National Award Winner
American Society for Horticultural Science
Extension Division

HIGH TUNNEL SERIES

Managing the Environment in High Tunnels for Cool Season Vegetable Production

Elizabeth Maynard
Clinical Engagement
Assistant Professor of Horticulture
Purdue University

Michael O'Donnell
Extension Educator
Organic and Diversified Agriculture
Purdue Extension

Introduction

Light, temperature, and relative humidity influence how crops grow and develop. In a high tunnel, or passive solar greenhouse, growers can influence these conditions but do not have precise control. This publication will first review plant responses to light levels, temperature, and relative humidity, and explain the principles governing their management. The second section provides practical suggestions for managing the environment in high tunnels used for cool season production in the midwestern United States.

What's in a Name

We use the term "high tunnel" because it has become a common term to describe poly-covered growing structures large enough to walk in that often have no active heating or cooling. Before "high tunnel," commonly used terms included "passive solar greenhouse," "low-tech greenhouse," "hoophouse" or "cold-frame." These structures represent one spot on a continuum of protective structures for crops. A low-tech end example is individual hot-caps for single plants. Then there are "low tunnels" that cover up to a few rows but aren't tall enough to walk in. High-tech examples include greenhouses and grow rooms with sophisticated heating, cooling and lighting systems. This publication primarily covers unheated high tunnels and the use of internal row covers.

In the Midwest, cool-season crops are grown in these structures from about September through March. Crops include leafy greens such as kale, chard, lettuce, mustard, and spinach; head-forming brassicas such as bok choy; and root crops including radishes and turnips. In structures with supplemental heat, tomatoes and other warm season crops may overlap with cool season crops, but this publication emphasizes managing the environment of high tunnels for cool season vegetable crop production.

The High Tunnel Environment – Light

Light provides the energy for photosynthesis that drives plant growth. Also, certain wavelengths, or colors, of light influence flowering, branching, leaf color, and other aspects of plant growth and development.

Characteristics of light important to plants

For photosynthesis, plants make use of certain wavelengths of light. This spectrum of light is called photosynthetically active radiation, or PAR. The brighter the light – or more accurately, the greater the intensity of PAR – the higher the rate of photosynthesis per unit leaf area, up to a point that varies depending on species of plant. Carbon dioxide concentration and temperature also influence the maximum PAR a plant can utilize. Above that point, the photosynthetic rate remains constant unless the intensity is great enough to injure the leaf. In full sun on a bright day there is more than enough light to maximize the photosynthetic rate for a leaf of a vegetable crop. In fall and winter the sun delivers less PAR, because it doesn't get as high in the sky and is farther away than in the summer. The PAR from bright summer sun may measure around 2000 micromoles per square meter per second ($\mu mol/m^2/s$), while a sunny day in winter could be less than half that, and on a cloudy winter day the value could be less than 200 $\mu mol/m^2/s$.

In addition to brightness or intensity, the more hours of light each day, the more a plant can photosynthesize. The total amount of PAR in a day is called the daily light integral, or DLI. Generally, plants grow slowly when the DLI is less than 10 $mol/m^2/day$.

Fig. 1 illustrates how average DLI outdoors varies with latitude from northern to southern Indiana from September through March. Fig. 2 illustrates the DLI measured inside a high tunnel in northern Indiana in fall and winter. It can vary from less than 1 $mol/m^2/day$ on a cloudy day in December, to over 20 $mol/m^2/day$ on a sunny day in late February or early March. From mid-November to mid-February, DLI is usually less than 10 $mol/m^2/day$. This corresponds closely to the period when there is less than 10 hours of daylight. Winter growing pioneer Eliot Coleman has termed this the "Persephone Period." In addition to time of year and latitude, clouds and haze affect DLI.

Low DLI in late fall, winter, and early spring means that light can limit crop growth even if temperature is adequate. A number of factors in a high tunnel influence the amount of light available to the crop. As a grower, you can manage these to maximize light for plant growth.

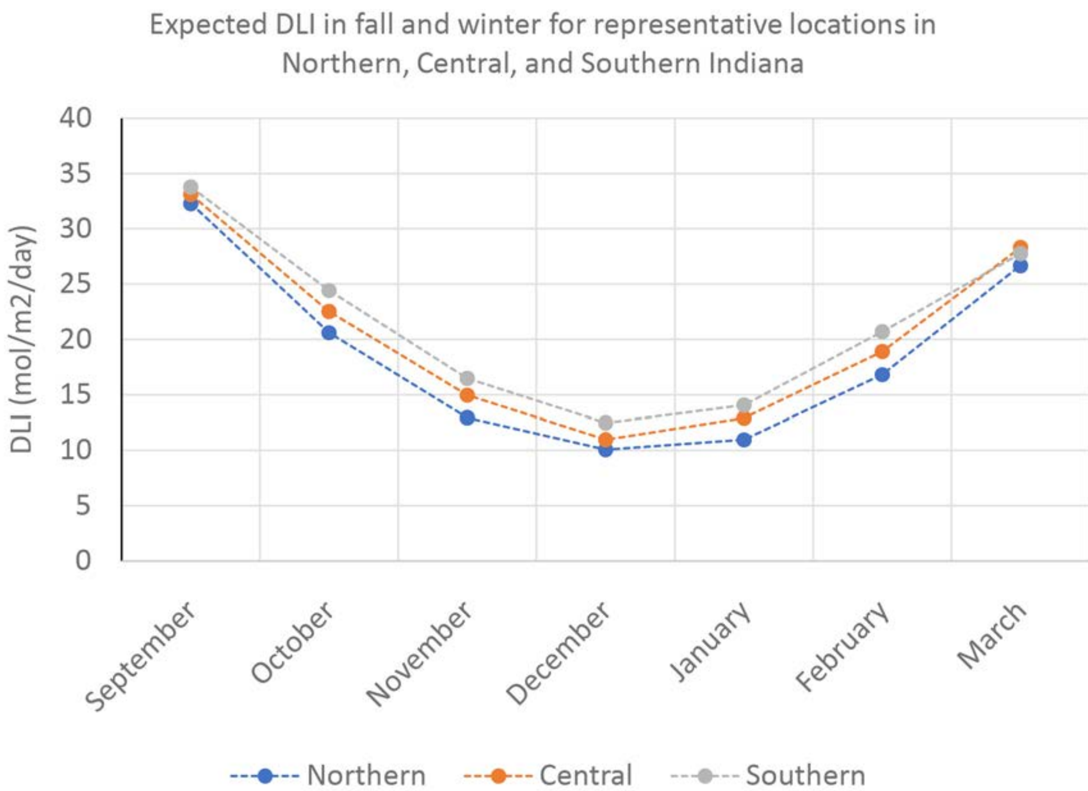


Figure 1. *Expected outside daily light integral (DLI) from September - March for representative locations in northern, central, and southern Indiana. Expected DLI is based on solar radiation data from 1998 to 2012 and converted to DLI using the conversion factor 0.0072664 mol/m2/day = 1 watt-hour/m2/day (Faust and Logan, 2018). This conversion factor provides only an estimate of DLI because it doesn't take into account variations in wavelengths of solar radiation that occur during the year. (Data provided by Faust and Logan.)*

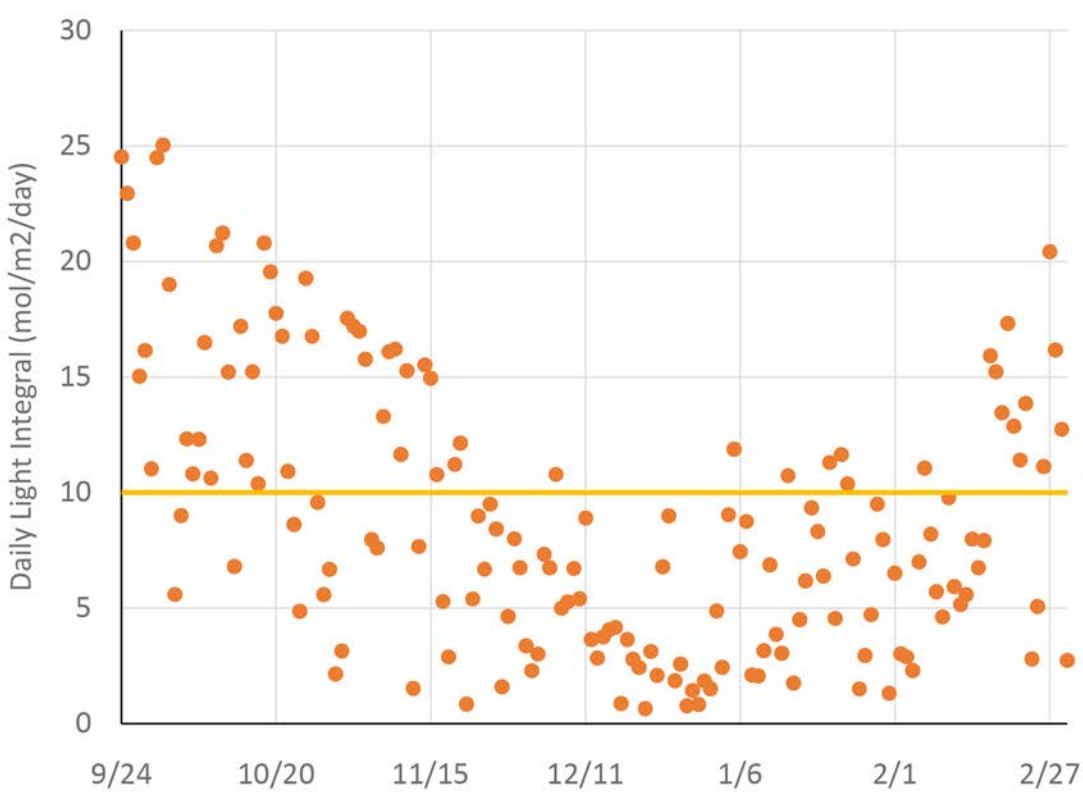


Figure 2. *Daily light integral (DLI) in an unheated high tunnel in Northern Indiana in fall and winter 2015 - 2016*

High tunnel features that influence light

Orientation

A tunnel with the longer side oriented north-south has a different light environment than the same tunnel oriented east-west. The difference is larger the farther north you go. In late fall and winter, the east-west orientation provides the most light because the sun is in the south and lower in the sky. A high tunnel with long sides facing south will let in more light at this time of year. However, a shadow cast by a hipboard or other structure running the length of the tunnel will fall close to the same place much of the day. If part of a crop is in the shaded zone, it may grow more slowly or use less water than the rest of the crop. These shadows are the reason gutter-connected structures are usually designed with ridges oriented north-south. The shadows of north-south gutters will move over the course of the day so there won't be just one shaded strip of crop. In a north-south oriented high tunnel, the south end wall can shade a good portion of the tunnel in the winter, especially in taller structures. The best orientation for a specific tunnel will be a compromise between various factors on a farm.

High tunnel covering

Greenhouse coverings vary in the amount of PAR they transmit. A single layer of plastic may transmit 88 to 92% of PAR under ideal conditions; a double layer only 77 to 85%. Actual DLI in a double poly greenhouse may average only 67% of the outside value (Giacomelli and Roberts, 1993). As plastic ages, transmission decreases.

In one instance, transmission in a double poly structure decreased from 73% to 68% over four years (Giacomelli and Roberts, 1993).

Some greenhouse plastics are designed to diffuse most of the light as it passes through the plastic. In high light conditions this is beneficial because the diffuse light is used more efficiently by plants. In the low light conditions of winter production this diffusion would probably not provide a benefit.

Condensation of water droplets on greenhouse film can significantly reduce light transmission. Greenhouse films with anti-condensate features prevent formation of water droplets and so can increase the light that gets to plants.

Common materials used for internal row-covers also reduce light. As discussed in detail below in the temperature section, row covers are often used to retain heat near crops when outside temperature drops below the mid-20s (Fig. 8). Row covers come in different weights; lighter ones do not reduce light as much but also do not provide as much insulation; heavier ones may cut out half the light but provide more insulation.

Table 1 illustrates how light is reduced by row cover in a high tunnel. Data were collected at the Pinney Purdue Agricultural Center in northwest Indiana in December through March, 2016-2017. The table compares DLI values for days when no row cover was used to days when a single layer of row cover was installed for the entire day. Without a row cover, DLI at plant level averaged 72% of outside DLI. With a row cover, DLI at plant level averaged 48% of outside DLI. Keeping the row cover on all day reduced light available to plants by about 1/3. This is especially significant in the low light periods of the year.

Table 1. *Daily light integral (DLI) values outside and inside high tunnels, with or without a row cover, for five pairs of dates. Date pairs had similar solar radiation levels; on one date no row cover was used, and on the other date a lightweight (0.55 oz./sq.yd.), spun-bonded polyester row cover was over the plants for the entire day. The two tunnels were each covered with a single layer of plastic.*

Row Cover Off				Row Cover On			
	*Daily Light Integral (DLI)**		*DLI Inside as % of Outside*		*Daily Light Integral (DLI)*		*DLI Inside as % of Outside*
Date	Outside	Inside		Date	Outside	Inside	
	($mol/m^2/day$)				($mol/m^2/day$)		
12/01/16	4.2	2.9	69%	12/11/16	5.1	2.3	46%
01/24/17	4.0	2.9	73%	01/28/17	3.9	1.9	48%
02/11/17	13.1	10.2	78%	02/04/17	12.8	6.5	51%
02/13/17	27.1	19.3	71%	02/09/17	27.5	13.2	48%
03/24/17	37.1	24.7	67%	03/15/17	38.9	19.2	49%
Average			*72%*				*48%*

*DLI outside was estimated from daily solar radiation measured within 1/2 mile of the high tunnels using the equation DLI (mol/m2/day) = Solar Radiation (megajoule/m2/day) X 2.05651298 (Sager and McFarlane, 1997). This is only an approximation of DLI. DLI inside was measured with PAR sensors located about 18 inches above the ground and under the row cover, if the row cover was on. Inside values are the average from two high tunnels at the Pinney Purdue Ag Center.

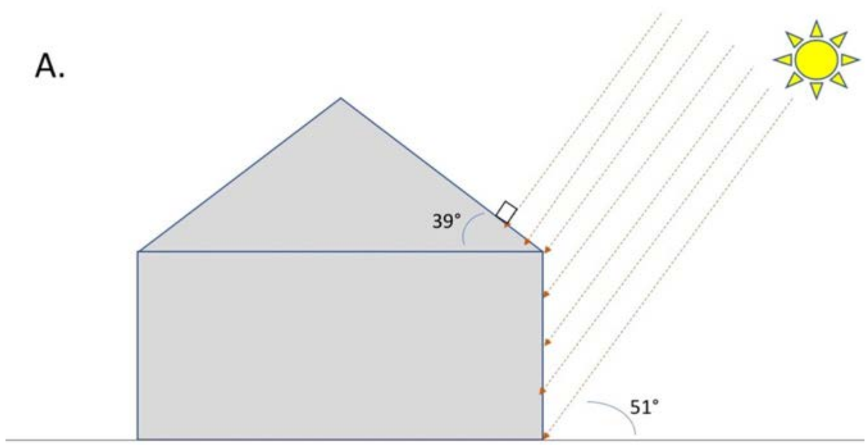
Shading

Shade is another factor that reduces light in the tunnel. Buildings, shrubs, trees, even tall weeds outside the structure cast shade. In midwinter their shadows will be long: 2.25 times their height at midday and longer earlier and later in the day. Place the structure far enough away to avoid this shade. Every bow, truss, purlin, and hipboard also creates shade and reduces light, as do hanging hoses, overhead sprinklers, and other objects in the tunnel. It is best to keep structure to the minimum needed and limit objects in the tunnel. Objects could be painted white so they reflect some light onto the plants.

Crop plants shade one another. Often bed, row and plant spacing are closer in the tunnel to maximize use of the valuable growing space. Wider spacings will reduce shading within a crop. Tall crops shade plants to the north of them. To avoid this, we recommend putting taller crops, such as kale, to be grown all winter, on the north side, and shorter crops to the south.

Shape

In practical terms, factors other than light usually play a bigger role in determining what shape of structure to build. The shape of the structure matters because the angle of the light rays as they pass through the covering influences how much light is transmitted. When the rays are perpendicular to the covering, transmission is greatest; the most light gets through. When the sun is low in the sky in December, tunnel sections at a 63° angle from the horizontal would let in the most light; when the sun is higher in September and March, tunnel sections that are 39° angle from the horizontal will let in more light (Fig. 3).



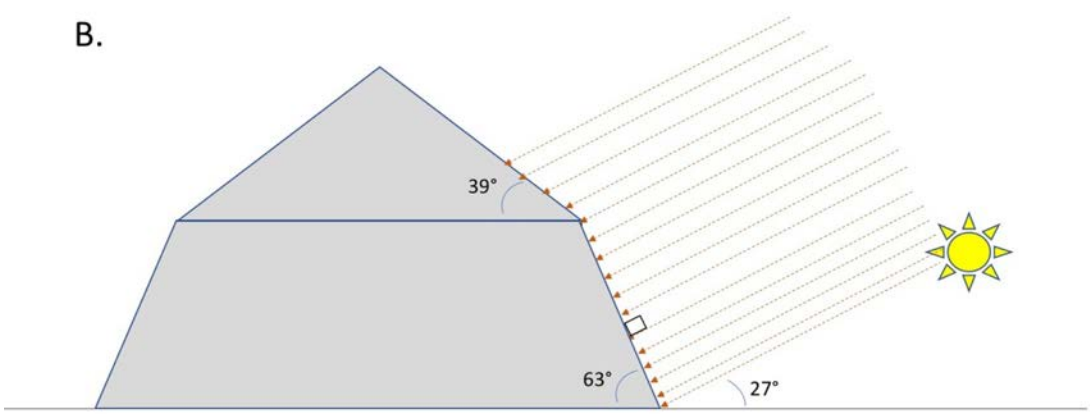


Figure 3. *The angle of the sun above the horizon influences transmission of solar radiation through different parts of a high tunnel. Sections oriented 90° to the rays of the sun will transmit the most radiation. A. Example at the Spring equinox in Indianapolis.*
The sun is 51° above the horizon at its highest point. At that time an angled roof at 39° from horizontal would be perpendicular
(90°, indicated by □) to the sun's rays and let in more radiation than the sidewalls. B. Example at the winter solstice in Indianapolis.
The sun is 27° above the horizon at its highest point. At that time an angled sidewall at 63° from horizontal would be perpendicular to the sun's rays and let in more radiation than the angled roof or a straight sidewall. Sun angles obtained from www.esrl.noaa.gov/gmd/grad/solcalc/

The High Tunnel Environment – Temperature

In this section we discuss relationships between temperature and plant growth and development, principles of energy flow and storage in high tunnels, and features of high tunnels that influence temperature.

Temperature and plant growth and development

At light levels high enough for growth, the warmer it is, the faster plants develop, up to an optimum temperature. Above and below the optimum, growth slows and eventually stops. The minimum temperature at which growth stops is known as the base temperature. For most cool season crops the optimum temperature is around 75-77°F and the base temperature is 35-40°F. When the temperature is between the minimum and optimum, the growth is closely related to the average daily temperature.

Growing degree days (GDD) are a measure that combines temperature and time into a single number. GDD take into account average daily temperature and also the base temperature for growth. GDD are calculated for each day, and then added up over the time period of interest. Under similar light levels, the number of GDD that have accumulated since emergence is a good predictor of the growth stage of a plant. We are used to talking about "days to harvest" from planting or seeding, but "GDD to harvest" can be more consistent when comparing growth under warmer and cooler temperatures.

Of course, enough light and adequate temperature are both necessary for growth. High temperatures can't substitute for low light, and high light doesn't eliminate the need to have temperatures in the range for growth.

Calculating Growing Degree Days

To calculate GDD, first determine the average 24-hour temperature. Without supplemental heat, average temperature is estimated as the maximum plus minimum divided by 2. Then subtract the base temperature for the crop of interest, 40°F for this example. The result is the GDD value for that day. As an example, consider a day with high of 70°F and a low of 50°F. The average temperature is: (70+50)/2 = 120/2 = 60°F.

Then subtract the base temperature: 60 – 40 = 20 GDD_{40} for that day. (A subscript may be used to indicate the base temperature used in calculation of GDD.) After 5 days at similar temperature, 5X20, or 100 GDD will accumulate.

Now, consider a day with a high of 60 and a low of 40. The average temperature is: (60+40)/2 = 100/2 = 50°F.

Subtract the base temperature of 40: 50-40=10 GDD_{40}.

After 5 days of these conditions, only 5X10, or 50 GDD will accumulate. It would take kale 10 days at an average temperature of 50°F to grow the same amount as in 5 days at an average temperature of 60°F.

One more example will illustrate calculation when the average temperature is below the base temperature. Consider a day with a high of 55 and a low of 20. The average temperature is: (55+20)/2 = 75/2=37.5°F. This is less than the base temperature and so no GDD accumulate that day.

High and low temperature injury and plant acclimation to temperature

Cool season crops can tolerate frost, but colder temperatures can injure crops. The temperature at which injury occurs and the amount of injury depend on the type of crop and also on conditions under which it was grown. Plants have a number of mechanisms to survive freezing. They create compounds that act as "antifreeze" so plant cells don't freeze as readily, switch to cold-hardy versions of key chemical building blocks that make up plant cells, and make proteins that protect cells from the dehydration that occurs as water between plant cells freezes. Plants acclimate to cold, or "harden off," by making these changes as they grow at cool temperatures above freezing. Unacclimated plants that have grown only at warm temperatures can't survive freezing.

For fall-planted crops, acclimation occurs as temperatures drop into the 40s or 30s at night, and the tunnel is open or vented on sunny days so it doesn't get too hot.

When temperatures drop into the low 20s or below, water between cells freezes, making leaves stiff with internal ice. Outdoors in a windy environment, or if leaves are handled, the sharp ice crystals between cells can damage the cells, killing leaves or the entire plant.

In a protected tunnel it is not so windy, and if plants are not disturbed by handling, as temperatures warm, the ice between plant cells melts, the plant recovers and can be harvested without damage.

If temperatures get low enough that the "antifreeze" inside the cells freezes (as well as the water between cells), cells will be damaged and injury will be visible. Injury from cold may appear as a slight puckering in the leaves (e.g., lettuce), death of leaves or growing point, or bleaching of leaves.

High temperatures can also injure plants. High temperatures can occur in tunnels in the winter on bright sunny days when there is little or no ventilation. The air temperature can go from below freezing to over 80°F in just a few hours. (See Fig. 4.) This rapid change can be especially damaging to plants if the soil is frozen and the roots can't take up water. In normal conditions, water moving from the roots to leaves and evaporating from the leaf surface (transpiration) keeps the leaf surface from getting too hot. If roots can't take up water on a sunny day, the leaf surface could easily get hot enough to kill leaf tissue, leaving a bleached appearance. Figure 5 shows spinach from a low tunnel where temperature of 80°F were recorded after a low near 20°F the previous night. Even if temperatures don't get high enough to cause this type of injury, the crop won't grow well when temperature is above the optimum. Ventilation can be important in winter to keep temperatures in the best range for the crop.

Figure 5. *Spinach in a low tunnel where temperatures reached 80°F after a low of 20°F the previous night. This photo was taken on Feb. 2, 2016. The bleaching and severely cupped leaf could be symptoms of high temperature injury. (Photo by D. Robb)*

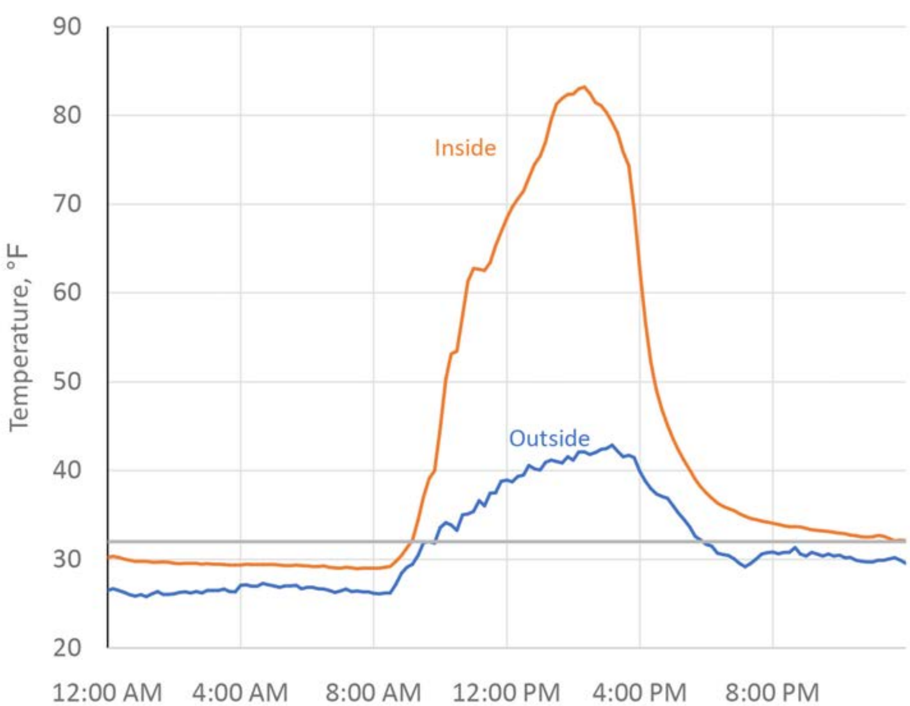


Figure 4. *Temperature outside and inside an unheated high tunnel on January 2, 2016.*

Vernalization

Some plants are triggered to develop flowers by extended periods of cool temperatures. This is called "vernalization." After vernalization, as temperatures warm, the flowering stem lengthens, flowers continue to develop, and eventually bloom. We say a plant has "bolted" when the flowering stalk lengthens and blooms. Crops subject to vernalization include many leafy brassicas (kale, mustard, cabbages, tatsoi, bok choy, mizuna, and others); several root crops (turnip, radish, carrot, beet); and in some cases swiss chard.

It is difficult to prevent vernalization for fall-planted high tunnel crops carried into the late winter and early spring. Once the plant has switched from vegetative to reproductive growth, which will typically occur by late winter, bolting and appearance of flowers can be delayed by growing under cooler temperatures, but blooming can't be prevented.

Blooming is often a problem because as plants develop flowers, vegetative growth (stems and leaves) slows, and the eating quality of leaves decreases. Flowering kale or mustards can be sold in some early spring markets as a colorful tender treat (e.g., kale rabe), and in those cases it may be desirable. Eating quality of root crops decreases even more quickly than for the leafy crops; roots should be harvested before regrowth starts in the spring.

For spring-planted crops, vernalization can be an even bigger problem because vernalized plants often bloom before they have developed to marketable size. Types and varieties of crops differ in how old they must be before vernalization can occur and the duration of cool temperatures required for vernalization. Kales, mustards, bok choy, and other plants in the mustard family are likely to flower while small if planted too early in the year.

Lettuce and spinach also bloom in the spring, but their flowering is not triggered by cool temperatures. Long days trigger the switch to flowering in spinach, and high temperature combined with longer days trigger flowering in lettuce.

Influence of soil temperature

Soil temperature also influences plant growth as well as seed germination. For most cool season crops the optimum soil temperature for germination is approximately 70°F and the minimum soil temperature for germination is 35°-40°F, with faster germination the warmer the soil. Lettuce and spinach seeds can go dormant at temperatures above 85°F. This can pose a problem for direct-seeding these crops in late summer when soil temperature is high.

Warmer soils also speed plant growth, up to a point. We don't yet have enough information to recommend the optimum soil temperature for different crops or the most cost-effective method of increasing soil temperature. Options for heating soil includes use of clear plastic mulches, warm irrigation water, earth-air and earth-water ground tube heat exchangers, and electric heating cables.

During much of the winter, soil remains unfrozen. If soil freezes, plants can't take up water. Under these conditions, injury is likely on sunny days when temperature in the structures rises rapidly.

Principles of Energy Flow and Storage as it Relates to Temperature

The temperature in a high tunnel is a balance between energy entering the tunnel, energy stored in the tunnel, and energy leaving the tunnel. Sunlight is the main source of energy entering a passive solar greenhouse (Fig. 6).

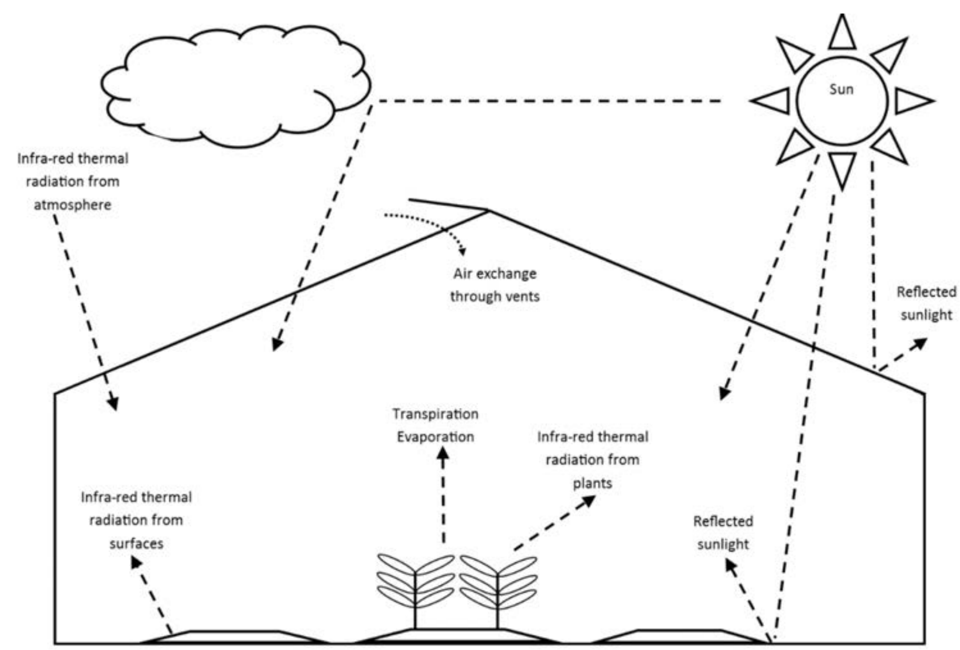


Figure 6. *Energy exchange between a greenhouse and the surroundings, showing the sun as the main source of energy. (Adapted from Figure 4-1, Aldrich and Bartok, 1989)*

When sunlight, or solar radiation, enters the structure, the plants, the soil, the structure, and other objects in the high tunnel absorb some of the radiation and reflect back the rest. Reflected radiation includes longer wavelengths that don't as readily pass back through the plastic covering of the tunnel, so energy is trapped inside and contributes to warming the air and items in the structure. This trapping of reflected radiation is commonly called the "greenhouse effect."

Objects and materials in the tunnel warm up as they absorb solar radiation: the soil and water in the soil, air and moisture in the air, tools, benches, and everything else. The heat stored in these items is important because it will keep the tunnel warm when the sun goes down. Materials or objects that can absorb a lot of energy are termed "heat sinks." Soil and water in the soil are often the largest heat sinks in a high tunnel.

When the sun goes down and it is colder outside than in the tunnel, heat escapes and the temperature inside drops. Conduction across the plastic covering and through the soil is responsible for most of the heat loss. Heat is also lost as the soil, structure, plants, and other objects warmed by the sun radiate energy to the cold night sky; by air movement through vents, cracks, and holes in the plastic; and by convection as wind blows across the structure (Fig. 7).

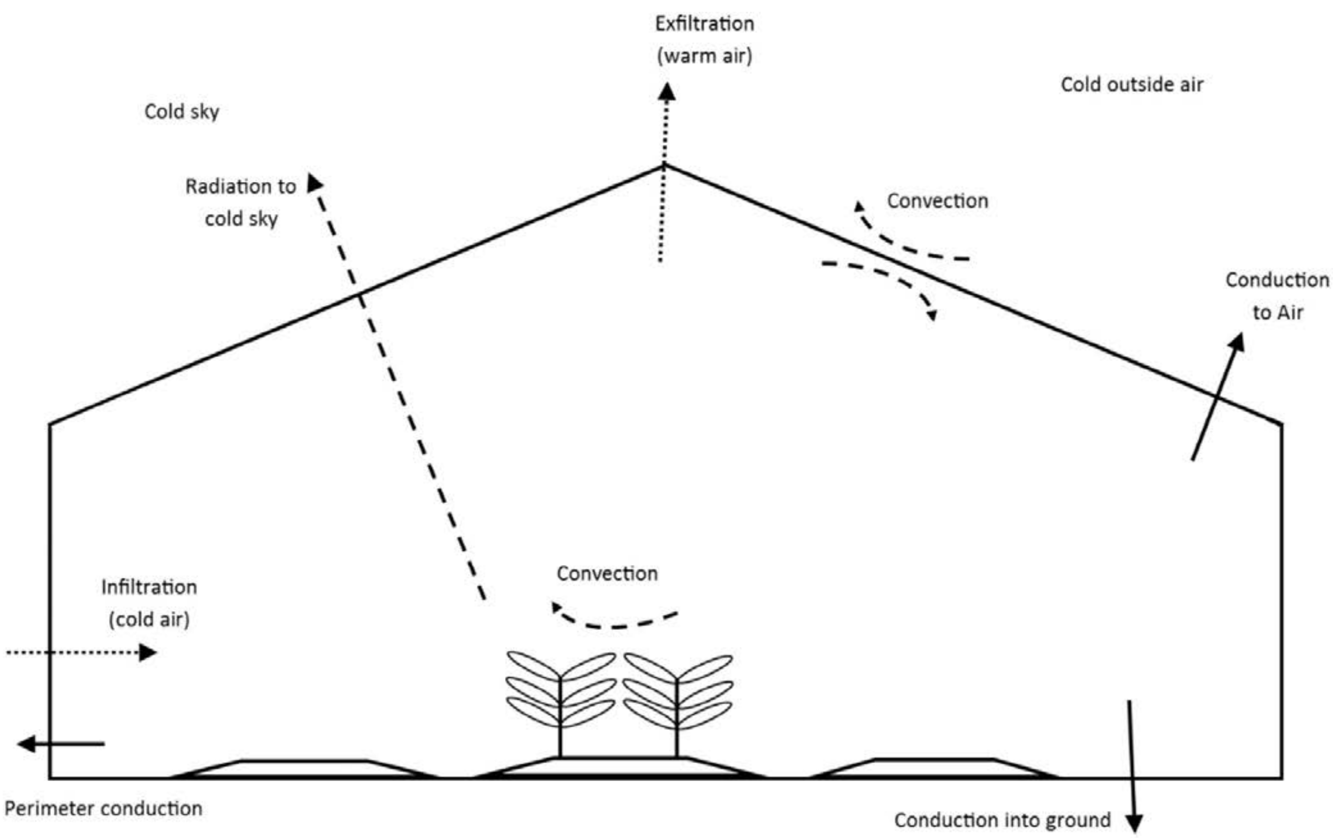


Figure 7. *Heat loss from a greenhouse. (Adapted from Figure 4-2, Aldrich and Bartok, 1989)*

On sunny days in the winter, temperature in a high tunnel is usually warm enough and may even be too warm. But keeping temperature from dropping too low is a bigger challenge. Strategies to increase average temperature during the winter include maximizing sunlight, increasing heat sinks, and minimizing losses.

Since sunlight is the number one source of heat, getting it into the high tunnel is very important. Ways to maximize sunlight are covered in the section above on light. Practical means of increasing heat sinks include keeping some moisture in the soil and using dark-colored mulches. Raised beds can absorb more heat because they have more surface area than flat soil. Water stored in tanks in the tunnel can provide an additional heat sink, but this practice is not widely used.

There are many ways to reduce heat loss. A double-layer inflated poly covering reduces heat loss compared to a single layer, so temperatures will not drop as low at night. The tradeoff is that light transmission is reduced. Greenhouse films that block infrared radiation, known as “thermic” or “IR” films, reduce the amount of heat lost through radiation. The more surface area a high tunnel has compared to its volume, the faster it will cool down. So, a long narrow tunnel will cool down faster than a short wide tunnel covering the same number of square feet. Sealing gaps and cracks in the structure and adding insulation belowground and/or around the base of the structure also keeps heat in the structure. In windy sites, a windbreak that protects the structure from winter winds will reduce heat loss. Row covers are another important means of reducing heat loss. These are typically lightweight, breathable fabrics placed over one or more beds or rows, sometimes resting directly on the crop, and sometimes supported slightly above the crop using hoops or frames of wire or conduit (Fig. 8). They provide additional insulation around the plant, trapping heat near the plants as it radiates from the soil. When moisture condenses on the row cover, the insulating effect increases. Row covers come in different weights: heavier ones provide more insulation but block more light if they are left on during the day.

Figure 8. *Row covers may cover an entire tunnel, several beds, or single beds. During the day they are often removed. (Photos by E. Bluhm, E.T. Maynard, and B. Hartman.)*

The High Tunnel Environment – Relative Humidity

Relative humidity (RH) is a measure of the amount of water vapor in the air relative to the saturated water vapor content—the maximum amount the air can hold at that air pressure and temperature. When air is at 100% RH it can hold no more water vapor. Warm air can hold more water vapor than cold air. Therefore, as air temperature increases, RH goes down. As the temperature drops, RH increases. If the air gets cold enough, moisture condenses out of the air as dew or rain. On a typical day, maximum air temperature occurs in midafternoon, and minimum occurs in the early morning. Thus, maximum RH in a high tunnel typically occurs in the early morning, and minimum RH occurs in the afternoon. These trends are illustrated in Fig. 9.

When a high tunnel is closed and row covers are placed over crops, humidity builds up from plant transpiration and evaporation from the soil (evapotranspiration). Increased relative humidity and moisture can lead to problems with plant growth and disease (discussed below). On cold nights, the humidity can be advantageous: when it condenses out of the air onto the plastic covering and row covers, the insulating effect of the materials is increased because the water or ice traps more radiant energy given off by the soil, creating a “cloud” or “igloo” effect. (Biernbaum, 2013). In the day, however, the condensation or ice reduces sunlight getting into the tunnel and under the row cover.

The amount of water vapor in the air can also be expressed as absolute humidity: the weight of water vapor in a cubic meter of air. For instance, at 86°F and 100% relative humidity, the absolute humidity is about 30 grams per cubic meter. Before discussing plants and relative humidity, it will be helpful to define another measurement that describes the amount of water vapor in the air. Vapor pressure deficit, or VPD, describes the difference between the amount of water vapor in the air and the amount of water vapor the air can hold when saturated with moisture. As the name suggests, the units of the measurement are pressure, commonly kilopascals (kPa). The “deficit” part of the name refers to the difference between the amount of water held in saturated air and the amount in the air being measured. At 100% RH there is no deficit, so VPD is 0 kPa. At 75° and 83% RH, the VPD increases to 0.5 kPa.

At 75° and 70% RH, the VPD is even larger: 0.9 kPa. At a cooler temperature of 60° and 70% RH, the VPD is smaller: 0.5 kPa. Because cooler air can hold less moisture than warm air, for any particular level of RH the VPD will be smaller at the lower temperature

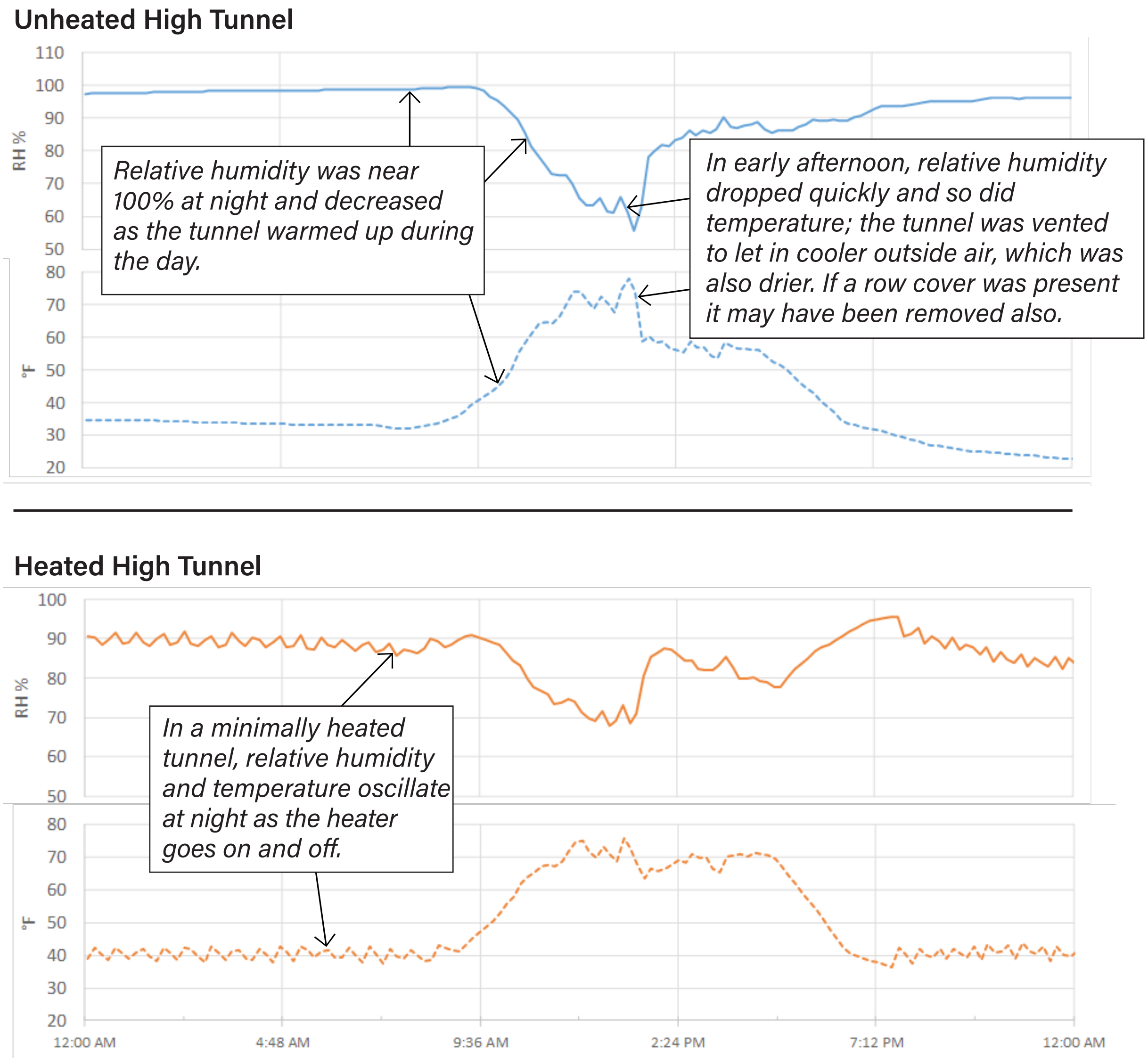


Figure 9. *Relative humidity and air temperature in unheated (top graph, blue lines) and heated (bottom graph, orange lines) high tunnels in northern Indiana on Feb. 17, 2016.*

Plants, Insects, Diseases and Relative Humidity

Plants

Plant water use is affected by RH. At a constant temperature, plants use less water when RH is high and more when it is low. To be more precise, it is the VPD that directly influences water use. The larger the deficit, the greater the demand for water.

Leaves tend to be larger when grown in high RH. Also, under high RH, leaves usually have less natural wax on the surface, making them more susceptible to water loss in low humidity conditions. A large VPD (low RH) combined with dry soil leads to water deficits in the plant that cause photosynthesis to slow, ultimately reducing plant growth rates. Because RH influences plant water uptake it also plays a role in physiological disorders associated with localized calcium deficiency, including tipburn of lettuce and blossom end rot of tomatoes and peppers. In greenhouse production, high humidity is associated with more tipburn of lettuce. This has not been studied closely in high tunnel winter production systems. Pollination is influenced by RH, but for crops grown in high tunnels in late fall and winter, this is not a concern because they are not fruiting crops that require pollination.

Diseases

Many fungal organisms are favored by high relative humidity, and some require water droplets on leaves in order to infect the leaf. Bacteria spread easily in water droplets. During the winter months, when the high tunnel structure is closed up and row covers are in place, the RH around plants can be very high for extended periods, particularly overnight and during the morning hours when moisture condenses out of the air and onto high tunnel plastic, row cover, and plant surfaces. This promotes disease.

Insects

Fungal organisms that kill insects are favored by high humidity. Even if RH is not managed for this purpose, this effect may be observed in high tunnels.

Managing Relative Humidity in High Tunnels

In high tunnels we manage RH mainly to reduce disease potential. Venting a high tunnel exchanges warmer, humid air in the tunnel with cooler, dryer air outside, and reduces RH. Removing row covers on sunny and/or warm days prevents buildup of moisture near the plants. Many growers don't seal all cracks and crevices, keeping their tunnels somewhat "leaky" or "drafty" to reduce RH without having to open and close vents so frequently. Of course, leaky tunnels won't be as warm, and if a heater is used it will cost more.

Managing the Environment – Standard Practice for Managing Light, Temperature, and RH

Managing Light

The combination of short days and sun low in the sky means that plants will have less light than they need much of time in the winter. It is possible to supply supplemental light, but we do not have research-based recommendations specifically for cost-effective lighting for winter production in high tunnels. Many cool season crops are classified as needing medium light levels for good growth (Hopper et al., 1997). For lettuce in greenhouse production under warm temperatures, "medium" translates to a DLI of 17-22 mol/m2/day (Hopper et al 1997; Brechner and Both, n.d.). Other than supplying artificial light, the main thing a grower can do is to position the structure to maximize light interception, and limit shade (Figs. 10-11).

Figure 10. *In this structure the side wall lets in more light than the plastic roof in late December because frost and/or snow reduce transmission through the roof plastic. This structure is oriented east-west, with south to the left of the picture, and so the shaded area will remain similar throughout the day as the sun moves across the southern sky. (Photo by E. Maynard)*

Figure 11. *For this structure, snow blocks much of the south sidewall where light would enter, and is also shading the roof. A snow pile on the north side of the structure would provide insulation and not block so much light. (Photo by E. Maynard)*

Remove shade

Do as much as possible to remove items that make shade in the tunnel. In an unheated tunnel, consider using single-layer plastic. It may seem reasonable to use as heavy a row cover as possible for insulation, but heavier covers reduce light more if left on during the day. Even with a lightweight row cover, removing it during the day can increase the light to the crop. More research is needed on row cover management in order to understand the most cost-effective way to optimize temperature and light. Sometimes managing temperature takes precedence over managing light.

Wavelength selective films may provide more options

Plastic greenhouse coverings that preferentially transmit or block certain wavelengths of light and radiation are available. The infrared blocking films mentioned above are commonly used to increase heat retention. The use of other wavelength selective films has not been fully explored in the context of winter production in high tunnels, but it is likely that they will provide additional means of managing light, temperature, and possibly insects and diseases in the future.

Managing Temperature

Design with temperature management in mind. Consider the many factors discussed above in the design and placement of your structure. Have a plan for standard daily management. Have a plan to minimize crop stress/injury in extremes.

Standard daily management will vary depending on time of year and crop. In early fall the main reason to manage temperature is to prevent overly high temperature, and protect crops from damage caused by sudden drops to below freezing. In a warm fall, end walls and side walls may remain open most of the time. When night temperature drops below 35-40°F, the tunnel may be closed up at night. As temperature rises during the day, the end walls, side walls, or other vents will need to be opened to keep temperature in the tunnel below 70° or 75°F.

In late fall and winter, the goal becomes keeping temperatures high enough to avoid crop injury and preventing extremely high temperatures. The tunnel is routinely closed up at night. Row covers are used at night when outside temperature goes below 25°F, and a second (or heavier) row cover may be added if the temperature goes below 20°F. In the morning as temperature in the tunnel rises above freezing, row covers can be removed. Some growers prefer to leave row covers in place in order to reduce labor costs. The tradeoff is that the row covers left on during the day reduce light that the plant could use for photosynthesis, reduce the amount of the sun's energy stored as heat in the soil, and maintain higher relative humidity near the plants. On a cold, cloudy day, these tradeoffs would not be as great. Some growers also use a layer of clear plastic over the row cover in very cold conditions. If a clear row cover is left in place on a sunny day, it can get too hot for the crop.

On many days during late fall and winter, it isn't necessary to vent the tunnel to manage the temperature: it does not get too hot. But on some sunny days the temperature in the tunnel will shoot up rapidly. It is important to be prepared to vent the tunnel to keep temperatures below 80°F.

For some crops in the tunnel in the winter, there is no need for growth: they were planted early enough to reach marketable size before light levels got too low, and the high tunnel is serving as a cold storage for live plants. Examples include napa cabbage, lettuce heads, radishes, carrots, turnips. For these crops, keeping temperatures around freezing and relative humidity high —but not so high that dew forms — should maintain the crop quality. For these crops, venting well before temperatures reach 80°F makes sense.

For other crops, growth is desired, even though it will be slow. This would include late plantings of leafy greens for harvest at young stages of growth or in the spring, and crops harvested with multiple cuttings, such as arugula, baby leaf lettuce, spinach, and kale. For crops to grow the temperature needs to be above 40°F in most cases, and days will need to be sunny.

By late winter and early spring, daily light levels are increasing and, if temperatures are warm enough, faster plant growth is visible. During this time it is usually cold enough to keep the tunnel closed at night. Sunny warm days when the tunnel requires venting are more common.

Sometimes temperature management is directed specifically to the soil. Managing soil temperature for germination may involve warming the soil with a clear plastic mulch in late winter to get seeds to germinate quickly; cooling the soil with shade and cold irrigation water in late summer to prevent dormancy of spinach seeds; or seeding into cold soil in winter and relying on the low temperature to delay crop emergence until air temperatures are high enough for seedlings to grow.

Standard Daily Practice

In an unheated tunnel with internal row covers, the standard daily routine from morning to evening might include:

- View the day's forecast on reliable weather websites that use data from the National Weather Service. If conditions will be extremely cold and overcast, venting and removal of row cover may not be necessary.
- Monitor internal high tunnel temperature. If a sunny/partly sunny day, or a warmer forecast, anticipate venting and removal of internal row covers. If overnight lows were extreme, be cautious about removing covers until covers and plant tissue are thawed.

- Vent to reduce condensation on plastic that reduces light
- Before cloud cover returns, or the sun gets too low in the horizon, prepare to replace row covers and close vents and sidewalls. Based on forecasted low temperature and conditions overnight (cloudy, clear, windy, etc.), you may need to place multiple layers of row cover.
- Remove snow or ice that shades and can be a structural stress.

Some growers leave vents high up on end walls partially open all the time, to reduce constant open and closing. The only management in this situation would be to roll up sidewalls and manage row covers as temperature in the tunnel rises.

Make close observations of plant performance, injury, and quality based on how row covers and venting are managed, and keep records. This will inform how your management changes over time to improve production from year to year.

Consider having a heater for emergency situations when extreme low temperatures are forecast or a rapid drop in temperature relative to recent conditions is forecast.

In minimally heated tunnels, a heater (natural gas, propane, wood, etc.) is used to maintain a minimum temperature, and possibly to increase the daily average temperature by boosting temperature during the day. This permits production of some of the less cold-tolerant crops throughout the winter, and higher yield of the more cold-tolerant crops. Row covers are typically not used in minimally heated tunnels, and some level of automated venting is fairly standard. Some growers set the heater to maintain temperature above 28- 32°F all the time. Another approach is to allow temperature to fall into the mid-20s at night, and then increase temperature quickly during the morning hours on sunny days when there is enough light for growth.

Plant growth responds to average daily temperature above the base temperature. It costs less energy to increase the temperature a few degrees in the morning on sunny days than to maintain it at 30°F through a cold night, so this approach can achieve similar crop growth while reducing heating costs. Heating soil using tubes of hot water or electrical heating systems is also being introduced into these production systems.

Managing Relative Humidity

Reducing RH is more often necessary than increasing it. Options include venting, increasing air flow, heating, and restricting moisture.

Venting

Venting is the most common way to reduce relative humidity. Outside air is usually cooler and drier than air in the tunnel. When venting is not necessary for cooling, small openings that allow for cross ventilation or air exchange are often adequate. Vents should be designed to avoid frigid air blowing directly on plants: temporary side walls from the base board partway up the side wall and vents placed high in the end wall, permit air exchange without cold air blowing directly on crops (Fig. 12). If the structure is heated at night, the best time to vent in order to reduce RH is just before nightfall. This permits exchange of warmer, moister, inside air for cooler outside air that will become drier as its temperature increases once inside the tunnel.

Figure 12. *The vents high in the endwall (A and B) and temporary sidewalls (C,D, and E) shown here prevent cold air flowing directly onto low-growing plants. The metal end wall vent shown (A) is operated by a wax-based vent opener. Temporary sidewalls can be removed when temperatures warm. (Photos by E. Bluhm, E.T. Maynard and S. Saha)*

Vent to reduce condensation on plastic that reduces light.

Remove row cover during the day to reduce RH within the crop canopy. Place the cover so it will dry during the day.

Increasing Air Flow

Horizontal air flow (HAF) fans suspended above the crop keep air constantly moving throughout the structure and will help reduce humidity. HAF fans are common in heated greenhouses but not in high tunnels.

Raising temperature

Increasing temperature will reduce RH but shouldn't be the main method for controlling RH.

Restricting water

Excess water in the soil from over-irrigation or poor drainage can make it more difficult to lower RH. Good management of irrigation and drainage will make it easier to manage RH.

Increasing RH

Low RH may be a problem if irrigation is not adequate or if soil is frozen and roots can't take up water. Under these conditions, RH around crops can be increased by using a row cover, reducing ventilation, and irrigating if possible.

Basics of Monitoring Environment

Systematic monitoring of the high tunnel environment will enable better management. The four key principles for monitoring are:

- Use trustworthy sensors
- Place sensors properly
- Record information regularly and in a reliable manner
- Review records periodically

This discussion focuses on sensors that capture data to inform decision making and understanding of high tunnel environment. It does not cover uses of sensors that monitor conditions and then feed that information into actuators (thermostats, etc) that control vents, fans, side walls, etc.

Trustworthy sensors

A trustworthy sensor is accurate enough for the purpose at hand and works reliably for long periods. Higher quality sensors are sold with specifications for accuracy and resolution. Checking the calibration of sensors and adjusting if necessary and possible is an important step in making a sensor trustworthy.

Proper placement

It's important to install sensors in the right locations to measure the environment of interest, and install them to avoid situations that reduce accuracy. Placement for specific sensors is covered in more detail below

Regular, reliable recording

Orderly, consistent, and reliable recordkeeping make the monitoring useful. If sensors are read manually, handwritten records are immensely useful. Many sensors come with options for automatic recording of information every few minutes to every day, depending on what the user sets.

Periodic review

Reviewing records on a regular basis alerts you to issues and provides information for making changes to practices. Short-term (daily and weekly) and long-term (seasonally) reviews are useful.

Recordkeeping Options

Handwritten records work well in many cases. Measurements should be recorded at a consistent time each day so that it is easy to see trends. If desired, handwritten records can be entered into a spreadsheet program, making it easier to graph them, and summarize conditions over a week, month, or year.

When sensors include a data-logging unit, the sensor is read automatically at some interval (predetermined or set by user), and the reading is stored electronically for later retrieval. Logging units make it easy to get detailed information about the environment throughout the day and night. In some cases the information is recorded in the device itself, and must be transferred to a computer to see all the records. Other equipment automatically sends the data to a website where it is stored and can be accessed. The datalogger will have a limited time frame that it can store data, based on the specified time interval and logger memory. The shorter the time interval, the more quickly the memory will be filled. For dataloggers without remote access, this will dictate how often you need to connect to the datalogger device to download data and free up memory to continue logging data. With many of these devices, when memory capacity has been reached, new readings will overwrite the oldest recorded data (in a circular fashion).

As with all electronic information, a glitch in the system can easily wipe out the records, so having a backup plan is advisable even if electronic records are taken: print out the records periodically, or hand-write the data at key times if it is important.

Monitoring Temperature

Temperature monitoring includes both air and soil temperature. Temperature can be monitored in numerous locations for greater insight into the high tunnel environment, including outside air temperature, air temperature in the high tunnel and below supplementary row covers (at crop canopy height), and soil temperature at various depths and locations within the tunnel. Numerous products are available at a reasonable cost to monitor temperatures, but like most technologies, cost can escalate quickly with more features, add-ons, accuracy, range, remote monitoring, cloud-based data storage, and more.

Types of Sensors

Thermometers and Temperature Sensors

A thermometer is simply a device that measures temperature. Thermometers can operate based on thermal expansion of solids and liquids, or pressure changes of a gas in response to temperature changes. The classic mercury-in-glass-tube thermometer is based on the thermal expansion of mercury, which is a liquid at room temperature. Infrared thermometers are designed to measure infrared energy given off by objects, which allows for temperature measurements without touching an object. Thermometers calibrated following the standards of the National Institute of Standards and Technology (NIST, www.nist.gov) are recommended.

Electronic temperature sensors are often based on thermocouple or thermistor technology. Thermocouples produce a voltage that is dependent on temperature. Thermistors are electrical resistors that change their electrical resistance with changes in temperature. The change in voltage or resistance is converted to a temperature measurement.

Max/Min Thermometer and Sensors

A max/min thermometer or temperature sensor displays and/or records the maximum and minimum temperatures between resets of the device. Tracking daily max and min temperatures give insight into daily temperature fluctuations and provides an estimate of average daily temperature.

Remote Data Access and Recording

Some basic temperature sensor devices include a remote readout device that communicates wirelessly with the temperature sensor (or sensors). The communication range is often limited to a couple hundred feet, and further limited by line of sight obstacles between the sensor(s) and readout. However, this does allow the user to monitor high tunnel temperatures remotely, e.g., in the house or barn. The readouts are often equipped with max/min daily readouts and other features.

Other sensors send information to the internet via WiFi or cellular connection, where it can be viewed from anywhere there is internet access, including through a smartphone. The information can be close to real time. Many systems allow the user to set alarms and notifications, e.g., when temperature crosses a specific max or min threshold. Some sensor systems have specific apps for accessing your data from a cloud-based server. Remote data access can be very useful to check on the status when you can't be physically present.

Datalogging options as described in the previous section are available with many temperature sensors.

Placement of temperature sensors

At crop level

For air temperature, readings at the crop or crop canopy level are of most interest. In the high tunnel, mount the sensor just above the crop canopy to prevent shading of the device by the crop (Fig 13). Also, pay attention to shading from high tunnel structure and other objects that may cast shadow on the device for more than intermittent periods during the day (e.g., in an E-W-oriented high tunnel, the hip board could shade the device all day during certain times of the fall/winter). Locations closer to side walls and end walls will be cooler, particularly at night, compared to more central locations in the tunnel due to heat loss from the walls. Outside air temperature is also of interest; it should be monitored at standard weather monitoring height, 4 to 6 feet above ground level, unless there is a particular interest in a different location.

Temperature sensors can be mounted on posts driven into the soil or suspended from a post or other fixture attached to the high tunnel structure. Suspended sensors might get in the way when using row covers. Try to locate and mount the sensor to limit its impact on subsequent cultivation, harvest, and other crop management activities. Read installation manuals and specifications for guidance from the manufacturer on mounting specific sensors.

Figure 13. *Temperature sensors inside the white radiation shields are installed so that when row cover is place over the hoop one sensor will be underneath the cover, and one above the cover. Also visible is a light (PAR) sensor that will be underneath the row cover. The white pot labels in the foreground mark cables leading to buried temperature and soil moisture sensors. (Photo by E. Maynard)*

Soil temperature sensors are usually located in the rootzone of the crop. Pay attention to manufacturer recommendations for installing the sensors to get accurate readings. Sensors are placed at a specific depth in the soil, usually 2-4". Avoid installing directly below drip irrigation emitters, or where other soil disturbance (cultivation) may damage or impact placement of the sensor during the growing season. Don't place the soil temperature sensor near the side or end walls unless you are specifically interested in monitoring the heat loss from the soil near the walls. Be sure to flag the sensor location for ease of removal at a later date and to avoid damaging it (Fig. 13). The last thing you want is to dig up the sensor and end up damaging the sensor wire or the sensor itself.

Protected from direct sun

Air temperature sensors need to be protected from direct sunlight in order to get accurate readings. If exposed direct to solar radiation, readings will be higher, especially on sunny days, due to heating of the sensing device from radiation. Temperature sensor manufacturers often supply radiation shields that should be used with the sensor, as shown in Fig. 13.

You can also consider making your own radiation shields (Fig. 14). The following publication provides details on how to build a simple shield that can be made with supplies from a hardware store: Design and evaluation of an inexpensive radiation shield for monitoring surface air temperatures www.fs.fed.us/rm/pubs_other/rmrs_2013_holden_z001.pdf (Holden et al., 2013). A video is available at www.youtube.com/watch?v=LkVmJRsw5vs

Figure 14. *A. Homemade radiation shield in use in a high tunnel. B. Close-up of radiation shield shown in A. C. Close-up of radiation shield showing location of temperature sensor between bottom and second layer of shield.*

Protected from heat buildup

In addition to limiting exposure to direct sunlight (solar radiation), the sensor should be installed in a location that limits heat buildup. Avoid locations with limited air circulation, e.g., corners of the tunnel. The ideal would be an aspirated radiation shield system to circulate fresh air around the sensor at regular intervals (e.g., www.apogeeinstruments.com/aspirated-radiation-shield/), but this is not essential.

Monitoring Relative Humidity

Relative humidity can be monitored to determine when venting should occur due to moisture buildup, and to understand daily and seasonal dynamics of humidity in the high tunnel environment. It might help pinpoint how management of the tunnel environment could be altered to alter growth or disease issues. But in many tunnels, the expense and effort of monitoring RH with sensors may not be worthwhile at this time because precise control of RH is not possible, temperature management often takes priority over RH management, and precise recommendations for optimum humidity levels in the system have not been developed. If you choose not to have RH sensing equipment, observe throughout the day to see when moisture condenses on row covers and plastic covering, how long it takes for ice to thaw and moisture to "burn off" in the morning, and watch for cloudy and high outside RH that may cause moisture to accumulate on and under row cover for extended periods. This will help you better understand the dynamics of RH and moisture in the high tunnel and inform when to vent and how to manage row covers.

Types of Sensors

A hygrometer is a sensor used to measure humidity. Modern electronic hygrometers use dew point or measure humidity differences through changes in electrical resistance or capacitance. The output of such sensors is a percentage RH.

Many temperature sensors have an RH sensor built into the same instrument. If you monitor temperature in a high tunnel, and the cost is minimal to have a combined temperature-RH sensor, it is worthwhile to purchase the combined sensor and gain more insight into RH dynamics.

If using a combination temperature and RH sensor, follow the sensor placement guidelines for the temperature sensor.

Monitoring Light

Keeping track of light levels and duration is less common than keeping temperature records, probably because most high tunnels don't have supplemental lighting and so there is little need for precise monitoring to guide control of lighting. But there is still opportunity for using the information to improve your understanding of the environment in high tunnels, guide decisions about changes to the structure, and help predict crop performance.

Types of Sensors

Various types of sensors measure light. A PAR sensor measures light in the wavelength range used by plants for photosynthesis, 400 to 700 nanometers. This is the best kind to use when the purpose of measuring light is related to plant growth. Measurements are reported in micromoles (μmol) of photons per square meter per second.

Photometers are used to measure light when the purpose is related to human vision; they measure light in the range that people see. These meters measure light in lux, lumens, or foot-candles. They aren't recommended for measuring light for plants.

Pyranometers measure radiation over a wider range of wavelengths, e.g., 400 to 1100 nanometers. These sensors are used for measuring total solar radiation, with the measurements reported as energy, or watts per square meter.

These different measurements of light are correlated with one another, and tables of conversion factors are available. However, the exact correlation will vary depending on the particular environment, so the conversion factors provide only an estimate.

Instantaneous versus Daily Light Integral

A PAR sensor measures light instantaneously and is useful for comparing light levels at different locations, or different times of day, or under different types of plastic or row cover. If measurements are taken at the same time each day, it can be used to track changes in light levels across the season.

As discussed in the section above on light and plant growth, the amount of light incident or received by a plant in an instant is not that important, but DLI, the total amount in a day, is. To record the DLI, a PAR sensor will need to be attached to, or contain, a recording device that keeps track of measurements made periodically during the day, and then adds them together to estimate DLI.

Placement

Light sensors should be placed just above crop foliage and away from atypical shade. They should be leveled for accurate readings. Fig. 15. shows placement of a light sensor above a crop canopy.

Figure 15. *The metal support extending over the lettuce supports a light (PAR) sensor (the black cylindrical object). The other sensors and nearby objects are below the level of the light sensor so they will not shade it. (Photo by E. Bluhm.)*

In Conclusion

Success with winter production in high tunnels is possible despite environmental challenges. Farmers provide crops the best environment they can by combining attention to factors that influence light, temperature and relative humidity in the high tunnel with knowledge about how the crops respond to the environment. This publication has introduced important factors to consider during design, operation, and daily management of high tunnels, and has explained plant responses to the environment. Farmers can supplement this general information by monitoring environmental conditions in their high tunnel, keeping records, and reviewing them alongside records of crop growth and condition. The specific monitoring and recording technologies described here are likely to become outdated quickly, but the principle of collecting farm-specific information and using it to improve management is timeless.

Resources and References

Suppliers

Sensors and data logging equipment are available from several manufacturers and suppliers. The list below is not meant to be all-inclusive. Inclusion on the list does not indicate endorsement nor does exclusion indicate lack of endorsement.

Acurite, www.acurite.com

Davis Instruments, www.davisnet.com

Extech, www.extech.com

Hobo, onsetcomp.com

Lascarelectronics, www.lascarelectronics.com

Meter, metergroup.com

Monarch, monarchinstrument.com

Spectrum Technologies, Inc., specmeters.com

Wireless Tag, wirelesstag.net

Publications

Growing for Market, growingformarket.com

Indiana High Tunnel Handbook, HO-296 mdc.itap.purdue.edu/item.asp?itemID=23206

References Cited in this Publication

Aldrich, R.A. and J.W. Bartok. 1989. Greenhouse Engineering. Northeast Regional Agricultural Engineering Service. Ithaca, NY. 203 pp.

Biernbaum, J. 2013. Hoophouse Environment Management: Light, Temperature, Ventilation. Michigan State University. www.hrt.msu.edu/uploads/535/78622/HT-LightTempManagement-2013-10pgs.pdf

Brecher, M. and A.J. Both. n.d. Hyrdoponic Lettuce Handbook. Cornell Controlled Environment Agriculture Program, Ithaca, NY. 48 pp. cea.cals.cornell.edu/attachments/Cornell%20CEA%20Lettuce%20Handbook%20.pdf

Coleman, E. 2009. Four Season Harvest. Chelsea Green Publishing, White River Junction, VT. 236 pp.

Coleman, E. 2009. The Winter Harvest Handbook: Year-round vegetable production using deep-organic techniques and unheated greenhouses. Chelsea Green Publishing, White River Junction, VT. 264 pp.

Faust, J. E. and J. Logan. 2018. Daily light integral: a research review and high-resolution maps of the United States. HortScience 53:1250-1257.

Giacomelli, G.A. and W.J. Roberts. 1993. Greenhouse covering systems. HortTechnology 3(1):50-58.

Holden, Z.A., A.E. Klene. R.F. Keefe, and G.G. Moisen. 2013. Design and evaluation of an inexpensive radiation shield for monitoring surface air temperatures. Agricultural and Forest Meteorology, 180:281-286.

Hopper, D.A., G.W. Stutte, A. McCormack, D.J. Barta, R.D. Heins, J.E. Erwin, and T.W. Tibbits. Crop Growth Requirements. pp. 217-225 in Langhans, R. W. and T. W. Tibbits (eds.) Plant growth chamber handbook, North Central Regional Research Publication No. 340. Iowa Agriculture and Home Economics Experiment Station, Ames. www.controlledenvironments.org/wp-content/uploads/sites/6/2017/06/Appendix.pdf and www.controlledenvironments.org/wp-content/uploads/sites/6/2017/06/Plant_Info_Table-1.pdf

Sager, J. C. and J. C. McFarlane. 1997. Radiation. pp. 1-29 in Langhans, R.W. and T.W. Tibbits (eds.) Plant growth chamber handbook, North Central Regional Research Publication No. 340. Iowa Agriculture and Home Economics Experiment Station, Ames. www.controlledenvironments.org/wp-content/uploads/sites/6/2017/06/Ch01.pdf

Acknowledgments

We thank Ben Hartman, Clay Bottom Farm; Nathan Fingerle, River Ridge Farm; and David Robb, Eden Prairie, for their suggestions and review of drafts of this publication and for their collaboration in recording environmental conditions on their farms over two winters. We are grateful to reviewers Krishna Nemali and Petrus Langenhoven, Purdue University, for their comments and suggestions that have improved the publication. This material is based upon work that is supported by the National Institute of Food and Agriculture, U.S. Department of Agriculture, under award number 2014-38640-22156 to the University of Minnesota, through the North Central Region SARE program under project number ONC15-008. USDA is an equal opportunity employer and service provider.

The views and conclusions contained herein are those of the authors and should not be interpreted as necessarily representing the official policies or endorsements, either expressed or implied, of the USDA or the U.S. Government.

NORTH CENTRAL SARE Sustainable Agriculture Research & Education

USDA United States Department of Agriculture National Institute of Food and Agriculture

Reference in this publication to any specific commercial product, process, or service, or the use of any trade, firm, or corporation name is for general informational purposes only and does not constitute an endorsement, recommendation, or certification of any kind by Purdue Extension. Individuals using such products assume responsibility for their use in accordance with current directions of the manufacturer.