11 The Greenhouse Environment

A greenhouse provides the luxury of producing almost any crop at any time of the year regardless of the outside conditions, provided care is taken to establish and maintain the correct environment inside. Precise control of nearly all of the factors affecting plant growth and development is what makes a greenhouse the productive structure that it is. Greenhouse management encompasses many factors including temperature, light, moisture, carbon dioxide levels, growing media, fertility, and pest management. All of the factors that affect plant growth in the field also affect greenhouse production except for possibly wind. While all of the factors previously listed impact greenhouse production, this chapter will focus on how temperature, light, moisture, and carbon dioxide management can profoundly affect greenhouse productivity.

Temperature

Two different aspects of temperature must be considered in greenhouse operations: (i) heating; and (ii) cooling. Heat for a greenhouse comes from natural heat from solar radiation and supplemental heat supplied by a source chosen by the grower. While the choice for supplemental sources of heat is entirely under the control of the grower, solar heating is not. Estimates of solar heat input can be made based on daylength and sun angle, but other factors such as cloud cover and outside temperature cannot. Cooling is accomplished through ventilation and the use of some form of supplemental cooling, most often one that relies on the evaporation of water. The level of cooling by evaporation is subject to the water content of the air.

Heat sources

Heat in a greenhouse produces two areas of concern for growers. One is that there may not be enough heat during cold winter months and the other is too much heat during the summer. The first is remedied by supplemental heating while the other is addressed via ventilation and cooling.

Solar heating

When solar radiation strikes an object, say a polyethylene (poly) greenhouse covering, a plant or a greenhouse bench, that energy can be reflected, absorbed, or transmitted through the object. With the poly covering, most of the energy is transmitted. With the plant, some is transmitted, some is absorbed, and some is reflected. With the bench, most is absorbed or reflected. Most of the solar radiation entering a greenhouse is short-wave radiation. Much of that radiation which is absorbed by objects is converted to heat or re-emitted as long-wave, mostly infrared radiation. Water in the greenhouse atmosphere absorbs much of the re-emitted far-red radiation and converts it to heat. Thus much of the solar energy entering a greenhouse becomes heat. The fairly small amount of energy that is not converted to heat is used in photosynthesis.

Some of this heat absorbed during the day is stored and released at night. Systems for heating a greenhouse with stored solar heat have long been used in homeowner and small establishments. Large darkly colored containers filled with water collect and store solar heat during the day and radiate it into the greenhouse at night. This heating is passive and cannot be controlled thermostatically. It is inexpensive and easy to use.

Commercially available solar collectors and heat distributors are extremely expensive and would not be cost effective for economical greenhouse production at this time (Buffington *et al*., 2010). However, these systems will probably become more affordable in the future.

Supplemental heating

During cooler months some form of supplemental heat is needed for nearly all greenhouse production schemes. Both traditional and not so traditional alternative heating systems can be used to supply this supplemental heat.

TRADITIONAL FUELS Oil, natural gas, and propane are traditional fuel sources for greenhouse heating. Fuel selection is based on burner type and economics (Bartok, 2005). Natural gas is piped from transmission lines to the greenhouse, thus no on-site storage is needed. It is generally economical, clean burning, and requires little equipment maintenance. Natural gas is sold by the therm, the volume of gas required to produce 100,000 British thermal units (BTU). One problem with natural gas is that some suppliers include an 'interruptible clause' in their sales contracts which allows them to divert gas to other customers in the event of severe cold weather. Thus an alternate heating source is needed as backup for the greenhouse.

Propane (liquefied petroleum gas) is a clean fuel like natural gas. It is liquid at moderate pressure and typical temperatures. Propane is normally stored on site in a large tank, thus it is available where natural gas is not. It is usually a little more expensive than natural gas, is sold by the gallon and contains about 95,000 BTU/gal (25,096 BTU/l).

Fuel oil No. 2 is about the same in cost as natural gas, except that oil burners require more maintenance than natural gas burners. It requires aboveground storage with a containment plan in case of a leak or spill.

Gas or propane burners often distribute the heat as forced hot air through poly tubes with holes punched in them. The tubes are mounted overhead and suitably distributed throughout the production area. The poly tubes can also be mounted under benches, keeping the heat in the plant zone. This type of heater is called a unit space heater (Fig. 11.1). The heater itself is mounted on the floor or hung from the greenhouse roof with the air distribution tubing appropriately installed to deliver the heated air to where it is needed. These units are moderately expensive and allow for easy greenhouse expansion if desired. It is extremely important to vent these units since combustion produces carbon dioxide, carbon monoxide, ethylene, sulfur dioxide, and unburned hydrocarbons. Many of these byproducts of combustion are potentially harmful to plants and humans if they are at elevated levels. High levels of carbon dioxide and water vapor that often develop at night when heaters are operating regularly are extremely conducive to growth of disease-causing organisms.

Fig. 11.1. A natural-gas-fueled greenhouse unit space heater. Notice the heater is well ventilated to the outside.

To ensure good heater ventilation, make sure the vent stack is appropriately sized for the heater (see manufacturer's recommendation) and at least 1.2 m higher than the highest point of the greenhouse (Buffington *et al.*, 2010). It is also important that ventilation to bring oxygen for combustion into the greenhouse is established, especially for tightly sealed greenhouses. Normally a vent 15–20 cm in diameter is located close to the heating unit to allow fresh air to be drawn in from the outside when the heater is on.

While space heaters are semi-permanent, many greenhouse furnace systems utilizing coal, oil, natural gas, or propane as fuel are permanent. They consist of a burner, a boiler, and a heat distribution system as well. The heat is normally distributed via either hot water or steam through a piping system appropriately configured for the greenhouse and the system. In general, hot water systems heat and cool more slowly and require more distribution piping than steam systems. Hot water systems are usually less expensive and simpler to install than steam systems. Hot water systems are usually used in smaller greenhouse ranges while steam systems are used in larger ones. Steam systems can also be used to sterilize soil.

In both systems, heat is often distributed through a system of tubing or pipes either embedded in a porous concrete floor or mounted to production benches. Tubing mounted to production benches maintain production containers at a suitable temperature resulting in improved plant growth and reduced fuel costs. Fuel costs are reduced since production containers are heated directly through conduction rather than by radiation or convection with associated heat loss through the air.

Another type of oil- or gas-fired heater called a return stack or 'salamander' heater designed for orchard frost protection should never be used to heat a greenhouse. They are not vented and cannot be thermostatically controlled. With no venting, combustion gases would accumulate inside the greenhouse potentially injuring plants or sickening humans working near them.

Thermostats for controlling the heating system must be mounted appropriately in the production area for accurate sensing. Sensors should be mounted at plant level rather than eye level and sensors should be distributed throughout the production area. They should not be in full sun, but rather, facing northwards or in a ventilated and aspirated shelter.

ALTERNATIVE FUELS Alternative fuels are often used to supplement traditional greenhouse heating systems rather than for supplying the majority of supplemental heat (Bartok, 2005). They are usually units that are separate from the main system, thus they incur an additional expense. They also normally require more effort in operation and greater maintenance. Alternative sources of heat include biomass, coal, waste oil, methane, waste heat, heat pumps, and geothermal sources.

Biomass fuel is a generic term for any fuel derived from biological material including, but not limited to, wood, crop residue, and biomass byproducts from industry (Jenkins, 1985). Biomass can be used directly as a fuel or after gasification. It is relatively inexpensive but is also produces less heat per unit than other sources of fuel. Fuel storage must be considered and fuel must be kept dry and accessible to the heating system. A consistent and reliable supply is also necessary. Particulate emissions may be a problem with biomass fuels and ash must be disposed of properly. If properly managed, biomass furnaces can: (i) save fuel costs; (ii) pay for themselves within 4 years; and (iii) substantially reduce carbon dioxide emissions compared with conventional systems (Callahan and Grubinger, 2010). Wood is probably the most widely used biomass fuel and an alternative energy source for supplemental greenhouse heating. Wood as fuel is available as traditional firewood, forest residue, lumber or paper mill waste, chips, and sawdust. It is relatively inexpensive, but does require a night fireman to feed the furnace.

Coal may be a viable alternative energy source depending on location and availability. One ton of coal has the heat value of about 640 l (160 gal) of fuel oil or 2300 therms of natural gas. A coal furnace also needs a fireman and ashes must be disposed of properly.

Waste oil from automobiles may be used as an alternative fuel, but it must be cleaned to remove sludge and water before use. It is also considered a hazardous waste, thus it must be handled appropriately. It has a heat value similar to fuel oil No. 2.

Methane is a gas produced from landfills and decomposing animal manure. Methane that is burned directly from the source has the heat value of about 17,657 BTU/m^3, or half that of clean methane.

Many manufacturing plants generate waste heat in their processes. This heat can be used for greenhouse heating if the two enterprises are in close proximity to each other. Often the waste heat is lower grade, meaning that it is water or steam at 65°C or less, but even so, it is a valuable source of supplemental heat.

Geothermal heating of the greenhouse is an alternative to fossil-fuel-generated heat. Heat from the earth or bodies of water such as lakes, wells or ponds is captured by heat pumps and transferred to greenhouses. Heat pump/geothermal systems are usually quite expensive, require electricity as a power source and must be located near a convenient source of transferable heat. For these reasons, heat pumps are an alternative heating source for greenhouses in very limited situations (Jenkins, 1985; Garco *et al.*, 1998).

Heat pumps use electricity to transfer heat from a source outside of the greenhouse to the interior growing area. Sources of the heat can be outside air, surface water, groundwater, soil, or solar radiation. The efficiency of the heat pump in extracting heat from the environment and transferring it to the greenhouse is called the coefficient of performance (COP) which can range from 1 to 4. When the temperature of the environment is closer to the desired temperature of the greenhouse, the COP has a higher value. A heat pump extracting heat from groundwater at 8°C to heat a greenhouse maintained at 15°C has a higher COP than a heat pump extracting heat from air at 3°C. When the COP is near 1, a heat pump is no more efficient at heating than an electrical resistance heater. Thus heat pumps should only be considered when a heat source fairly close to the desired greenhouse temperature is available. In addition, electricity costs must be evaluated compared with other heating systems and their fuel sources.

Maintenance

To most effectively, efficiently and economically utilize greenhouse space, it is important to semi-annually check certain components of the greenhouse, its structure, and its heating and ventilation systems (Bucklin *et al*., 2002). This is particularly important for winter production. It's a good idea to schedule a thorough inspection of greenhouse facilities before each production cycle. Structural integrity of the greenhouse frame as well as the covering must be maintained. Repair or replace any component that is in disrepair. Fiberglass, glass and poly coverings should be checked for holes and for gaps between the covering and framework. Unnecessary shading should be removed and side panels should be cleaned to allow maximum light penetration. If possible, an inner layer of poly should be added to single layer coverings to insulate the greenhouse. Approximately 10 cm should separate the inner and outer coverings and the space between the two coverings should be maintained with inflation fans. Warm, dry air should be used for inflation to minimize condensation between the two layers.

Vents and ventilation fans should be checked for proper operation. If thermal blankets are used, they should also be checked for tears and to see that they operate properly. Since many greenhouse operations rely on a standby generator in case of a power outage, this too should be regularly inspected, tested, and serviced. The heating system should be inspected by a trained professional. Efficient and proper operation often relies on delicate adjustments best left to professionals. The cost of service is likely to be recouped via fuel savings with a properly adjusted system.

Calculating heat requirements

Appropriately sized supplemental heating systems must be used for efficient production. In order to select the correctly sized unit, an estimate of the heat loss from the greenhouse is required. Since many growers are incorporating high tunnels into their production scheme, let's determine the appropriate heating unit for supplemental heating that might be required on occasion for such a unit. Consider a 14.5 m (48 ft) long caterpillar high tunnel, 3.7 m (12 ft) wide and 2.1 m (7 ft) tall (Johnny's Selected Seeds, 2011).

A fairly accurate method for estimating heating requirements is easily obtained by multiplying the surface area of the high tunnel by the maximum temperature difference between the inside and outside air, then multiplying this number by a factor which adjusts for covering material and construction quality (Buffington *et al*., 2010). The adjustment factor for the high tunnel covered in polyethylene ranges from 1 for very tight construction to 1.5 for less than perfect construction. To be on the safe side, assume less than perfect construction.

The first step is to calculate the exposed surface area (A) of the high tunnel covering. A reasonable approximation to the surface area of the covering must consider the area of the two end walls plus the area of the tunnel. The tunnel arch consists of 6.1 m (20 ft) of appropriately bent pipe to produce the 2.1 m (7 ft) height at the center. Thus the area of the covering is $6.1 \times 14.5 = 88.5$ m^2 ($20 \times 48 = 960$ ft^2). Each end is approximately 0.5 times the surface area of a circle that has a radius of 2.1 m (7 ft), thus each end has a surface are of $0.5 \times (\pi\, r^2) = 0.5 \times (\pi \times 2.1^2) = 6.9$ m^2 (77 ft^2). Thus the total area (A) for the covering is ($88.5 + 6.9 + 6.9 = 102.3$ m^2) (($960 + 77 + 77) = 1114$ ft^2).

Suppose the high tunnel is being used for an early tomato crop where we wish to maintain a minimum temperature of 15.5°C (60°F) (a cultivar tolerant of cooler temperatures is utilized). The minimum outside temperature anticipated is –9.5°C (15°F) (assuming an unexpected cold snap is better than not being prepared for one). The maximum temperature difference would be $15.5 - (-9.5) = 25$°C ($60 - 15 = 45$°F). The approximate heating requirement for our high tunnel is $(102.3 \times 25 \times 1.5) \times 19.6 = 1114 \times 45 \times 1.5 = 75195$ BTU/h. The factor of 19.6 is required to adjust values derived from metric measurements. One BTU is the amount of energy it takes to increase the temperature of 0.454 kg of water from 3.8°C to 4.4°C (or the energy needed to raise 1 lb of water 1°F from 39 to 40°F).

Once the heating requirement is determined, the selection of a heating system is primarily based on the economics of purchasing and operating the system. The least expensive, most reliable system should be chosen. Fuel type often determines operating costs. If possible, a system that allows conversion from one fuel type to another is desirable. Besides cost, reliable fuel availability should also be considered. If the greenhouse operation is located in a remote area which often experiences electrical power outages, an electrical system should not be considered even if it is the least expensive option. Heating efficiency and heat production for common greenhouse heater fuels is presented in Table 11.1. With these figures and local cost estimates, it is fairly easy to calculate costs associated with the various fuels based on heating requirements previously calculated.

In all but the simplest operations, an expert should always be consulted in order to determine the best heating system for a greenhouse. Careful planning virtually eliminates large problems down the road.

Ventilation

Ventilation is an extremely important component of greenhouse temperature and moisture management. It replaces warm humid air inside the greenhouse with cooler drier air from the outside. In addition, ventilation renews carbon dioxide levels in houses where carbon dioxide enrichment is not practiced. This is particularly important in smaller houses during the winter months. Ventilation may be forced or it may be accomplished naturally.

Table 11.1. Combustion efficiency and heat production for various fuels used in common greenhouse heating systems (after Buffington *et al*., 2010).

Fuel	Efficiency (%)	Heat produced per unit (BTU)
Coal (bituminous)	60	13,000/lb
Wood	70	8,000/lb
Natural gas	80	100,000/therm
Propane	80	92,000/gal
Fuel oil No. 2	70	138,000/gal
Electricity	100	3,413/kwh

Natural ventilation

Natural ventilation is often accomplished by rolling greenhouse sidewalls up or down depending on configuration, allowing outside air to enter (Fig. 11.2). Ridge vents and open roof greenhouses accomplish the same thing with a different approach (Fig. 11.3). The degree of ventilation is regulated via the amount the side curtain is raised or lowered. While inexpensive and easy to operate, this type of ventilation is not easily regulated as much of the air exchange depends on wind. In addition, if curtains are manually regulated, someone must be available to open and close the curtains every day. Ideally, curtains should roll downwards to open. This allows colder air from outside to mix with the warmer greenhouse air before coming into contact with the plants. This is especially important when ventilating sensitive plants on cold, windy days. Greenhouse orientation should be such that the prevailing winds blow across the greenhouse rather than along its length.

Forced air ventilation

Forced air ventilation is accomplished by having a louvered vent at one end of the greenhouse and an exhaust fan at the other. Both are operated by a thermostat with the vent opening several degrees before the fan to prevent the development of a vacuum inside the greenhouse. Once the desired temperature is reached, the fan shuts off and the louvers close.

A good general rule of thumb for greenhouse production is that during ventilation, the air inside

Fig. 11.2. Natural ventilation of a high tunnel using roll-up sides.

Fig. 11.3. Natural ventilation of an open roof greenhouse.

the greenhouse should be exchanged with outside air once a minute. A fan of sufficient capacity must be used to ensure that the volume of air in the greenhouse can effectively be drawn out of the greenhouse in about 1 min. Fans are often capable at operating at two speeds, a lower speed for minimal ventilation and a high speed for maximum needs. Single-speed fans run the risk of bringing in too much cool air which might harm sensitive species during times of minimal ventilation.

Fans are most often selected based on how much air they can move in a specific amount of time, normally cubic feet per minute (CFM). The volume of air a fan can move depends on: (i) blade diameter; (ii) motor horsepower; and (iii) housing shape. Another important variable in calculating air flow is the system static pressure. As more air is moved, the resistance to flow increases, thus the amount of air that can be moved begins to decrease. A good rule to follow is to make sure you purchase a fan that can deliver the desired air flow at a minimum of 0.125 inches of static pressure. Fan manufacturers supply performance charts to indicate air movement of their fans at various static pressures. The louvers used in the ventilation system should be about 1.5 times larger than the fan frame to allow sufficient airflow.

Estimating the size of greenhouse exhaust fans is easily accomplished using the following formula (Snyder, 1992):

Exhaust fan capacity needed (CFM) = 8 × (Length of greenhouse (ft) × Width of greenhouse (ft))

Estimating the size of greenhouse vents is easily accomplished using the formula (Snyder, 1992):

Vent size (ft^2) = (8 × (Length of greenhouse × Width of greenhouse)/700

Greenhouse air movement

Part of a ventilation strategy should consider keeping air moving inside the greenhouse even at times when the outside air is not being vented in. This keeps temperature and humidity levels fairly even within the greenhouse and moving air helps eliminate condensation of water on plant leaves in cool pockets.

Air movement inside the greenhouse is often a component of the poly tube heat delivery system. Even when the heat is not needed or in cases where heat distribution is not accomplished via a poly tube, air circulation within the greenhouse could be accomplished with a poly tube. The poly tube system directs air down the center of the greenhouse via a high velocity fan through an overhead pressurized polyethylene tube with strategically spaced outlets. The tube runs the length of the greenhouse. A vent is often included as part of the system to allow outside air to be drawn in if needed for cooling purposes. The air exiting the tube via the outlets is moving at a high velocity and mixes the air around and within the plant canopy.

Another option is the horizontal air flow system which consists of 40–60 cm (16–24 inch) diameter fans positioned about 1.2 m (4 ft) above the crop every 9–12 m (30–40 ft) along the length of the greenhouse. Fans are located about one-fourth the width of the greenhouse in from the exterior wall along both sides of the greenhouse. Fans are positioned in such a way as to move the air down one side of the greenhouse and up the other in a somewhat circular direction. Use high efficiency fans specifically designed for horizontal air movement. They should blow parallel to the ground, not pointed downwards or upwards as sometimes suggested (Runkle, 2012a). Fans should also be mounted solidly, not hanging from chains, as horizontal movement of fans can alter air movement within the greenhouse. If possible, fans should cycle off when ventilation is occurring. It is especially important to have fans operating at night to prevent pockets of cool air from developing throughout the greenhouse. Air movement at night also minimizes condensation on plants as they cool.

Cooling the greenhouse

Most greenhouses reach excessive temperatures during the summer growing season and are unfit for crop production unless cooled. Evaporative cooling is the most widely used method of greenhouse cooling (Bucklin *et al.*, 2011). Air conditioning can be used, but installation and operation costs are prohibitive.

To obtain a measure of potential cooling with evaporation, obtain the wet bulb temperature in the early afternoon. This is when maximum cooling will be required. With a well-managed and maintained system, the greenhouse temperature can be cooled to within 1 or 2°C of the wet bulb temperature.

Evaporative cooling of greenhouses is accomplished by evaporating water into an airstream usually with a fan-and-pad system. High pressure fogging systems can also be used, but are substantially more expensive.

The fan-and-pad system consists of an exhaust fan located at one end of the greenhouse which draws outside air through a vent at the other end of the greenhouse. As the air enters the greenhouse through the vent it passes through a porous pad, usually made of cellulose, through which water is trickled with a circulating pump. It is important to have a tightly sealed greenhouse so that air enters only through the pad to maximize evaporation. Water evaporates and cools the air entering the greenhouse. Each gallon of water evaporating removes 8100 BTU of heat from the air entering the greenhouse. Air is coolest immediately after passing through the pad and entering the greenhouse and warms slightly as it approaches the fan. The temperature gradient should be as small as possible. Air may warm by as much as 1°C every 6 m it travels. Additionally, the cooled air tends to travel in an angle up and away from the plants it was intended to cool. In a cross-greenhouse flow configuration, this is usually not a problem, as gutters connecting roof sections of large greenhouses provide baffles to deflect cool air downwards. In smaller greenhouses, the distance from side to side is short, thus the air divergence is not of great concern. In lengthwise-flow configurations, baffles should be created every 10 m and extend from the roof of the greenhouse down to just above crop level.

Estimating the size of greenhouse cooling pads is easily accomplished using the following formula (Snyder, 1992):

Pad height (ft) = (Air flow rate)/(Pad length)/(Air velocity)

The air flow rate is the volume of the greenhouse since you want one air exchange per minute, thus air flow rate = greenhouse length × greenhouse width × 8. The pad length is usually about 2 feet shorter than the greenhouse width. Air velocity (in feet per minute) is how fast the air can move through the cooling pad. This number is obtained from the manufacturer and is approximately 250 for a 4-inch cellulose pad, 380 for a 6-inch cellulose pad, and 165 for an aspen pad.

If the efficiency of the cooling system is known, the temperature of the air exiting the cooling pad can be estimated as follows:

$$T_{cool} = T_{out} = (\text{Percentage efficiency})(T_{out} = T_{wb})$$

Where:
T_{cool} = temperature of cooled air
T_{out} = temperature of outside air
T_{wb} = wet bulb temperature of outside air

A well-designed system can have an efficiency of up to 85%. To illustrate how effective pad cooling systems can be, a system with 85% efficiency can take outside air at 32.2°C and a relative humidity (RH) of 50% down to 24.7°C. That's a 7.5°C decrease in temperature.

Greenhouse temperature and plant growth

When contemplating greenhouse temperature management it is wise to consider the many ways in which temperature influences plant growth and development. The rates of many plant processes are highly dependent on temperature. Within a range, warmer temperatures tend to increase while cooler temperatures tend to decrease the rates of metabolic reactions involved in these processes. Seed germination is highly regulated by soil temperature. Vegetative propagation is also affected by soil temperature. Photosynthesis, respiration, transpiration, and many other metabolic processes involved in synthesis and degradation are affected by temperature. Flower formation and production may be highly regulated by temperature in some species. Water and nutrient absorption are affected by temperature which ultimately may affect crop maturity.

Greenhouse temperature settings vary among species and are generally set to maximize yield. Night temperature is often emphasized for two reasons. One is that this is the time where the temperature normally has the greatest opportunity to fall below optimum levels. Secondly, much of a plant's growth occurs at night.

A species optimum temperature changes as a plant grows from a seedling to a mature plant. Growth only occurs if photosynthesis is greater than respiration, since a surplus from photosynthesis is needed for growth to occur. When a plant is young, it often has a great deal of leaf area (mostly photosynthesis) relative to stem and root area (mostly respiration). Warmer temperatures are usually favored by younger plants. Even though warmer temperatures cause increased rates of both photosynthesis and respiration, warmer temperatures favor photosynthesis and net growth in younger plants since there is less stem and root tissue compared with older plants. As the plant ages, more stem and root tissues develop, thus warmer temperatures start to favor respiration. Lower temperatures reduce photosynthesis but also reduce respiration, thus generally favoring a surplus of photosynthates that can be used for growth.

Plant growth in cooler greenhouses

In an attempt to lower heating costs, many greenhouse growers consider lowering greenhouse temperatures during the colder months. The feasibility of such a move is totally dependent on the crop in production. Every plant species on earth has an optimum temperature for growth. Additionally, many of the growth stages a plant passes through are affected by temperature. Thus it is extremely important to have a thorough understanding of the temperature requirements for the crop in production.

Each plant species has an optimum temperature for seed germination. This must be considered in setting the greenhouse temperature. Heating cables can be used to warm the germinating media while keeping the greenhouse air temperature cooler, however, the impact of the cooler greenhouse air temperature on seedling growth after germination must also be considered. It is usually not a very good idea to try and conserve heat by lowering the thermostat during germination.

Every plant species has a low temperature at which it stops growing. This temperature is called the base temperature. There is also a temperature, warmer than the base temperature, at which plant growth is at a maximum. This temperature is called the optimum temperature. Plant growth generally steadily increases between the base and optimum temperatures. Above the optimum, growth starts to decrease. In general, plants originating in cooler climates have lower base and optimum temperatures than those originating in warmer climates.

Many species will grow fairly well at temperatures below the optimum. The main consequence of less than optimum temperatures during growth is a delay in development. Thus at lower temperatures each production cycle occupies the greenhouse space for a longer time period. One needs to consider whether or not producing more product in a given time outweighs the savings accrued by lowered heating costs. A major consequence of lowered temperatures is the number of days to flower. Decreasing the temperature by 0.5°C (1°F) delays flowering in petunia by 3 days! If the thermostat was lowered by only 2.7°C (5°F), bloom is delayed by 2 weeks.

Depending on species, lateral branching and the number of flowers often increase with cooler temperatures. In some crops this may be desirable while in others it is not. In some species flowering is inhibited altogether if temperatures are too cool. Thus it is imperative that the temperature requirements for each species in production be thoroughly understood before attempting to save money by reducing the greenhouse temperature.

With cooler temperatures, water evaporates more slowly, thus disease incidence often increases with cooler temperatures, especially with some diseases such as *Botrytis*. Crops also require less water when grown at cooler temperatures. It is a good idea to water cooler greenhouses between 10 a.m. and noon to ensure that excess water evaporates before nightfall. Avoid watering too early in the day, especially if using cold water sources since the water will cool the roots and retard growth. With later watering, the growing media has had a chance to warm up a bit, thus the cooling caused by the cold water is not as drastic.

When the greenhouse temperature is reduced to save fuel, there is a greater difference between the day and night temperatures compared with crops grown at optimum temperatures. This greater difference can lead to greater stem elongation (see the section on DIF which follows this section).

If lowering the greenhouse thermostat is necessary, make sure to consider only crops that grow well under cooler conditions. Trying to grow a crop needing warm temperatures in a cool greenhouse is futile. Some crops to avoid in a cool greenhouse (<20°C(<68°F nights)) include tomatoes (*Solanum lycopersicum*), peppers (*Capsicum annuum*), cucumbers (*Cucumis sativa*), *Alternanthera*, New Guinea impatiens (*Impatiens × hawkeri*), *Lantana, Vinca, Celosia, Cleome*, coleus (*Solenostemon* spp.), *Cosmos, Gomphrena, Ipomoea, Melampodium, Portulaca*, and sunflowers (*Helianthus annuum*).

Crops to consider growing in a cool greenhouse include lettuce (*Lactuca sativa*), salad greens, *Argyranthemum, Osteospermum*, annual phlox (*Phlox drummondii*), *Nemesia, Calibrachoa, Diascia*, snapdragon (*Antirrhinum*), *Alyssum, Dianthus*, and pansies (*Viola*). Remember that even though crop quality may not suffer with lower temperatures in these species, production time will be lengthened considerably. It is a good idea to grow even these cool-tolerant crops at optimum temperatures for 2 or 3 weeks after germination to establish a good root system. Only then lower the thermostat.

One way to reduce heating costs is to modify production scheduling, especially in colder climates. By delaying the date for a finished product by only 1 month or so in the spring, huge savings in heating costs can be realized (Runkle, 2012a). For example, changing the date of finishing several floricultural crops from 15 April to 15 May in the northern USA reduced heating costs by 70%! Of course it depends on the species in production and whether or not the finishing date can be moved or not whether this is a viable option. Another course of action to reduce heating costs is to change the crops grown. Selecting a crop with a lower base temperature may allow production of a similarly valued crop at a lower heating cost, compared with a warmer selection. Greenhouse crops can be categorized based on their base temperature as presented in Table 11.2 (after Runkle, 2012a).

While temperature regulates plant growth and development, it should not be considered exclusively when selecting crops or managing them in the greenhouse. Light levels can greatly alter the selection of temperature for production. When light levels are less than optimum, crops should generally be grown at less than optimum temperatures. This accounts for a reduction in photosynthates available for growth due to reduced light levels. If the temperature were maintained at optimum levels, photosynthates would be used for respiration with little left over for growth. Free software is available at www.virtualgrower.net to estimate heating costs for various crops.

Average daily temperature (ADT) is an important concept in greenhouse temperature management. It is an average temperature that considers the length of time each day that a greenhouse is at a specific temperature rather than simply what the high and low set points are. The ADT is important in that plant development generally responds to this value rather than the high and low temperatures of a greenhouse. If plants are not developing fast enough to meet production deadlines, the ADT can be increased. If the crop is developing too rapidly, the ADT can be decreased. The ADT is easily calculated by multiplying the number of hours in each 24 h cycle that a plant is exposed to each set temperature with that temperature, adding them, and then dividing by 24. For example if a crop is exposed to 10 h at 25.6°C, 6 h at 17.8°C, and 8 h at 15.6°C, the ADT would be $[(10 \times 25.6) + (6 \times 17.8) + (8 \times 15.6)]/24$, or 20.3°C. A grower could compare a new ADT estimate based on proposed thermostat settings for saving fuel and calculate a reasonable estimate of any change in production. An even more precise estimate on the effect changing the temperature would have on production would consist of calculating the heat units needed for production of the crop in question and comparing actual accumulation with the accumulation that would occur with new temperature settings.

Table 11.2. Temperature sensitivity of various greenhouse crops based on their base temperature (after Runkle, 2012a).

Species	Base temperature (°F)
Cold-tolerant plants – base temperature 39°F or lower	
Ageratum, Alyssum, Campanula, Cineraria, Diascia, Easter lily (*Lilium longiflorum*), *Gaillardia, Leucanthemum, Nemesia, Rudbeckia, Scabosia*, Thanksgiving cactus (*Schlumbergera*)	–[a]
Dianthus (Super Parfait series)	39
Marigold (African, Moonstruck series) (*Tagetes erecta*)	37
Marigold (French, Janie series) (*Tagetes patula*)	34
Osteospermum Passion series	35
Petunia (Grandiflora) Dreams series	37
Petunia (Milliflora) Fantasy series	37
Snapdragon Montego series (*Antirrhinum*)	36
Viola Sorbet series	39
Cold-temperate plants – base temperature between 40 and 45°F	
Calibrachoa, Coreopsis	–[a]
Cosmos sulphureus Cosmic series	45
Dahlia Figaro series	42
Gazania Daybreak series	41
Geranium (seed) Florever series (*Pelargonium*)	41
Impatiens (seed) Accent series	43
Lobelia Riviera series	41
Marigold (African) Antigua series (*Tagetes erecta*)	40
Petunia (Spreading) Easy wave series	45
Petunia (Spreading) Wave series	42
Rudbeckia (annual) Becky series	40
Salvia splendens Vista series	45
Verbena Obsession series	44
Verbena Quartz series	41
Wax begonia Sprint series (*Begonia*)	43
Cold-sensitive plants – base temperature of 46°F or higher	
African violet (*Saintpaulia*), banana (*Musa* spp.), *Begonia* (fibrous), *Cladium, Gazania, Hibiscus*, New Guinea impatiens (*Impatiens* × *hawkeri*), pepper (*Capsicum*), *Phalaenopsis* orchid, poinsettia (*Euphorbia pulcherrima*), purple fountain grass (*Pennisetum setaceum*), rose (*Rosa*)	–[a]
Ageratum High Tide series	46
Angelonia Serena series	50
Blue salvia Victoria series	49
Browallia Bell series	48
Celosia Gloria series	50
Pentas Graffiti series	49
Portulaca Margarita series	48
Vinca Viper series	53

[a]Specific base temperatures have not been determined for these crops.

For example, suppose a grower had a floricultural crop with a base temperature of 10°C that required 10 weeks in the greenhouse at an ADT of 20°C. This ADT is achieved with thermostat settings of 12 h at 22.2°C and 12 h at 17.8°C. These values would correspond to heat unit requirements of (20 – 10) = 10 heat units/day × 7 days/week × 10 weeks = 700. Now suppose the grower wanted to investigate changing the temperature regime of the greenhouse to 12 h at 23.3°C (easy to keep the greenhouse this warm during the day) and 12 h at 15.6°C. This would produce an ADT of 19.4°C. To translate this value into a more useful piece of information, the heat units associated with this change would be (19.4 – 10) = 9.4 heat units/day. We need 700 to bring the crop to harvest, thus we need 700/9.4 which is ~74 days at this temperature regime. It would take 4 more days to produce the crop, but we would save quite a bit in lowering the night temperature to 15.6°C.

Day/night temperature difference (DIF)

Recall the concept of DIF that was presented in Chapter 9 of this volume. DIF is the difference between the day temperature and the night temperature, and it is an extremely important management tool for greenhouse growers. Managing DIF reduces a grower's dependence on applied growth regulators for managing stem elongation in many greenhouse crops.

If days are warmer than the nights, a positive DIF (+DIF) exists, and if the night is warmer than the day, a negative DIF (-DIF) exists. Stem elongation is enhanced with a more positive DIF, and plants remain short statured if the DIF is around zero or negative. By controlling DIF, growers can manipulate the size of their plants, but only to the extent that a species responds. Some species that exhibit a large response to DIF include Easter, Oriental and Asian lilies (*Lilium* spp.), *Dianthus, Chrysanthemum*, tomato (*S. lycopersicum*), poinsettia (*Euphorbia*), green bean (*Phaseolus vulgaris*), *Salvia*, watermelon (*Citrullus lanatus*), *Celosia*, sweet corn (*Zea mays*), *Fuchsia, Impatiens, Portulaca, Gerbera, Petunia*, snapdragon (*Antirrhinum*), geranium (*Pelargonium*), and rose (*Rosa*). Species with little to no DIF response include squash (*Cucurbita* spp.), *Platycodon*, French marigold (*Tagetes patula*), tulip (*Tulipa*), hyacinth (*Hyacinthus orientalis*), *Narcissus*, and *Aster*. The DIF response is observed when the plant is normally undergoing significant stem elongation. If a grower knows the crop growth characteristics well, they can time the DIF to occur only during the period of most significant stem elongation and not the entire growth cycle.

In general a DIF of -5°C is sufficient to induce shorter internode length and therefore shorter plants. If the DIF is too negative, undesirable responses such as chlorosis may occur. In addition, growers need to be cautious when using DIF as a method of growth regulation since the rate of crop development is affected by temperature as well. Any DIF treatment that results in an increase in the ADT will be likely to result in accelerated crop development and any treatment that reduced the ADT would retard growth and development.

In order to achieve a negative DIF, significant greenhouse heating at night is needed. However, lowering the greenhouse temperature below the night temperature for 2 h at sunrise (which creates a negative DIF) is just as effective as maintaining the negative DIF with heating for the entire night. This procedure is called the 'cool morning pulse'. It reduces the need for excessive heating during the night to maintain a negative DIF.

The DIF response may be a response to gibberellin production. Warmer days and cooler nights (+DIF) often stimulates internode elongation by enhancing gibberellin synthesis or action.

Floral initiation and development

Flower bud initiation and development of many greenhouse grown crops is highly regulated by temperature. Two types of temperature regulation of flowering are observed in sensitive species. A qualitative response is observed in species that have an absolute requirement for a specific number of days at a precise temperature for flowering. Plants with a quantitative requirement are those where the flowering response may be modified by changing the temperature, but temperature itself does not determine whether or not the plant will flower. These types of plants will eventually flower regardless of temperature, but temperature regulates at what stage of development flowering will occur.

An example of the quantitative flowering response can be observed in day-neutral strawberries (*Fragaria* × *ananassa*); they eventually flower no matter what temperature they are gown at (within reason of course), however, they flower more rapidly when grown at cooler temperatures. An example of a qualitative flowering response is vernalization (studied in Chapter 9 of this volume) and observed in many flowering bulbs. Some species that are not bulbs have a qualitative low temperature requirement for flowering. These species include *Cineraria, Calceolaria, Hydrangea*, and *Cymbidium* orchids. Other species have a qualitative high temperature requirement for flowering and include Azalea (*Rhododendron* spp.), *Clarkia*, and annual Larkspur (*Consolida*).

Temperature and greenhouse vegetable production

In many greenhouse vegetable-production operations, temperature can greatly influence productivity not only by its effects on general growth rates, but by specific effects on certain stages of development. In tomato (*S. lycopersicum*), for example, fruit set is greatly reduced when day temperatures are above 32.2°C, and nights are above 23.9°C or below 13.9°C. Prolonged growth of cucumber (*C. sativus*) at temperatures above 29.4°C leads to reduced fruit quality. Lettuce (*L. sativa*) grown at excessively warm temperatures tends to become bitter and flower prematurely. Additionally, lettuce seed will not germinate if temperatures are too high.

Light

The lighting environment of a greenhouse is crucial to its success or failure. Both the quantity and the quality of light utilized in a greenhouse can impact plant growth and development. When evaluating the light levels in a greenhouse, two sources of light must be considered: (i) natural; and (ii) artificial. Photoperiod is another important aspect of greenhouse lighting. Many species respond to daylength during their growth and development and certain developmental stages such as flowering may be highly regulated by photoperiod. It is important to distinguish between effects due the length of the daily light period and effects due to the length of the dark period. Responses due to the length of the dark period are true photoperiodic effects and are controlled by the light-sensing pigments especially phytochrome.

Both quantity and quality must be taken into consideration when discussing light with respect to plants and their responses. Even though light levels are often reported as foot candles, lux, etc., the most appropriate measurement for light levels associated with growing plants is micromoles of photosynthetically active radiation (PAR) per square meter per second (μmol PAR/m^2/s). In greenhouse production, it is often best to consider the daily light integral (DLI) which is the daily total of photosynthetically active light (PAR, 400–700 nm) measured in moles per square meter per day (mol/m^2/day). During the summer on a cloudless, long day, mid-latitudes receive approximately 60 mol/m^2/day. In contrast, during a short, cloudy, winter day, less than 5 mol/m^2/day might be received on a greenhouse bench. This is important in that the DLI is directly related to plant productivity and therefore yield. If an insufficient DLI is received by a crop, productivity will suffer, perhaps even to the point of crop failure.

A general goal DLI for many greenhouse situations is 10–12 mol/m^2/day. Sensitive or shade-tolerant crops such as African violets (*Saintpaulia ionantha*) or *Impatiens* grow well at half that amount. While there are maps that provide estimates of DLI for various times of the year at different locations, it is best to measure the actual DLI yourself. The investment in a good light sensor is well worth it.

Natural

Natural light is provided by the sun. Only a portion of solar radiation striking the greenhouse actually reaches the plants inside the greenhouse. The quantity and quality of that light are affected by: (i) time of year; (ii) time of day; (iii) prevailing weather conditions; and (iv) greenhouse covering material. In general a grower is seeking to maximize the amount of natural light reaching the plants inside his or her greenhouse. During winter when the greenhouse is most likely being used to force an out-of-season crop, lighting may pose a double problem. Depending on longitude, days may be very short and light levels very low due to the low declination of the sun during winter in many climates. Even though natural light levels may be at an unacceptably low level during winter, there are a number of things a greenhouse manager can do to enhance the lighting inside the greenhouse.

Aim for about 50% light transmission into the greenhouse during the winter months (Runkle, 2012b). Invest in a reliable light meter, preferably one that measures PAR so that you really know how much light there is in the greenhouse. Once you have a good light meter, understand how to use and maintain it. When taking measurements, make sure the sensor is perfectly level, at canopy height and not in a shadow. If the sensor is permanently mounted, make sure it is not in the path of traveling shadows during the day and try to keep it dry. Even though the sensor may be waterproof, water droplets may contain dissolved solids that could build up over time as the droplets dry on the sensor which could lead to faulty readings. Consult the manufacturer for how often the sensor should be recalibrated.

To maximize light entering the greenhouse, make sure the greenhouse covering is clean, and if it can’t be cleaned, make sure it’s renewed for the following winter season. In addition, try using anti-condensation materials for the inside of poly covers to minimize light absorption or reflection by water droplets. Make sure there aren’t too many hanging baskets overhead as they can significantly reduce the light hitting bench crops.

Above all, understand the lighting requirements of the crop you are growing. Know what the DLI requirement is to bring your crop to a salable condition and investigate whether or not photoperiodic stimulation is warranted. Don't try to grow a crop that you are not equipped to produce. If natural light levels are too low and you can't afford supplemental lighting, consider changing which crop you'll grow.

Supplemental lighting

Since many greenhouse crops are produced when the natural DLI is below an optimum level, supplemental lighting is required to enable production. When thinking about supplemental lighting for your greenhouse, remember there are two main reasons to consider it. One is to supplement the natural DLI to enhance photosynthesis and thereby enhance plant growth and productivity and the other is for photoperiodic stimulation. Be sure you understand which of the two you are dealing with. In many cases, you will probably be concerned with both.

Photosynthetic needs

CROP LIGHT REQUIREMENTS Every greenhouse crop whether flower, fruit, herb or vegetable has a specific requirement for a minimum DLI needed to bring the crop to market. By knowing the light requirements for your crop, you will know how feasible it is to provide supplemental lighting economically. For most crops, increasing the DLI decreases the time to flower and increases plant quality (numbers of flowers or fruit, improved branching, thicker stems), but only up to a point. The point at which increasing the DLI has no positive effect on a crop varies among species and is called the saturation DLI. By understanding the crop you are growing, you would know if increasing the DLI is worth it. In general, increasing the DLI above 15 isn't warranted unless you are dealing with a specialty crop where you know there is a benefit.

Greenhouse lettuce (*L. sativa*) production requires a minimum of 12–13 mol/m^2/day, sweet pepper (*C. annuum*) needs at least 12 mol/m^2/day while tomatoes (*S. lycopersicum*) require at least 6 mol/m^2/day for seedling production ultimately increasing to at least 30 mol/m^2/day for fruit production (Dorais, 2003). Cucumber (*C. sativus*) production requires at least 5.5 mol/m^2/day but fruit development can be reduced from 24 days at 5.5 mol/m^2/day to 10 days at 30 mol/m^2/day (Dorais, 2003).

A second consideration when increasing the DLI is to take into account any effect the lighting for enhanced DLI might have on a photoperiodic response. For example, supplementing light to enhance flowering of short-day plants might be offset by the delay in flowering caused by longer days under supplemental lighting to enhance DLI. Some estimates of saturation DLI values are given in Table 11.3.

LIGHT SOURCES, TIMING, DURATION, AND INTENSITY The high pressure sodium lamp is still the recommended light source for increasing the DLI (Runkle, 2012b). As technology of light emitting diodes (LED) improves, this recommendation may change. However, LED units are much too expensive still to warrant their use in commercial settings.

To determine the amount of supplemental lighting required for any specific situation, verify the DLI needed to bring the crop to market. The Internet provides a rich source of references for determining this value. Once this value is derived and the lamp source, number of units, and light supplied per unit are known, the duration needed to supply the needed radiation can be determined.

There are many options available when selecting supplemental lighting configurations for greenhouse production. As a point of reference, let's assume we are using high pressure sodium lamps that can provide 150 μmol/m^2/s PAR. Our estimated DLI is 4 mol/m^2/day. We want to grow lettuce (*L. sativa*) which requires a minimum of 12–14 mol/m^2/day, thus we need to supply at least 12–4 = 8 mol/m^2/day. Lights providing 150 μmol/m^2/s PAR would provide 540,000 μmol/m^2/h PAR (150 × 60 × 60) which is 0.54 mol/m^2/h PAR. To determine the length of time the lights must be illuminated, divide the supplemental lighting molar requirement by the per hour molar light production. For example, if we need 8 mol/day extra illumination and our lighting system supplies 0.54 mol/m^2/h PAR, we would need 14.8 h (8/0.54) of illumination per day to meet the minimum requirements. If we needed 14 mol/m^2/day, we would need to provide 10 mol/m^2/day extra or 18.5 h (10/0.54) of supplemental illumination.

Longer light periods at lower illumination tend to increase productivity compared with shorter

Table 11.3. Saturation daily light integrals (DLI) for a number of bedding plants normally produced in the greenhouse (adapted from Runkle, 2012b).

Crop	Estimated saturation DLI (mol/m^2/day) PAR
Angelonia Serena series	5
Browallia Bell series	11
Celosia Gloria series	10
Cosmos sulphureus Cosmic series	4
Dahlia Figaro series	11
Dianthus Super Parfait series	6
Gazania Daybreak series	20
Geranium (seed) (*Pelargonium*) Florever series	12
Impatiens (bedding) Accent series	<4
Lobelia Riviera series	5
Marigold (African) (*Tagetes*) Antigua series	5
Marigold (African) (*Tagetes*) Moonstruck	8
Marigold (French) (*Tagetes*) Bonanza series	6
Marigold (French) (*Tagetes*) Janie series	6
Osteospermum Passion series	12
Pentas Graffiti series	7
Petunia (Grandiflora) Dreams series	7
Petunia (Milliflora) Fantasy series	17
Petunia (Spreading) Easy wave series	9
Petunia (Spreading) Wave series	9
Portulaca Margarita series	8
Rudbeckia (annual) Becky series	7
Salvia (blue) Blue Bedder	10
Salvia (red) Vista series	10
Snapdragon (*Antirrhinum)* Montego series	12
Verbena Obsession series	10
Verbena Quartz series	13
Vinca Viper series	5
Viola Sorbet series	>12
Wax begonia (*Begonia*) Sprint series	7
Zinnia Dreamland series	8

durations of higher intensity light. Continuous illumination often leads to metabolic perturbations such as chlorosis and reduced growth (Sysoeva *et al*., 2010). In general, if photoperiod is not constrained by other physiological responses to it, supplemental lighting is often provided for 10–20 h to provide the required DLI.

Computer programs have been created to monitor the DLI and adjust supplemental lighting accordingly. Lights may be turned off if the DLI is reached. The decision to limit the DLI is important in those crops for which a saturation DLI has been established.

Photoperiodic needs

As you move farther away from the equator, the length of the daily light period or photoperiod dramatically changes over the course of a year. Daylength at the equator is always 12 h. In either hemisphere, as the season changes from summer into winter, days become increasingly shorter until the winter solstice on 21 or 22 December (depends on the year), when at any given point between the equator and the corresponding North or South Pole, the daylength is at a minimum. After this date, daylength gradually increases until the summer solstice on 20 or 21 June when the daylength is longest. The process then begins all over again.

Plants readily detect changes in the length of the day via the pigment phytochrome. Sunlight favors the formation of the far-red form of phytochrome (P_{fr}). During the dark, P_{fr} gradually reverts to the red form of phytochrome (P_r). True photoperiodic plant responses are regulated by the relative amounts of

P_{fr} and P_r remaining after the dark cycle. Shorter dark cycles result in a greater amount of P_{fr} remaining with less P_r. Thus a long-day response is actually a response to a short dark cycle and an elevated level of P_{fr}.

Plant leaves absorb more red light than far-red light. Sunlight has a red:far-red light ratio of 1.2, thus there is a little more red light than far-red light in sunlight, so the balance of P_r:P_{fr} favors P_{fr}. At the end of the day, much of the phytochrome in a plant is in the physiologically active P_{fr} form. Phytochrome in the physiologically active form (P_{fr}) promotes shorter, highly branched plants with small thick leaves. Leaves intercepting light that has passed through a leaf is receiving light with a red:far-red ratio of 0.13! This light has a large amount of far-red light in it, thus the favored form of phytochrome in this instance would be P_r, the physiologically inactive form. This leads to a preponderance of phytochrome in the red form, which is the physiologically inactive form. With P_{fr} is lacking, as is the case in an overcrowded greenhouse or on a greenhouse bench shaded by hanging baskets, plant stems elongate, leaves grow larger and thinner, and branching is greatly reduced. The 'shade avoidance response' can be attributed to a lack of phytochrome in the physiologically active form, P_{fr}.

One of the most important plant responses to photoperiod is flowering and many greenhouse crops are photoperiodically sensitive with respect to flowering (Table 11.4). With respect to flowering plants are day-neutral, short-day or long-day plants.

Day-neutral plants are not sensitive to daylength when it comes to flowering. Some common greenhouse crops that are day-neutral include African violets (*S. ionantha*), cucumbers (*C. sativus*), rose (*Rosa*), and tomatoes (*S. lycopersicum*).

Short-day plants are those species that will only flower or flower more rapidly after exposure to days that are shorter than a defined critical photoperiod. The critical photoperiod is often different for different species, but they all must be exposed to days shorter than their critical photoperiod before they will flower. Some short-day crops include poinsettia (*Euphorbia*), and *Chrysanthemum*.

Conversely, long-day plants will only flower or flower more rapidly after exposure to days that are longer than a critical photoperiod. As in short-day plants, the critical photoperiod is often different for different long-day species, but they all will only flower after exposure to days longer than the critical photoperiod. Some long-day species include *Rudbeckia*, lettuce (*L. sativa*), and spinach (*Spinacia oleracea*).

Some species such as strawberry (*Fragaria × ananassa*) include cultivars that are day-neutral, short-day or long-day.

In addition to the daylength, the number of cycles required by individual species varies from as little as one to as many as 14 or more. The intensity of flowering is often related to the number of photoperiodically inductive cycles a plant has been exposed to. Profuse flowering often follows exposure to several or to many cycles while sparse flowering follows exposure to only a few. If plants are exposed to too many inductive cycles, they may become dormant. To complicate matters even more, temperature can moderate the response to

Table 11.4. Photoperiodic requirements for flowering of some major greenhouse crops (adapted from Runkle, 2012b).

Crop	Day-neutral	Short-day	Long-day
Begonia	X		
Dahlia		X	
Geranium (*Pelargonium*)	X		
Impatiens	X		
French marigold (*Tagetes*)	X		
Pansy (*Viola*)			X
Petunia			X
Snapdragon (*Antirrhinum*)			X
Black-eyed Susan (*Rudbekia*)			X
Campanula			X
Columbine (*Aquilegia*)	X		
Coreopsis			X
Hosta			X
Lobelia			X
Shasta daisy (*Leucanthemum*)			X
African violet (*Saintpaulia*)	X		
Chrysanthemum		X	
Cyclamen	X		
Poinsettia (*Euphorbia*)		X	
Rose (*Rosa*)	X		
Strawberry (*Fragaria*)	X	X	X
Tomato (*Solanum*)	X		
Cucumber (*Cucumis*)	X		
Pepper (*Capsicum*)	X		

photoperiod. In general, cooler temperatures mimic shorter days while warmer temperatures mimic longer days.

Besides flowering, photoperiod also influences vegetative growth, plant height, branching, and other general growth characteristics.

Greenhouses are often used to produce commodities out of season. Often the natural daylength is not suitable for certain aspects of a crop's production cycle and may need to be altered. Daylength may need to be either shortened or lengthened depending on the crop and time of year.

DECREASING THE PHOTOPERIOD When photoperiods are too long, they can be artificially shortened by draping black plastic or black cloth over plants at a pre-specified time during the day followed by appropriate removal (Fig. 11.4). Shorter days may be desired to induce flowering in short-day plants or prevent flowering in long-day plants. The black cloth or plastic should not be placed over the plants too early in the day or removed too late the following day or excessive heat may build up. The covering must be complete since even small amounts of light entering through slits or cracks can be perceived by plants. Even under natural short days, growers should be mindful of light from parking lots or other sources of light that might be perceived by plants in the greenhouse. When particularly sensitive species are grown, black cloth or plastic may be used even under natural short days to ensure that plants are in absolute darkness during the nyctoperiod.

LENGTHENING THE PHOTOPERIOD Under naturally short days, the daylength can be lengthened for a photoperiodic response using the night interruption (NI) technique (Fig. 11.5). This red-light effect on phytochrome was described in detail in Chapter 8 of this volume. In general, this technique uses low level light applied for 3–4 h during the middle of the normal dark period. Alternatively, the daylength can be extended with similar lighting from sunset until the desired daylength is reached. In either approach, the light source should provide at least 10 foot candles. Incandescent lamps are often used to elicit the daylength response since they are inexpensive and easy to use. They do have the drawback of emitting significant far-red light which often promotes stem elongation in many species. The red:far-red ratio of light emitted by incandescent lights is 1.07 (Downs and Thomas, 1982) thus even though they do emit far-red light, enough red light is emitted to favor a preponderance of P_{fr} at the end of the interruption. Recall that the idea behind the NI or daylength extension with low level lighting is to convert P_r to P_{fr} such that an effectively high enough level of P_{fr} remains at the end of the dark cycle. In the case of the NI technique, we want a high level of P_{fr} at the end of the dark cycle that follows the interruption.

To avoid stem elongation, widely spaced sodium or metal halide lamps set high above the plant canopy can be used to provide the low level of light desired without inducing stem elongation.

Water

Water management is crucial for successful greenhouse management. Besides the obvious need to supply plants in a greenhouse with water since they are not exposed to natural rainfall, management of the water vapor in the air of a greenhouse is one of the most important and difficult attributes of greenhouse management. Temperature and light levels can be automatically adjusted with the help of automation. Humidity regulation is more complex. In order to understand greenhouse humidity management techniques, a thorough understanding of air water vapor is important.

The water vapor content of air is often expressed as RH (relative humidity). RH is the ratio of the weight of water in a unit volume of air to the water holding capacity of that unit volume of air at a specific temperature and pressure. The pressure of the air in a greenhouse does not change that rapidly or dramatically, therefore its influence on RH is minimal. Temperature is another matter. It can change rapidly and dramatically and has a large impact on the RH of the air in a greenhouse. It is this influence of temperature on RH that makes it particularly difficult to control.

As air warms, it can hold more water. Air at 21°C can hold twice the water of air at 10°C. Warming a specific volume of air without changing the absolute amount of water vapor in it reduces its RH. Cooling the same parcel leads to an increase in RH. Even though the RH changes with temperature, the amount of water in the given volume of air is not changing.

The dew point (wet bulb temperature) is another important characteristic of a parcel of air. It is the temperature at which water will condense out of the air. As soon as an object reaches

(a)

(b)

Fig. 11.4. Strawberry (*Fragaria* × *ananassa*) plug plants before being placed in the greenhouse for winter (New Jersey, USA) production. (a) Prior to short-day photoperiod treatment. (b) Receiving short-day photoperiod treatment by being draped in black plastic.

the dew point, water will begin to condense on it. The dry bulb temperature of the air is the commonly measured air temperature. Dew point is directly related to RH. When the RH is high the dew point is very close to the dry bulb temperature. At a lower RH, the dew point is much lower than the dry bulb temperature. For example, if the RH is 85% and the dry bulb temperature is 15.5°C, water will condense on objects at 12.7°C. Increase the RH to 95% (which is easy to do in a greenhouse at night) and water condenses on objects at 15°C.

Fig. 11.5. Strawberries (*Fragaria* × *ananassa*) grown during December (New Jersey, USA) using the night interruption (NI) technique with incandescent lighting to promote inflorescence elongation and flowering, both long-day responses. Note the incandescent bulb at the top middle of the photo.

While humidity deficits may occur in greenhouses in some arid regions, the RH inside a well-constructed greenhouse can usually be increased with misting or humidifiers. Briefly wetting the floor also helps raise humidity, however, free-standing water is not desirable. More often than not, problems in a greenhouse occur as excessively high RH at night. High RH at night in a greenhouse is a problem due to condensation.

Even a small difference in RH, in the previously discussed case 85% versus 95%, can make a big difference in the amount of water that can condense on plant leaves and the temperature at which it condenses. Again, this is especially important at night. During the day the dry bulb temperature is almost always higher than the dew point, except on cloudy, rainy days. Thus condensation is usually not much of a problem during the day. But why is condensation at night a problem? The answer is disease control. Condensed water on leaves is a perfect medium for the germination of fungal spores that cause significant disease problems in greenhouse crops. In addition, dripping or splashing water spreads spores throughout the greenhouse.

Botrytis and powdery mildew (*Erysiphe, Leveillula, Microsphaera*, and *Spaerotheca*) are two important greenhouse disease problems which may be hard to control under humid conditions. To control disease development in the greenhouse, the RH must be controlled. There are a number of cultural practices which can greatly reduce problems associated with high night-time RH. Remember, even a small difference in the RH can make a big difference in the temperature at which water condenses out. A key to good greenhouse RH management is to enter the night with the greenhouse as dry as possible.

Proper greenhouse watering is important. Good floor drainage prevents water from puddling and watering early in the day allows excess water to evaporate and be removed from the greenhouse atmosphere via ventilation during the day. Proper plant spacing on mesh benches allows good air movement within the greenhouse which helps to keep the RH a bit lower. Canopies that are too close trap transpired water and raise the RH immediately around the plant. When watering, apply only enough water to thoroughly moisten the growing medium. Avoid wetting the foliage if possible. Watering too heavily can create puddles of standing water and also it leaches nutrients from the soil mix. Excessive watering can also lead to waterlogged root systems, resulting in poor growth, root rot, and epinasty. Keep weeds out of the greenhouse. Besides being unsightly and potential sources of disease and insect contaminants, weeds transpire water from the soil into the air.

Heating below the plants via cables or hot water/steam pipes increases air circulation around the plants as the air rises from the heat source, plus it increases the surface temperature of plant tissues, potentially preventing condensation on them.

If the greenhouse is a poly cover, using a cover with a wetting agent incorporated into it or spraying a wetting agent on an existing cover helps moisture that condenses drain down the curve of the covering rather than drip onto the plants below. If the cover is rigid such as glass, make sure the roof is pitched steeply enough to ensure good drainage rather than dripping.

Air movement within the greenhouse with overhead poly tubes or horizontal air flow fans (see earlier in this chapter) helps mix the air and maintain a lower RH. Mixing air removes cold pockets where moisture could more easily condense and also facilitates mixing of the air around plant canopies.

Heating and ventilation are two powerful tools in controlling greenhouse humidity. Heating raises the air temperature which raises the amount of water the air can hold before condensing out while ventilation exchanges drier air from outside with moist air from inside the greenhouse. Neither alone is sufficient in controlling humidity, but used together, they can help regulate humidity at acceptable levels.

The approach to humidity control with heating and venting depends on the greenhouse set up. In houses with passive venting (no fans) such as smaller, homeowner units, the heat should be turned on for a while, then the vents opened to allow heated, rising air to exit the greenhouse. Cooler drier air from outside will replace this air, reducing the RH inside.

With forced ventilation greenhouses (houses with fans), operate the ventilation fans for a few minutes to remove humid inside air with drier outside air. Once the fans are turned off, the heat is turned on to warm up the outside air that has been drawn into the greenhouse. The key is to operate the vents and the heat separately; they should not be operating at the same time. This venting-followed-by-heating process should be performed several times an hour for several hours after sunset and several hours before sunrise. The length of time each venting cycle is on depends on the exchange rate of the venting system. One full exchange of greenhouse air is desired per cycle. High capacity systems may only require venting for 2 or 3 min each cycle while a lower rate system may take much longer.

A good hygrometer or a sling psychrometer is a wise investment for measuring humidity levels in the greenhouse. A general guideline for desirable humidity levels is based on the observation that plants can tolerate a higher RH at warmer temperatures. The RH in the greenhouse should be no higher than 83% if the greenhouse temperature is 10°C, 89% at 16.1°C, 91% at 20°C, and 95% at 30°C (Prenger and Ling, 2000). Besides disease problems associated with high RH, reduced transpiration by plants under high humidity may lead to reduced nutrient uptake and therefore smaller, weaker plants.

Carbon Dioxide Enrichment

Carbon dioxide (CO_2) is a major substrate for one of the most important biochemical processes on our planet: photosynthesis. The average CO_2 concentration in the atmosphere has risen from 382 ppm in 2007 to 392 ppm in 2012, or about 2 ppm/year (Tans, 2012). While elevated atmospheric CO_2 levels are a concern of global climate change, elevated levels of CO_2 are often desirable in greenhouse environments to increase productivity. Enhanced CO_2 levels in the greenhouse nearly always results in enhanced yield and or quality of crops grown in them. This is especially true in winter greenhouse production situations in regions with short days and naturally low light intensities. Combining CO_2 enrichment with supplemental lighting has a synergistic effect (Dorais, 2003).

The reason CO_2 enrichment works centers around a key enzyme involved in photosynthesis, RuBisCo. Recall that RuBisCo is a dual function enzyme, it can fix CO_2 (desired) or O_2 (not desired). The main effect of CO_2 enrichment is to shift the balance between carboxylation and oxygenation via RuBisCo towards carboxylation (Tremblay and Gosselin, 1998). This effect is consistent over a wide range of light levels, indicating that CO_2 enrichment is effective at any time of the year. The optimum level of CO_2 in greenhouses lies between 700 and 900 ppm. In general, the greatest benefits to CO_2 enrichment are observed in the vegetative growth of young seedlings (Kimball, 1983).

C3 plants generally show a greater growth response to elevated CO_2 levels compared with C4 plants (Prior *et al.*, 2011). This is not surprising since C3 plants experience photorespiration and C4 plants do not, and carboxylation rather than oxygenation by RuBisCo is enhanced by elevated CO_2. Besides reduced photorespiration under elevated CO_2 levels, enhanced net photosynthesis also results in both C3 and C4 species. There is generally a 33–40% increase in net photosynthesis for C3 species and a 10–15% increase for C4 species (Kimball, 1983).

In addition to stimulated photosynthesis, elevated CO_2 leads to altered carbon partitioning towards below-ground organs which leads to an increased root:shoot ratio. Plants will often allocate carbon towards tissues responsible for acquiring the limiting component(s) of a metabolic process. Under conditions of elevated CO_2, water and nutrients are limiting photosynthesis, thus carbon is allocated to roots to enhance water and nutrient uptake. The extra carbon allocated to roots can be stored for utilization by the plant when carbon may become limiting (i.e. under stress conditions), or the extra carbon may be allocated for increased root growth. Root colonization by mycorrhizae which enhance water and nutrient uptake increases with elevated CO_2.

Most greenhouse crops are grown in containers that limit root growth, thus the response to elevated

CO_2 might be limited compared with plants with unrestricted root systems. Even with the limitations imposed by containers of greenhouse-grown plants, CO_2 enrichment is advantageous in that it allows plants to reach a marketable size more rapidly compared with plants grown under ambient CO_2 levels.

CO_2 enrichment not only enhances photosynthesis, it decreases transpiration rate thereby increasing plant water use efficiency (WUE) (Woodrow *et al.*, 1987) and enhancing subsequent drought tolerance. Enhanced seedling growth in the greenhouse induced by CO_2 enrichment translates into healthier, more productive plants in the production field that tolerate transplanting shock rather well (Tremblay and Gosselin, 1998). Enhanced seedling growth in the greenhouse renders plants ready for transplanting in less time, thus freeing up valuable greenhouse space.

Elevated CO_2 leads to more efficient water relations in both C3 and C4 plants by reducing transpiration induced by partial stomatal closure. Reduced transpiration combined with increased photosynthesis leads to enhanced WUE (the ratio of carbon fixed per unit of water transpired). On average WUE is doubled when CO_2 is doubled. Elevated CO_2 may reduce drought stress, however, much of the work to suggest this is in greenhouses or growth chambers with artificially induced drought conditions.

The increased WUE may be offset by increased water use of larger plants caused by elevated CO_2 levels. With enhanced WUE, plants may need watering less frequently under elevated CO_2 environments. As water rights become increasingly important, reduced frequency of watering would be a major benefit for greenhouse managers.

The most common method of enriching the greenhouse atmosphere with CO_2 is by controlled burning of a hydrocarbon, often propane, butane, alcohol, or natural gas. One of the problems with burning a hydrocarbon fuel is the production of carbon monoxide (CO) and ethylene under conditions of incomplete combustion. Incomplete combustion is most often associated with poor burner calibration or low oxygen levels. CO is toxic at very low levels to both plants and humans and ethylene is a plant growth regulator. If a hydrocarbon is burning with a blue or whitish flame it is burning with nearly complete combustion with little or no CO/ethylene generation. If the flames are yellow, orange or red, incomplete combustion is occurring and CO and/or ethylene are being generated. Other byproducts of CO_2 generation by hydrocarbon burning are heat production of water vapor. The quantities of heat, water vapor and CO_2 produced per unit of fuel vary with the fuel being burned and the rate of burning.

The second most common method of CO_2 enrichment is via injection of pure CO_2. Compressed CO_2 comes in metal cylinders or tanks holding 20 or 50 lbs of CO_2 under high pressure (1600–2200 psi). To utilize this method of CO_2 enrichment, an appropriate set up including the tank of gas, pressure regulator, flow meter, valves, and controller is needed. The system must be calibrated to deliver the appropriate amount of gas for the greenhouse volume being enriched during the photosynthetic period. Once the initial control equipment is purchased, this type of system is fairly economical to operate.

Composting organic matter and animal manures has been suggested as a way of economical and sustainable CO_2 generation, however, widespread commercial adoption of these approaches have not yet occurred.