 40 days at 58°F to 20 days at 73°F (Figure 1). At the same DLI, 'Wave Purple' flowered almost five weeks later at 58°F versus 73°F (Figure 2). Petunia 'Fantasy Blue' grown under 10 $mol{\cdot}m^{-2}{\cdot}d^{-1}$ and at 58, 63, 68, 73 or 79°F flowered in 27, 22, 19, 17 and

15 days, respectively. Petunia 'Easy Wave Coral Reef' grown under 10 mol·m^{-2}·d^{-1} and at 58, 63, 68 or 73°F flowered in 46, 35, 28, 23 and 19 days, respectively.

An increase in DLI also accelerated flowering of petunia. For example, for plants grown at 63°F, time to flower decreased by four days in 'Dreams Neon Rose,' 13 days in 'Fantasy Blue,' and 11 days in 'Easy Wave Coral Reef' and 'Wave Purple' when DLI increased from 4 to 10 mol·m^{-2}·d^{-1}. The estimated saturation DLI for the shortest time to flower was 10.5 mol·m^{-2}·d^{-1} for 'Dreams Neon Rose,' 16 mol·m^{-2}·d^{-1} for 'Easy Wave Coral Reef,' and 14 mol·m^{-2}·d^{-1} for 'Wave Purple.' In other words, increasing the DLI above these values did not shorten crop time. Flowering time continued to decrease as DLI increased for 'Fantasy Blue' and thus, the saturation DLI is greater than 20 mol·m^{-2}·d^{-1}. Using this research data, we identified dates that 288-cell plugs grown under long days need to be transplanted for two market dates when grown at different temperatures under long days (Table 1).

The number of flower buds at first flowering increased as average daily temperature decreased and as DLI increased. For example, in petunia 'Wave Purple', the number of flower buds increased by 75 percent as DLI increased from 5 to 15 mol·m^{-2}·d^{-1}. In all petunias, plants had the fewest flowers when grown at the warmest temperature (79°F) and under the lowest DLI (4 mol·m^{-2}·d^{-1}). Plant height at flower increased as DLI decreased.

As most growers already know, crop timing varies significantly among petunia varieties. In the four petunias we studied, crop timing at 68°F varied from 19 to 37 days even when light conditions were nearly identical during the plug and finish stages. Similarly, increasing the DLI had different promotive effects on the varieties studied. However, all crops flowered faster, and plants were of higher quality, when the DLI was increased to at least 10 mol·m^{-2}·d^{-1}.

Heating Costs

This crop timing information can be used with Virtual Grower to identify the most energy-efficient production temperature for different dates and locations. According to our predictions, heating costs for a crop

Location	Estimated Heating Cost (U.S. Dollars Per Square Foot Per Crop)							
	April 1				May 15			
	58°F	63°F	68°F	73°F	58°F	63°F	68°F	73°F
	Petunia 'Dreams Neon Rose'							
San Francisco, Calif.	0.08	0.10	0.12	0.13	0.06	0.08	0.09	0.10
Tallahassee, Fla.	0.07	0.07	0.07	0.09	0.01	0.01	0.02	0.03
Grand Rapids, Mich.	0.31	0.26	0.24	0.24	0.12	0.11	0.11	0.11
New York, N.Y.	0.22	0.19	0.18	0.18	0.06	0.06	0.07	0.07
Charlotte, N.C.	0.10	0.11	0.12	0.12	0.03	0.04	0.04	0.05
Cleveland, Ohio	0.27	0.23	0.22	0.22	0.11	0.10	0.11	0.11
Fort Worth, Texas	0.07	0.07	0.07	0.08	0.01	0.01	0.02	0.04
	Petunia 'Wave Purple'							
San Francisco, Calif.	0.14	0.16	0.18	0.20	0.11	0.12	0.14	0.16
Tallahassee, Fla.	0.15	0.13	0.13	0.14	0.05	0.04	0.04	0.05
Grand Rapids, Mich.	0.58	0.45	0.40	0.37	0.28	0.21	0.20	0.19
New York, N.Y.	0.40	0.35	0.31	0.30	0.17	0.13	0.13	0.14
Charlotte, N.C.	0.26	0.19	0.19	0.20	0.09	0.08	0.09	0.10
Cleveland, Ohio	0.54	0.43	0.37	0.34	0.23	0.19	0.18	0.18
Fort Worth, Texas	0.17	0.14	0.14	0.15	0.03	0.03	0.04	0.05

Table 2. Estimated heating costs to produce flowering petunia 'Dreams Neon Rose' and 'Wave Purple' (from a 288-cell plug; see Table 1) at different temperatures and locations for first flowering on April 1 or May 15. Cities were chosen from each of the seven leading garden plant-producing states. Calculations performed with Virtual Grower 2.01 software with constant temperatures. Greenhouse characteristics include: eight spans each 112 × 24 feet, arched 12-foot roof, 9-foot gutter, polyethylene double layer roof, polycarbonate bi-wall ends and sides, forced air unit heaters burning natural gas at $1 per therm ($10.24 MCF), 50 percent heater efficiency, no energy curtain and an hourly air infiltration rate of 1.0.

of petunia 'Dreams Neon Rose' grown for April 1 in San Francisco, Calif., Tallahasee, Fla., Charlotte, N.C., or Fort Worth, Texas, would be 13 to 38 percent lower at a constant 58°F versus 73°F (Table 2). To produce the same crop in northern locations such as Grand Rapids, Mich., New York, N.Y., or Cleveland, Ohio, heating costs per square foot would be 22 to 29 percent higher at 58°F versus 73°F. In other words, it is more energy-efficient for growers in the north to start spring production later and grow at a warmer temperature.

Petunia 'Wave Purple' grown under 10 $mol \cdot m^{-2} \cdot d^{-1}$ for April 1 in Grand Rapids, Mich., New York, N.Y., or Cleveland, Ohio would cost 9 to 21 cents less per square foot if grown at 68 or 73°F versus 58°F. Therefore, a grower with a half-acre greenhouse would save $1,960 to $4,574 on heating costs per crop by transplanting later and growing warm. In addition, 'Wave Purple' grown at 68 or 73°F would flower four to five weeks earlier than at 58°F, which would make production space available for additional crops.

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 turns and overhead costs, should also be considered when choosing the most economical growing temperature for each floriculture crop producer. **GG**

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Part 7 of 12
To see the first six articles in this series go to GreenhouseGrower.com.

Energy-Efficient Annuals:
Geraniums & Zinnias

Researchers from Michigan State University present research-based information for scheduling annuals in a more energy-efficient and predictive manner.

by **MATTHEW BLANCHARD** and **ERIK RUNKLE**

MOST bedding plants are produced in heated greenhouses from January through May, when high energy inputs can be required to maintain a desirable temperature. With shrinking profit margins and volatile energy prices, scheduling crops in an energy-efficient manner is increasingly desirable. At Michigan State University (MSU), we have performed experiments with many seed-propagated annuals to quantify how temperature and daily light integral (DLI) influence flowering time and plant quality.

In the seventh article of this series, we present crop timing data on seed geranium and zinnia and then use the information to estimate greenhouse heating costs at different locations, growing temperatures and finish dates. We also highlight the effect of DLI on flowering of these two crops.

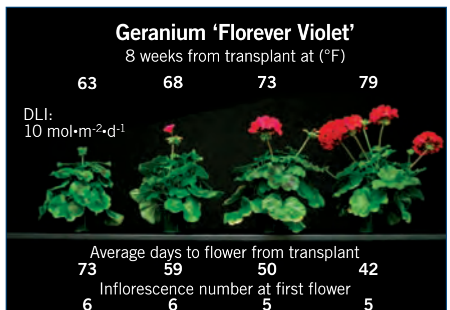

Figure 1. **The effects of average daily temperature on time to flower and number of inflorescences (at first flowering) in seed geranium 'Florever Violet.' Plants were grown under a 16-hour photoperiod and an average daily light integral of 10 mol·m^{-2}·d^{-1}. Photograph was taken eight weeks after transplant from a 288-cell plug tray that was grown under long days.**

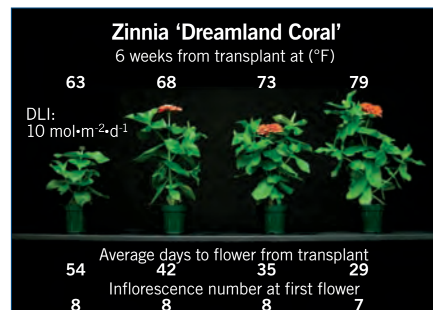

Figure 2. **The effects of average daily temperature on time to flower and number of inflorescences (at first flowering) in zinnia 'Dreamland Coral.' Plants were grown under a 16-hour photoperiod and an average daily light integral of 10 mol·m^{-2}·d^{-1}. Photograph was taken six weeks after transplant from a 288-cell plug tray that was grown under long days.**

Market Date	Average Temp.	Date Of Transplant Of 288-Cell Plugs For Desired Market Dates	
		Seed Geranium	Zinnia
April 1	63°F	January 18	February 6
	68°F	February 1	February 18
	73°F	February 10	February 25
	79°F	February 18	March 3
May 15	63°F	March 3	March 22
	68°F	March 17	April 3
	73°F	March 26	April 10
	79°F	April 3	April 16

Table 1. **Date of transplant of 288-cell plug trays of seed geranium 'Florever Violet' and zinnia 'Dreamland Coral' to achieve first flowering when grown at different temperatures for two market dates. Time to flower is presented in Figures 1 and 2. Plugs were grown at 68°F and under a 16-hour long day. Transplant dates assume a 16-hour long day and an average daily light integral of 10 mol·m^{-2}·d^{-1} during the finish stage.**

Materials & Methods

Geranium and zinnia seeds were sown in 288-cell plug trays by C. Raker & Sons, then grown in controlled environmental growth chambers at MSU at 68°F (20°C). Inside the chambers, the photoperiod was 16 hours and the DLI was 9 to 11 mol·m^{-2}·d^{-1}.

When plugs were ready for transplant (29 days after seed sow for geraniums and 16 days after seed sow for zinnias), they were thinned to one seedling per plug and transplanted into 4-inch (10-centimeter) pots and grown in greenhouses with constant temperature set points of 63, 68, 73 and 79°F (17, 20, 23 and 26°C).

At each temperature, plants were grown under a 16-hour photoperiod with two different DLIs provided by sunlight, a combination of shade curtains and different supplemental lighting intensities from high-pressure sodium lamps.

Seed geranium is a day-neutral crop and

thus, day length has no effect on flowering time. Many zinnias are facultative short-day plants. Although they flower under long days, flowering can be accelerated under short days.

Our experiments were performed twice to obtain average DLIs that ranged from 3 to 19.5 $mol \cdot m^{-2} \cdot d^{-1}$. To give perspective, a DLI of 3 $mol \cdot m^{-2} \cdot d^{-1}$ is representative of light conditions received by a Northern greenhouse on a cloudy day in the winter. A DLI of 19.5 $mol \cdot m^{-2} \cdot d^{-1}$ is typical for inside a greenhouse on a mid- to late spring day. The flowering date was recorded for each plant when geraniums had an inflorescence with five open flowers and zinnias had one whorl of petals fully reflexed. When each plant flowered, plant height, number of leaves and number of flowers and flower buds were recorded.

Crop timing data were used to develop mathematical models to predict flowering time and plant quality under different temperature and DLI conditions. The scheduling models were validated by growing a crop of geranium 'Pinto Red' at 71°F to compare predicted flowering times with actual times. Crop models for zinnias were validated by growing plants at three different constant temperatures. The Virtual Grower software (available free at **VirtualGrower.net**) was used to estimate the cost to heat a 21,504-square-foot greenhouse (about half an acre) to produce each crop for different finish dates and at different locations in the United States.

Results

Time to flower for seed geraniums and zinnias decreased as average daily temperature increased. For example, in geraniums grown under a DLI of 10 $mol \cdot m^{-2} \cdot d^{-1}$, time to flower from a 288-cell plug decreased from 73 days at 63°F to 42 days at 79°F (Figure 1). Zinnias grown under the same DLI flowered 3.5 weeks earlier at 79°F versus 63°F (Figure 2). Our crop timing data for zinnias is for plants grown under long days, and flowering could have been accelerated if short days had been provided. Regardless of daylength, we anticipate similar temperature trends on crop development rates.

Time to flower also decreased as the DLI increased until some saturating value. For example, as the DLI increased from 4 to 12 $mol \cdot m^{-2} \cdot d^{-1}$, time to flower for geraniums grown at 68°F decreased by four weeks and zinnias decreased by 12 days. The estimated saturation DLI for the shortest time to flower was 18 $mol \cdot m^{-2} \cdot d^{-1}$ for geraniums and 12.5 $mol \cdot m^{-2} \cdot d^{-1}$ for zinnias (Figure 3).

In other words, increasing the DLI above these values did not shorten crop time. Figure 3 also illustrates that the value of supplemental lighting is greatest when the natural DLI is lowest. Plants grown under a high DLI developed fewer leaves on the primary stem before flowering and thus flowered earlier compared to a lower DLI.

The geranium and zinnia crop models predicted time to flower within five days for at least 94 percent of the validation data. To illustrate the effect of temperature on crop times, we identified dates that 288-cell plugs grown under long days would need to be transplanted for two market dates when grown long days and 10 mol·m^{-2}·d^{-1} of light (Table 1).

In geranium, inflorescence number increased slightly as temperature decreased and as DLI increased. Geraniums grown at 63°F and under 16 mol·m^{-2}·d^{-1} had two more inflorescences than plants grown at 79°F and under 4 mol·m^{-2}·d^{-1}.

In zinnias, the number of flower buds at first flowering was primarily influenced by DLI. For example, plants grown at 73°F and under a DLI of 15 mol·m^{-2}·d^{-1} had almost twice as many inflorescences than plants grown at the same temperature, but under 4 mol·m^{-2}·d^{-1}.

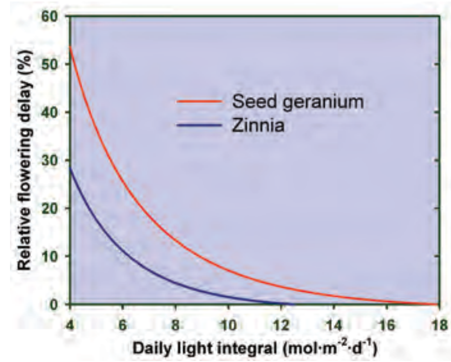

Figure 3. The relative delay in flowering as the daily light integral (DLI) decreases in seed geranium and zinnia grown under a 16-hour photoperiod. The estimated saturation DLI for the shortest time to flower was 18 mol·m^{-2}·d^{-1} for geranium and 12.5 mol·m^{-2}·d^{-1} for zinnia. For example, compared to flowering time under a DLI of 18 mol·m^{-2}·d^{-1}, flowering of geranium would be delayed by 4 percent if grown under a DLI of 12 mol·m^{-2}·d^{-1} and by 26 percent if grown under 6 mol·m^{-2}·d^{-1} of light.

Plant height at flower increased as DLI decreased. For example, geranium and zinnias grown at 73°F and under 4 mol·m^{-2}·d^{-1} were 4 to 7 inches (10 to 18 centimeters) taller than plants grown at the same temperature, but under 18 mol·m^{-2}·d^{-1}. The number of branches in zinnias increased as temperature decreased and as DLI increased.

More Online
For estimated heating costs for 'Florever Violet' and 'Dreamland Coral,' go to **www.GreenhouseGrower.com.**

Heating Costs

We used our crop timing data to determine if it is more energy-efficient to transplant a spring crop earlier and grow cool versus transplanting later and growing warm. We estimated that to produce a geranium crop for April 1 in Grand Rapids, Mich., New York, N.Y., Charlotte, N.C. or Cleveland, Ohio, heating costs per square foot would be 16 to 20 percent lower at 79°F versus 63°F.

In contrast, to produce the same crop in San Francisco, Calif., Tallahasee, Fla. or Fort Worth, Texas, heating costs would be 7 to 26 percent higher at 79°F versus 63°F. To produce zinnia for April 1, transplanting the crop early and growing at 63°F was the most energy-efficient scheduling strategy for only San Francisco, Calif. and Fort Worth, Texas.

At some locations, the most energy-efficient production temperature was different between market dates. For example, zinnia grown for April 1 in Charlotte, N.C. would consume the least heat at 68°F, while the same crop grown for May 15 would save the most heat if grown at 63°F. Heating costs are lower to produce a crop for later spring market dates because outside temperatures are warmer and energy inputs for heating are less. Among these seven cities, we predicted geraniums or zinnias grown at 63 to 79°F would require 18 to 67 percent less energy to produce a crop for May 15 versus April 1. **GG**

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Correction

In last month's article on petunias, the average days to flower from transplant and flower number at first flower for petunia 'Wave Purple' were listed incorrectly in a graphic. To view the correct graphic, visit **GreenhouseGrower.com**.

A Special Thank You

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Energy-Efficient Annuals: Rudbeckia & Viola

Researchers from Michigan State University present research-based information for scheduling annuals in a more energy-efficient and predictive manner.

by **MATTHEW BLANCHARD** and **ERIK RUNKLE**

SCHEDULING bedding plants in flower for exact market dates is challenging considering the diversity of crops produced. Rising energy costs and shrinking profit margins have made it important to improve scheduling and efficiency of crop production. At Michigan State University (MSU), we have performed experiments with many seed propagated annuals to quantify how temperature and daily light integral (DLI) influence flowering time and plant quality.

In the eighth article of this series, we present crop timing data on annuals rudbeckia (*Rudbeckia hirta*) and viola (*Viola cornuta*) and then use that information to estimate greenhouse heating costs at different locations, growing temperatures and finish dates.

Materials & Methods

Seeds of rudbeckia 'Becky Cinnamon Bicolor' and viola 'Sorbet Plum Velvet' were sown in 288-cell plug trays by C. Raker & Sons, then grown in controlled environmental growth chambers at MSU at 68°F (20°C). Inside the chambers, the photoperiod was 16 hours and the DLI was 9 to 11 mol·m^{-2}·d^{-1}.

When plugs were ready for transplant (31 to 38 days after seed sow), they were thinned to one seedling per plug and transplanted into 4-inch (10-centimeter) pots and grown in greenhouses with constant temperature set points of 58, 63, 68 and 73°F (14, 17, 20 and 23°C).

At each temperature, plants were grown under a 16-hour photoperiod with two different DLIs provided by sunlight, a combination of shade curtains and different supplemental lighting intensities from high-pressure sodium lamps. Rudbeckia is an obligate long-day crop and must be grown under long days for flowering. Violas do not require long days for flowering, but flower faster if grown under long days.

Our experiments were performed once with viola and twice with rudbeckia to obtain average DLIs that ranged from 3.5 to 20 mol·m^{-2}·d^{-1}. To give perspective, a DLI of 3.5 mol·m^{-2}·d^{-1} is representative of light conditions received by a northern greenhouse on a cloudy day in the winter. A

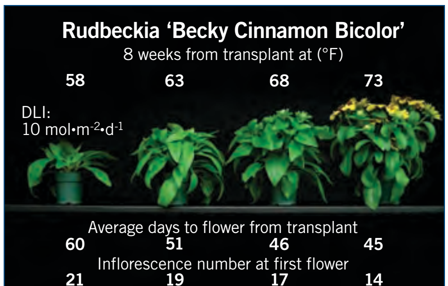

Figure 1. The effects of average daily temperature on time to flower and number of inflorescences (at first flowering) in rudbeckia 'Becky Cinnamon Bicolor.' Plants were grown under a 16-hour photoperiod and an average daily light integral (DLI) of 10 mol·m^{-2}·d^{-1}. Photograph was taken eight weeks after transplant from a 288-cell plug tray that was grown under long days.

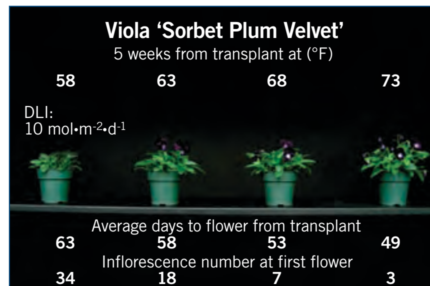

Figure 2. The effects of average daily temperature on time to flower and number of flower buds (at first flowering) in viola 'Sorbet Plum Velvet.' Plants were grown under a 16-hour photoperiod and an average daily light integral (DLI) of 10 mol·m^{-2}·d^{-1}. Photograph was taken five weeks after transplant from a 288-cell plug tray that was grown under long days.

Market Date	Average Temp.	Date Of Transplant Of 288-Cell Plugs For Desired Market Dates	
		Rudbeckia	Viola
April 1	58°F	January 9	February 26
	63°F	January 27	March 5
	68°F	February 7	March 10
	73°F	February 15	March 13
May 15	58°F	February 22	April 11
	68°F	March 12	April 18
	73°F	March 23	April 23
	79°F	March 31	April 26

Table 1. Date of transplant of 288-cell plug trays of rudbeckia 'Becky Cinnamon Bicolor' and viola 'Sorbet Plum Velvet' to achieve first flowering when grown at different temperatures for two market dates. Time to flower is presented in Figures 1 and 2. Plugs were grown at 68°F and under a 16-hour long day. Transplant dates assume a 16-hour long day and an average daily light integral of 10 mol·m^{-2}·d^{-1} during the finish stage.

DLI of 20 $mol \cdot m^{-2} \cdot d^{-1}$ is typical for inside a greenhouse on a mid- to late spring day.

The flowering date was recorded for each plant when rudbeckia had one whorl of petals fully reflexed and when viola had one open flower. When each plant flowered, plant height, number of leaves and number of flowers and flower buds were recorded.

Crop timing data were used to develop mathematical models to predict flowering time and plant quality under different temperature and DLI conditions. The Virtual Grower software (available free at **VirtualGrower.net**) was used to estimate the cost to heat a 21,504 square foot greenhouse (about half an acre) to produce each crop for different finish dates and at different locations in the United States.

Results

Time to flower of rudbeckia and viola decreased as average daily temperature increased. In rudbeckia grown under a DLI of 10 $mol \cdot m^{-2} \cdot d^{-1}$, time to flower from a 288-cell plug decreased from 82 days at 58°F to 45 days at 73°F (Figure 1). This data illustrates

Location	Estimated Heating Cost (U.S. Dollars Per Square Foot Per Crop)							
	April 1				May 15			
	58°F	63°F	68°F	73°F	58°F	63°F	68°F	73°F
Rudbeckia								
San Francisco, Calif.	0.20	0.22	0.25	0.28	0.15	0.18	0.20	0.23
Tallahassee, Fla.	0.20	0.21	0.23	0.24	0.08	0.08	0.07	0.11
Grand Rapids, Mich.	0.78	0.69	0.64	0.59	0.42	0.36	0.31	0.32
New York, N.Y.	0.58	0.50	0.48	0.47	0.27	0.23	0.21	0.23
Charlotte, N.C.	0.35	0.34	0.31	0.30	0.14	0.14	0.14	0.17
Cleveland, Ohio	0.69	0.63	0.60	0.56	0.37	0.31	0.31	0.28
Fort Worth, Texas	0.23	0.24	0.23	0.25	0.07	0.06	0.08	0.10
Viola								
San Francisco, Calif.	0.07	0.09	0.11	0.12	0.05	0.07	0.08	0.09
Tallahassee, Fla.	0.05	0.06	0.07	0.08	0.01	0.01	0.01	0.02
Grand Rapids, Mich.	0.24	0.22	0.23	0.23	0.10	0.09	0.09	0.10
New York, N.Y.	0.18	0.17	0.17	0.17	0.04	0.06	0.06	0.06
Charlotte, N.C.	0.09	0.10	0.11	0.11	0.03	0.03	0.03	0.03
Cleveland, Ohio	0.22	0.22	0.20	0.21	0.08	0.09	0.10	0.10
Fort Worth, Texas	0.05	0.06	0.06	0.08	0.01	0.01	0.02	0.03

Table 2. Estimated heating costs to produce flowering rudbeckia 'Becky Cinnamon Bicolor' and viola 'Sorbet Plum Velvet' (from a 288-cell plug; see Table 1) at different temperatures and locations for first flowering on April 1 or May 15. Cities were chosen from each of the seven leading garden plant-producing states. Calculations performed with Virtual Grower 2.5 software with constant temperatures. Greenhouse characteristics include: eight spans each 112 × 24 feet, arched 12-foot roof, 9-foot gutter, polyethylene double-layer roof, polycarbonate bi-wall ends and sides, forced air-unit heaters burning natural gas at $1 per therm ($10.24 MCF), 50 percent heater efficiency, no energy curtain and an hourly air infiltration rate of 1.0.

that flowering of rudbeckia is considerably delayed when grown at cool temperatures.

For example, rudbeckia grown at 58°F would flower almost three weeks later than if the crop was grown at 63°F under the same light conditions. Viola had a comparatively faster crop time: Time to flower from a 288-cell plug decreased from 34 days at 58°F to 19 days at 73°F when the DLI was 10 $mol \cdot m^{-2} \cdot d^{-1}$ (Figure 2).

An increase in DLI also accelerated flowering of rudbeckia and viola. For example, when DLI increased from 4 to 10 $mol \cdot m^{-2} \cdot d^{-1}$, time to flower decreased by 12 days in rudbeckia and 17 days in viola when grown at 63°F. The estimated saturation DLI for the shortest time to flower was 10.5 $mol \cdot m^{-2} \cdot d^{-1}$ for rudbeckia. In other words, increasing the DLI above this value did not shorten crop time. Viola was only grown under a DLI of 3.5 to 12 $mol \cdot m^{-2} \cdot d^{-1}$ and the saturation DLI is greater than 12 $mol \cdot m^{-2} \cdot d^{-1}$.

To illustrate the effect of temperature on crop times, we identified dates that 288-cell plugs grown under long days would need to be transplanted for two market dates when grown long days and 10 $mol \cdot m^{-2} \cdot d^{-1}$ of light (Table 1). The crops grown at the same temperatures but under lower light levels or under a short photoperiod (less than 14 hours) would take longer to flower.

The number of inflorescences or flower buds at first flowering increased as average daily temperature decreased and as DLI increased. For example, at 63°F, as DLI increased from 4 to 12 $mol \cdot m^{-2} \cdot d^{-1}$, the number of flower buds increased by 66 percent in rudbeckia and by 38 percent in viola. Plants grown at 73°F and under 4 $mol \cdot m^{-2} \cdot d^{-1}$ had the fewest flowers and were the poorest quality. Therefore, there is a tradeoff with quick crop timing and high plant quality, especially when the DLI is low.

Rudbeckia were shortest at flower when grown cool and under high light. In viola, temperature and DLI did not influence plant height.

Heating Costs

The production temperature that had the lowest estimated heating costs to produce a flowering crop of rudbeckia and viola varied among locations and market dates. We estimated that to produce a flowering crop of rudbeckia for April 1, a greenhouse located in Grand Rapids, Mich., New York, N.Y., Charlotte, N.C., or Cleveland, Ohio, would consume 14 to 24 percent less heating per square foot if the crop was transplanted on February 15 and grown at 73°F compared to the same crop transplanted earlier and grown at 58°F (Table 2).

In other words, a shorter crop time at a warm temperature required less energy for heating on a per-crop basis than a longer crop time at a cool temperature. However, for a greenhouse located in San Francisco, Calif., Tallahassee, Fla., or Fort Worth, Texas, heating costs would increase 9 to 40 percent if rudbeckia were grown for April 1 at 73°F, instead of 58°F.

At a temperature of 58 to 73°F and under a DLI of 10 $mol \cdot m^{-2} \cdot d^{-1}$, viola had a four- to seven-week shorter crop time than rudbeckia. Thus, for all locations and finish dates, a finish crop of viola was predicted to consume 56 to 88 percent less energy for heating than to produce rudbeckia. At some locations, the most energy-efficient production temperature varied between market dates.

For example, rudbeckia grown for April 1 in Grand Rapids, Mich., New York, N.Y., or Charlotte, N.C. is projected to require less heating when grown at 73°F, while a crop grown for May 15 would consume the least amount of energy for heating if grown at 68°F.

We encourage growers to use this crop scheduling information with Virtual Grower to determine the most energy-efficient production temperature for your location and market date. 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 turns and overhead costs, should also be considered when choosing the most economical growing temperature for each floriculture crop producer. The impact of temperature and DLI on plant quality, and response variability among cultivars, should also be considered. **GG**

About the authors: Matthew Blanchard (**mgblanch@msu.edu**) is a Ph.D. candidate and Erik Runkle (**runkleer@msu.edu**) is associate professor and floriculture extension specialist in the Department of Horticulture at Michigan State University.

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To see the first eight articles in this series go to GreenhouseGrower.com.

Energy-Efficient Annuals: Dahlia & Osteospermum

Researchers from Michigan State University present research-based information for scheduling annuals in a more energy-efficient and predictive manner.

by **MATTHEW BLANCHARD** and **ERIK RUNKLE**

PRODUCING spring bedding plants in an energy-efficient manner requires information on how crops respond to average daily temperature and daily light integral (DLI) so bedding plants can be more precisely scheduled. At Michigan State University (MSU), we have performed experiments with numerous seed-propagated annuals to quantify how these environmental factors influence flowering time and plant quality.

In the ninth article of this series, we present crop timing data on dahlia (*Dahlia × hybrida*) and osteospermum (*Osteospermum ecklonis*) and then use that information to estimate greenhouse heating costs at different locations, growing temperatures and finish dates.

Materials & Methods

Seeds of dahlia 'Figaro Mix' and osteospermum 'Passion Mix' were sown in 288-cell plug trays by C. Raker & Sons and grown in controlled environmental growth chambers at MSU at a constant 68°F (20 °C). Inside the chambers, the photoperiod was 16 hours and the DLI was 9 to 11 mol·m^{-2}·d^{-1}. This DLI is typical of that received in greenhouses in early spring in the Northern United States.

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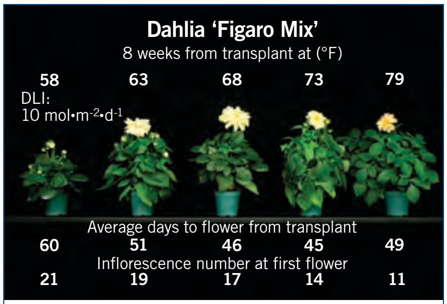

Figure 1. The effects of average daily temperature on time to flower and number of inflorescences (at first flowering) in dahlia 'Figaro Mix.' Plants were grown under a 16-hour photoperiod and an average daily light integral (DLI) of 10 mol·m^{-2}·d^{-1}. Photograph was taken eight weeks after transplant from a 288-cell plug tray that was grown under long days.

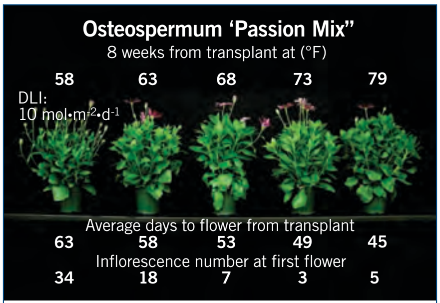

Figure 2. The effects of average daily temperature on time to flower and number of flower buds (at first flowering) in osteospermum 'Passion Mix.' Plants were grown under a 16-hour photoperiod and an average daily light integral (DLI) of 10 mol·m^{-2}·d^{-1}. Photograph was taken eight weeks after transplant from a 288-cell plug tray that was grown under long days.

Market Date	Average Temp	Date Of Transplant Of 288-Cell Plugs For Desired Market Dates	
		Dahlia	Osteospermum
April 1	58°F	January 31	January 28
	63°F	February 9	February 2
	68°F	February 14	February 7
	73°F	February 15	February 11
May 15	58°F	March 16	March 13
	63°F	March 25	March 18
	68°F	March 30	March 23
	73°F	March 31	March 27

Table 1. Date of transplant of 288-cell plug trays of dahlia 'Figaro Mix' and osteospermum 'Passion Mix' to achieve first flowering when grown at different temperatures for two market dates. Time to flower is presented in Figures 1 and 2. Plugs were grown at 68°F and under a 16-hour day. Transplant dates assume a 16-hour day (long days) and an average daily light integral of 10 mol·m^{-2}·d^{-1} during the finish stage.

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When plugs were ready for transplant (26 to 30 days after seed sow), they were thinned to one seedling per plug and transplanted into 4-inch (10-cm) pots and grown in greenhouses with constant temperature set points of 58, 63, 68, 73 and 79°F (14, 17, 20, 23 and 26°C). At each temperature, plants were grown under a 16-hour photoperiod with two different DLIs provided by sunlight, a combination of shade curtains and different supplemental lighting intensities from high-pressure sodium lamps.

Dahlia is typically a facultative short-day plant. Although plants flower under long days, flowering is accelerated under short days. In contrast, osteospermum is typically a facultative long-day plant, meaning plants flower faster under long days.

Our experiments were performed twice to obtain average DLIs that ranged from 4 to 19 $mol{\cdot}m^{-2}{\cdot}d^{-1}$. To give perspective, a DLI of 4 $mol{\cdot}m^{-2}{\cdot}d^{-1}$ is representative of light conditions received by a northern greenhouse on a cloudy day in the winter; a DLI of 19 $mol{\cdot}m^{-2}{\cdot}d^{-1}$ is typical for inside a greenhouse on a mid- to late spring day. We recorded the flowering date when each plant had an inflorescence with one whorl of petals fully reflexed. On that date, plant height and number of inflorescences (flower number) were recorded.

Crop timing data were used to develop mathematical models to predict flowering time and plant quality under different temperature and DLI conditions. The Virtual Grower 2.5 software (available free at **VirtualGrower.net**) was used to estimate the cost to heat a 21,504-square-foot greenhouse (about half an acre) to produce each crop for different finish dates and at different locations in the U.S.

Results

In both dahlia and osteospermum, time to flower decreased as average daily temperature increased from 58 to 73°F. For example, in dahlia grown under a DLI of 10 $mol{\cdot}m^{-2}{\cdot}d^{-1}$, time to flower from a 288-cell plug decreased from 60 days at 58°F to 45 days at 73°F (Figure 1). Our crop model predicted the shortest flowering time in this dahlia variety occurs at an average daily temperature of 72°F, and flowering is delayed at warmer temperatures. The crop timing data for dahlia is for plants grown under long days, and flowering may have been accelerated if short days had been provided. Regardless of day length, we anticipate similar temperature trends on crop development rates.

In osteospermum, plants grown under a DLI of 10 $mol{\cdot}m^{-2}{\cdot}d^{-1}$ and at 73°F flowered two weeks earlier than plants grown under the same DLI, but at 58°F (Figure 2). To illustrate the effect of temperature on dahlia and osteospermum crop times, we identified dates 288-cell plugs grown under long days would need to be transplanted for two market dates when finished under long days and a DLI of 10

$mol{\cdot}m^{-2}{\cdot}d^{-1}$ (Table 1).

As the DLI increased, time to flower in both crops decreased. For example, in plants grown at 63°F, increasing the DLI from 5 to 15 $mol{\cdot}m^{-2}{\cdot}d^{-1}$ accelerated flowering of dahlia by 15 days and of osteospermum by three weeks. The estimated saturation DLI for the shortest time to flower was 16.4 $mol{\cdot}m^{-2}{\cdot}d^{-1}$ for dahlia and 18.8 $mol{\cdot}m^{-2}{\cdot}d^{-1}$ for osteospermum. In other words, increasing the DLI above these values did not shorten crop times.

The influence of DLI on flowering time also illustrates the benefit of using supplemental lighting is greatest when the natural DLI is lowest (during the winter and early spring). For example, our models predict osteospermum grown at 68°F would flower 16 days earlier if the DLI was increased from 5 to 10 $mol{\cdot}m^{-2}{\cdot}d^{-1}$, and only three days earlier if the DLI was increased from 10 to 15 $mol{\cdot}m^{-2}{\cdot}d^{-1}$.

In both crops, flower number increased as average daily temperature decreased and as DLI increased. For example, under a DLI of 10 $mol{\cdot}m^{-2}{\cdot}d^{-1}$, as average daily temperature decreased from 79 to 58°F, flower number increased twofold in dahlia and sevenfold in osteospermum (Figure 1 and 2). In both crops, plants grown at 79°F and under 4 $mol{\cdot}m^{-2}{\cdot}d^{-1}$ developed only four to six inflorescences before flowering, and plant quality was low.

Plant height at flower decreased as DLI increased and as average daily temperature decreased. Dahlia and osteospermum grown cool and under high light (58°F and DLI of 18 $mol{\cdot}m^{-2}{\cdot}d^{-1}$) were 9 inches (23 centimeters) shorter than plants grown warm and under low light (73°F and DLI of 4 $mol{\cdot}m^{-2}{\cdot}d^{-1}$).

Heating Costs

We used this crop timing information and Virtual Grower to predict the amount of energy consumed to produce a flowering crop of dahlia and osteospermum for April 1 or May 15. Our models project the least amount of heating is required on a per-crop basis when grown at 58 or 63°F in all seven locations tested (see Table 2).

For example, osteospermum grown in Charlotte, N.C., at 58°F instead of 73°F would save growers 26 percent on heat if grown for a finish date of April 1. Growers would save 56 percent on heat if grown for a finish date of May 15. Similarly, a greenhouse located in Grand Rapids, Mich., would consume 14 to 28 percent less heat per square foot per crop if grown at 63°F compared with 73°F.

For dahlia and osteospermum, it was more energy efficient to transplant earlier in the spring and grow crops at a cool temperature than to transplant later and finish warm. Furthermore, plant quality was considerably higher when crops were grown at these lower temperatures, especially in osteospermum. For many of the other crops we have discussed in this article series, such as seed geranium (see

Greenhouse Grower, September 2009), energy consumption was lowest when crops were grown more quickly by using a warmer temperature (at least 68°F). Therefore, energy-efficient production of a variety of bedding plants requires some crops to be grown cool and others to be grown in separate greenhouse sections at warmer temperatures.

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 turns and labor availability, should also be considered when choosing the most economical growing temperature for each floriculture crop producer. The impact of temperature and DLI on plant quality, and response variability among cultivars, should also be considered. **GG**

About the authors: Matthew Blanchard (**mgblanch@msu.edu**) is a Ph.D. candidate and Erik Runkle (**runkleer@msu.edu**) is associate professor and floriculture extension specialist in the Department of Horticulture at Michigan State University.

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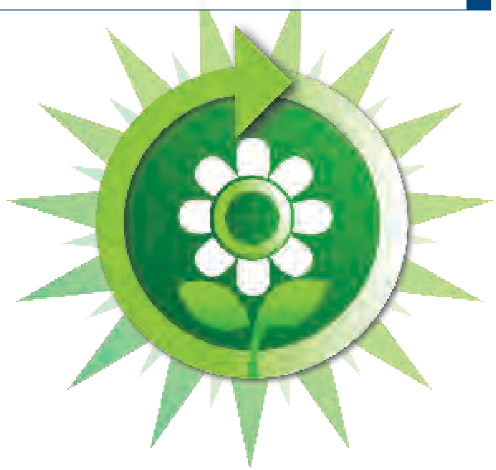
The authors thank research technician Mike Olrich for his greenhouse assistance; Project GREEEN, the American Floral Endowment, the Fred C. Gloeckner Foundation, the USDA-ARS Floriculture and Nursery Research Initiative and private floriculture companies for their financial support. They also thank Jonathan Frantz of USDA and Paul Fisher of the University of Florida for their assistance.

Part 10 of 12

To see the first nine articles in this series go to GreenhouseGrower.com.



Energy-Efficient Annuals: Vinca & Wax Begonia

Researchers from Michigan State University present research-based information for scheduling annuals in a more energy-efficient and predictive manner.

by **MATTHEW BLANCHARD** and **ERIK RUNKLE**

EFFICIENT production of bedding plants requires information on how temperature, photoperiod and daily light integral (DLI) influence crop timing and flowering characteristics. At Michigan State University (MSU), we have performed experiments with numerous seed-propagated annuals to quantify how average daily temperature and DLI influence flowering time and plant quality.

In the 10th article of this series, we present this cropping information on vinca (*Catharanthus roseus*) and wax begonia (*Begonia semperflorens-cultorum*) and then use that information with Virtual Grower to estimate greenhouse heating costs at different locations, growing temperatures and finish dates.

Materials & Methods

Seeds of vinca 'Viper Grape' and wax begonia 'Sprint Blush' were sown in 288-cell plug trays by C. Raker & Sons, then grown in controlled environmental growth chambers at MSU at a constant 68°F (20°C). Inside the chambers, the photoperiod was 16 hours and the DLI was 9 to 11 mol·m^{-2}·d^{-1}. This DLI is typical of that received in greenhouses in early spring in the Northern United States.

When plugs were ready for transplant (38 to 45 days after seed sow), they were transplanted into 4-inch (10-centimeter)

Market Date	Average Temp.	Date Of Transplant Of 288-Cell Plugs For Desired Market Dates	
		Vinca	Wax Begonia
April 1	63°F	February 6	February 16
	68°F	February 23	February 25
	73°F	March 4	March 3
	79°F	March 11	March 8
May 15	63°F	March 22	April 1
	68°F	April 8	April 10
	73°F	April 17	April 16
	79°F	April 24	April 21

Table 1. Date of transplant of 288-cell plug trays of vinca 'Viper Grape' and wax begonia 'Spring Blush' to achieve first flowering when grown at different temperatures for two market dates. Time to flower is presented in Figure 1. Plugs were grown at 68°F for 38 to 45 days under a daily light integral (DLI) of about 10 mol·m^{-2}·d^{-1}. Transplant dates assume an average DLI of 10 mol·m^{-2}·d^{-1} during the finish stage.

Location	Estimated Heating Cost (U.S. Dollars Per Square Foot Per Crop)							
	April 1				May 15			
	63°F	68°F	73°F	79°F	63°F	68°F	73°F	79°F
Vinca								
San Francisco, Calif.	0.18	0.18	0.18	0.17	0.14	0.14	0.14	0.14
Tallahassee, Fla.	0.17	0.13	0.12	0.12	0.04	0.04	0.04	0.05
Grand Rapids, Mich.	0.57	0.40	0.33	0.30	0.25	0.20	0.17	0.15
New York, N.Y.	0.41	0.31	0.26	0.24	0.16	0.13	0.12	0.11
Charlotte, N.C.	0.25	0.19	0.18	0.17	0.09	0.09	0.08	0.08
Cleveland, Ohio	0.51	0.37	0.31	0.27	0.25	0.18	0.16	0.15
Fort Worth, Texas	0.17	0.14	0.13	0.12	0.05	0.04	0.05	0.07
Wax Begonia								
San Francisco, Calif.	0.15	0.17	0.18	0.20	0.11	0.13	0.15	0.16
Tallahassee, Fla.	0.13	0.12	0.13	0.14	0.03	0.04	0.04	0.06
Grand Rapids, Mich.	0.42	0.37	0.35	0.34	0.19	0.18	0.18	0.17
New York, N.Y.	0.31	0.29	0.27	0.27	0.12	0.12	0.12	0.13
Charlotte, N.C.	0.17	0.18	0.19	0.19	0.07	0.08	0.09	0.10
Cleveland, Ohio	0.39	0.34	0.32	0.31	0.16	0.17	0.16	0.18
Fort Worth, Texas	0.12	0.13	0.14	0.14	0.03	0.04	0.05	0.07

Table 2. Estimated heating costs to produce flowering vinca 'Viper Grape' and wax begonia 'Sprint Blush' from a 288-cell plug (see Table 1) at different temperatures and locations for first flowering on April 1 or May 15. Calculations were performed with Virtual Grower software with constant temperatures. Greenhouse characteristics include: eight spans each 112 × 24 feet, arched 12-foot roof, 9-foot gutter, polyethylene double-layer roof, polycarbonate bi-wall ends and sides, forced air-unit heaters burning natural gas at $1 per therm ($10.24 MCF), 50 percent heater efficiency, no energy curtain and an hourly air infiltration rate of 1.0.

pots and grown in greenhouses with constant temperature set points of 63, 68, 73 and 79°F (17, 20, 23 and 26°C). At each temperature, plants were grown under a 16-hour photoperiod with two different DLIs provided by sunlight, a combination of shade curtains and different supplemental lighting intensities from high-pressure sodium lamps. Vinca and wax begonia are day-neutral crops and thus, day length has no effect on flowering time.

Our experiments were performed twice to obtain average DLIs that ranged from 3.5 to 20 $mol \cdot m^{-2} \cdot d^{-1}$. A DLI of 3.5 $mol \cdot m^{-2} \cdot d^{-1}$ can be considered very low and is representative of light conditions received inside a northern greenhouse on a cloudy day in the winter. A DLI of 20 $mol \cdot m^{-2} \cdot d^{-1}$ can be considered moderately high and is typical for inside a greenhouse on a mid- to late spring day. The flowering date was recorded when vinca had one flower open and when wax begonia had an inflorescence with one open flower. When each plant flowered, plant height and flower bud number were recorded.

Crop timing data were used to develop mathematical models to predict flowering time and plant quality under different temperature and DLI conditions. The Virtual Grower 2.51 software (available free at **VirtualGrower.net**) was used to estimate the cost to heat a 21,504-square-foot greenhouse (about half an acre) to produce each crop for different finish dates and in seven locations in the U.S.

Results

In both vinca and wax begonia, time to flower decreased as average daily temperature increased from 63 to 79°F. Under a DLI of 10 $mol \cdot m^{-2} \cdot d^{-1}$ and at 79°F, vinca flowered 33 days earlier and wax begonia flowered 20 days earlier than plants grown under the same DLI, but at 63°F (Figure 1). The low temperature at which plant development was predicted to stop (sometimes referred to as the base temperature) was estimated to be 53°F for vinca and 43°F for wax begonia. These high base temperatures indicate wax begonia and especially vinca are cold-sensitive plants. These crops should not be grown near the base temperature because production time is significantly delayed and plants may show symptoms of chilling damage.

To illustrate the effect of temperature

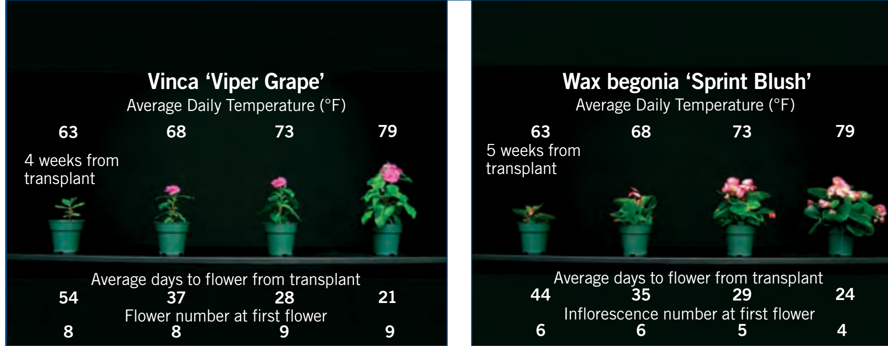


Figure 1. The effects of average daily temperature on time to flower and number of flowers or inflorescences (at first flowering) in vinca 'Viper Grape' and wax begonia 'Sprint Blush.' Plants were grown under a 16-hour photoperiod and an average daily light integral (DLI) of 10 $mol \cdot m^{-2} \cdot d^{-1}$. Photographs were taken four or five weeks after transplant from a 288-cell plug tray that was grown under long days.

on vinca and wax begonia crop times, we identified dates that 288-cell plugs grown under long days would need to be transplanted for two market dates when finished under long days and a DLI of 10 $mol \cdot m^{-2} \cdot d^{-1}$ (Table 1).

Under low light conditions, flowering of vinca and wax begonia was slightly accelerated if the DLI was increased. For example, when DLI increased from 4 to 8 $mol \cdot m^{-2} \cdot d^{-1}$, time to flower at 68°F decreased by three days in vinca and six days in wax begonia. DLI had a greater influence on decreasing crop time at cooler than warmer temperatures. The estimated saturation DLI for the shortest time to flower was 8 $mol \cdot m^{-2} \cdot d^{-1}$ for vinca and 10.5 $mol \cdot m^{-2} \cdot d^{-1}$ for wax begonia. In other words, increasing the DLI above these values did not shorten crop time.

In vinca, flower number at first flowering increased as average daily temperature and DLI increased. In wax begonia, inflorescence number increased as average daily temperature decreased and as DLI increased. For example, wax begonia grown at 73°F had twice as many flowers under a DLI of 18 $mol \cdot m^{-2} \cdot d^{-1}$ compared with a very low DLI of 3 $mol \cdot m^{-2} \cdot d^{-1}$. Therefore, plant quality of both crops continued to improve with an increase in DLI, although flowering time was not accelerated beyond a DLI of 10.5 $mol \cdot m^{-2} \cdot d^{-1}$.

Heating Costs

The crop timing data generated in this research was used with Virtual Grower to estimate if it is more energy efficient to transplant a spring crop earlier and grow cool versus transplanting later and growing warm. To produce a finished vinca crop for April 1 in all seven locations tested (San Francisco, Calif., Tallahassee, Fla., Grand Rapids, Mich., New York, N.Y., Charlotte, N.C., Cleveland, Ohio, or Fort Worth, Texas), the least amount of energy for heating was consumed by transplanting on March 11 and growing at 79°F (Table 2). Energy costs per crop increased as temperature decreased because flowering of vinca was delayed considerably at cooler temperatures.

To produce wax begonia for April 1, the most energy-efficient production strategy for greenhouse production in Grand Rapids, New York and Cleveland was to transplant late and grow at 79°F. In contrast, we project the same crop grown in San Francisco, Tallahassee, Charlotte and Fort Worth would require less heating per crop if transplanted earlier and grown at 63 or 68 °F.

For a market date of May 15, the most energy-efficient temperature varied by location and crop. For example, vinca grown in Grand Rapids, New York, Charlotte and Cleveland would consume 11 to 56 percent less energy per crop at 73 or 79°F versus 63°F. To produce wax begonia for May 15, heating costs were predicted to be lower at a cool versus warm temperature in all locations except Grand Rapids.

We encourage you to use this crop scheduling data with Virtual Grower to determine the most energy-efficient production strategy for your location and market date. 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 turns and overhead costs, should also be considered when choosing the most economical growing temperature for each floriculture crop producer. The impact of temperature and DLI on plant quality, and response variability among cultivars, should also be considered. **GG**

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American Floral Endowment

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Project GREEEN

Energy-Efficient Annuals: Angelonia & Browallia

Researchers from Michigan State University present research-based information for scheduling annuals in a more energy-efficient and predictive manner.

by **MATTHEW BLANCHARD** and **ERIK RUNKLE**

SCHEDULING annual bedding plants in flower for specific market dates is of increasing importance to greenhouse growers. Plants not in flower when planned or in flower too early can create greenhouse space challenges, delay shipping and reduce plant quality.

During the past several years at Michigan State University (MSU), we have performed experiments with seed propagated annuals to quantify how temperature and daily light integral (DLI) influence flowering time and plant quality. In the 11th article of this series, we present crop timing and scheduling information on angelonia (*Angelonia angustifolia*) and browallia (*Browallia speciosa*), and then use that information with Virtual Grower to estimate greenhouse heating costs at different locations, growing temperatures and finish dates.

Materials & Methods

Seeds of angelonia 'Serena Purple' and browallia 'Bells Marine' were sown in 288-cell plug trays by C. Raker & Sons, then grown in controlled environmental growth chambers at MSU at a

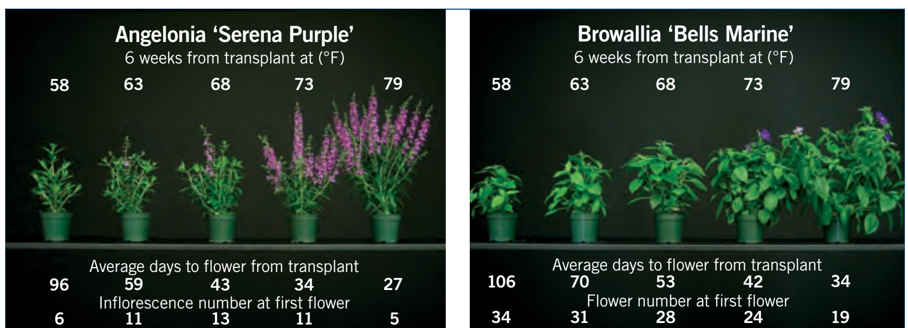

Figure 1. The effects of average daily temperature on time to flower and number of flowers or inflorescences (at first flowering) in angelonia 'Serena Purple' and browallia 'Bells Marine.' Plants were grown under a 16-hour photoperiod and an average daily light integral (DLI) of 10 mol·m^{-2}·d^{-1}. Photographs were taken six weeks after transplant from a 288-cell plug tray that was grown under a DLI of 9 to 11 mol·m^{-2}·d^{-1}.

Market Date	Average Temp.	Date Of Transplant Of 288-Cell Plugs For Desired Market Dates	
		Angelonia	Browallia
April 1	63°F	February 1	January 21
	68°F	February 17	February 7
	73°F	February 26	February 18
	79°F	March 5	February 26
May 15	63°F	March 17	March 6
	68°F	April 2	March 23
	73°F	April 11	April 3
	79°F	April 18	April 11

Table 1. Date of transplant of 288-cell plug trays of angelonia 'Serena Purple' and browallia 'Bells Marine' to achieve first flowering when grown at different temperatures for two market dates. Time to flower is presented in Figure 1. Plugs were grown at 68°F for 40 days under a daily light integral (DLI) of about 10 mol·m^{-2}·d^{-1}. Transplant dates assume an average DLI of 10 mol·m^{-2}·d^{-1} during the finish stage.

constant 68°F (20°C). Inside the chambers, the photoperiod was 16 hours and the DLI was 9 to 11 mol·m^{-2}·d^{-1}. This DLI is typical of that received in greenhouses in early spring in the Northern United States.

When plugs were ready for transplant (40 days after seed sow), they were transplanted into 4-inch (10-centimeter) pots and grown in greenhouses with constant temperature set points of 58, 63, 68, 73 and 79°F (14, 17, 20, 23 and 26°C). At each temperature, plants were grown under a 16-hour photoperiod with two different DLIs provided by sunlight, a combination of shade curtains and different supplemental lighting intensities from high-pressure sodium lamps. Angelonia and browallia are day-neutral crops and thus, day length has no effect on flowering time.

The average DLI during the finish stage ranged from 4 to 16 mol·m^{-2}·d^{-1}. No growth regulators were applied during the plug or finish stage. Plant and flowering characteristics were measured when each plant first flowered. Crop timing data were used to develop mathematical models to predict flowering time and plant quality under different temperature and DLI conditions. The Virtual Grower 2.51 software, available free at **VirtualGrower.net**, was used to estimate the cost to heat a 21,504-square-foot greenhouse (about half an acre) to produce each crop for different finish dates and in seven locations in the U.S.

Results

In both angelonia and browallia, time to flower decreased as average daily temperature increased from 58 to 79°F. Under a DLI of 10 mol·m^{-2}·d^{-1} and at 79°F, plants flowered 32 to 36 days earlier than plants grown under the same DLI, but at 63°F (Figure 1). The low temperature at which plant development was predicted to stop (sometimes referred to as the base temperature) was estimated to be 48 to 50°F for both crops. Not surprisingly, these high base temperatures indicate angelonia and browallia are cold-sensitive plants.

As average temperature decreases toward the base temperature, production time is increasingly delayed. For example, plants flowered an average of five weeks later at 58°F versus 63°F. A temperature below 60°F can cause chilling damage on these crops and thus, should generally be avoided. To illustrate the effect of temperature on angelonia and browallia crop times, we identified dates 288-cell plugs would need to be transplanted for two market dates when finished under an average DLI of 10 mol·m^{-2}·d^{-1} (Table 1).

When the DLI was low, an increase in DLI accelerated flowering. For example, an increase in DLI from 4 to 8 $mol \cdot m^{-2} \cdot d^{-1}$ decreased time to flower by five days in angelonia and 18 days in browallia when grown at 68°F. The estimated saturation DLI (the minimum DLI for rapid flowering) was 8 $mol \cdot m^{-2} \cdot d^{-1}$ for angelonia and 16 $mol \cdot m^{-2} \cdot d^{-1}$ for browallia. In other words, an increase in the DLI above these values did not shorten crop time.

In angelonia, inflorescence number at first flowering increased as average daily temperature increased from 58 to 68°F, and as DLI increased (Figure 1). In browallia, flower number increased as average temperature decreased and as DLI increased from 4 to 10 $mol \cdot m^{-2} \cdot d^{-1}$. For example, at 68°F, increasing the DLI from 4 to 10 $mol \cdot m^{-2} \cdot d^{-1}$ increased the number of flower buds by 35 percent in angelonia and by 55 percent in browallia. Branch number also increased as DLI increased.

Heating Costs

The production temperature that had the lowest estimated heating costs to produce a flowering crop varied among locations and market dates. To produce a flowering crop of angelonia and browallia for April 1, a greenhouse located in Grand Rapids, Mich., New York, N.Y., Charlotte, N.C., Cleveland, Ohio, Tallahassee, Fla., or Fort Worth, Texas is estimated to consume 9 to 41 percent less heating per square foot if the crop was transplanted later and grown at 73 or 79°F compared to the same crop transplanted earlier and grown at 63°F (Table 2).

In other words, a warm temperature and short crop time consumed less energy for heating per crop compared to a cool temperature and longer crop time. In contrast, heating costs for a greenhouse located in San Francisco, Calif. would be 10 to 12 percent greater if these crops were grown for April 1 at 79°F instead of 63 or 68°F.

For a market date of May 15, the most energy-efficient temperature varied by location and crop. For example, a greenhouse in Grand Rapids, New York and Cleveland would consume the least energy per crop at 73 or 79°F. In San Francisco and Fort Worth, heating costs would be similar at 63 to 73°F. Therefore at these two locations, other factors could be considered when selecting a growing temperature.

We encourage growers to use this crop scheduling data with Virtual Grower to determine the most energy-efficient production temperature for their location and market date. The cost of energy for heating is one of the many

Location	Estimated Heating Cost (U.S. Dollars Per Square Foot Per Crop)							
	April 1				May 15			
	63°F	68°F	73°F	79°F	63°F	68°F	73°F	79°F
Angelonia								
San Francisco, Calif.	0.20	0.20	0.21	0.22	0.16	0.16	0.17	0.18
Tallahassee, Fla.	0.19	0.17	0.16	0.16	0.05	0.06	0.06	0.07
Grand Rapids, Mich.	0.64	0.48	0.41	0.38	0.31	0.24	0.22	0.20
New York, N.Y.	0.45	0.37	0.34	0.31	0.19	0.16	0.15	0.16
Charlotte, N.C.	0.30	0.21	0.22	0.22	0.11	0.11	0.12	0.11
Cleveland, Ohio	0.55	0.45	0.38	0.37	0.27	0.21	0.20	0.20
Fort Worth, Texas	0.20	0.17	0.16	0.17	0.05	0.05	0.06	0.08
Browallia								
San Francisco, Calif.	0.25	0.25	0.26	0.28	0.20	0.20	0.21	0.22
Tallahassee, Fla.	0.23	0.23	0.21	0.21	0.09	0.07	0.09	0.10
Grand Rapids, Mich.	0.77	0.64	0.55	0.49	0.40	0.31	0.29	0.27
New York, N.Y.	0.58	0.48	0.43	0.48	0.27	0.21	0.20	0.21
Charlotte, N.C.	0.39	0.31	0.27	0.28	0.17	0.14	0.15	0.16
Cleveland, Ohio	0.70	0.60	0.50	0.46	0.37	0.31	0.27	0.26
Fort Worth, Texas	0.26	0.23	0.22	0.22	0.08	0.08	0.09	0.11

Table 2. Estimated heating costs to produce flowering angelonia 'Serena Purple' and browallia 'Bells Marine' from a 288-cell plug tray (see Table 1) at different temperatures and locations for first flowering on April 1 or May 15. Calculations performed with Virtual Grower software with constant temperatures. Greenhouse characteristics include: eight spans each 112 × 24 feet, arched 12-foot roof, 9-foot gutter, polyethylene double layer roof, polycarbonate bi-wall ends and sides, forced air unit heaters burning natural gas at $1 per therm ($10.24 MCF), 50 percent heater efficiency, no energy curtain and an hourly air infiltration rate of 1.0.

production expenses for greenhouse crops. Other factors, such as the number of crop turns and overhead costs, should also be considered when choosing the most economical growing temperature for each floriculture crop producer. The impact of temperature and DLI on plant quality, and response variability among cultivars, should also be considered. **GG**

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To see the first 11 articles in this series go to GreenhouseGrower.com.

Energy-Efficient Annuals: Pentas & Verbena

Researchers from Michigan State University present research-based information for scheduling annuals in a more energy-efficent and predictive manner.

by **MATTHEW BLANCHARD** and **ERIK RUNKLE**

EFFICIENT production of bedding plants requires information on how temperature, photoperiod, and daily light integral (DLI) influence crop timing and flowering characteristics. During the past several years at Michigan State University (MSU), we have performed experiments with seed-propagated annuals to quantify how temperature and DLI influence flowering time and plant quality.

In the 12th and final article of this series, we present crop timing and scheduling information on pentas (*Pentas lanceolata*) and verbena (*Verbena ×hybrida*). Based on that information, we used Virtual Grower to estimate greenhouse heating costs for two market dates at different locations and growing temperatures.

Materials & Methods

Seeds of pentas 'Graffiti Lavender' and verbena 'Obsession Lilac' and 'Quartz Waterfall Mix' were sown in 288-cell plug trays by C. Raker & Sons, then grown in controlled environmental growth chambers at MSU at a constant 68°F (20°C). Inside the chambers, the photoperiod was 16 hours and the DLI was 9 to 11 mol·m^{-2}·d^{-1}. This DLI is typical of that

Market Date	Average Temp.	Date of Transplant of 288-Cell Plugs for Desired Market Dates		
		Pentas 'Graffiti Lavender'	Verbena 'Obsession Lilac'	Verbena 'Quartz Waterfall Mix'
April 1	63 °F	January 9	February 22	January 31
	68 °F	January 30	March 1	February 11
	73 °F	February 12	March 7	February 19
	79 °F	February 21	March 11	February 25
May 15	63 °F	February 22	April 7	March 16
	68 °F	March 15	April 14	March 27
	73 °F	March 28	April 20	April 4
	79 °F	April 6	April 24	April 10

Table 1. Date of transplant of 288-cell plug trays of pentas 'Graffiti Lavender' and verbena 'Obsession Lilac' and 'Quartz Waterfall Mix' to achieve first flowering when grown at different temperatures for two market dates. Time to flower for two of these crops is presented in Figure 1. Plugs were grown at 68 °F for six weeks (pentas) or four weeks (verbena) under a daily light integral (DLI) of about 10 mol·m^{-2}·d^{-1}. Transplant dates assume an average DLI of 10 mol·m^{-2}·d^{-1} during the finish stage.

Location	Estimated Heating Cost (U.S. Dollars Per Square Foot Per Crop)							
	April 1				May 15			
	63°F	68°F	73°F	79°F	63°F	68°F	73°F	79°F
Pentas								
San Francisco, Calif.	0.31	0.29	0.29	0.31	0.24	0.24	0.24	0.25
Tallahassee, Fla.	0.28	0.26	0.26	0.25	0.13	0.10	0.11	0.13
Grand Rapids, Mich.	0.93	0.77	0.63	0.58	0.53	0.41	0.34	0.33
New York, N.Y.	0.72	0.58	0.52	0.47	0.37	0.28	0.25	0.25
Charlotte, N.C.	0.46	0.40	0.33	0.32	0.21	0.18	0.18	0.19
Cleveland, Ohio	0.83	0.68	0.61	0.55	0.48	0.37	0.32	0.31
Fort Worth, Texas	0.32	0.29	0.27	0.26	0.12	0.10	0.11	0.13
Verbena 'Quartz Waterfall Mix'								
San Francisco, Calif.	0.20	0.23	0.26	0.28	0.16	0.18	0.20	0.23
Tallahassee, Fla.	0.19	0.20	0.21	0.22	0.05	0.07	0.09	0.11
Grand Rapids, Mich.	0.65	0.56	0.53	0.51	0.32	0.29	0.28	0.28
New York, N.Y.	0.46	0.44	0.42	0.42	0.20	0.19	0.20	0.21
Charlotte, N.C.	0.31	0.27	0.26	0.29	0.12	0.13	0.14	0.17
Cleveland, Ohio	0.56	0.54	0.49	0.47	0.28	0.27	0.26	0.27
Fort Worth, Texas	0.20	0.21	0.21	0.23	0.06	0.07	0.08	0.11

Table 2. Estimated heating costs to produce flowering pentas 'Graffiti Lavender' and verbena 'Quartz Waterfall Mix' from a 288-cell plug (see Table 1) at different temperatures and locations for first flowering on April 1 or May 15. Calculations performed with Virtual Grower software with constant temperatures. Greenhouse characteristics include: 8 spans each 112 × 24 feet, arched 12-foot roof, 9-foot gutter, polyethylene double layer roof, polycarbonate bi-wall ends and sides, forced air unit heaters burning natural gas at $1 per therm ($10.24 MCF), 50 percent heater efficiency, no energy curtain, and an hourly air infiltration rate of 1.0.

received in greenhouses in early March in the northern United States.

When plugs were ready for transplant (six weeks for pentas; four weeks for verbena), they were transplanted into 4-inch (10-centimeter) pots and grown in greenhouses with constant temperature set points of 58, 63, 68, 73 and 79°F (14, 17, 20, 23 and 26°C). At each temperature, plants were grown under a 16-hour photoperiod with two different DLIs provided by sunlight, a combination of shade curtains and different supplemental lighting intensities from high-pressure sodium lamps. These pentas and verbena varieties do not require long days for flowering, but plants flower faster if long days are provided.

The average DLI during the finish stage ranged from 3 to 20 $mol \cdot m^{-2} \cdot d^{-1}$. No growth regulators were applied during the plug or finish stage. Plant and flowering characteristics were measured when each plant first flowered. Crop timing data were used to develop mathematical models to predict flowering time and plant quality under different temperature and DLI conditions. The Virtual Grower 2.51 software (available free at **VirtualGrower.net**) was used to estimate the cost to heat a 21,504-square-foot greenhouse (about half an acre) to produce each crop for different market dates and in seven locations in the U.S.

Results

In pentas and verbena, time to flower decreased as average daily temperature increased from 58 to 79°F. For example, under an average DLI of 10 $mol \cdot m^{-2} \cdot d^{-1}$, time to flower of pentas from a 288-cell plug decreased from 81 days at 63°F to 38 days at 79°F (Figure 1). At the same DLI, verbena 'Quartz Waterfall Mix' flowered 25 days later at 63°F versus 79°F. Verbena 'Obsession Lilac' grown under 10 $mol \cdot m^{-2} \cdot d^{-1}$ of light and at 58, 63, 68, 73 or 79°F flowered in 51, 38, 30, 25 and 21 days, respectively.

Therefore, verbena 'Obsession Lilac' flowered 34 to 40 percent faster than 'Quartz Waterfall Mix.' The low temperature at which plant development was predicted to stop (sometimes referred to as the base temperature) was estimated to be 49°F for pentas and 41 to 44°F for the two verbena cultivars studied.

An increase in DLI also accelerated flowering. For example, time to flower at 68°F decreased by 13 days in pentas, 10 days in verbena 'Obsession Lilac' and 24 days in verbena 'Quartz Waterfall Mix' when DLI increased from 4 to 10 $mol \cdot m^{-2} \cdot d^{-1}$. The estimated saturation DLI for the shortest time to flower was 11 $mol \cdot m^{-2} \cdot d^{-1}$ for pentas and 17 $mol \cdot m^{-2} \cdot d^{-1}$ for verbena 'Obsession Lilac.' In other words, increasing the DLI above these values did not shorten crop time. Flowering time continued to decrease as DLI increased for verbena 'Quartz Waterfall Mix' and thus, the saturation DLI is greater than 20 $mol \cdot m^{-2} \cdot d^{-1}$. Using this research data, we identified dates that 288-cell plugs need to be transplanted for two market dates when finished under long days and an average DLI of 10 $mol \cdot m^{-2} \cdot d^{-1}$ (Table 1).

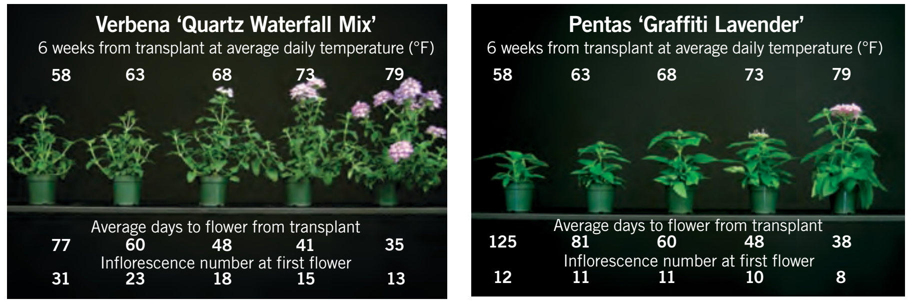

Figure 1. The effects of average daily temperature on time to flower and number of inflorescences (at first flowering) in pentas 'Graffiti Lavender' and verbena 'Quartz Waterfall Mix.' Plants were grown under a 16-hour photoperiod and an average daily light integral (DLI) of 10 $mol \cdot m^{-2} \cdot d^{-1}$. Photographs were taken six weeks after transplant from a 288-cell plug tray that was grown under a DLI of 9 to 11 $mol \cdot m^{-2} \cdot d^{-1}$.

The number of inflorescences at first flowering increased as average daily temperature decreased and as DLI increased (Figure 1). For example, at 68°F, the number of inflorescences increased by 31 percent in pentas and by 69 percent in verbena 'Quartz Waterfall Mix' as DLI increased from 5 to 15 $mol \cdot m^{-2} \cdot d^{-1}$. In both species, plant height at flower increased as DLI decreased.

Heating Costs

Heating costs for a crop of pentas grown for first flowering on April 1 in Tallahassee, Fla., Grand Rapids, Mich., New York, N.Y., Charlotte, N.C., Cleveland, Ohio, or Fort Worth, Texas, were predicted to be 11 to 38 percent lower at a constant 79°F versus 63°F (Table 2). Therefore, at these locations, it is more energy efficient to start spring production later and grow at a warmer temperature. To produce the same crop in San Francisco, Calif., heating costs per square foot would be 11 percent higher at 63 or 79°F versus 68 or 73°F.

We predicted verbena finished for April 1 would require the least amount of energy for heating if grown at 63°F in San

Francisco, Tallahassee and Fort Worth and at 73 or 79°F in Grand Rapids, New York, Charlotte and Cleveland. For a market date of May 15, the most energy-efficient temperature varied among locations and market dates. For example, in New York, pentas would consume the least amount of energy per crop at 73 or 79°F and verbena at 68°F.

The identification of energy-efficient production temperatures for all of the crops reported in this article series can make it possible to group species with similar environmental responses. For example, dahlia, French marigold, osteospermum, petunia Dreams series, snapdragon and viola grown for a market date of May 15 in a greenhouse located in Grand Rapids would consume the least amount of energy per square foot per crop at 58°F to 63°F. For the same location and market date, ageratum, angelonia, browallia, cosmos, seed geranium, pentas, verbena, vinca, wax begonia and zinnia would consume less energy for heating at 73 to 79°F versus cooler temperatures.

We encourage growers to use the crop scheduling data from this series along with Virtual Grower to determine the most energy-efficient production temperature for your location and market date. The cost of energy for heating is one of the many production expenses for greenhouse crops. Other factors, such as the number of crop turns and overhead costs, should also be considered when choosing the most economical growing temperature for each floriculture crop producer. The impact of temperature and DLI on plant quality, and response variability among cultivars as observed here with verbena, should also be considered. **GG**

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