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

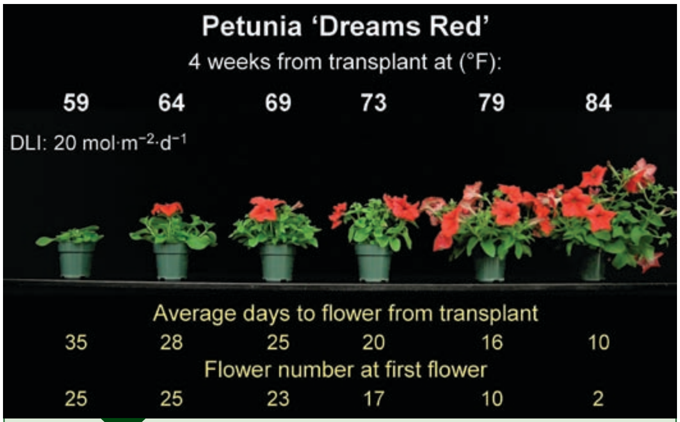

Figure 1. The effects of average daily temperature on time to flower and number of flower buds in petunia. Plants were grown under a 16-hour photoperiod and an average daily light integral of 20 mol·m–2·d–1. The photograph was taken four weeks after transplant from a 288-cell plug tray.

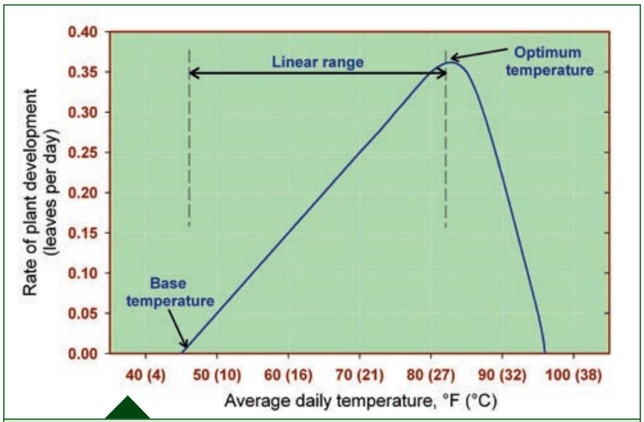

Figure 2. Conceptual diagram of the rate of plant development (such as leaf unfolding) in relation to the average daily temperature. The shape of the curve varies from crop to crop.

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 experi-

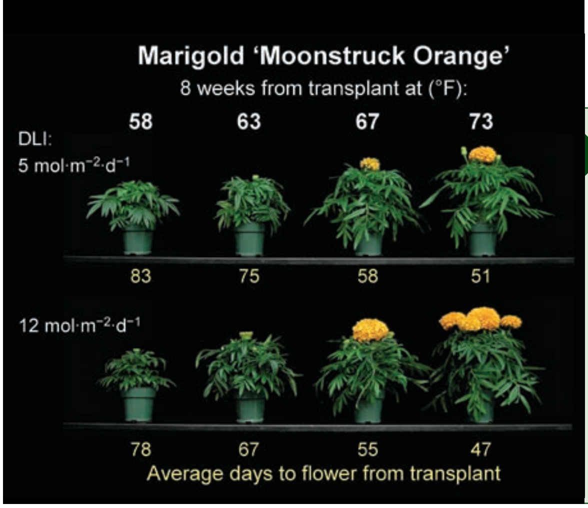

Figure 3. Effects of average daily temperature and daily light integral (DLI) on time to flower in marigold 'Moonstruck Orange.' Plants were grown under a 16-hour photoperiod. Photograph was taken eight weeks after transplant from a 288-cell plug tray.

ments 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.

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**.

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).

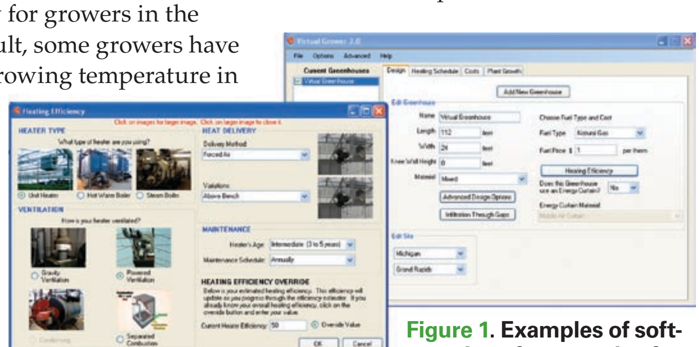

Figure 1. Examples of software interface panels of Virtual Grower. This program can be downloaded free at VirtualGrower.net and can be used to estimate greenhouse energy costs throughout the United States.

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

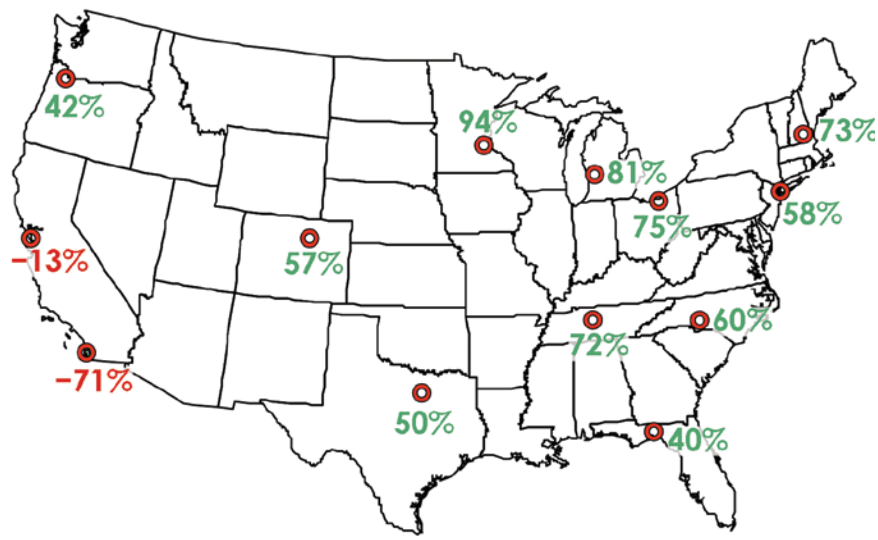

Figure 2. The estimated increase (in green) or decrease (in red) in heating costs by growing petunia 'Easy Wave Coral Reef' at 58°F instead of 68°F for first flowering on April 1 given our virtual greenhouse characteristics. In this example, the increase in energy consumption is because crop timing is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

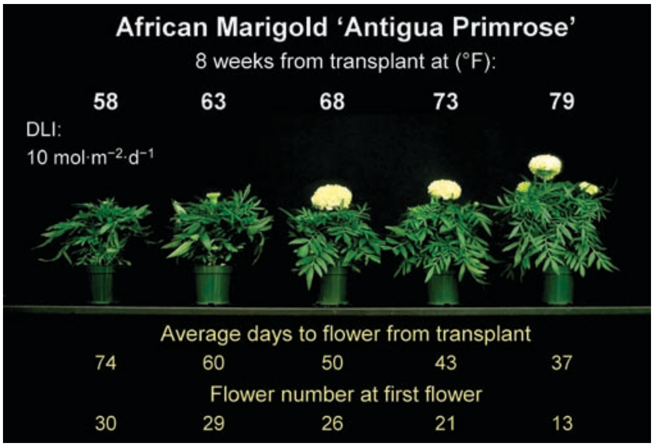

Figure 1. The effects of average daily temperature on time to flower and number of flower buds (at first flowering) in African marigold. Plants were grown under a 16-hour photoperiod and an average daily light integral of 10 mol·m^{-2}·d^{-1}. Photograph was taken eight weeks after transplant from a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

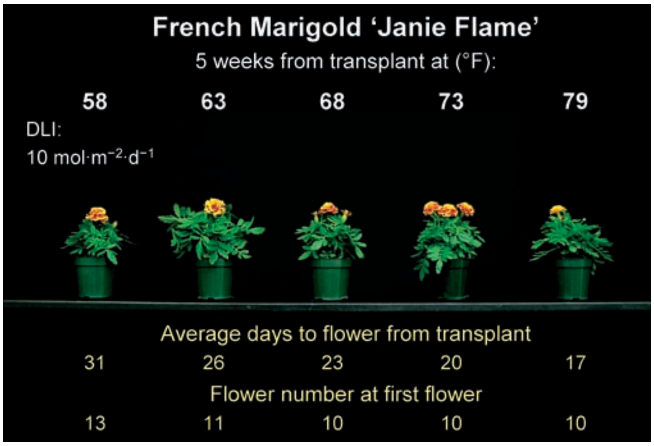

Figure 2. The effects of average daily temperature on time to flower and number of flower buds (at first flowering) in French marigold. Plants were grown under a 16-hour photoperiod and an average daily light integral of 10 mol·m^{-2}·d^{-1}. Photograph was taken five weeks after transplant from a 288-cell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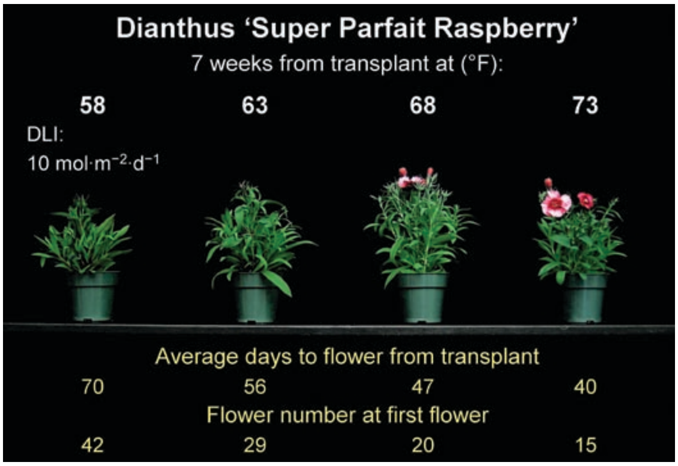

Figure 1. The effects of average daily temperature on time to flower and number of flower buds (at first flowering) in dianthus. Plants were grown under a 16-hour photoperiod and an average daily light integral of 10 mol·m^{-2}·d^{-1}. Photograph was taken seven weeks after transplant from a 288-cell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

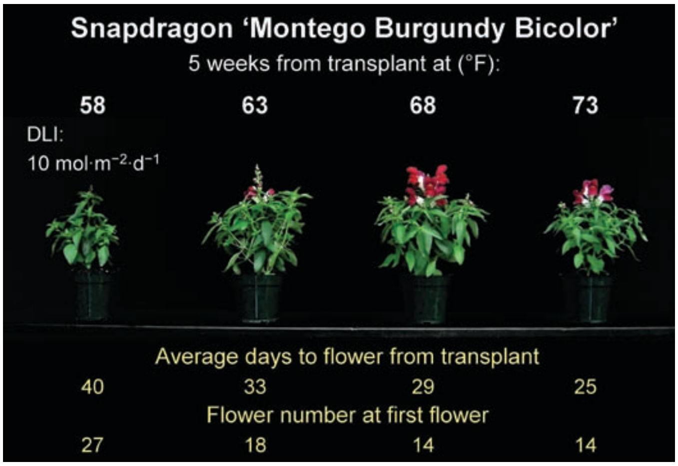

Figure 2. The effects of average daily temperature on time to flower and number of flower buds (at first flowering) in snapdragon. Plants were grown under a 16-hour photoperiod and an average daily light integral of 10 mol·m^{-2}·d^{-1}. Photograph was taken five weeks after transplant from a 288-cell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

continued from page 26

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.

continues on page 30

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.

continued from page 28

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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