Section 2

Temperature and Scheduling

Improving Greenhouse Production Efficiency

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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 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.

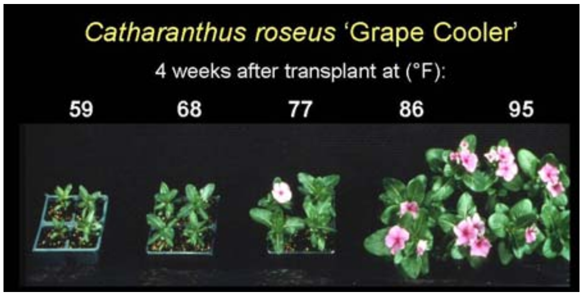

Figure 11. The effects of average daily temperatures from 59 to 95 °F (15 to 35 °C) on the development of 'Grape Cooler' vinca (*Catharanthus roseus*). Photo courtesy of Royal Heins, Michigan State University.

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 11** 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 12**). 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 12**). 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

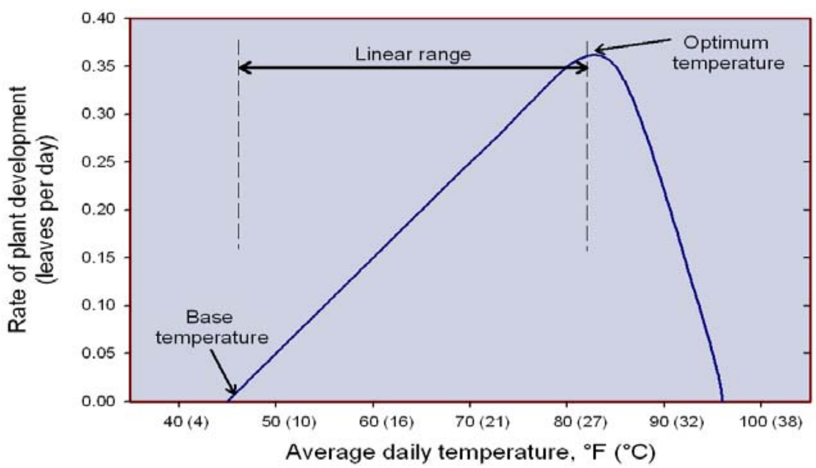

Figure 12. The rate of plant development (such as leaf unfolding) is linear between the base temperature and the optimum temperature.

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 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 13**. 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.

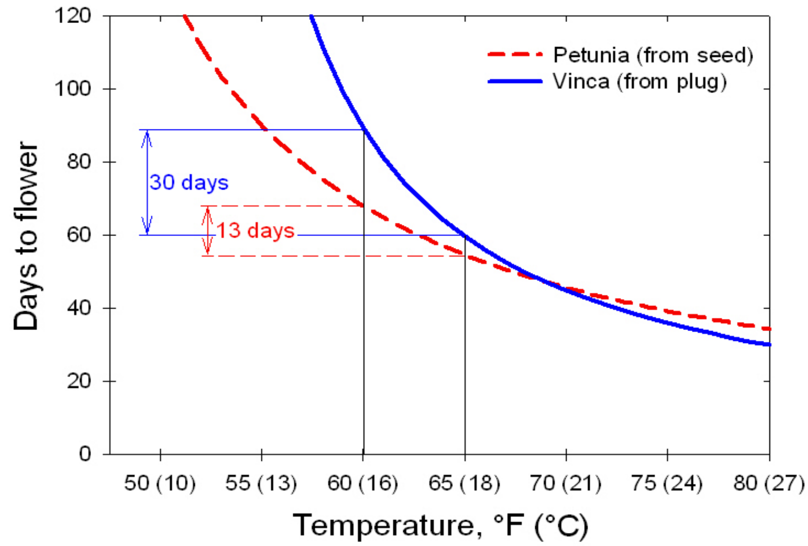

Figure 13. The effect of temperature on time to flower of petunia (*Petunia ×hybrida*) from seed and vinca (*Catharanthus roseus*) from a small plug. When temperature is decreased, there is a larger delay in flowering for plants with a high base temperature (vinca) compared to plants with a lower base 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 6** 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 14** 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

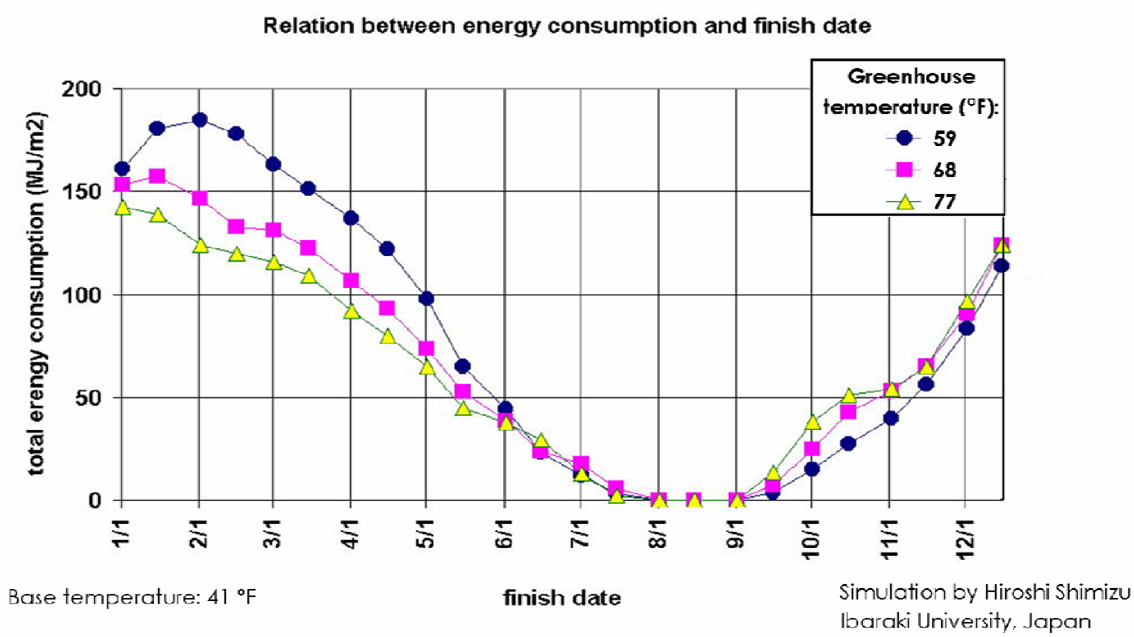

Figure 14. The estimated amount of energy required to produce a crop at different growing temperatures throughout the year in Michigan. This simulation indicates that the total amount of energy consumed to produce a flowering crop increased as growing temperature decreased from winter through mid-summer.

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 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 15**. 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].

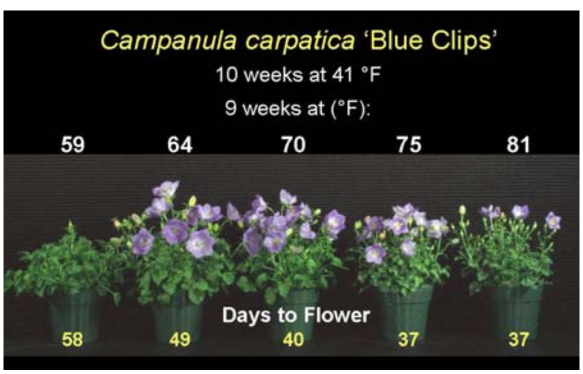

Figure 15. The effects of forcing temperatures from 59 to 81 °F (15 to 27 °C) on plant quality of 'Blue Clips' Carpathian harebell (*Campanula carpatica*). At a warmer temperature, plants flowered earlier but flower size was reduced compared to plants forced at a cooler temperature. Photo courtesy of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

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 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.

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 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.

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.

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.

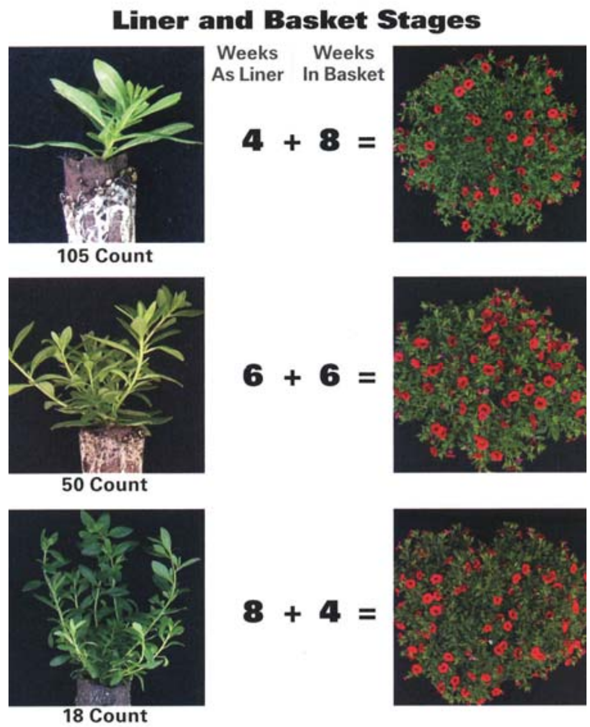

Figure 17. The effects of liner size on finishing time in 12-inch (31-cm) hanging baskets with five liners per basket. Cuttings were stuck into 25-mm (105-count), 40-mm (50-count), or 70-mm (18-count) liner trays and transplanted into hanging baskets after 4, 6, or 8 weeks, respectively. Photographs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

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Tables

Table 6. 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)