Improving Greenhouse Production Efficiency

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There are a variety of strategies that can be used to reduce greenhouse energy costs. This section focuses on environmental factors (temperature and light) that can be manipulated to produce crops in a relatively short period of time, thus improving the space use efficiency of your greenhouse. Ideally, concepts in this section are implemented and integrated with other energy-conservation strategies.

Two primary environmental factors that control plant growth and development are temperature and light. Although these two factors have distinct effects on plants, they interact in many ways. In order for growers to be able to optimize crop production, knowledge of how these factors influence plant growth and development is very important. This section discusses the fundamentals of temperature and light and how this information can be used to improve production efficiency and reduce production time. In addition, the effects of plug and liner size on finishing time is also discussed.

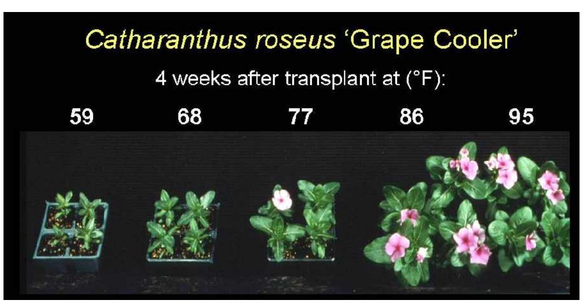

Figure 1. The effects of average daily temperatures from 59 to 95 °F (15 to 35 °C) on the development of 'Grape Cooler' vinca (*Catharanthus roseus*). Photo courtesy of Royal Heins, Michigan State University.

Temperature Optimization and Integration

The rate of plant development (time to flower or the production of roots) is primarily influenced by the average daily temperature. The average daily temperature is the mathematical average temperature over a series of 24-hour periods and can be calculated as:

Average daily temperature = [(day temperature × hours) + (night temperature × hours)] ÷ 24

The average daily temperature is important to calculate because it determines the rate of plant development. Generally, the warmer the average daily temperature, the faster a plant grows. It's analogous to how fast you drive your automobile to get to work. The faster you drive, the earlier you arrive at work. Similarly, the warmer your crops are grown, the quicker they will grow and become ready for market. Therefore, if you lower the average daily temperature in the greenhouse, plants will take longer to become marketable. This applies to plugs, flats, potted crops, hanging baskets, and any other size of plant or container. There are also other factors that influence crop timing, including photoperiod and the average daily light integral, both of which are discussed later.

How can we use average daily temperature to schedule a crop? Many greenhouse crops produce a set number of leaves before flower initiation and we are able to track the rate of progress towards flowering by counting the number of leaves that unfold each day. Easter lily growers are familiar with this leaf counting technique to track plant development and ensure that their crop is on schedule. We can control the rate of leaf unfolding and flowering time by raising or lowering the average daily temperature. **Figure 1** shows an example of vinca (*Catharanthus roseus*) grown at an average daily temperature of 59 to 95 °F (15 to 35 °C). At a cool temperature (59 °F or 15 °C) the rate of leaf unfolding is very slow and time to flower is >100 days, whereas at a warm temperature (86 °F or 30 °C), leaf unfolding is faster and time to flower is ≈30 days.

Base and Optimum Temperature

The relationship between average daily temperature and growth and development is linear between the base and optimum temperature (**Figure 2**). The *base temperature* is a cool temperature at which a plant stops growing. The base temperature can vary considerably from crop to crop. For example, the base temperature for seed petunia is about 39 °F (4 °C), which means that at or below this temperature, petunias essentially stop growing. For a warm-growing crop such as vinca, the base temperature is much higher, around 50 °F (10 °C). Experienced growers can often predict which crops have a low base temperature because they are usually grown cooler than plants that have a high base temperature. During the winter and spring, floriculture crops are often grown about 20 to 30 °F (11 to 17 °C) higher than their base temperatures.

We rarely want to grow plants at or near the base temperature because plant development is too slow. One of the few times when a growing temperature near the base temperature is desirable is when plants need to be held because the markets are not available to receive plants, which can occur when sales are slow following an extended period of rainy weather. Another example is when perennials or bulbs are provided with cool temperature treatments to satisfy a vernalization response.

Growers should also know what the optimum temperature is for a crop. The *optimum temperature* is the temperature at which plant development is most rapid (**Figure 2**). As temperature increases beyond the optimum value, growth slows as plants show symptoms of heat stress. Therefore, in most instances, crops are grown above the base temperature but not above the optimum temperature of the crop. The optimum temperature can be around 70 °F (21 °C) for cool-season crops such as pansy and alyssum, or as high as 90 °F (32 °C) for warm-season crops such as vinca and hibiscus. Note that the optimum temperature for plants is not based on plant quality attributes, and thus the optimum temperature is not necessarily the most desirable growing temperature.

During production, it is important to consider actual plant temperature and not just the surrounding air temperature. Actual plant temperature is influenced by many factors including conduction, convection, transpiration, and radiation and thus plant temperature can be several degrees warmer or cooler than air temperature. Later in this section, we discuss how adding supplemental lighting in the greenhouse can affect plant temperature and crop development. The best tool to determine the actual plant temperature of your crop is to use an infrared thermometer. Infrared thermometers are very accurate and can be a great investment for any greenhouse grower.

As discussed earlier, the average daily temperature of the greenhouse can be adjusted to speed up or slow down the development of a crop. However, the effects of changing the

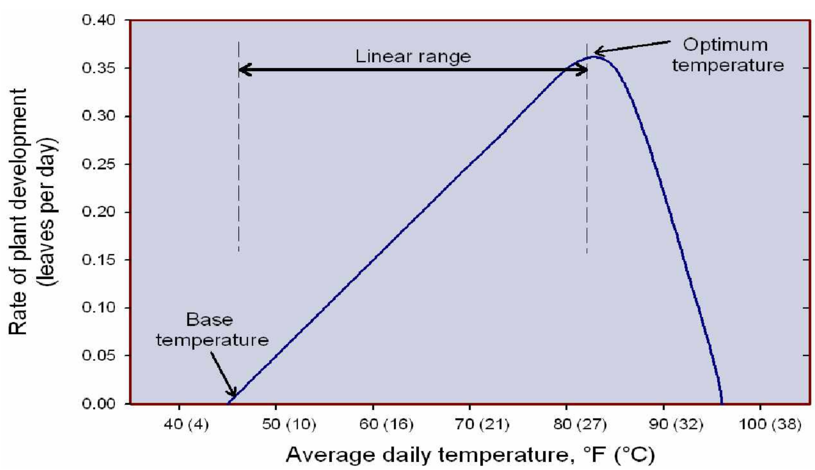

Figure 2. The rate of plant development (such as leaf unfolding) is linear between the base temperature and the optimum temperature.

average daily temperature depends on the species, the magnitude of the change, and the original temperature setpoint. For example, the effect of changing the average daily temperature on crop timing of petunia and vinca is illustrated in **Figure 3**. Lowering the temperature by 5 °F has a somewhat small effect at warm temperatures, and has a larger effect at cooler temperatures. For example, lowering the average daily temperature by 5 °F from 65 to 60 °F delays a petunia crop (from seed) by about 13 days, and lowering the temperature from 60 to 55 °F delays petunia by 22 days. The effect of lowering the temperature can have a more dramatic effect on cold-tolerant crops. For example, lowering the temperature from 65 to 60 °F increases time to flower of vinca (from a plug) by about 30 days – much longer than the delay in petunia with the same temperature decrease.

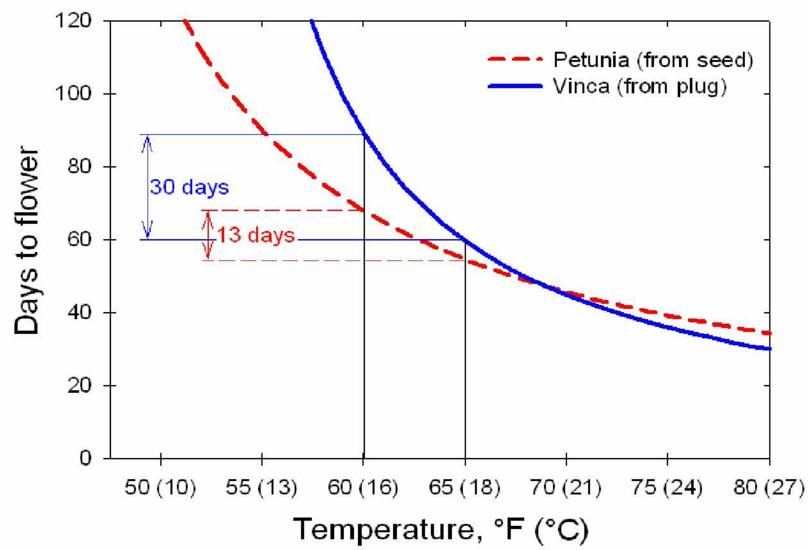

Figure 3. The effect of temperature on time to flower of petunia (*Petunia ×hybrida*) from seed and vinca (*Catharanthus roseus*) from a small plug. When temperature is decreased, there is a larger delay in flowering for plants with a high base temperature (vinca) compared to plants with a lower base temperature (petunia).

Cold-Tolerant and Cold-Sensitive Crops

Plants respond differently to temperature partly because they have different base temperatures. Plants with a base temperature of 39 °F (4 °C) or lower can be called "cold-tolerant plants" and those with a base temperature of 46 °F (8 °C) or higher can be called "cold-sensitive plants". We categorize plants by their base temperature because they differ in how they respond to lowering the greenhouse temperature; generally cold-sensitive plants are more responsive to lowering the greenhouse temperature than cold-tolerant species. So, if you are determined to lower your greenhouse temperature set point, you'll likely delay crop timing more with cold-sensitive crops. See **Table 1** for a list of plants categorized by their base temperatures. Ideally, crops with different base temperatures should be grown in separate greenhouses with different temperature set points to produce crops in an energy-efficient manner.

Temperature Integration

The concept of "temperature integration" has been used by many Dutch greenhouse growers in recent years. This term describes how plants respond to temperature over a period of time. Simply put, the rate of plant development is dependant upon the average daily temperature from the time you plant the crop. This is a very simple but powerful concept. Plants respond to the temperature constantly, and they grow progressively faster as temperature increases, and grow progressively slower as temperature decreases. The exception to this rule is when cool-season crops are grown very warm, and at some high temperature (above the optimum) these plants begin to experience stress and the rate of crop development begins to decrease. In addition, once crops are exposed to temperatures at or below their base temperature, a further temperature decrease does not influence crop timing.

What is the implication of temperature integration? If your day and night are each 12 hours long, and if you lower your night temperature without increasing your day temperature the same amount, your average daily temperature will decrease. Thus, cooler nights without warmer days will increase the time it takes for your crop to become shippable or transplantable. If your night temperature settings are longer than 12 hours, then you need to offset the shorter day temperature set point even more so that your 24-hour average temperature stays the same.

New technology in greenhouse climate controls now utilizes the concept of temperature integration to reduce energy consumption for heating. For example, during conditions when solar radiation is high and greenhouse temperature naturally increases, climate controls maintain a higher day temperature. To offset the warm day temperature and save on energy, the climate control system lowers the night temperature set point. Although the heating and ventilation set points change often, a similar average daily temperature is maintained over time, and the crop finishes on schedule. These new climate control systems also incorporate weather forecasting to make adjustments to the temperature settings. Growers in The Netherlands are already using this technology, and we expect similar systems will be used by large growers in the United States in the near future. For more information in this topic, see article by Rijsdijk and Vogelezang, 2000.

Does Lowering Temperature Save Fuel?

This is a common question many greenhouse growers ask. As discussed previously, lowering the average daily temperature can increase the production time of a crop. If you lower the temperature set point, but still plan to finish the crop on the same market date as in previous years, then adjustments will need to be made to your production schedule. One option is to begin production with a more mature crop (such as transplanting from a 128-cell plug instead of a 588-cell seedling), which will reduce production time in the finished container (see our discussion on this topic later). A second option to compensate for the lengthened production time at the lower temperature is to transplant the crop earlier in the year. If you transplant earlier in the year, chances are you're going to open up the greenhouse earlier in the year, when it is colder outside and thus energy consumption for heating is relatively high. A simple question follows: is it economical to increase the production time to compensate for a lower average greenhouse temperature?

During the winter and early spring, it can be more energy-intensive to grow crops at cooler temperatures than to open up the greenhouse later and use a warmer growing temperature. A lower temperature set point requires less heating, which translates into less fuel consumption per month. However, a temperature reduction also increases crop timing, meaning that plants are in the greenhouse longer. A longer production time has several negative consequences, including:

- overhead expenses (cost per ft^2 per week) are greater for that crop
- the crop takes longer to finish, so you will turn fewer crops per year
- a longer crop time means that you will have to heat the crop longer and possibly open up a greenhouse earlier, when it is colder outside.

There are other consequences to growing crops in a cool greenhouse. One concern is that plants take longer to dry out, so they stay wet longer. Also, because cool air holds less moisture than warmer air, the relative humidity can be higher in a cool greenhouse. Pathogens can be more problematic when crops are kept moist and when the humidity is high.

Energy Consumption Models

Hiroshi Shimizu at the University of Ibaraki in Japan developed a sophisticated model to predict how much energy is consumed to heat a greenhouse to produce a crop. The simulations are complex and depend on environmental factors (outdoor temperature, light levels, and wind speed), numerous greenhouse factors (glazing type, use of thermal curtains, sidewall and floor insulation, etc.), the crop grown and the greenhouse temperature set point. **Figure 4** illustrates the predicted energy consumption to heat a crop in Michigan with different finish dates and three temperature set points. This simulation was based on Michigan weather data, a greenhouse crop with a base temperature of 41 °F (5 °C), and several assumptions for a "typical" double-poly greenhouse.

From winter until mid-summer, the model predicts that the total amount of energy used to heat a crop (from transplant to flowering) actually *increased* as the growing temperature decreased. In other words, it was more expensive to heat a crop planted earlier in the year and grown at a cool temperature compared to opening a greenhouse later and using a higher temperature set point. The opposite was true for crops grown in the fall; an earlier planting date and a lower greenhouse temperature consumed the least amount of energy.

A more user-friendly software program to predict greenhouse energy consumption, *Virtual Grower,* has been developed by Jonathan Frantz and colleagues at the USDA-ARS Greenhouse Production Research Group in Toledo, Ohio. This software provides the ability for growers to predict heating costs based on user-defined inputs such as growing temperature, greenhouse location and structure, time of year, fuel type, fuel cost, etc. *Virtual Grower* is a great tool for greenhouse growers, but a limitation to this software is that data on crop timing are not included. Future versions of *Virtual Grower* will include specific crop data so growers can predict both crop timing and energy consumption at different temperature set points. For more information on *Virtual Grower* or to download a free copy, visit www.ars.usda.gov/Research/docs.htm?docid=11449.

Temperature Effects on Plant Quality

There is one major benefit to growing crops relatively cool in the winter and spring, when light is limiting in northern latitudes. Crops

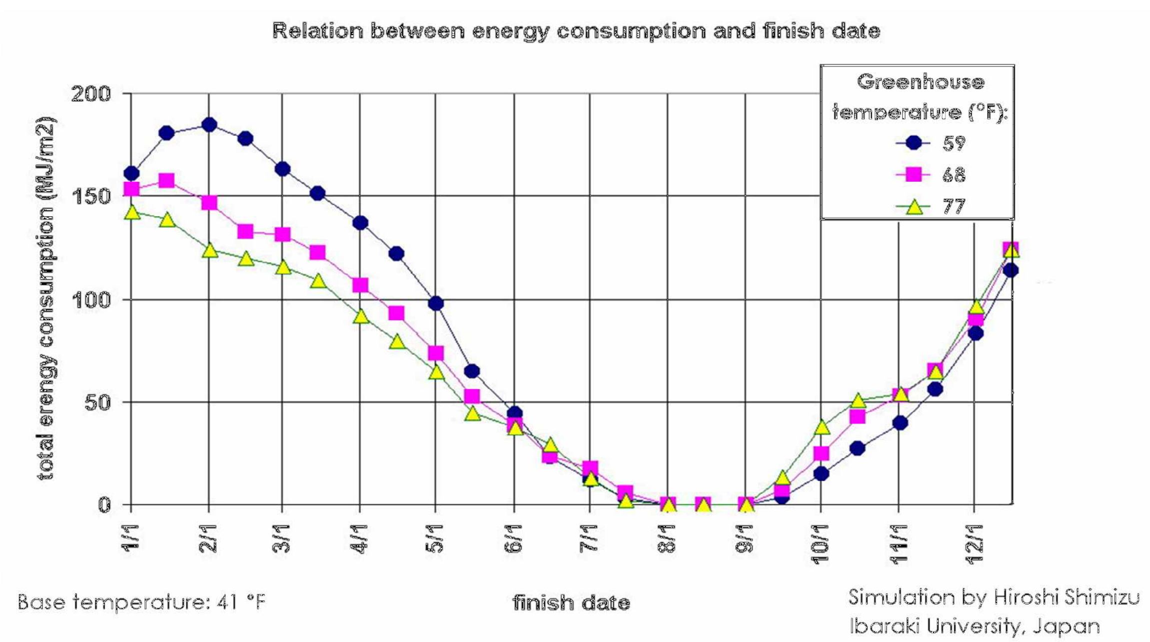

Figure 4. The estimated amount of energy required to produce a crop at different growing temperatures throughout the year in Michigan. This simulation indicates that the total amount of energy consumed to produce a flowering crop increased as growing temperature decreased from winter through mid-summer.

grown cool take longer to flower, and thus they have a longer period of time to harvest light. Because of this, many plants (especially cold-tolerant crops) are of higher quality when grown at moderately cool temperatures. When ready for transplant, plugs grown at cool temperatures often have thicker stems, better rooting, and greater branching. Similarly, finish crops grown cool can have more branching and produce more, larger flowers. The effects of forcing temperature on flower size of 'Blue Clips' Carpathian harebell (*Campanula carpatica*) is illustrated in **Figure 5**. At a warm forcing temperature (70 °F or 21 °C) plants flowered in 7 to 8 weeks, while at a cool forcing temperature (60 °F or 15 °C), plants flowered after 10 to 11 weeks. However, plants forced at a warm temperature had a significant reduction in flower size. There are some floriculture crops, such as hibiscus, that do not perform well at cool temperatures. For such tropical crops, plant quality is highest when grown at a moderately warm temperature [70 °F (21 °C) or higher].

Therefore, there is often a trade-off between high quality crops and crop timing. Cooler temperatures produce higher quality plants but they take longer to reach maturity and energy consumption per crop can be greater. Crops grown at warm temperatures develop faster and thus have shorter crop times and require less energy for heating, but the quality of plants is

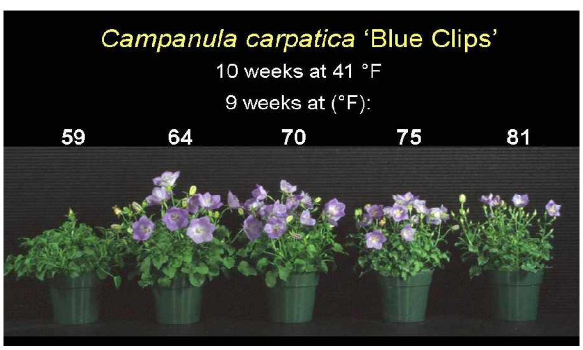

Figure 5. The effects of forcing temperatures from 59 to 81 °F (15 to 27 °C) on plant quality of 'Blue Clips' Carpathian harebell (*Campanula carpatica*). At a warmer temperature, plants flowered earlier but flower size was reduced compared to plants forced at a cooler temperature. Photo courtesy of Cathy Whitman, Michigan State University.

often not as high. If a grower is unable get a higher price for a higher quality crop, then there is little incentive to grow cool.

Use of Lighting to Accelerate Crop Timing

Light has primarily two functions during plant growth and development. First, light influences plant growth (stem thickness, rooting, branching, etc.) through the process of photosynthesis. Secondly, light influences several developmental processes, such as seed germination and flowering. During crop production, growers can manipulate the length of the day to influence flowering of crops sensitive to photoperiod, and add supplemental lighting to a crop to increase the amount of photosynthesis and thus plant growth.

Photoperiodic Lighting

Flowering in many greenhouse crops is regulated by the duration of light that a plant receives in every 24-hour period, which is referred to as *photoperiod*. For example, a 16-hour photoperiod is 16 hours of light and 8 hours of darkness. Research has shown that the duration of darkness – not the duration of light – is what controls the photoperiodic response in plants. Plants can be categorized according to how photoperiod influences flowering:

- *Long-day plants* flower when the night length is shorter than a critical duration (the photoperiod is long).
- *Short-day plants* flower when the night length is longer than a critical duration (the photoperiod is short).
- *Day-neutral plants* flower under all photoperiods and flowering is not regulated by photoperiod.

Plants that flower in response to photoperiod can be further classified as having a *facultative* or *obligate* photoperiodic response. A facultative response describes a plant that will flower faster under a particular photoperiod, but will eventually flower under any photoperiod. A plant having an obligate photoperiodic response

Figure 6. The effects of photoperiod on flowering of Black-eyed Susan (*Rudbeckia fulgida* 'Goldstrum'). Rudbeckia is an obligate long-day plant with a critical photoperiod of 13 hours following a cold treatment (as shown below) and 14 hours without a cold treatment. When the photoperiod is shorter than the critical photoperiod, *Rudbeckia* will remain as a rosette. Photo courtesy Erik Runkle, Michigan State University.

will only flower if grown under the appropriate photoperiod. For example, black-eyed Susan (*Rudbeckia fulgida* 'Goldstrum') is an obligate long-day plant with a critical photoperiod of 13 hours following a cold treatment and 14 hours without a cold treatment (**Figure 6**). When the photoperiod is shorter than the critical photoperiod, *Rudbeckia* do not flower and plants remain as a rosette.

Knowing the photoperiodic response of different greenhouse crops can help to schedule plants in flower for specific dates and also reduce production time. For example, many bedding plants grown in spring are long-day plants and providing photoperiodic lighting can greatly accelerate time to flower and thus reduce production costs. Wave petunia is an obligate long-day plant with a critical photoperiod of 14 hours. In order to have wave petunia in flower for April 1, long days need to be provided artificially to induce flower initiation. **Table 2** and **3** provide a list of many common greenhouse crops and their photoperiodic response groups.

Although a majority of bedding plants are long-day crops, there are a few species that are short-day plants, such as African marigold (*Tagetes erecta*), celosia (*Celosia plumosa*), cosmos (*Cosmos bipinnatus*), and some cultivars of zinnia (*Zinnia elegans*). Providing short days to these crops can significantly reduce time to flower. For example, 'Sonata Pink' cosmos is a facultative short-day plant, and when grown under continuous long days at 68 °F (20 °C), flowers in approximately 65 days. The same cultivar grown at the same temperature but grown under continuous short days flowers in 29 days (**Figure 7**). Research by Ryan Warner at Michigan State University has shown that for some short-day annuals, plants do not have to be grown under continuous short days to stimulate flowering. For example, providing only three weeks of short days to crops such as 'Gloria Scarlet' celosia is sufficient for flower initiation and time to flower is similar to plants grown under continuous short days.

Manipulating Photoperiod

The natural photoperiod depends on the location and time of year. The duration of a short day or long day required to elicit a response depends on the crop grown. For example, some long-day plants flower if the photoperiod is at least 14 hours, whereas others require 15 or 16 hours of light. In general, short

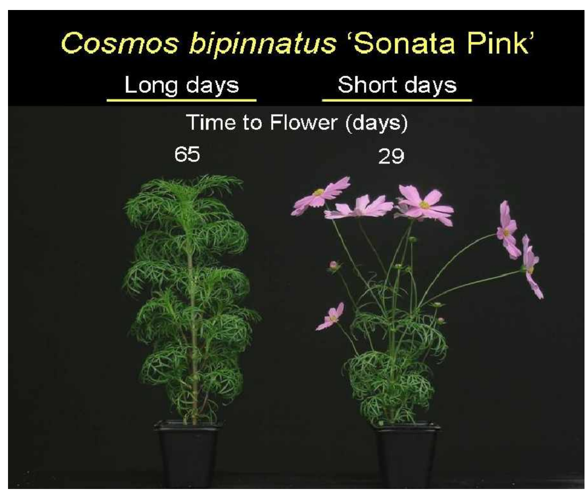

Figure 7. The effect of photoperiod on flowering in the facultative short-day plant cosmos (*Cosmos bipinnatus* 'Sonata Pink'). Plants were grown at 68 °F (20 °C) and under a 4-hour night interruption (long days) or a constant 9-h photoperiod (short days). Photo courtesy of Ryan Warner, Michigan State University.State University.

days exist naturally in the United States and Canada from about October 1 to March 1. Long days occur naturally from about April 15 to September 1. **Figure 8** can be used to more precisely estimate the natural photoperiod at your location. In order to grow plants under a desirable photoperiod for flower induction, it is necessary to understand the options that are available to manipulate photoperiod in the greenhouse.

Creating short days. How can we create short days when natural photoperiods are long? Short days can be created by pulling black plastic or cloth over a crop to block out the light. This can be accomplished manually by employees or with an automated blackout system. After the blackout cloth is pulled over a crop, it is important to look for small gaps where light can enter through the curtain. Some plants are able to perceive very low light intensities, so light levels should be <0.5 footcandles (<0.1 $\mu mol \cdot m^{-2} \cdot s^{-1}$) in a blackout situation. Another important consideration when pulling blackout cloth over a crop is the potential for heat accumulation under the cloth, especially when the system is closed before darkness. Exposure to high temperatures can delay flowering in some crops such as poinsettia (*Euphorbia pulcherrima*). To avoid heat accumulation under a blackout system, growers can: (1) wait until after darkness to close the blackout system and delay opening the system in the morning; (2) pull blackout cloth early in the morning before sunrise and retract later in the morning after plants have been exposed to an appropriate length of darkness; or (3) use a blackout system with an aluminum material to reflect solar radiation.

Creating long days. How can long days be created in the greenhouse when natural photoperiods are short? Long days can be created by breaking up the dark period (night-interruption lighting) or by extending the length of the day (day-extension lighting). Night-interruption lighting or "mum lighting" can be used by turning on the lights in the greenhouse

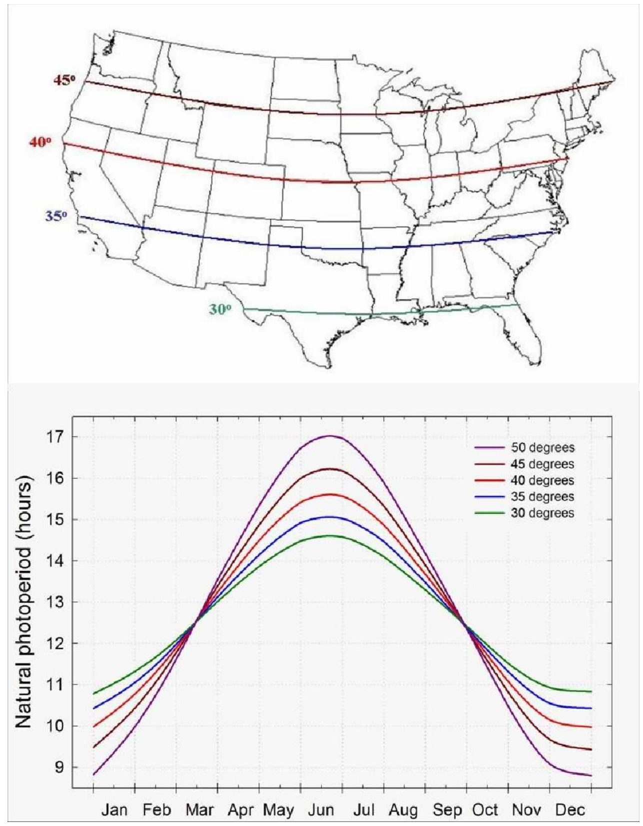

Figure 8. The natural photoperiod, which is approximately 30 minutes longer than from sunrise to sunset, depends on the time of year and geographic location. To estimate the natural photoperiod, determine the approximate latitude of your location (for example, Indianapolis, Indiana is near 40 °N), then use the corresponding curve in the bottom graph.

for four hours continuously (e.g., 10 p.m. to 2 a.m.) to break the night into two short dark periods. Day-extension lighting can be used by turning the lights on at sunset and then turn them off after the critical photoperiod has been provided. Many different lamp types can be used for photoperiodic lighting, such as incandescent or high-pressure sodium lamps (HPS), as long as the minimum light intensity at plant level is at least 10 footcandles (2 $\mu mol \cdot m^{-2} \cdot s^{-1}$).

Another strategy to create long days in the greenhouse is to use cyclical lighting or intermittent lighting. Cyclic lighting can be provided by using incandescent lamps on a timer and setting them to turn on in the middle of the dark period for a specific cycle (e.g., 6 minutes on and 24 minutes off) for a total of four to six hours. Cyclical lighting can save on electrical costs and reduce electrical load. Cyclic lighting is only practical with incandescent lamps, because bulb life of HPS and fluorescent lamps is based on the number of times the lamp is turned on. In addition, HPS lamps require a long time to warm up. However, HPS lamps can be used for cyclic lighting by mounting them on a moving boom and programming the boom to move over the crop about every 5 to 10 minutes for at least 4 hours during the middle of the night.

A relatively new strategy to deliver cyclic lighting is to use a stationary HPS lamp that has an oscillating reflector (such as a Beamflicker). The reflector moves the light across the crop as it rotates, and thus provides intermittent light over the crop. This lighting strategy is very energy efficient because relatively few HPS lamps are required to create long days in the greenhouse.

Supplemental Lighting

High-intensity lamps are used in greenhouses to provide supplemental lighting to increase the rate of photosynthesis, especially during periods when the intensity of sunlight is low. Lighting to promote photosynthesis requires much higher light intensities than that for photoperiodic lighting and is usually provided by HPS or metal halide lamps.

Irradiance

Irradiance refers to the amount of light that a plant receives at a specific point in time. To measure irradiance, greenhouse growers can use hand-held light meters that report light intensity in units of footcandles or mico moles per square meter per second ($\mu mol \cdot m^{-2} \cdot s^{-1}$). Measuring light intensity in $\mu mol \cdot m^{-2} \cdot s^{-1}$ is more appropriate than measurements in footcandles because $\mu mol \cdot m^{-2} \cdot s^{-1}$ quantifies the amount of light energy used for plant photosynthesis. One $\mu mol \cdot m^{-2} \cdot s^{-1}$ of sunlight is equal to approximately 5 footcandles and 54 lux. For more information on measuring irradiance and converting between units of measurement, see chapter 1 in Fisher and Runkle, 2004 and article by Runkle, 2006.

Daily Light Integral

A limitation in reporting light quantity as an instantaneous measurement (e.g., footcandles or $\mu mol \cdot m^{-2} \cdot s^{-1}$) is that it can not be correlated to

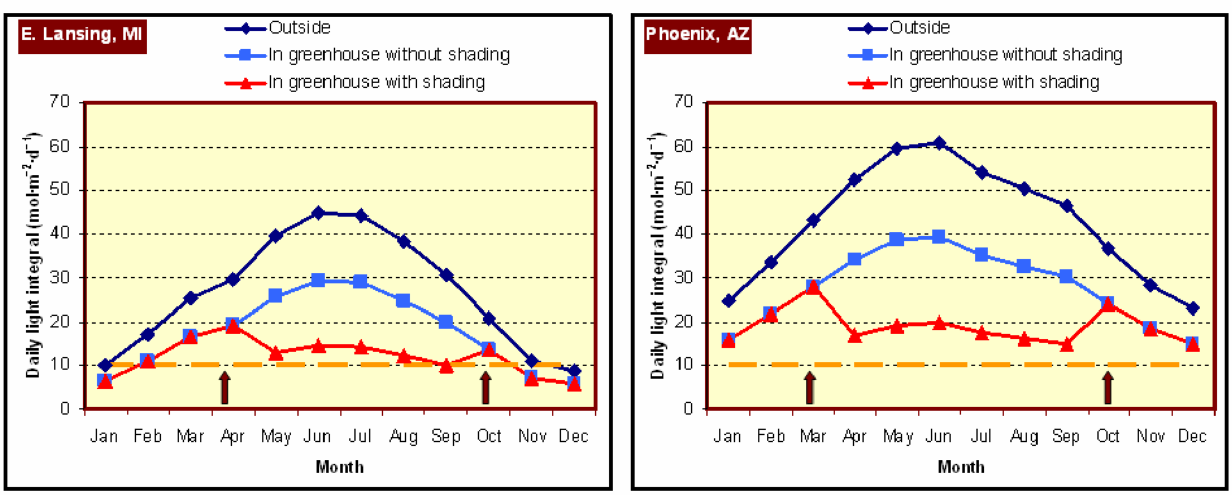

Figure 9. The average daily light integral throughout the year in East Lansing, Michigan (43 °N latitude) and Phoenix, Arizona (33 °N latitude) outside and inside a typical greenhouse (65% light transmission) with or without shading. Arrows indicate when whitewash (50% light transmission) would normally be applied or removed by the grower during the year. The dashed orange line indicates the minimum desirable daily light integral, 10 $mol \cdot m^{-2} \cdot d^{-1}$, to produce most high quality floriculture crops.

plant photosynthesis over time. Daily light integral (DLI) describes the cumulative amount of light that a plant receives in a 24-hour period and is expressed as moles per square meter per day ($mol{\cdot}m^{-2}{\cdot}d^{-1}$). During the year, DLI in a greenhouse can range from low values (5 $mol{\cdot}m^{-2}{\cdot}d^{-1}$) to high values (20 $mol{\cdot}m^{-2}{\cdot}d^{-1}$), due to factors such as the seasonal angle of the sun, cloud cover, day length, and light transmission of the greenhouse structure. For most greenhouse crops, the recommended minimum DLI for finish production is 10 to 12 $mol{\cdot}m^{-2}{\cdot}d^{-1}$. When producing crops during winter in the northern United States, the DLI in the greenhouse is often below 10 $mol{\cdot}m^{-2}{\cdot}d^{-1}$ and supplemental lighting is beneficial to maintain plant quality and crop schedules. **Figure 9** shows the average DLIs throughout the year in East Lansing, Michigan (43 °N latitude) and Phoenix, Arizona (33 °N latitude) outside and inside a typical greenhouse (65% light transmission) with or without shading. In East Lansing, Michigan, the average the DLI inside a greenhouse can range from 5 to 29 $mol{\cdot}m^{-2}{\cdot}d^{-1}$, while in Phoenix, Arizona, the average DLI can vary from 15 to 40 $mol{\cdot}m^{-2}{\cdot}d^{-1}$. It is also important to remember that the greenhouse structure, glazing material, overhead equipment, etc. can also reduce the DLI inside the greenhouse. When hanging baskets are placed overhead, the amount of light reaching the crop below can be reduced considerably and plant quality may be poor, especially in early spring (**Figure 10**).

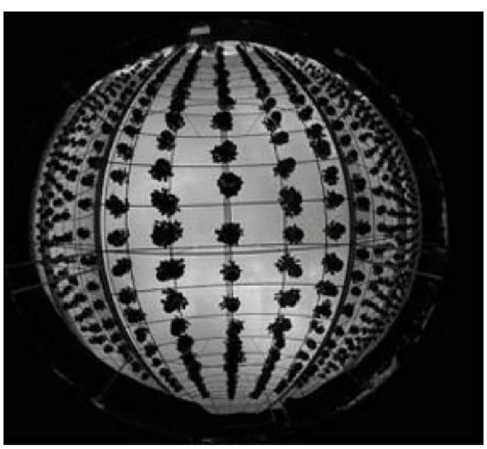

Figure 10. A "plant's eye" view from a greenhouse bench of hanging baskets overhead at a density of 1.5 baskets per square meter of greenhouse space. The hanging baskets in this example intercepted 27% of the incoming solar radiation. Photo courtesy of James Faust, Clemson University.

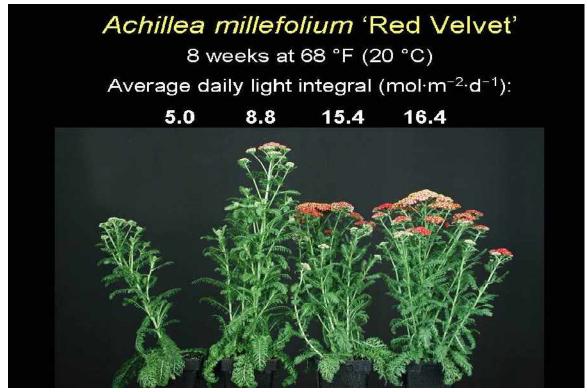

Figure 11. The effects of daily light integral (DLI) on lateral branching, number of flowers, and flower quality in *Achillea millefolium* 'Red Velvet'. Plants were grown for 8 weeks at 68 °F (20 °C) and under an average DLI of 5.0, 8.8, 15.4, or 16.4 $mol{\cdot}m^{-2}{\cdot}d^{-1}$. Photo courtesy of Beth Fausey, Michigan State University.

Adding supplemental lighting to a greenhouse is a relatively expensive investment and operational costs can be high. To minimize operational costs and save on electrical energy, consider only using supplemental lights on cloudy days when irradiance is low. Computers that control the greenhouse environment can be configured so supplemental lights only turn on when ambient light levels outside are below a minimum value, such as 300 $\mu mol{\cdot}m^{-2}{\cdot}s^{-1}$ (1,500 footcandles). Two added benefits to using HPS lamps are (1) heat is emitted from these lamps, which can save on heating fuel, and (2) the energy from the lamps can increase plant temperature, thereby accelerating crop development. For more information on determining if installing supplemental lighting is a good investment for your operation, see chapter 6 in Fisher and Runkle, 2004.

Generally, plants grown under a higher DLI will have smaller and thicker leaves, increased stem diameter, shorter internodes, increased rooting, and more lateral branches and flowers. **Figure 11** shows an example of the effect of increasing DLI on lateral branching, flower number, and flower quality of *Achillea millefolium* 'Red Velvet'. It is also important to monitor and manage DLI during seedling production and rooting of cuttings. For example, 'Vista Red' salvia (*Salvia splendens*) seedlings grown under a high DLI (16 mol·m^{-2}·d^{-1}) had increased rooting in a plug tray compared to seedlings grown under a low DLI (6 mol·m^{-2}·d^{-1}) (**Figure 12**). In addition, during vegetative propagation of petunia Tiny Tunia 'Violet Ice', as the DLI increased from 1.6 to 8.5 mol·m^{-2}·d^{-1}, rooting was accelerated by several days and plugs were ready for transplant earlier (**Figure 13**). For more information on managing light during propagation, see article by Lopez and Runkle, 2005.

Irradiance Response Groups

In some species, plants grown under a higher DLI will also flower faster than plants grown under a lower DLI. The acceleration of flowering under a high DLI is party due to increased plant temperature from supplemental lighting. Some species also develop and flower at a younger stage of maturity when grown under a high DLI compared to a low DLI. Research at the University of Minnesota has shown that plants can be categorized based

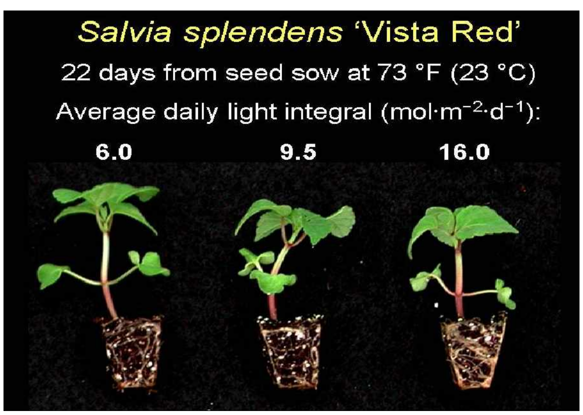

Figure 12. The effect of average daily light integral (DLI) on rooting of 'Vista Red' salvia (*Salvia splendens*). Plants were grown for 22 days after seed sow at 73 °F (23 °C) and under an average DLI of 6.0, 9.5, or 16.0 mol·m^{-2}·d^{-1}. Photo courtesy Lee Ann Moccaldi, Michigan State University.

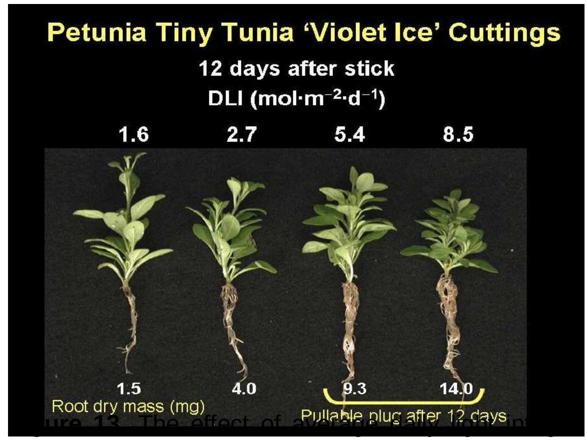

Figure 13. The effect of average daily light integral (DLI) during propagation on rooting of petunia Tiny Tunia 'Violet Ice'. Air temperature was maintained at 79 °F (26 °C) and media temperature was maintained at 75 °F (24 °C). Cuttings were rooted under an average DLI of 1.6, 2.7, 5.4, or 8.5 mol·m^{-2}·d^{-1}. Photograph was taken 12 days after cuttings were stuck. Photo courtesy of Roberto Lopez, Michigan State University.

upon how light quantity affects the flowering response:

- *Facultative irradiance response*- increasing DLI causes plants to develop fewer nodes below the first flower and thus plants flower earlier.
- *Irradiance indifferent response*- increasing DLI does not affect the number of nodes below the first flower and time to flower is not affected.

Table 4 provides a list of several bedding plants and their irradiance response groups. For more information on this topic, see articles by Erwin and colleagues, 2005a, 2005b, 2005c. Knowledge of which crops will flower earlier when provided with supplemental light can be used to reduce production time. In general, the value of supplemental lighting for many ornamental crops begins to diminish once the average DLI in the greenhouse is about 10–12 mol·m^{-2}·d^{-1}. It is important to remember that light and temperature interact to influence plant growth and development. For example, in 'Vista Red' salvia, flowering was hastened by 35 days as temperature increased from 57 to 79 °F (14 to 26 °C) and DLI increased from 6 to 26

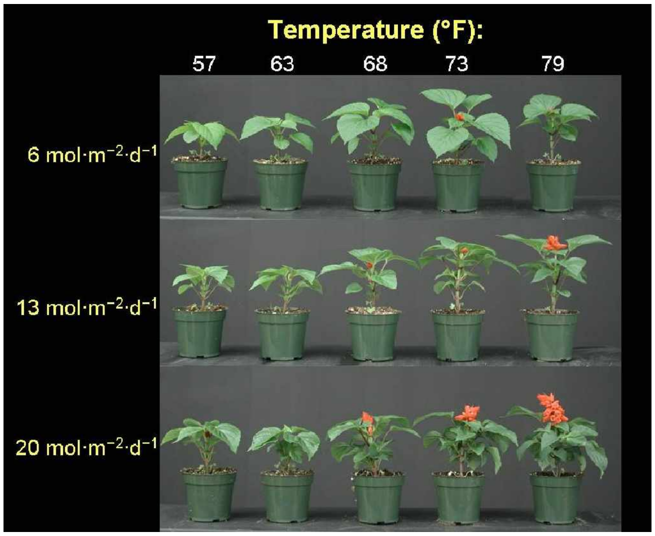

Figure 14. Growth and development of 'Vista Red' salvia (*Salvia splendens*) during the finish stage, after 19 days (from transplant of a 288-cell plug) at various temperatures from 57 to 79 °F (14 to 26 °C) and under an average daily light integral of 6, 13, or 20 $mol{\cdot}m^{-2}{\cdot}d^{-1}$. Photo courtesy of Lee Ann Moccaldi, Michigan State University.

$mol{\cdot}m^{-2}{\cdot}d^{-1}$ (**Figure 14**). For more information on the interaction between temperature and light during bedding plant production, see article by Pramuk and Runkle, 2003.

Providing Supplemental to Plugs

During crop production, one of the most cost-effective uses of supplemental lighting is during the plug and liner stages. Adding supplemental light during this stage is especially important in the northern United States and Canada because a majority of plugs and liners are produced late in the winter and in early spring, when the natural DLI is low. Providing supplemental light to plugs has many advantages including faster growth, shorter internodes, thicker stems, increased root development, and improved quality. Plants grown under supplemental lighting can be several degrees warmer than the ambient air temperature, which can accelerate crop development. The reduced production time from using supplemental lighting during the plug stage provides the opportunity for increased revenue because more crop turns are possible.

The benefits of lighting plugs can become even more apparent after plugs are transplanted into the finish container. In some species, lighting during the plug stage can lead to earlier flowering by reducing the number of leaves formed before the first flower initiates (**Figure 15**). For example, research at Michigan State University has showed that a celosia plug grown under an average DLI of 12 $mol{\cdot}m^{-2}{\cdot}d^{-1}$ flowered 8 days earlier after transplant compared to a plug grown at the same temperature but under an average DLI of 4 $mol{\cdot}m^{-2}{\cdot}d^{-1}$.

How much does is cost to use supplemental lighting on plugs and liners? Calculation estimates indicate that providing supplemental light to plugs adds very little to the cost of a plug. For example, the cost of lighting a 288-cell plug tray for three weeks with HPS lamps is approximately $0.74, which equals about one-third of a cent per plug. Thus, the installation and use of supplemental lighting on plugs can be a cost-effective strategy to shorten crop time and increase plant quality.

Figure 15. The effect of daily light integral (DLI) during the seedling stage on subsequent days to flower in five bedding plant species. After transplant, plants were grown in a common environment at 70 °F (21 °C) and under a 16-hour photoperiod. Information based on research at Michigan State University.

Average DLI ($mol{\cdot}m^{-2}{\cdot}d^{-1}$)	Species				
	Celosia	Impatiens	Marigold	Pansy	Salvia
	Days to Flower				
4	43	37	21	43	28
8	39	28	18	33	25
12	35	25	17	32	21

Greenhouse Space Efficiency

As energy costs continue to rise, greenhouse growers are evaluating the space efficiency of their production area to determine if there are opportunities for improvement. One strategy is to purchase larger plugs or liners for transplanting into finished containers. By purchasing larger liners, the production time in the finish container is reduced and the crop is in the greenhouse for a shorter period. This strategy can improve space-use efficiency and provides the opportunity for an additional crop turn. An additional benefit is the savings in energy for greenhouse heating; when starting with larger liners, production can begin later in the spring when less greenhouse heating is required.

How much production time is saved by transplanting larger liners versus smaller liners? Research by Paul Fisher at the University of Florida has helped to answer this question. **Figure 16** provides an example of how liner size and age influences the production time for finishing *Calibrachoa* 'Superbells Red' grown in 4.5-inch (11-cm) pots. Production time from transplant to finish of calibrachoa can be reduced by 17 days by starting with a 40-mm liner (50-count tray) versus a 20-mm liner (144-count tray). For a complete list of finishing times for various bedding plants, see chapter 16 in Styer and Koranski, 1997.

Liner size	Production Time (Days): Stick to Finished Liner	Production Time (Days): Transplant to Finished Pot
20 mm (144-count)	28	36
23 mm (125-count)	28	34
25 mm (105-count)	35-42	26
30 mm (72-count)	35-42	20
40 mm (50-count)	42	19
50 mm (32-count)	42-49	11

Figure 16. The effect of liner size on time to produce a finished rooted liner of *Calibrachoa* 'Superbells Red' from a direct-stuck cutting and time from transplanting a rooted liner to a finished 4.5-inch (11-cm) pot. Plants were grown at 70 °F (21 °C) under a 16-hour photoperiod and an average daily light integral of 9.3 $mol{\cdot}m^{-2}{\cdot}d^{-1}$. Photo courtesy of Paul Fisher, University of Florida.

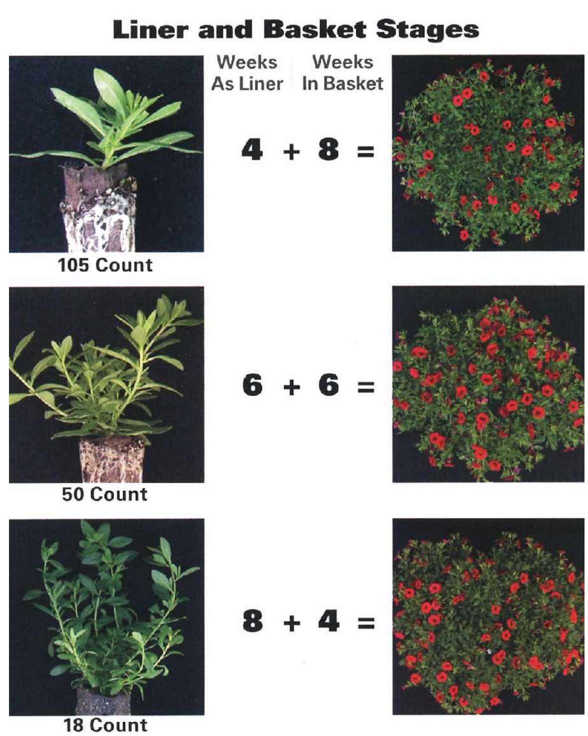

Figure 17. The effects of liner size on finishing time in 12-inch (31-cm) hanging baskets with five liners per basket. Cuttings were stuck into 25-mm (105-count), 40-mm (50-count), or 70-mm (18-count) liner trays and transplanted into hanging baskets after 4, 6, or 8 weeks, respectively. Photographs of liners were taken at the time of transplant into hanging baskets. Photo courtesy of Paul Fisher, University of Florida.

Paul Fisher has also shown that a similar production time can be achieved by substituting time in the liner stage for time in the finished container. For example, when starting with small liners (105-count tray) that are 4 weeks old, plants require 8 weeks to finish in a 12-inch hanging basket, whereas only 4 weeks are needed to finish the hanging basket when starting with large liners (18-count tray) that are

8 weeks old (**Figure 17**). In both scenarios, the total production time is similar, 12 weeks. For a complete summary of this research project, see article by Fisher and colleagues, 2006).

Although starting with larger liners can reduce production time in the finished pot, large liners can be costly to purchase and ship. The most important question is: Does the cost of purchasing larger liners outweigh the savings from reduced production time in the finished container? Paul Fisher has performed a financial analysis to answer this question. The simple answer is that if the savings in cost per square foot week from starting production later are greater than the cost of purchasing a larger liner, then it makes economic sense. However, the amount of savings will be dependent on the greenhouse location, time of year, and labor, overhead, and heating fuel costs. For an example of how to calculate the potential savings from starting with a larger liner, see article by Fisher, 2006.

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Tables

Table 1. Plants can be categorized by their base temperature, which is the temperature at or below which plant development ceases. "Cold-tolerant crops" are those with a base temperature of 39 °F (4 °C) or lower, "intermediate crops" are those with a base temperature of 40 to 45 °F (4 to 7 °C) and "cold-sensitive crops" are those with a base temperature of 46 °F (8 °C) or higher. Information based on research at Michigan State University and published research-based articles.

Cold-sensitive crops [base temperature of 46 °F (8 °C) or higher]
Angelonia gardnerii (Angelonia)
Begonia ×semperflorens-cultorum (Fibrous begonia)
Caladium bicolor (Caladium)
Capsicum annuum (Pepper)
Catharanthus roseus (Vinca)
Celosia argentea (Celosia)
Colocasia antiquorum (Elephant ears)
Euphorbia pulcherrima (Poinsettia)
Gazania rigens (Gazania)
Hibiscus spp. (Hibiscus)
Impatiens hawkeri (New Guinea impatiens)
Musa ornata (Banana)
Pennisetum setaceum 'Rubrum' (Purple fountain grass)
Phalaenopsis spp. (Phalaenopsis orchid)
Rosa ×hybrida (Rose)
Saintpaulia ionantha (African violet)
Salvia farinacea (Blue salvia)
Intermediate crops [base temperature of 40 to 45 °F (4 to 7 °C)]
Calibrachoa ×hybrida (Calibachoa)
Coreopsis grandiflora (Coreopsis)
Dahlia pinnata (Dahlia)
Oenothera fruticosa (Sundrops)
Impatiens wallerana (Seed impatiens)
Salvia splendens (Red salvia)
Cold-tolerant crops [base temperature of 39 °F (4 °C) or lower]
Ageratum houstonianum (Ageratum)
Antirrhinum majus (Snapdragon)
Campanula carpatica (Campanula)
Diascia spp. (Twinspur)
Gaillardia ×grandiflora (Blanket flower)
Leucanthemum ×superbum (Shasta daisy)
Lilium longiflorum (Easter lily)
Lilium spp. (Asiatic and Oriental lily)
Lobularia maritima (Alyssum)
Nemesia strumosa (Nemesia)
Pericallis ×hybrida (Cineraria)

Petunia ×hybrida (Petunia)
Rudbeckia fulgida (Black-eyed Susan)
Scabiosa caucasia (Pincushion flower)
Schlumbergera truncata (Thanksgiving cactus)
Tagetes patula (French marigold)
Viola ×wittrockiana (Pansy)
Zygopetalum spp. (Zygopetalum orchid)

Table 2. Bedding plants can be categorized according to their response to photoperiod. Information based on research-based articles.

Long-day plants	**Facultative (F) or Obligate (O)**
Ageratum houstonianum (Ageratum)	F
Antirrhinum majus (Snapdragon)	F
Bracteantha bracteata (Strawflower)	O
Dianthus chinensis (Dianthus)	F
Fuchsia ×hybrida (Fuchsia)	F or O
Gazania rigens (Gazania)	O
Helianthus annus (Sunflower)	F
Lathyrus odoratus (Sweet Pea)	O
Lobelia erinus (Blue lobelia)	O
Petunia ×hybrida (Petunia, Grandiflora types)	O
Petunia ×hybrida (Wave petunia)	O
Rudbeckia spp. (Black-eyed Susan)	O
Salvia farinacea (Blue salvia)	F
Salvia splendens (Scarlet salvia)	F
Verbena ×hybrida (Verbena)	F
Viola ×wittrockiana (Pansy)	F
Short-day plants	
Celosia plumosa (Celosia)	F
Cosmos bipinnatus (Cosmos)	F
Dahlia ×hybrida (Dahlia)	F
Gomphrena globosa (Globe amaranth)	F
Ipomoea tricolor (Morning glory)	F
Lablab purpureus (Hyacinth bean)	O
Sanvitalia procumbens (Creeping zinnia)	F
Tagetes erecta (African marigold)	O
Tagetes tenuifolia (Signet marigold)	F
Day-neutral plants	
Amaranthus hybridus (Amaranthus)	
Begonia ×semperflorens-cultorum (Fibrous begonia)	
Catharanthus roseus (Vinca)	
Cleome hasslerana (Cleome)	
Convolvulus tricolor (Dwarf morning glory)	
Dianthus barbatus (Sweet William)	

Impatiens hawkeri (New Guinea impatiens)
Impatiens walleriana (Impatiens)
Lobularia maritima (Alyssum)
Lycopersicon esculentum (Tomato)
Nicotiana alata (Flowering Tobacco)
Origanum vulgare (Oregano)
Pelargonium ×hortorum (Geranium)
Pelargonium peltatum (Ivy geranium)
Scabiosa columbaria (Pincushion flower)
Tagetes patula (French marigold)
Thunbergia alata (Thunbergia)

Table 3. Herbaceous perennials can be categorized according to their response to photoperiod. Information based on research-based articles.

Long-day plants	**Facultative (F) or Obligate (O)**
Achillea millefoilium (Yarrow)	O
Agastache ×'Blue Fortune' (Hyssop)	O
Asclepias tuberosa (Butterfly milkweed)	O
Astilbe chinensis (Chinese astilbe)	F
Brunnera macrophylla (Siberian bugloss)	O
Campanula carpatica (Carpathian harebell)	O
Campanula punctata (Spotted bellflower)	O
Ceratostigma plumaginoides (Leadwort)	O
Coreopsis grandiflora (Tickseed)	O
Coreopsis verticillata (Thread leaf tickseed)	O
Digitalis purpurea (Foxglove)	O
Echinacea purpurea (Purple cone flower)	F
Gaura lindheimeri (Gaura)	O
Helenium autumnale (Sneezeweed)	O
Hibiscus moscheutos (Rose mallow)	O
Hosta plantaginea (Hosta)	F
Lavandula angustifolia (English lavender)	O
Leucanthemum ×superbum (Shasta daisy)	F
Lobelia ×speciosa (Lobelia)	O
Lysimachia ciliata (Fringed loosestrife)	O
Lysimachia punctata (Yellow loosestrife)	O
Monarda didyma (Beebalm)	O
Nepeta faassenii (Catmint)	O
Oenothera speciosa (Evening primrose)	F
Pennisetum setaceum 'Rubrum' (Purple fountain grass)	F
Phlox paniculata (Garden phlox)	O
Physostegia virginiana (Obedient plant)	O
Polemonium spp. (Jacob's Ladder)	O
Rudbeckia fulgida (Black-eyed Susan)	O

Salvia ×superba (Hybrid sage)	F
Sedum spp. (Stonecrop)	O
Long-day short-day plants	
Chelone glabra (Turtlehead)	
Eupatorium rugosum (White snakeroot)	
Helianthus angustifolius 'First Light' (Perennial sunflower)	
Helianthus salicifolius 'Low Down' (Willow-leafed sunflower)	
Solidago rugosa 'Fireworks' (Rough goldenrod)	
Day-neutral plants	
Ajuga reptans (Buglewweed)	
Alchemilla mollis (Lady's mantle)	
Aquilegia ×hybrida (Columbine)	
Armeria maritima (Sea thrift)	
Campanula portenschlagiana (Dalmation bellflower)	
Delphinium grandiflorum (Larkspur)	
Dianthus gratianopolitanus (Cheddar pink)	
Dicentra spectabilis (Bleeding heart)	
Digitalis grandiflora (Foxglove)	
Euphorbia epithymoides (Cushion spurge)	
Geranium 'Rozanne' (Cranesbill)	
Heuchera spp. (Coral bells)	
×*Heucherella* spp. (Foamy bells)	
Iberis sempervirens (Candytuft)	
Lamium spp. (Spotted deadnettle)	
Lychnis flos-cuculi (Ragged robin)	
Nepeta faassennii 'Snowflake' (Catmint)	
Perovskia atriplicifolia (Russian sage)	
Phlox divaricata (Wild blue phlox)	
Phlox subulata (Creeping phlox)	
Platycodon grandiflorus (Balloon flower)	
Pulmonaria spp. (Lungwort)	
Salvia guaranitica (Blue anise sage)	
Salvia nemorosa (Garden sage)	
Scabiosa columbaria (Pincushion flower)	
Tiarella spp.(Foam flower)	
Veronica longifolia (Speedwell)	
Veronica spicata (Spike speedwell)	

Table 4. Irradiance classification of several bedding plants based on research at the University of Minnesota.

Facultative irradiance plants	**Irradiance indifferent plants**
Antirrhinum majus (Snapdragon)	*Ageratum houstonianum* (Ageratum)
Begonia semperflorens (Wax begonia)	*Amaranthus hybridus* (Amaranthus)
Cleome hasslerana 'Rose Queen' (Cleome)	*Ammi majus*
Convolvulus tricolor (Dwarf morning glory)	*Celosia plumosa* (Plumed celosia)
Cosmos bipinnatus 'Sensation White' (Cosmos)	*Centaurea cyanus* (Bachelor's Buttons)
Gazania rigens (Gazania)	*Cleome hasslerana* 'Rose Queen' (Cleome)
Hibiscus moscheutos (Rose mallow)	*Cosmos bipinnatus* 'Diablo' (Cosmos)
Lathyrus odoratus (Sweet Pea)	*Dianthus chinensis* (Dianthus)
Nicotiana alata (Flowering Tobacco)	*Gomphrena globosa* (Globe Amaranth)
Origanum vulgare (Oregano)	*Helianthus annus* (Sunflower)
Pelargonium ×hortorum (Geranium)	*Lobelia erinus* (Lobelia)
Petunia (Purple wave petunia)	*Salvia splendens* (Scarlet salvia)
Salvia farinacea (Blue salvia)	*Sanvitalia procumbens* (Creeping zinnia)
Viola ×wittrockiana (Pansy)	*Thunbergia alata* (Thunbergia)
	Tithonia rotundifolia (Mexican sunflower)
	Zinnia elegans (Zinnia)