Energy-efficient production of greenhouse crops

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Abstract

Photoperiod, the photosynthetic daily light integral (DLI), and mean daily temperature are three environmental parameters that have the largest effects on plant growth and development. During commercial production of floriculture crops, one or more of these factors is often manipulated so that crops are marketable when desired. In temperate climates (e.g., >35 °N latitude), high-intensity (photosynthetic or supplemental) lighting is provided to increase growth and accelerate flowering when ambient light conditions are low. In addition, growers provide low-intensity (photoperiodic) lighting to deliver long days, which accelerates flowering of long-day plants. Finally, growers often control temperature, which influences cropping time and plant quality attributes. Since a substantial amount of energy is used to heat greenhouses located in cold climates, growers need to optimize temperature so that energy costs are minimized on a per-crop basis. This paper describes how light and temperature influence growth and flowering of floriculture crops and presents information to improve the energy efficiency of greenhouse crop production based heavily on recent research performed at Michigan State University.

Introduction

Floriculture crops are commonly grown in controlled greenhouse environments so that they are of desired quality and are ready for market on predetermined dates. Light and temperature primarily control growth and development and thus, are the two factors commonly manipulated during crop production. Light regulates photosynthesis, which controls plant growth attributes (shoot and root mass, flower bud number, etc.) but it can also influence extension growth and flowering. Temperature primarily controls plant rate of development and thus, has a strong effect on the duration that crops are in the greenhouse. A common goal of floriculture crop producers is to minimize the amount of time that crops are in the greenhouse, as well as to consume the least amount of energy for heating, especially when outdoor temperatures are low. Temperature is manipulated so that both of these considerations are minimized.

There are three dimensions of light that each influence plant growth and development. Light quantity or intensity refers to the instantaneous or cumulative amount of photosynthetic light received in a period of time (usually s or d) in a defined area (usually m^2) and is expressed in μmol or mol of photons (Thimijan and Heins, 1983). Light quantity primarily influences photosynthesis and thus root and shoot growth of plants. Light quality refers to the spectral distribution of light, for example, the ratio of red (R, 600 to 700 nm) to far red (FR, 700 to 800 nm) photons (Smith, 1994). Light quality can influence flowering and plant morphogenesis, such a stem extension and branching. Third, light duration refers to the photoperiod, or the duration of light and darkness each day. Many ornamental crops are sensitive to photoperiod with respect to flowering and thus, photoperiod is commonly truncated or increased to inhibit or promote flowering, whichever is desired.

In commercial greenhouse production of ornamental crops, supplemental lighting is sometimes provided to increase the photosynthetic daily light integral (DLI), depending primarily on growing location, time of year, and crop grown. Generally, the relative value of supplemental lighting is greatest for high-light (shade-avoiding) plants, in temperate climates from late autumn to early spring (e.g., when the DLI is <10 $mol \cdot m^{-2} \cdot d^{-1}$), at night or under cloudy conditions, and when plant density is high. Low-intensity lighting is even more widely used to shorten the dark period to promote flowering of long-day plants (LDP) or inhibit flowering of short-day plants (SDP).

Many factors are motivating growers to consider energy-efficient lighting strategies. For example, the incandescent bulb, which has been a common lamp type for photoperiodic lighting, is or will be unavailable in some countries because of its inefficiency at converting electricity into light. The cost of electricity in many countries also continues to increase, which makes operating lights more expensive. In addition, growers are increasingly conscious of their environmental footprint. Here, we highlight some of the recent research performed at Michigan State University that is focused on energy-efficient, effective, and economical production of floriculture crops.

Supplemental lighting

Commercial production of ornamentals typically consists of two distinct phases: the young plant (plug or liner) stage and the finish stage. When the ambient DLI is low, increasing the DLI with supplemental lighting is often cost-effective when producing young plants; lighting cost on a per-plant basis is low yet effects on growth and subsequent development can hasten crop timing. For example, mean shoot dry weight per internode increased as DLI increased from 4 to 12 $mol \cdot m^{-2} \cdot d^{-1}$ in five annual bedding plant species (Pramuk and Runkle, 2005b). In addition, subsequent

time to flower of all five species decreased as the DLI under which seedlings were grown increased. In a separate study, rooting and quality of New Guinea impatiens (*Impatiens hawkeri*) and petunia (*Petunia×hybrida*) cuttings increased and subsequent time to flower decreased as mean propagation DLI increased from ≈2 to 8-10 mol·m^{-2}·d^{-1} (Lopez and Runkle, 2008). During the finish plant stage, lighting costs often increase dramatically on a per-plant basis because plant density decreases.

Supplemental lighting during the entire production period of ornamentals is often economically infeasible because significant investments in lighting equipment and operation are required. For example, a simple estimated purchase and installation cost to provide supplemental lighting from 400-W high-pressure sodium (HPS) lamps was US$ 0.80 per μmol·m^{-2}·s^{-1} for each m^2 of greenhouse (Fisher and Both, 2004). In addition, an increase in rate of development of many annual ornamentals begins to saturate at a mean DLI of 12 to 15 mol·m^{-2}·d^{-1} (Blanchard, 2009). Thus, the value of providing supplemental lighting is diminished for many ornamental crops when the mean ambient DLI inside a greenhouse exceeds ≈15 mol·m^{-2}·d^{-1}. Therefore, growers with limited greenhouse lighting have queried at which young plant stage is supplemental lighting of most benefit.

In a recent study with petunia and pansy (*Viola ×wittrockiana*), seedlings were grown under a 16-h photoperiod with lighting from HPS lamps at 90 μmol·m^{-2}·s^{-1} (supplemental lighting) or 3 μmol·m^{-2}·s^{-1} (photoperiodic lighting; Oh et al., 2010). Seedlings remained under the lighting treatments for the entire production period (27 d for petunia and 33 d for pansy) or were exposed to the higher intensity for one-third or two-thirds of the seedling stage. In both species, supplemental lighting during the last two-thirds or the entire plug stage increased shoot dry weight and the number of leaves compared with supplemental lighting during the earlier stage or at the low intensity. In addition, supplemental lighting during the last two-thirds or the entire

plug stage accelerated flowering. Supplemental lighting provided for only one-third of the production period produced the greatest increase in shoot mass and leaf number when delivered during the last third period compared with the first or second period.

Photoperiodic lighting

There is a quantitative relationship between the irradiance (intensity and duration) of photoperiodic lighting and the flowering response of many LDP (Thomas and Vince-Prue, 1997). For example, flowering of lance coreopsis (*Coreopsis grandiflora*) and perennial rudbeckia (*Rudbeckia fulgida*) was increasingly promoted as the duration of night interruption (NI) lighting from incandescent lamps increased from 0.5 to 4 h during a 15-h skotoperiod (Runkle et al., 1998). A target minimum irradiance for photoperiodic lighting at plant height is 1 $\mu mol \cdot m^{-2} \cdot s^{-1}$, but many species respond to a lower irradiance (Whitman et al., 1998). Flowering of some LDP is more rapid when low-intensity lighting contains FR light. The spectral distribution of light generally has less effect when photoperiodic lighting is provided to inhibit flowering of SDP.

Lighting from incandescent lamps, either at the end of the day or during the middle of the night, has been the traditional way that growers have shortened the night length. Incandescent lamps have been used extensively primarily because of their low purchase and installation costs. Strings of lamps can be hung above crops readily and can be moved with ease. The incandescent lamp emits light with a R:FR of ≈0.7, which is effective at inducing flowering in LDP and inhibiting flowering of SDP. There are also undesirable characteristics of incandescent lamps when used in the commercial production of ornamentals: they are only ≈10 to 12% efficient at converting electricity into photons within the 400 to 800 nm waveband and thus, they require a large electrical capacity (Thimijan and Heins, 1983). In addition, their low

R:FR promotes stem extension, which is often undesirable in the production of containerized plants.

To reduce energy consumption, incandescent lamps can be pulsed during the night (cyclic lighting) instead of operating continuously. For example, campanula (*Campanula carpatica*) and threadleaf coreopsis (*Coreopsis verticillata*) flowered comparably when the middle of a 15-h night was interrupted with a continuous 4 h with incandescent lamps, or when lamps were illuminated 20% of that time (6 min of light every 30 min for 4 h) (Runkle et al., 1998). In contrast, flowering of petunia and annual rudbeckia (*Rudbeckia hirta*) was delayed by 9 to 16 d when plants were grown at 20 ℃ under a 4-h, 20% cyclic NI lighting regimen compared with a continuous 4 h (Blanchard and Runkle, 2010).

Metal halide, HPS, and fluorescent lamps can also be effective at shortening the night length, particularly when used to extend the day (Whitman et al., 1998). These lamp types are more efficient at converting electricity into light, with ≥22% of the energy used to emit photons within the 400 to 800 nm waveband (Thimijan and Heins, 1983). In contrast with the incandescent lamps, the bulb lifespan of these three lamp types is negatively influenced by the on/off cycles and thus, they are usually not operated in a traditional cyclic manner. Given the high intensity of light from metal halide and HPS lamps, they can be widely spaced so that the minimum light intensity at crop height is ≥1 $\mu mol \cdot m^{-2} \cdot s^{-1}$.

Recently, we performed experiments to assess the efficacy of compact fluorescent (CF) lamps compared with incandescent lamps for providing long days to a variety of flowering annuals and herbaceous perennials (unpublished data). Plants were grown at 20 ℃ under a truncated 9-h photoperiod with or without a 6-h day extension to create a 15-h photoperiod, or a 2- or 4-h NI. Lighting was provided by incandescent (R:FR = 0.6) and CF lamps (R:FR = 8.4), alone or combined (R:FR =

0.9), at a photosynthetic photon flux (PPF) of 1.4 to 3.5 μmol·m^{-2}·s^{-1}. Time to flower of petunia was most rapid under incandescent lamps alone or alternating with CF lamps. In contrast, incandescent and CF lamps were similarly effective at inducing flowering of annual rudbeckia and inhibiting flowering of chrysanthemum (*Chrysanthemum*×*grandiflorum*). We conclude that, given their relative energy efficiency, CF lamps are, in some respects, an appealing replacement to incandescent lamps for many, but not all, photoperiodic crops.

An alternative photoperiodic lighting strategy is to use HPS lamps that either move over crops (e.g., on irrigation booms) or have a rotating reflector that casts a beam of light across crops (rotating HPS lighting). Although greenhouse growers have reported successful use of "boom lighting", to our knowledge, no scientific studies have provided a foundation for lighting guidelines or recommendations, such as how lighting frequency, intensity, and duration of irradiance interact to achieve desirable results. Growers have reported successful use of boom lighting with HPS or mercury lamps mounted approximately 3 to 4 m apart and 1 to 2 m above the crop. Generally, the lamps and booms are operated for 4 to 6 h during the middle of the night with a goal of illuminating plants at least once every 30 min.

We recently evaluated the effectiveness of rotating HPS lighting to inhibit flowering of SDP and promote flowering of LDP. The experiment was performed during natural short days and one 600-W rotating HPS lamp was mounted at one end of the greenhouse and operated for 4 h as NI lighting. Plants were grown at lateral distances of 1 to 13 m from under the rotating HPS lamp, which provided a maximum PPF of 25.4 to 0.3 μmol·m^{-2}·s^{-1}, respectively. Compared with a constant 4-h NI with incandescent lamps, flowering of lance coreopsis and annual rudbeckia was delayed at all lateral distances from under the HPS lamp (Blanchard and Runkle, 2010). In campanula and petunia, plants within 7 m and 10 m, respectively, from under the

rotating HPS lamp flowered at a similar time as plants under the 4-h incandescent NI treatment. Petunia within 10 m from under the rotating HPS lamp flowered earlier than under the 20% cyclic lighting, whereas flowering time of campanula was similar under the cyclic lighting as plants up to 10 m from under the rotating HPS lamp. In florists' (potted) chrysanthemum, the rotating HPS lamp was only effective at preventing flowering when plants were within 7 m from under the lamp (Blanchard and Runkle, 2009).

Generally, commercial growers have reported successful use of rotating HPS lamps to regulate flowering of photoperiodic ornamentals. In agreement with our research results, growers have reported that flowering is uneven and delayed in some long-day crops when the rotating HPS lamps are positioned too far apart. In addition, in our experiment with one lamp, chrysanthemum plants that were >7 m from the lamp had vegetative shoots on the side facing the lamp and reproductive shoots on the side opposing the lamp. Because we only used one lamp in this study, it is difficult to make spacing guidelines for rotating HPS lamps because most commercial growers would install multiple lamps and thus, plants could receive light from two or more fixtures.

From a commercial greenhouse grower's perspective, goals of photoperiodic lighting are that (1) it is sufficiently effective to control plant development, (2) purchase and installation costs are low, and (3) electricity costs for operation are low. To help address this later goal, we estimated weekly electricity consumption for six photoperiodic lighting strategies for 140 m^2 of greenhouse space, which is an estimate for the space that one rotating 600-W HPS lamp can sufficiently cover. However, as discussed previously, some of these lighting strategies were more effective than others on some crops. Comparisons were made with light from incandescent, CF lamps, and HPS lamps. The primary drawback of continuous 4-h NI lighting from incandescent

lamps is clear. The rotating HPS lamp is estimated to consume only 17% of the electrical consumption as the continuous 4-h NI with incandescent lamps, while electrical consumption for 25% cyclic incandescent lighting was comparable to constant 4-h lighting from CF or HPS lamps.

Future lighting considerations

At least in North America, growers in temperate climates continue to invest in lighting systems and learn how to cost-effectively manage their use. In the production of ornamentals, investing in photoperiodic lighting is typically much less expensive because of the number of floriculture species that are photoperiodic, the comparatively low purchase and installation costs, and the potential to reduce crop production time by a week or more. Ornamental growers in North America use supplemental lighting much less frequently, primarily because of the high investment costs and the challenge of obtaining a higher price for a higher quality plant. However, many of the more sophisticated growers in northern latitudes have installed HPS lamps, particularly in the production of rooted cuttings and seedlings, for reasons discussed previously.

Growers and scientists alike have had increasing interest in the development and potential use of light-emitting diodes (LEDs) for greenhouse applications, especially since 2008. Review articles about the virtues, opportunities, and limitations of LEDs in horticulture have been published (Massa et al., 2008; Morrow, 2008). An increasing number of companies produce and/or market LEDs for plant applications. Most companies are focusing on developing high-intensity lighting from LEDs to increase plant photosynthesis. The following criteria should be considered by lighting manufacturers and greenhouse growers alike:

- High electrical efficiency. This is a major reason why LEDs are so promising. Although current LEDs are only as electrically efficient as HPS lamps, their efficiencies are improving rapidly and will soon be more efficient than HPS lamps at converting electrical energy into photons of light. This efficiency can be quantified as micromoles of photosynthetic light ($\mu mol \cdot m^{-2} \cdot s^{-1}$) per watt of energy per area ($W \cdot m^{-2}$); the higher the value, the more efficient the lamp.

- High relative quantum efficiency (RQE). The RQE describes the efficiency of particular wavelengths of photons at driving photosynthesis (McCree, 1971; Fig. 1). Red light had the highest RQE, meaning that it was the most effective at eliciting photosynthesis. Blue light is about 70 to 75% as effective as red light, and green light is even less effective.

- Uniform distribution of light. Greenhouse lighting must be evenly distributed to ensure uniform crop response.

- Durable and reliable. LED arrays must be engineered and constructed to optimize light output, be of high quality, and be able to withstand extreme greenhouse conditions. For example, heat must be dissipated from LEDs sufficiently so that they operate at a favorable temperature; otherwise, their useful life can decrease.

- Compact size. Arrays should be as compact as possible so that shading to crops is minimized.

- Acceptable cost. The cost of these new technologies must be low enough that their purchase price can be offset by electricity savings or improved crop growth within a reasonable period of time (e.g., within 5 years). Because many greenhouses use supplemental lighting for only 3 or 4 months of the year, returns on investment can be longer. However, mass production and sales will rapidly reduce costs of equipping greenhouses compared to initial prototype models.

- Acceptable effect of light quality on plant morphology. The spectral output of lamps can influence plant height and chlorophyll concentration. Therefore, effects of lighting on plant morphology and appearance must also be considered.

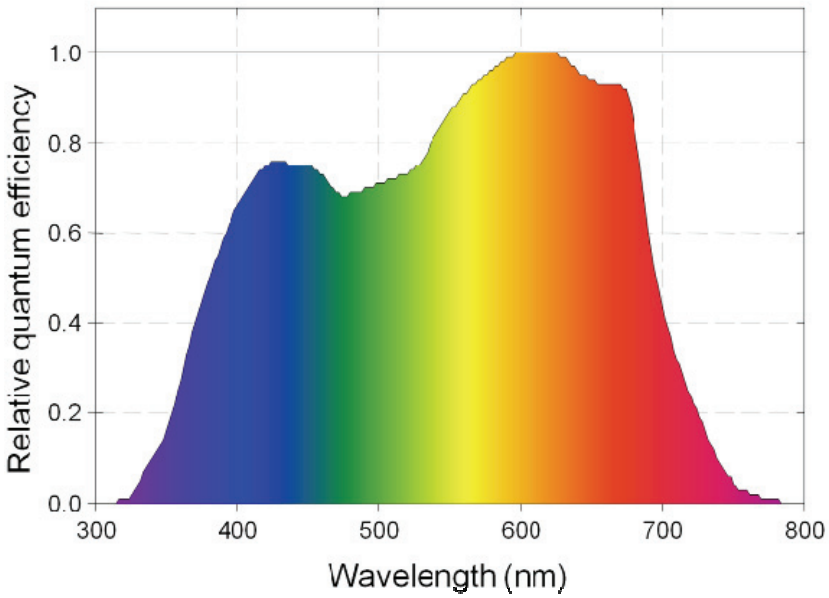


Fig. 1. The relative quantum efficiency curve developed by McCree (1971), which compares the efficacy of different wavelengths of light at eliciting photosynthesis.

Mean daily temperature

Temperature is the most commonly manipulated environmental factor in greenhouse production. The growing temperature used by commercial growers depends on numerous factors including: time of year, greenhouse location, environmental control systems, fuel cost for heating, crop finish dates, desired plant quality and size, stage of development, and plant species. Temperature also influences plant quality parameters such as flower number and size, branching, and mass. For example, flower bud number and flower size of lance coreposis, blanket

flower (*Gaillardia* ×*grandiflora*), and Shasta daisy (*Leucanthemum* ×*superbum*) increased as average daily temperature decreased from 27 °C to 15 °C (Yuan et al., 1998).

Efficient and predictable commercial production of greenhouse crops requires information on how species respond to the environment so that they can be accurately scheduled to finish for predetermined market dates. Studies have been performed on many economically important floriculture crops to quantify how light and temperature influence growth and development. Data from these experiments have been used to generate crop models that predict how changing environmental factors, such as mean daily temperature (MDT), affect the rate of plant development. Several analytical approaches have been described to model plant development rate in response to environmental conditions.

Plant developmental responses to temperature, such as flowering or leaf unfolding rate, are primarily controlled by the integrated mean daily temperature (MDT). The time required for the completion of a developmental event (e.g., time to unfold one leaf or time to anthesis) can be converted to a rate by calculating the reciprocal of time (e.g., 1/days). The parameters of the model are specific to a genotype or a development stage (Summerfield et al., 1991). In this model, the relationship between MDT and development rate is linear between the base temperature (T_{min}) and optimum temperature (T_{opt}). T_{min} is the temperature at or below which the rate of progress toward a developmental stage is zero and varies considerably among plant species (Roberts and Summerfield, 1987). T_{opt} is defined as the temperature at which the rate of progress toward a developmental event is maximal and also is species specific. Polynomial and exponential equations have also been used to describe the influence of MDT on development rate. The rate of plant development can also be secondarily influenced by other environmental factors, and

multiplicative models have been developed that combine factors such as MDT, photoperiod, and/or DLI. For example, we have developed such models for several ornamental annual crops (Moccaldi and Runkle, 2007; Pramuk and Runkle, 2005a), and models for >20 ornamental species are currently under development (Blanchard, 2009).

Temperature can also influence flower initiation and development. For example, temperature is the primary factor that controls inflorescence initiation and development of *Phalaenopsis* orchids. Undifferentiated buds at the base of each node remain dormant indefinitely when exposed to constant temperatures of ≥27 ºC (Sakanishi et al., 1980). After at least three weeks of exposure to temperatures <26 ºC, one or more of these buds can elongate and become an inflorescence (Sakanishi et al., 1980; Lee and Lin, 1984). For example, plants uniformly initiated inflorescences when grown at day/night temperatures of 25/20 ºC or 20/15 ºC for 4 to 5 weeks.

Constant and fluctuating day/night temperatures have similarly promotive effects on inflorescence initiation of *Phalaenopsis* when both are <26 ℃; a day/night temperature fluctuation does not accelerate flowering (Blanchard and Runkle, 2006). However, daily or periodic exposure to temperatures ≥26 ℃ can delay or completely inhibit flowering. High temperature flowering inhibition is apparently dependent on the cultivar, plant maturity, and the timing, duration, frequency, and magnitude of the high temperature. For example, inflorescences did not emerge from *Phalaenopsis* Miva Smartissimo × Canberra '450' or Brother Goldsmith '720' plants within 20 weeks when grown at a 12-h day temperature of 29 ℃ and a night temperature of 17, 23, or 29 ℃ (Blanchard and Runkle, 2006).

High-temperature inhibition of the emergence of an inflorescence was first reported by Sakanishi et al. (1980) on *Phalaenopsis amabilis*: 84% of plants exposed to 28 ℃ for 12 h developed an inflorescence, whereas only 46% of plants developed

an inflorescence when the high temperature was delivered for 14 h. Flowering of *Doritaenopsis* 'Lava Glow' plants was completely prevented when grown at a 12-h day temperature of 30 ℃ and night of 20 ℃ (Wang, 2007). Interestingly, none of the plants grown at a 12-h day/night of 25/30 ℃ or 30/25 °C flowered. In *Doritaenopsis* 'Newberry Parfait', 80% of plants flowered when exposed to 8 h at 29 ℃ each day (the remaining time was at 20 ℃), but time to flower was 7 to 8 weeks later than that of plants at a constant 20 ℃ (Newton and Runkle, 2009).

Once an inflorescence has initiated, time to the first open flower is dependant on the variety and mean temperature. However, if a plant with an inflorescence <10 cm is subsequently grown at ≥28 ℃, an inflorescence can elongate indefinitely without flowering, flower buds can abort, and a vegetative plant can develop on the inflorescence instead of flower buds (Sakanishi et al., 1980). At temperatures ≤26 ℃, time to appearance of an inflorescence and time to flower is increasingly delayed as mean temperature decreases. For example, time from inflorescence appearance to first open flower of two *Phalaenopsis* cultivars was delayed by 9 to 17 d as temperature decreased from 23 to 20 ℃ (Blanchard and Runkle, 2006). In addition, inflorescence and flower bud number were generally greater when *Phalaenopsis* were grown at lower temperatures (e.g., ≤20 ℃; Lee and Lin, 1984; Blanchard and Runkle, 2006).

Greenhouse temperature and energy consumption

In temperate climates, high energy inputs can be required to maintain a desirable greenhouse temperature, making fuel for heating one of the largest floriculture production expenses (Bartok, 2001). In the Netherlands, greenhouses account for 79% of the energy used by the agricultural sector and 7% of the country's total energy consumption (Lansink and Ondersteijn, 2006). Rising and volatile fuel costs for

heating greenhouses have motivated many growers to improve energy conservation and to minimize energy inputs for greenhouse crop production.

Models that predict the effect of temperature on plant development can be used to estimate crop production time periods at a range of greenhouse temperatures. For example, petunia 'Wave Purple' grown under a long day takes approximately 64 days from transplant of a seedling until first flowering at an MDT of 14 ℃, whereas time to flower is less than half that time at 23 ℃ (Fig. 2).

The Virtual Grower computer program can be used to estimate greenhouse heating costs in the United States. The program was developed by Jonathan Frantz and colleagues at the USDA-ARS in Toledo, Ohio and is available free at www.virtualgrower.net. Version 2.6 was released in June 2010 and the program continues to be developed. Once the program is downloaded and installed, the user can create a virtual greenhouse and enter information such as their location, greenhouse dimensions and design, greenhouse construction materials, heating system characteristics, fuel type and price, heating schedule, and presence and type of energy curtain. That information is used to estimate heating costs per square foot per month. By changing one or more variables, such as planting date or temperature setpoint, one can predict the effect on fuel costs. For example, using the scheduling information of petunia 'Wave Purple' from Fig. 2, the estimated heating cost to produce plants in flower on April 1 in Grand Rapids, Michigan at 17 ℃ is $0.45 per square foot of production space (Fig. 3). If transplanted later and grown at 23 ℃, the estimated heating cost is reduced by 11% to $0.40 per square foot. As expected, heating costs are lower for a greenhouse with the same characteristics but located in a warmer climate. Thus, with adequate crop information and software such as Virtual Grower, growers can identify a temperature regimen that consumes the least amount of energy on a per-crop basis.

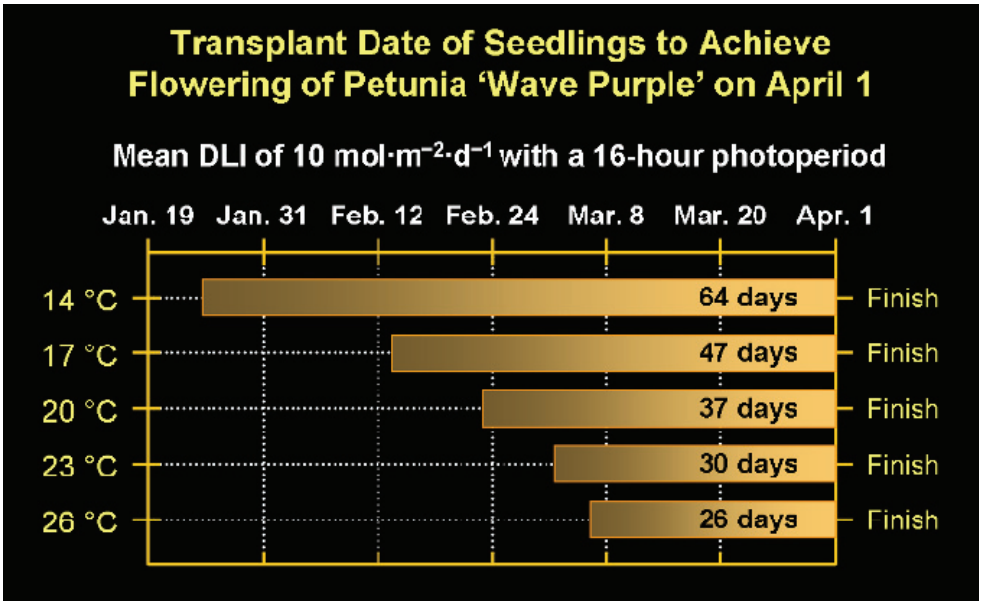


Fig. 2. The effect of mean daily temperature on crop timing and estimated planting date of petunia 'Wave Purple' so that plants are in flower on April 1.

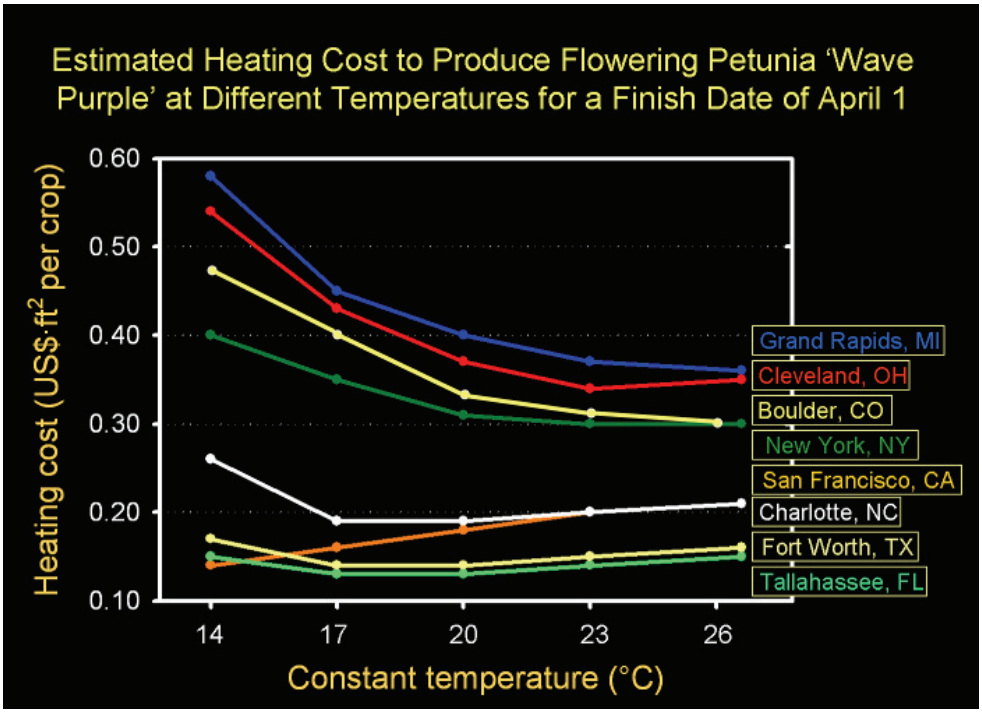


Fig. 3. Estimated heating costs to produce flowering petunia 'Wave Purple' for April 1 at a range of locations in the United States using Virtual Grower software.

Literature cited

Bartok, J. W. Jr. 2001. Energy conservation for commercial greenhouses. Natural Resource, Agriculture, and Engineering Service Cooperative Extension, Ithaca, NY.

Blanchard, M. G. 2009. Manipulating light and temperature for energy-efficient greenhouse production of ornamental crops. Ph.D. thesis. Michigan State Univ., East Lansing.

Blanchard, M. G. and E. S. Runkle. 2010. Intermittent light from a rotating high-pressure sodium lamp promotes flowering of long-day plants. HortScience 45: 236-241.

Blanchard, M. G. and E. S. Runkle. 2006. Temperature during the day, but not during the night, controls flowering of *Phalaenopsis* orchids. J. Expt. Bot. 57:4043-4049.

Blanchard, M. G. and E. S. Runkle. 2009. Use of a cyclic high-pressure sodium lamp to inhibit flowering of chrysanthemum and velvet sage. Scientia Hort. 122: 448-454.

Fisher, P. and A. J. Both. 2004b. Supplemental Lighting Technology and Costs. p. 43-46. In: P. Fisher and E. Runkle (eds.), Lighting Up Profits: Understanding Greenhouse Lighting. Meister Media Worldwide, Willoughby, Ohio.

Lansink, A. O. and C. Ondersteijn. 2006. Energy productivity growth in the Dutch greenhouse industry. Amer. J. Agr. Econ. 88: 124-132.

Lee, N. and G. M. Lin. 1984. Effect of temperature on growth and flowering of *Phalaenopsis* white hybrid. J. Chinese Soc. Hort. Sci. 30: 223-231.

Lopez, R. G. and E. S. Runkle. 2008. Photosynthetic daily light integral during propagation influences rooting and growth of cuttings and subsequent development of New Guinea impatiens and petunia. HortScience 43: 2052-2059.

Massa, G. D., H. H. Kim, R. M. Wheeler, and C. A. Mitchell. 2008. Plant productivity in response to LED lighting. HortScience 43: 1951-1956.

McCree, K. J. 1961. The action spectrum, absorptance, and quantum yield of photosynthesis in crop plants. Agric. Meteorol. 9: 191-216.

Moccaldi, L. A. and E. S. Runkle. 2007. Modeling the effects of temperature and photosynthetic daily light integral on growth and flowering of *Salvia splendens* and *Tagetes patula*. J. Amer. Soc. Hort. Sci. 132: 283-288.

Morrow, R. C. 2008. LED Lighting in Horticulture. HortScience 43: 1947-1950.

Newton, L. A. and E. S. Runkle. 2009. High-temperature inhibition of flowering of *Phalaenopsis* and *Doritaenopsis* orchids. HortScience 44: 1271-1276.

Oh, W., E. S. Runkle, and R. M. Warner. 2010. Timing and duration of supplemental lighting during the seedling stage influence quality and flowering in petunia and pansy. HortScience (in press).

Pramuk, L. A. and E. S. Runkle. 2005a. Modeling growth and development of celosia and impatiens in response to temperature and photosynthetic daily light integral. J. Amer. Soc. Hort. Sci. 130: 813−818.

Pramuk, L. A. and E. S. Runkle. 2005b. Photosynthetic daily light integral during the seedling stage influences subsequent growth and flowering of *Celosia*, *Impatiens*, *Salvia*, *Tagetes*, and *Viola*. HortScience 40: 1336-1339.

Roberts, E. H. and R. J. Summerfield. 1987. Measurement and prediction of flowering in annual crops, p. 17-50. In: Atherton, J.G. (ed.). Manipulation of flowering. Butterworths, Kent, UK.

Runkle, E. S., R. D. Heins, A. C. Cameron, and W. H. Carlson. 1998. Flowering of herbaceous perennials under various night interruption and cyclic lighting treatments. HortScience 33: 672-677.

Sakanishi, Y., H. Imanishi, and G. Ishida. 1980. Effect of temperature on growth and flowering of *Phalaenopsis amabilis*. Bull. Univ. Osaka Prefecture, Series B: Agri. Biol. 32: 1-9.

Smith, H. 1994. Sensing the Light Environment: The Functions of the Phytochrome Family. p. 377-416. In: R.E. Kendrick and G. H. M. Kronenberg (eds.), Photomorphogenesis in Plants 2nd ed. Dordrecht, The Netherlands, Kluwer Academic Publ.

Summerfield, R. J., E. H. Roberts, R. H. Ellis, and R. J. Lawn. 1991. Towards the reliable prediction of time to flowering in six annual crops. I. The development of simple models for fluctuating field environments. Expt. Agr. 27: 11-31.

Thimijan, R. W. and R. D. Heins. 1983. Photometric, radiometric, and quantum light units of measure: A review of procedures for interconversion. HortScience 18: 818-822.

Thomas, B. and D. Vince-Prue. 1997. Photoperiodism in Plants, 2nd ed. Academic Press, London.

Wang, Y. T. 2007. Average daily temperature and reversed day/night temperature regulate vegetative and reproductive responses of a *Doritis pulcherrima* Lindley Hybrid. HortScience 42: 68-70.

Whitman, C. M., R. D. Heins, A. C. Cameron, and W. H. Carlson. 1998. Lamp type and irradiance level for daylength extensions influence flowering of *Campanula carpatica* 'Blue Clips', *Coreopsis grandiflora* 'Early Sunrise', and *Coreopsis verticillata* 'Moonbeam'. J. Amer. Soc. Hort. Sci. 123: 802-807.

Yuan, M., W. H. Carlson, R. D. Heins, and A. C. Cameron. 1998. Effect of forcing temperature on time to flower of *Coreopsis grandiflora*, *Gaillardia* ×*grandiflora*, *Leucanthemum* ×*superbum*, and *Rudbeckia fulgida*. HortScience 33: 663-667.