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Indiana High Tunnel Handbook

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The authors assume responsibility for any errors or flaws.

Why High Tunnels?

High tunnel crop production has grown immensely in the past decade, particularly among specialty crop growers who sell directly to consumers. High tunnels (also called hoop houses) are low-cost, plastic-covered structures used for growing plants that make use of the sun's passive solar energy. The structures protect plants from weather-induced temperature extremes and adverse weather conditions (such as heavy rains, winds, and frosts), which safeguards crops for earlier planting, later harvesting, and protection from certain diseases and pests. High tunnels are often defined as unheated or passive solar greenhouses, but our survey revealed that farmers use a continuum of practices.

In this publication, we define high tunnels as poly-film-covered structures big enough to walk in that are used for growing plants — regardless of the heat system they use or don't use. Most of the discussion refers to structures without heat or with minimal heat. Hoop house is a term used interchangeably with high tunnel.

Research has shown great potential for high tunnels to increase the quality, yield, and shelf life of fresh fruits and vegetables. We developed this handbook based on a study of Indiana farmers' use of high tunnels. We learned from more than 130 Hoosier farmers about their experience growing in high tunnels through mailed surveys and on-farm interviews.

High tunnels are a new variation on greenhouses. Growers are using this low-cost technology to strengthen the viability of small-scale diversified farms that supply fresh produce for local food systems by facilitating the production of high-quality vegetables and fruits during the growing season — especially during the cooler shoulder seasons.

Farmers indicated that installing and growing in a high tunnel:

- Improved their farms' economic stability
- Improved harvest quality
- Reduced some disease problems and weed pressure
- Increased product shelf life and yield
- Protected produce from adverse weather

Overall, we found that Indiana high tunnel growers have had positive experiences. In particular, they said high tunnels helped extend the growing season and improve product quality and yield year-round. Nearly half of the growers we spoke to are now harvesting in the cooler months and planting earlier in the spring (crops such as lettuce, spinach, and kale). Another half only use the structures in summer to improve the growth and production of warm-season crops like tomatoes, peppers, and cucumbers.

Indiana farmers report annually earning a total revenue of about $1.70 per square foot of high tunnel space. Consequently, high tunnels are an increasingly important piece of farm infrastructure. However, high tunnels can be labor-intensive and high tunnel production is vulnerable to a number of weather, disease, and pest-related challenges that require advanced preparation and knowledge along with an adequate investment of time and money to manage successfully.

This publication is a resource for those who are considering high tunnel production or are relative beginners. This resource describes: selecting the right size and type of high tunnel for your operation, choosing a site location, constructing a high tunnel, determining planting dates, laying out beds, spacing plants, understanding environmental factors, monitoring soil health, and managing pests and diseases. Furthermore, this publication features information from the lived experience of farmers via survey data and on-farm case studies. Our goal is to build upon important work happening across the United States to better understand the ins and outs of producing in high tunnels.

We hope you find the handbook useful and we appreciate hearing any feedback you have. Send feedback to James Farmer (jafarmer@indiana.edu) or Liz Maynard (emaynard@purdue.edu).

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1. Opportunities and Challenges

High tunnel technology presents a unique opportunity for farmers to increase their revenue per square foot, improve the quality and yield of their crops, and extend the growing season of their operations (and thereby expand market opportunities). Hoosier farmers are using high tunnels in a variety of ways by adapting them to meet their individual needs and farm business goals.

Indiana farmers are using high tunnels as the center of their farm businesses, using them to diversify their existing operations, or using them as a way to start farming.

The Center of the Farm Business

Some farms have made high tunnel production the center of their business. These farms produce specialty crops year-round in their high tunnels. They plant root vegetables and winter greens in the late summer and early fall and harvest them through the winter and early spring. They get a head start on early tomatoes and other summer fruiting crops that fetch a price premium and continue producing into the fall. Farmers who have made high tunnel production the center of their business typically keep their high tunnel in use year-round.

Here are some advantages to centering your farm on high tunnel production:

- You can take advantage of off-season markets such as winter farmers' markets, restaurants, and winter CSAs
- You can demand a price premium for early and late produce
- You can earn year-round income
- You can attract and keep great workers
- You can grow greenhouse-specific, high-yielding varieties

This farm uses numerous high tunnels as a foundation for their specialty crop production business.

A Way to Diversify

Some farms use high tunnels to provide additional revenue streams on the side. In such cases, the primary focus might be field crops, an orchard, or field vegetable production. For these operations, the high tunnel is a side business, perhaps for their teenage kids or other family members.

Here are some advantages to using high tunnels to diversity your operation:

- You can experiment with growing high-value specialty crops such as cut flowers, delicate perennials, or berries
- You can add a unique or popular product to attract customers at farmers' markets or make your CSA more competitive
- You can add a side revenue stream (such as transplant or bedding plant production)

The high tunnels shown here are behind open fields, which marks a diversified and integrated approach to growing under cover.

A Way to Start Farming

Some farms use high tunnels as a way to start small-scale vegetable operations geared for selling produce at local farmers' markets.

Here are some advantages to using high tunnels as a way to begin a farming operation:

- High tunnels are an opportunity for beginning farmers with limited experience to increase their income as they learn and grow
- High tunnels offer a strategy for maximizing income on limited or marginal land

- The Natural Resources Conservation Service (NRCS) provides higher cost-share incentive payments to beginning, socially disadvantaged, veteran, and limited income farmers through the Environmental Quality Incentives Program (EQIP). Advance EQIP payments for high tunnels are also available.

Some farms construct DIY high tunnels while they are just getting started with the technology or when they are involved in specialty crop production.

High tunnels present many opportunities, but the decision to invest in a high tunnel should not be made lightly. High tunnels require you to significantly invest time and money to reap the benefits. The most common experience we heard from Indiana farmers growing with high tunnels was: "You get out what you put into it."

In other words, receiving a significant return on your high tunnel investment depends on how much labor and attention you give to managing your high tunnel. Farmers who invest more time and labor in their high tunnels are also obtaining a higher return. These farmers typically manage at least two tunnels and have made them the center of their farm businesses.

However, if you are already struggling to keep up with your farm business, adding a high tunnel may be a burden if you don't have the time to put into it. Likewise, if you don't have the financial resources to invest in a high-quality high tunnel, you could be at higher risk of losing your tunnel to strong winds or of experiencing structural damage that requires more time and money to fix. Be sure you are ready before you buy and know what you're getting into!

Learn from a Farmer: Harvest Moon Flower Farm

Autumn flowers bloom in front of the high tunnels at Harvest Moon Flower Farm where high tunnels have been in use for decades.

Harvest Moon Flower Farm is a small, sustainable, year-round operation in Owen County that has been owned and operated for more than 30 years by Linda Chapman. Although growing and selling flowers is their "bread and butter," they also grow a diverse assortment of herbs, vegetables, and fruit crops primarily grown for local chefs.

To round out their year on both ends, they offer a very diverse selection of garden bedding plants in the spring. For the fall and holiday seasons they create dried flower and evergreen wreaths, and other seasonal items.

Overall Management Strategy
Chapman said she is constantly cycling new flowers, herbs, salad mix, greens, and carrots in and out of the farm's six high tunnels. Some of the tunnels are heated. There is no rest period and it's very rare for there to be any bare ground that's not planted with something.

Rather than follow a set rotation of specific crops, the farm maintains a great deal of diversity and complexity in terms of plant varieties, timing of planting/harvesting, and rotations. Chapman said she follows her intuition and experience of what specific flower varieties do best in which tunnels, but she also goes by what seedlings and space she has.

Harvest Moon Flower Farm considers its emphasis on diversity to be a large contributor to its success and strength. A diversity of crops grown with knowledge and care ensures that customers get the quality the farm has become known for — be it flower bouquets, herbs, micro-greens, vegetables, fruits, plants, wreaths, or wedding florals.

"High tunnels have been fabulous for growing my business as they allowed me to start doing winter market and having income in the winter," Chapman said. "High tunnels have expanded my income substantially. They've allowed me to do weddings in November, December, and March. It's been real sweet, not to mention I get to eat really good food all winter long, which is really important, too. Efficiently utilizing our hoop houses has vastly improved the quality of what we do here and has generally allowed us to charge at least a little more than most vendors — certainly for the flowers and even sometimes for the food (our salad mix particularly). But our customers know that the quality is there and they're willing to buy it."

Greens, salad mixes, kale, and spinach flourish in the raised beds of this well-used high tunnel.

2. Considerations for New Users

In this chapter, we examine several considerations that are important when you plan to construct a high tunnel. While we discuss each factor separately, these factors are related and can affect your structure's longevity and durability, as well as your overall high tunnel experience.

In this section, we will examine:

- High tunnel selection
- Site selection and preparation
- Construction tips and considerations

High Tunnel Selection

High tunnel structures vary in shape and design. When you're selecting high tunnels, think of basic design, think of how permanent you want the structure to be, and think about how large of a structure you need for the next season and three to five years down the road.

Basic Designs

The classic Quonset tunnel is a ground-to-ground half-circle. Some Quonsets are set on higher ground posts so there are straight sides before the half-circle.

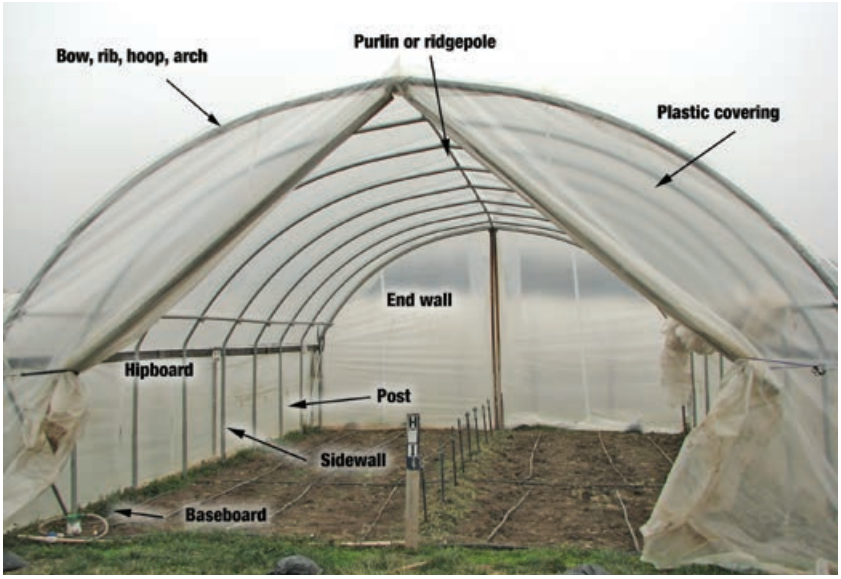
The gothic high tunnel design has a pointed roof that rises diagonally from the sidewalls to form a peak.

Single sections (or bays) of Quonset or gothic structures can be connected side-by-side to form gutter-connected multi-bay structures. These are more commonly used as heated greenhouses than unheated high tunnels.

Some multi-bay high tunnel designs are for three-season production; the structure won't support a snow load, so the plastic must be removed in the winter. These designs often cover a fairly large area; a small one might cover 1/3 acre.

Caterpillar tunnels are smaller, low-cost, less permanent structures. The plastic covering is held down with ropes, giving them the segmented appearance of a caterpillar. Lightweight hoops provide little structural support and so they are usually less than 14 feet wide. A caterpillar tunnel can be a low-cost entry point for individuals getting into tunnel production, but they also can play a role in a whole farm plan, as they do at Full Hand Farm (page 10).

High tunnels vary in structural complexity and strength. ***A.*** *A caterpillar tunnel.* ***B.*** *A caterpillar tunnel with plastic held in place by ropes.* ***C.*** *A Quonset-style tunnel with hoops made of PVC tubing and added wooden support beam.* ***D.*** *A Quonset-style tunnel with longer ground posts to create vertical sidewalls and simple vertical poly curtain end wall.* ***E.*** *A gothic-style tunnel with metal-framed polycarbonate paneled end walls, a large roll-up curtain doorway, and end-wall vents above the door.* ***F.*** *A gothic-style tunnel with roof vent.*



Anatomy of a high tunnel.

Choose the Right High Tunnel for Your Farm

When you think about investing in a high tunnel, you should carefully examine a number of things about your goals and your operation. In this section, we describe a number of important factors you should consider (and the questions you should be asking) before you decide.

General Questions

When choosing a high tunnel, you should start with some basic questions — here are six questions you should consider.

1. What Kind of Site Do You Have Available?

Consider if your site can accommodate a high tunnel and still avoid shade, sloped ground, and water seepage that would compromise the success of your high tunnel.

2. What Crops Do You Want to Grow?

What you plan to grow will affect the type of tunnel that will work best for you.

Quonset-style tunnels typically cost less, but they have very low headroom over the edge beds unless they have tall sidewalls. Low headroom would limit crops that grow tall (like trellised tomatoes). Plus, low headroom can be uncomfortable for a person who is using a walk-behind seeder or tiller near a sidewall.

The taller sides of gothic-style structures provide more useable space along the sides for working and crop production. If you plan to grow tomatoes, some trellis systems require greater height for interior and perimeter rows. Gothic-style tunnels typically have higher roll up sides, which provide better airflow over tall crops.

These trellised tomatoes are just starting to ripen. The high tunnel provides extra heat for an early crop.

3. What Seasons Do You Want to Grow In?

When you want to grow will also influence the tunnel style. Some styles work better for warm-season crops and others are better for winter growing. Choose a structure based on the season and crops you intend to emphasize.

For instance, if you're unsure that you'll have the time and energy to continue production through the fall and winter, then choose a structure and add-ons based on summer crops. If you are already busy during the summer growing season and are investing in a tunnel to extend the season, consider options that support cool-season production.

This moveable high tunnel is held in place by cables and turnbuckles connected to ground anchors. Peppers (foreground) and basil are thriving.

Key Considerations for Summer Production

If you plan to use a high tunnel for summer production:

- Be sure the structure has good ventilation and possibly fans
- Consider a design with a taller roof and that includes vents in the roof or end walls. The vents allow hot air to escape and draw cool air into the structure, which will improve airflow through side vents and out vents in roof or end walls.
- Look for designs with large doors or end walls that you can completely remove to improve ventilation
- Remember that it is more difficult to get enough cross-ventilation with very wide tunnels that just have roll-up sides

- Know that the open roll-up sides on ground-to-ground Quonset-style tunnels can expose some of crops to rain and other adverse weather

The growers have prepared the beds with peppers and tomatoes to capitalize on the heat trapped in these Quonset-style high tunnels in early spring. The tunnels have 90-degree vertical sidewalls that reach about 4 feet before the arch begins.

Key Considerations for Fall/Winter Production

If you plan to use a high tunnel for fall or winter production, then remember:

- A low structure will heat up more quickly than a taller one
- A long, narrow structure will cool down more quickly than a short, wide structure
- A gothic shape will be warmer than a Quonset shape
- Wide tunnels are easier to manage and keep heated for winter production
- Double poly covering will retain heat better. Infrared plastic is also an option to consider.
- A baseboard will protect plants on the edge beds and keep in heat. Note that certified organic production will not allow you to use treated lumber for a baseboard for crops grown in the soil — you can use untreated lumber. An alternative is to use straw bales or another insulating material to keep cold air out, particularly for quick hoops or moveable tunnels. However, using straw bales carries the risk of encouraging rodents to nest near or in the tunnel.
- If you use a heating system, your costs will be lower for structures that have lower roofs, are short and wide (vs. long and narrow), have double poly (vs. single poly), and are gothic-style designs (vs. Quonset-style).

The USDA-Agricultural Resource Service offers free "Virtual Grower" software you can use to estimate heating costs for many types of structures. Visit www.ars.usda.gov/research/software/download/?softwareid=309.

This spring mix flanked by kale has enjoyed a row cover used to trap extra heat and buffer against cold temperatures that otherwise would damage the profitable crop.

4. Do You Receive High Winds or Heavy Snows?

If you have high winds or heavy snows in your area, then remember:

- Low-profile structures with strong frame materials and extra bracing and anchoring withstand high winds better
- Poly curtain end walls are particularly vulnerable to wind damage — growers reported more problems with that type of end wall. Sturdier end wall designs fare better in Indiana, unless you have good windbreaks to protect your tunnel.
- You should purchase a structure that's been engineered to handle heavy snow loads if that's common in your area. The manufacturer will specify how much snow the structure is designed to withstand.
- If snow or ice is more than a structure can stand, then you will need to remove the snow or ice to avoid collapse, or you will need to remove the plastic covering in the winter if you are not using the high tunnel. A Quonset-style structure handles lower snow loads than comparable gothic-style structures. If

necessary, you can brace a structure by putting 2x4 boards under the ridgepole, purlins, or bows to support the structure.

- Gothic-style high tunnels typically have metal or lumber trusses that add structural stability.

High winds ripped the poly off this high tunnel.

5. What Equipment Do You Want to Use?

The equipment you want to use in your tunnel (such as tractors, rototillers, etc.) will influence the tunnel design.

When considering a tunnel:

- Make certain the end wall has a door or removable panels that are large enough for your equipment to get in and out. Poly curtain doors, overhead garage doors, sliding panels, and removable panels all provide openings big enough for tractors.
- The structure must be tall enough to operate the equipment inside.
- Remember that you can get away with smaller doors in the end wall if you do not plan to use large equipment.

This high tunnel has an 8-foot doorway to ensure accessibility for the larger equipment that might be used during the growing season.

Learn from a Farmer: Full Hand Farm

Full Hand Farm is a central Indiana vegetable farm operated by husband-and-wife team Eli Robb and Genesis McKiernan-Allen.

They currently grow about four acres of organic vegetables, which includes about 9,000 square feet of tunnel space. They make sales most weeks out of the year. They said they could make sales every week but opted to take some weeks off here and there to focus on other matters.

They use season extension, intensive farming strategies, and an emphasis on crop and market diversity to be successful.

Overall Management Strategy
At the center of Full Hand Farm's business and success is a complex rotation through four moveable and three stationary high tunnels.

Learn from a Farmer, continued

The couple started with caterpillar tunnels that they constructed themselves and are still part of their rotation.

They also have four, 20-foot x 48-foot moveable tunnels that are on skids. Each moveable tunnel has three positions or plots where they move the tunnel during the course of the year. They pull the tunnels with a winch and tractor twice a year. From April to October the tunnels cover the first position where they grow summer fruiting crops (such as tomatoes) and herbs (such as basil).

In October or November, the couple pull the tunnels off the summer crops and place them over winter crops that have already been planted. In this system, they're able to get a head start on planting their winter crops — jump-starting them before they actually need the protection of the high tunnel. That way, the winter crops are big and robust before they get covered with the tunnel.

Another benefit of this approach is that they don't have to rip out their summer crops to plant their winter crops. Often, they're still able to harvest tomatoes into the fall, as they don't need the space to plant winter crops. Another major advantage is that this system allows the couple to plant a cover crop in the third position of each high tunnel site. This creates a much longer rotation for each crop in one high tunnel site.

For instance, they only plant tomatoes once every five years on the same site. The complex and lengthy rotation reduces pest and weed pressure and ensures that any salts and minerals that build-up in the soil get flushed with a season of rain. It also allows them to have a cover crop in every rotation without losing prime high tunnel space. By rotating between the three positions per moveable tunnel and between the four moveable and three stationary high tunnels, they are able to achieve a level of diversity that has proven very successful.

The spinach in the foreground of this photo will soon be covered by the high tunnel in the back — once the tomatoes currently in the tunnel terminate and winter nears. Moveable high tunnels allow for dynamic production systems that change with the seasons.

6. What Options Are Worth Paying For?

Of course, the answer to this question is unique to your operation. However, based on survey responses and interviews with Indiana high tunnel growers, we compiled a list of high tunnel options that experienced growers commonly purchase and recommend.

Taller Structures

Many growers reported that it was worth the extra expense to invest in a taller high tunnel.

Gothic-style tunnels typically cost more, but their higher ceilings provide much better ventilation through higher end wall vents. In addition, their angled roofs shed water that condenses on the interior of the plastic, rather than dripping on plants below. It is important to avoid extra moisture as much as possible.

You can increase the height of both gothic and Quonset structures by using longer ground posts — this can offset some of the disadvantages of a simple Quonset.

Heavier Gauge Steel and Strong Structures

Many growers have had problems with high winds that damage their plastic covering — and in some cases the structure itself.

Investing in heavier gauge steel for the bows will enhance the structure's ability to handle stronger winds and greater snow loads (with obvious limitations for extreme situations). Gauge refers to the thickness of the pipe wall — the smaller the gauge the thicker the wall. For bows, the minimum suggestion is gauge 14.

Some tunnels are designed with better truss systems and more cross bracing to withstand extreme stresses. Study or ask about a product's engineering specifications to best understand what a structure can handle.

High-quality Poly

Several growers say it is worth the additional expense to purchase a higher-quality, longer-lasting polyethylene cover. They say you will gain extra seasons or years from the added investment.

Adequate Ventilation

A typical high tunnel uses sidewalls as the main ventilation (once opened). Good ventilation is critical for crop production, especially in the summer. Additional ventilation options add cost, but many growers say the expense is worth it.

Adequate airflow is important for several reasons. First, airflow helps maintain a more stable temperature at the plant level. Sufficient air flow over your plants is particularly important if you're growing tomatoes with a trellis system and winter greens — you need to get air moving over the plants even when it's cold out. Second, ventilation is critical for managing certain diseases. Finally, air movement also moves plants, which stimulates changes in their cell walls that make plants sturdier.

Here are options some growers recommended.

- **Roof vents.** Growers say roof vents are especially helpful for summer production of trellised crops like tomatoes.
- **End-wall vents near the peak (gable vents)**. Growers said these vents are especially helpful for winter growing and in the shoulder seasons when it may be too cold to open the sides but your crops need ventilation for cooling or to reduce humidity
- **Thermostatically-controlled, automated vents and/or roll-up sides**. Growers said these options are especially useful for the shoulder seasons and for times when it is difficult for someone to be on-hand to manually open and close the sides. For instance, on a cool spring or fall day, the temperatures can spike suddenly when the sun emerges on an otherwise cloudy day. Farmers without automation always need to stop what they are doing and adjust the tunnel accordingly.
- **Exhaust fans**. Farmers said exhaust fans are useful when paired with vents on the opposite wall. The combination speeds up air exchange.

In addition to investments for taller, stronger, and better ventilated structures, some growers have realized benefits from adding heaters, collecting and storing rainwater, or using moveable tunnels. The pros and cons of these add-ons are outlined below.

Heating Options

Adding heat to a high tunnel extends the growing season, speeds crop growth during cool periods and provides insurance against unexpected cold. You can use a heated tunnel for early-season transplant production, although there may be restrictions about growing plants in containers if you received USDA-NRCS funding.

In our interviews, we encountered successful operations with and without heat. If you know you want a production system that relies on additional heat, it makes sense to plan for that from the start. If you are not sure, or don't have the funds for a heater, it is possible to design a structure so that you can add a heating system later.

However, take caution: Any kind of heater, whether electric, heat, gas, or woodstove, should be designed for use in the greenhouset to reduce the risk of fire and the buildup of toxic fumes inside the structure.

Remember that a heating system will require fuel, which will be an ongoing expense. The cost of heating traditional greenhouses limits their profitability in Indiana. And some growers may not want to include heat for philosophical reasons — using biofuels, gas, or electricity adds to carbon dioxide in the atmosphere. Keep in mind that one thing that makes high tunnels attractive is that they extend the growing season without the need for adding any energy beyond the sun.

Rainwater Collection and Storage Systems

Growers that invested in systems to collect and store rainwater reported that it was worth the extra expense. Our conversations also revealed disadvantages. A typical system involves attaching gutters along the hipboards and directing the water into a storage tank. Water from the tank is pumped or flows by gravity into an irrigation system. In some operations, gutters are used to direct water away from the structure, and there is no water storage.

The pros of these systems include:

- They reduce the need for to install drainage away from tunnel.
- They reduce soil erosion by controlling the run-off.
- They provide a source of soft water, which may be helpful if well water is hard.

The cons of these systems include:

- Food safety concerns may restrict how you can use stored water for irrigating or spraying edible crops. Check with a food safety specialist.
- Algae can grow in the water tank.
- Snow and ice can accumulate in the collection system and cause problems.
- You still need an overflow drainage system for times when the tank can not hold all the rainwater.

Ventilation options. ***A.*** *This tunnel has standard louvers that are thermostatically controlled to encourage better airflow lengthwise through the tunnel.* ***B.*** *This tunnel combines automated sidewalls and automated roof vents to support summer temperature control and increased airflow.* ***C.*** *This clearstory-style roof peak allows excessive heat to escape while drawing cooler air from outside the tunnel.*

End wall options. ***A.*** *These corrugated plastic panels are a lightweight, partially-transparent material that are used for enclosing end walls.* ***B.*** *These poly end walls have oversized doors that allow for equipment access and increased airflow in and around plants.* ***C.*** *These rollup end walls have large openings. This grower installed lath fencing to safeguard against vermin.*

Moveable Tunnels

As the name suggests, moveable tunnels are designed to be moved to cover a different plot of soil, usually an adjacent plot in line with the other. There are three main movable tunnel systems:

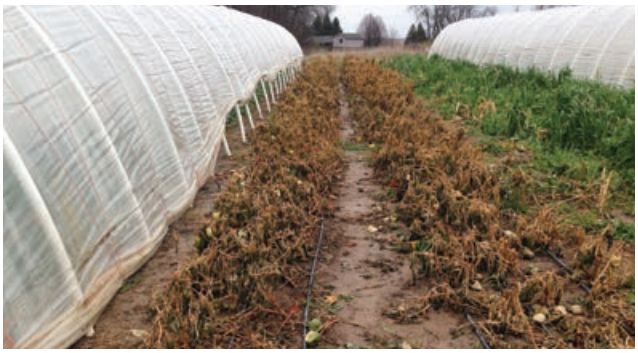
- **A rail frame system**. In this system, the tunnel frame has wheels at the base of bows and rests on a rail. Users can roll the tunnel along the rails to relocate it.

This high tunnel has a rail system frame with wheels at the base of its bows. The wheels rest on a rail, which the owner can roll it on.

- **A sled frame system**. With this system, the tunnel frame rests on a sled, which you can drag to a new location.

This high tunnel has a sled frame, which allows the owner to drag it to a new location.

- **A simple hoop system** (caterpillar). With this system, the tunnel is a simple hoop structure with no baseboard or hip board and has only a center ridge pole that connects the bows. You can move the tunnel sideways by lifting the ends of each bow on one side of the structure, rotating it 180°, and then anchoring it to the ground in the new location.



This high tunnel is a simple hoop with no baseboards (also known as a caterpillar). One end of each bow can be lifted and each bow rotated to move the tunnel to a new location.

To get full use of a movable tunnel you must carefully plan crop rotations, planting dates, and moving plans.

Most growers we interviewed had stationary tunnels. Full Hand Farm was an example of an operation that has successfully incorporated moveable tunnels (see page 10).

The pros of moveable tunnels include:

- It is easier to rotate crops to different areas of soil, which may reduce disease pressure.
- When the soil spends time uncovered, excess nutrients and salts can leach out of the soil.
- You can start cool-season crops outside in fall while the warm-season crop is still in the tunnel. When the warm season crop is finished you can move the tunnel over the cool-season crops for the winter. In the spring you can then move the tunnel off the cool-season crop to where you will plant the warm-season crop. In short, you do not have to remove one crop in order to plant the next.
- It is easier to use large equipment when ground is not covered by a tunnel.

The cons of moveable tunnels include:

- They are harder to seal along the base of the tunnel, so they are colder in winter.
- They cost more.
- They may not be as stable as fixed structures.
- Their designs are still being developed and improved, and some moveable structures can be difficult to move.
- They require additional maintenance.

USDA Programs to Finance High Tunnels

The USDA-Natural Resources Conservation Service (NRCS) assists farmers in extending the growing season for high-value crops in an environmentally safe manner through its High Tunnel System Initiative. The initiative falls under the USDA-NRCS Environmental Quality Incentives Program (EQIP).

The initiative aims to improve plant quality, improve soil quality, reduce nutrient and pesticide transport, reduce transportation inputs, and reduce energy use by providing consumers with local fresh produce.

Information about the initiative is available in the "Seasonal High Tunnel Assistance" fact sheet: prod.nrcs.usda.gov/Internet/FSE_DOCUMENTS/nrcs144p2_030914.pdf.

More information about the High Tunnel System Initiative is available at www.nrcs.usda.gov/wps/portal/nrcs/detailfull/national/programs/?cid=stelprdb1046250.

Program Details

The USDA-NRCS provides farmers with financial assistance for high tunnels that cover a maximum of five percent of 1 acre, or a total of 2,178 square feet. Landowners can purchase and install larger high tunnels, but the USDA-NRCS program will only pay for the first 2,178 square feet. Participants may install more high tunnels at their own expense or may already have high tunnels installed.

In addition, farmers must plant their crops in the ground or in permanent raised beds — not in containers. The high tunnels may be planned for a fixed location or planned to be portable, which means they can be rotated within or among eligible land under the participant's control.

Since water runoff from high tunnels can cause erosion, pooling, and other environmental concerns, USDA-NRCS may require you to install additional conservation measures as a condition.

Additional conservation measures include:

- Runoff management
- Filter strips
- Drain structures for water control
- Critical area planting

USDA-NRCS provides advanced payments for beginning, socially disadvantaged, veteran, and limited income farmers. The Indiana EQIP webpage has information about applying for assistance: www.nrcs.usda.gov/wps/portal/nrcs/in/programs/financial/eqip.

In some cases, high tunnel companies offer to ship a kit with an agreement that the farmer (with an EQIP contract) assign the materials portion of the EQIP payment to the company when the high tunnel is completed.

It's also important to note that state programs can change with legislation and budgets.

The USDA-Farm Service Agency (FSA) may also offer loans for farmers to help purchase materials.

3. Site Selection and Preparation

Before you invest in a high tunnel system, you'll need to carefully think about the site you want to use and you'll need to prepare the area. In this section, we'll address:

- Site considerations
- Weather considerations
- Site preparation
- Site drainage

Site Considerations

Before you place a high tunnel on your site, there are a number of conditions you should look for. Here are some of the most important:

- **Find a site with maximum sun exposure.**

You will need to orient your tunnel to avoid shade and maximize sun exposure (for both light and heat). This is particularly important if you plan for fall or winter production. To avoid shade from structures to the south, a good rule of thumb is to place the tunnel at a distance at least two times the height of the structure.

- **Site high tunnels downwind of existing tree rows.**

This will protect them from the wind. You should also keep them outside of shaded areas. Consider planting a windbreak that could help reduce the effects of wind and snow.

- **Evaluate east-west versus north-south orientation.**

A tunnel placed east-west will allow more sunlight in the structure in the winter, which is recommended for winter production north of latitude 40° north. Indiana ranges from about 39° to 42° north, so an east-west orientation is not as critical as it would be for more northern areas.

For summer production of trellised or tall crops, a north-south orientation has the advantage that crop rows oriented lengthwise in the structure will receive more uniform light on both sides of the rows, and one row won't shade the next row or rows to the north. If you have gutter-connected structures, you should orient them with the long axis north-south so that shade from the gutters doesn't stay in one location all day.

You should also consider ventilation and wind in relation to orientation. You should orient major ventilation openings (such as roll-up sidewalls) perpendicular to the direction of the prevailing wind.

- **Choose a location where the natural slope is less than 5 percent, if possible.**

A steeper slope can pose problems for drip irrigation and fertilization systems and result in uneven application of water and nutrients to your crops.

- **Avoid low-lying sites.**

Low-lying sites may collect water and often pose long-term drainage problems.

- **If you need electricity, be sure the site will work.**

If you plan on installing ventilation fans, heaters, or other electrical devices, you need to site the tunnel so that you have easy access to electricity.

- **Make sure you have easy access.**

Try to place your tunnel on a site that fits the flow of your farm. The closer it is to the main activity and main walking paths, the better. Access is one of the most important issues when siting a high tunnel. Be sure to account for flow to and from the structure for harvest, planting, and vehicles.

- **Place your tunnel near a frost-free water source.**

You will need to irrigate your crops. Be sure you can provide adequate water from a source that will not freeze.

- **Check the quality of the irrigation water at your site.**

Whether your irrigation water will come from a well, municipal source, pond, or other location, you need to be sure that it is safe and plentiful. You may need to consider ways to amend water quality.

- **Plan for the future.**

Make certain the site you choose for a high tunnel will accommodate the space and access you will need for future structures — whether you are just thinking about them or know that you will be installing them.

- **Check local zoning regulations.**

High tunnels are usually considered nonpermanent structures. Zoning was not mentioned as an issue in our survey, but restrictions can vary from place to place and may change over time.

Site Preparation

How you lay out your high tunnel is so important for later success. After you choose a site, be sure to prepare it before installing the high tunnel.

At a minimum, you should:

- **Prepare the soil before installing.**

It is crucial to prepare soil before you put up a tunnel! So, before you build, consider applying high-quality compost and organic matter, liming to adjust pH (if needed), removing perennial weeds, addressing any compaction issues, and attending to anything else you won't be able to do once the ends are framed in.

- **Run electrical and water lines first.**

If you are going to run water and electric lines to the tunnel site, do so before all the ground work is done and the tunnels location is set. Never run lines where a ground post will go.

- **Level the site well and square it out.**

Leveling the site before constructing your tunnel is much easier than afterward, and squaring it out will help with the construction process.

Site Drainage

Many growers have had to retrofit drainage around the tunnels they installed, because water flowed through their tunnel or seeped in on one or both sides. You need a way to move water away from the structure during heavy rains and snowmelt to avoid flooding the soils inside and to limit freezing in the winter.

It can be a challenge to get your drainage system right before construction, but be sure to at least develop a plan when you site the tunnel. Many farmers regretted not planning for drainage ahead of time.

Even if the site is not wet now, realize that rainwater that falls on the tunnel (and snowmelt) will need to go somewhere. If you have a 96 x 30-foot tunnel, that's 1,795 gallons of runoff water for every inch of rain. Consider installing an underground outlet or directing water to a stable area with permanent vegetation to avoid creating an erosion problem.

You may need to build up the high tunnel footprint compared to the surrounding soil to ensure that water flows away from the tunnel. That said, be careful not to build up too much on top of existing grade (less than 12 inches), because building on fill soil gives a less solid footing. If you have to, consider purchasing longer ground posts to ensure deep footings into original soil.

This photo shows why site preparation is so important for minimizing excessive drainage through the high tunnel. With the extra impermeable surface, water removal is an important consideration.

Some drainage options to consider include:

- Swales
- French drains
- Rainwater catchment or diversion systems
- Ditches

Be sure to use clean gravel around any drainage pipes you install. An added benefit of perimeter drains is that they can make it harder for tunneling creatures to get into the tunnel.

Remember that the USDA-NRCS can provide expertise and assistance with drainage issues. To find your local USDA-NRCS service center, visit www.nrcs.usda.gov/wps/portal/nrcs/in/contact/local.

Weather Considerations

Understanding the weather conditions at a potential high tunnel site is very important. But it also includes many considerations of its own. Of the more than 130 farmers we spoke with and learned from, most said weather was the greatest challenge for choosing a successful high tunnel site. Many farmers spoke about losing poly coverings to windstorms, which quickly exposed plants to frigid conditions, driving rain, and more.

In the section on siting the tunnel above, we mentioned the importance of knowing the prevailing wind direction so that the ventilation openings can be oriented perpendicular to that direction, and so you can use existing windbreaks. The construction and operation suggestions below also will help protect the structure from damage due to high winds.

When planning for the weather:

- **Use support straps.**

Install support straps outside of the polyethylene that covers the juncture where it stretches over the trusses, braces, and ribs. This will help hold the covering in place during high winds.

- **Install concrete bases for ground posts.**

Ground posts anchored in concrete are more likely to stay put than ground posts anchored in the soil alone.

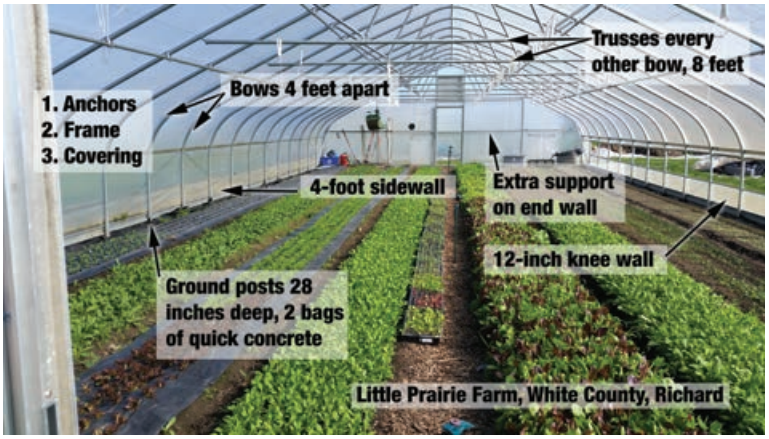
- **Consider ground anchors.**

In very high wind areas, consider ground anchors in addition to ground posts.

- **Prepare for bad weather.**

When bad weather is coming, batten down the hatches. Close and secure all doors, vents, and sides. If strong winds get into the tunnel, the structure acts like an airplane wing and tries to "take off." That puts additional stress on the plastic and structure, and often pulls posts out of the ground.

Wind can seriously damage high tunnels. These photos show a high tunnel with bent metal structures and posts pulled out of the ground. A nearby weather station recorded sustained winds of more than 20 mph and gusts of more than 50 mph. After the damage, the owner installed a vertical post to reinforce the wide curtain end wall (you can see this in the center of the bottom photo). The post also helps prevent the end wall from billowing inward during high wind.



These illustrations show the inside and outside of a structure designed for a windy location.

4. High Tunnel Construction

Whether you receive an EQIP-funded high tunnel or purchase one completely out-of-pocket, it takes time and resources to get a high tunnel up and producing. That's why it is worth giving special attention to the construction process and carefully considering decisions that can improve or hinder production, affect the structure's long-term cost effectiveness, determine the tunnel's ease of use, and influence the high tunnel's lifespan.

For starters, safety is paramount. Remember to know what's below and call before you dig. This is particularly critical in areas where underground utilities are common — think urban farms.

Indiana residents can locate their utilities online at indiana811.org. You can also call 811.

Who Should Build the Tunnel?

Should you go DIY and build your own tunnel, or should you hire someone to construct it? The short answer is: It depends.

Before you decide, consider these questions:

- **Do you really have the time to construct the high tunnel?**

The USDA-NRCS estimates that it takes 80 hours of labor to install a 30 x 72-foot high tunnel.

- **How quickly do you want to start growing in the high tunnel?**

If you want to get started as soon as possible, you may find that a contractor can install a tunnel faster than you could.

- **Do you have to wait for reimbursement from a grant or financial assistance program?**

Consider that you will be out several thousand dollars and need to get the tunnel up and constructed before receiving reimbursements in cost-share programs.

- **Do you have the needed skills?**

You need to determine if you are able to properly lay out and square the ground framing. Be certain you have the mechanical skills and physical ability needed to put the bows together and set them.

- **Do you have the help you need to see the project to completion?**

Lifting 30-foot bows and setting on ground posts is likely impossible for one person. Will you have help to get the work done and maintain safety for all involved?

- **Do you have access to necessary equipment and tools?**

See Tools (page 21) for a list of equipment and tools you might need.

Obviously, constructing your own high tunnel will save you the expense of hiring someone. Still, you may need to plant your crop soon, get your EQIP reimbursement as soon as possible, or have limited skills or help from others. If any of these apply to you, you may want to consider contracting the construction.

Only a handful of high tunnel companies in Indiana offer full service from sales to installation. You will likely need to schedule construction well in advance to ensure the high tunnel is up and running when you need it.

Other benefits to hiring a contractor to construct a high tunnel include:

- Certain warranties may require professional installation
- If materials are damaged during the building process due to construction problems, the contractor will have to cover the replacement cost
- An experienced team will generally provide a better end product that will work more effectively and last longer.
- Instruction manuals can be challenging to interpret. When you work with a contractor, they will have dealt with common issues and know how to solve them.

These photos highlight a high tunnel build at Harvest Moon Flower Farm. Many hands are needed, particularly when it's time to pull and fasten the poly into place.

Tips for DIYers

If you do decide to build your own tunnel, be sure to have everything you need before you start — tools, labor, and materials. When you receive your kit, double-check the contents and ensure that every single part is there (down to the nuts and bolts). Once you inventory the items, organize them in a way that works with the job flow. When you do, you'll want to keep the poly covering in a safe place where it won't be walked on or run over with machinery. And you'll want to keep materials dry, so tarp them until ready.

Before you begin construction create a plan or follow the one provided. The number one way to slow down the process is to do things out of order. When you go out of order, it will cause backtracking and often confusion.

Another common mistake do-it-yourselfers face is using the wrong hardware — and they frequently don't notice that until it's needed for a specific use. For example, if you have a 2 ¼-inch bolt and a 2 ½-inch bolt, the longer bolt might work for the connection that the shorter one is meant for. But when you need that longer bolt later on, you will have to backtrack and remove all the longer bolts and replace them to get the hardware you need.

Work Flow

Generally, this is the sequence a build should follow after you have performed the groundwork:

- Inventory parts
- Organize parts
- Prepare tool table or area
- Square the tunnel and set ground posts to the desired height
- Build bows (preferably on the ground and then lift them in place)
- Attach baseboards
- Set first end wall bows and construct framing (may be done later in some models)
- Set the rest of the bows, ending with the last end wall (this may depend on kit model)
- Attach side purlins
- Attach top purlins
- Attach hip boards
- Attach wind bracing
- Attach all U-channels for wiggle wire (if possible attach the end wall channels before lifting in place)
- Skin the end walls with poly or polycarbonate
- Install wind/corner baffles (if part of a kit)
- If separate from top poly, hang the sidewall curtains
- Attach roll up bars and controls
- Add wind ropes and any roll bar cradles
- Pull top poly over and attach wiggle wire or quick-lock it in
- Install doors, louvers, and any electrical devices
- Trim all excess poly materials

Pulling Poly

Although you can build the structure's frame at any point and in most weather conditions, pulling the top poly is very weather dependent. It should be calm, sunny, and warm. Mornings are often the calmest part of the day. If you pull the poly covering when it is cold, the poly will sag once it turns hot and you will need to adjust the poly again.

It is ideal to have four to six people on hand to pull the poly cover over the tunnel. It is preferable to use ropes and tennis balls to pull the poly over the frame. You can use tennis balls to tie rope to the poly to grip the plastic as you pull it over the hoop structure. This helps prevent ripping holes in the plastic.

Be sure everyone is ready and on the same page about the procedure before starting. Be careful when you roll out the poly prior to the pull. Remove any debris from the ground and roll it out slowly.

Always, no matter how subtle the wind, pull the poly into the wind. If you pull with the direction of the wind there is greater risk that the plastic will flip over itself and cause a mess that will likely damage the poly. The team that pulls the ropes attached to the poly (three to seven ropes depending on size), should be ready to shout, "Stop," if there is a snag. Another team of two or three will be on the ends and in the rafters helping get the poly over. Two people will be on the opposite sides of the rope team, fluffing and making sure the poly unravels well. They then will be the ones to attach the first side to the framing. If you use two layers of poly, it is best to pull them at the same time, one on top of the other.

Be sure to face the poly the correct way so the correct side is facing inside. If you use two layers of poly, be sure the clear or protective layer is on top.

Tools

The tools that you will need to construct a high tunnel will, of course, vary. But you can probably count on needing these items:

- Tractor with loader
- Post pounder (hand-, gas-, or air-powered)
- Laser transit
- Cordless drills or drivers
- Reciprocating saw
- Circular saw
- Clamps
- Post levelers
- Tape measures
- Reel measures
- Post puller
- Large and small sledges
- Wooden stakes
- Ropes and tennis balls (for pulling poly)
- Impact bits
- Drill bits
- Wire cutters
- Adjustable wrenches
- Pliers
- Scissors
- Tall adjustable ladders
- Eye and ear protection
- Shovels
- Mattocks
- Hoes

This photo from a high tunnel build highlights the many tools and supplies that are needed to construct the tunnel's infrastructure.

5. Planting Dates

High tunnel planting dates are determined largely by temperatures inside the tunnel, marketing plans, and particular crop requirements. For production during the cool season, day length is also a consideration.

Warm-season crops like tomatoes, peppers, and melons need air temperatures above 50°F and soil temperatures should be in the 50s or even 60s. Temperatures below 45°F or 50°F can injure warm-season crops, especially very tender crops like cucumbers and melons that require soil temperatures above 60°F. Below-freezing temperatures in the tunnel can further injure and even kill warm-season crops.

If you don't provide supplemental heat, transplanting tomatoes into high tunnels about a month before your area's frost-free date is typically about right. You may still need to protect them from frost with row covers. More tender crops could go into the tunnel about two weeks later.

You should plant most cool-season crops for late fall and winter harvests in mid- to late August or early September for the greatest yield potential. By planting this early they can grow to full or nearly full size before cold and low light slow growth to almost nothing. Early planting is especially important for crops that are harvested as full-size heads or plants. Four-week-old transplants are often used for crops like full-size kale leaves and lettuce heads. Direct-seeding is common for spinach and densely-planted salad greens.

Later plantings (through the middle of October) are possible for crops for which you harvest individual leaves or smaller plants. They will take longer to get to harvestable size and will produce less yield than earlier plantings. But, if you space out several plantings a few weeks apart in succession, it will yield a supply of fresh young leaves over a longer period than a single planting. Most crops seeded after the middle of October won't be ready to harvest until a month or more into the following year unless you harvest very tiny plants.

Some cool-season crops for spring harvest are overwintered from fall plantings. Others can be seeded or transplanted to the tunnels in late January or February. As days grow longer and temperatures increase, the crops will grow more quickly.

Crops in the cabbage family (including kale, mustards, bok choy, and others) are likely to flower after grown in cool conditions, which limits their spring harvest. The overwintered crops will make flower stalks with smaller leaves. Newly planted crops may bloom before they make marketable leaves. Customers may still purchase the blooming stems, but it is important to realize it that these are different products and should not expect them to be the same as before flowering. Early spring plantings may not be productive for many varieties of these crops. Plant some test rows before you commit to a particular variety and planting date.

Warm-season Vegetables
(tomatoes, cucumbers)

November	December	January
February	March	April
May	June	July
August	September	October

Cool-season Vegetables
(kale, spinach)

November	December	January
February	March	April
May	June	July
August	September	October

This diagram shows the general planting and harvest periods for warm- and cool-season crops in unheated structures. Yellow cells indicate planting period. Green cells indicate harvest period. Blue cells indicate potential overlap of harvest and planting periods.

6. Planting Arrangements and Spacing

Space in a high tunnel is valuable, so it is important to use it efficiently. Many growers plant on 24- to 36-inch beds separated by 12-to 24-inch walkways. Tall crops that support themselves or are supported take advantage of the vertical space, too. They can even use the space over the walkways if their trellises or support systems angle out from the bed. Indeterminate tomatoes and cucumbers are good examples of crops that use vertical space.

Intercropping smaller, short-season crops with larger, long-season crops is another way to intensify production. Growers are experimenting with intercropping to find best practices. For example, spring-sown beets and lettuce can be grown along the edge of a bed of transplanted tomatoes and will be harvested before the tomato plants get large.

Bed size and arrangement influence work efficiency and the effective growing area. For a given bed and alley width, long-ways beds will provide more plantable square feet. You can use the percent of total square footage in a tunnel available for planting to compare different bed and alley arrangements. For crops planted in single or double rows on beds, the amount of crop space is sometimes expressed as linear bed feet. Since you can fit more beds in a tunnel if they are narrower, using narrow beds will create more linear bed feet. See Table 1.

Long beds are also easier to prepare with equipment, because there is a longer run before you need to turn around the equipment. Long beds may also be more efficient because at least one alley way will be close to the center of the end wall, which will make it easy to move harvest bins and larger equipment the length of the structure. Many high tunnels are planted in long beds for these reasons.

You may also use crossway beds, which can be the preferred choice in some cases. For instance, in an east-west oriented tunnel, it may be desirable to grow a crop of tomatoes in north-south beds so the shade from one tomato row moves around during the day instead of always falling on the next row to the north.

These images show common bed arrangements and spacing. ***A.*** *A longways bed or row on 4- to 6-foot centers.* ***B.*** *A longways bed or row on 4- to 6-foot centers with two rows of strawberries.* ***C.*** *Beds that are 2.5 to 3.5 feet across with densely planted kale, lettuce, and other greens, with narrow walkways between the beds.* ***D.*** *Crossway beds with a variety of crops in a fairly wide high tunnel.*

In addition to the amount of square footage for planting and work efficiency, consider how much space you need to move and work in the alleys and how much space you need between the end of the crop and the end walls. Tunnel corners are often underused because they are difficult to get to. Consider planting a perennial herb or plants that provide habitat or food for beneficial insects in such areas. Locating alleys along edges and end walls can be helpful, because those areas are typically cooler and wetter, which make them less desirable for plant growth.

Table 1. Examples of plantable area and linear bed feet for various long and crossway bed arrangements in a 96 x 30-foot high tunnel.

Bed Width	Number of Beds	Alley Width (feet)[1]	Plantable Area (sq. ft.)	Plantable Area (%)	Linear Bed Feet
Long beds (90 feet long with a 3-foot alley along each end wall)					
2.5	8	1	1,800	62.5	720
3	7	1	1,890	65.6	630
3.5	6	1.25	1,890	65.6	540
3.75	6	1	2,025	70.3	540
Crossway beds (27 feet long with a 1.5-foot alley along each side wall)					
2.5	28	1	1,822	63.3	729
3	23	1	1,863	64.7	621
3.5	19	1.25	1,796	62.3	513
3.75	19	1	1,928	66.8	513

[1]The number of alleys is always one more than number of beds.

The microenvironment varies in the tunnel, so when growing multiple kinds of crops, place crops where they are best adapted (to the extent that's possible). The edges of the tunnel will be colder, especially in the winter, so that is the place for the most cold-hardy crops like spinach and kale. Edges will also be windier when the sides or end walls are open. Keep in mind that every tunnel seems to have wet spots — whether it is just a low area, or along an entire side or end where water seeps in after rain.

Some areas in the tunnel may receive more shade than others, and tall crops will shade shorter ones to the north. Put tall crops on the north side of the tunnel, unless there is something that you specifically want to grow in the shade, or unless the tunnel is not tall enough on the side. You can also plant tall crops up the middle to give them the maximum space to climb in the highest part of the tunnel.

Understanding the microenvironment is also important for pest management. Mites tend to appear first in hot, dry areas; root diseases in wet areas; foliar diseases in locations where the humidity remains high due to wet soil and/or shade.

Poorly drained areas in tunnels contribute to high humidity and increase the risk of plant diseases.

7. Environmental Management

Air and soil temperature, relative humidity, and light all influence plant growth and, to some extent, you can manage them in a high tunnel. Air temperature is the most common focus.

Understanding the factors that influence air temperature will help you to manage it. hen sunlight enters a tunnel, some of the radiation hits the soil (and other objects in the tunnel), and then gets reflected back toward the sky as longer wavelengths. The tunnel's plastic covering does not permit infrared wavelengths to pass through as easily, so these wavelengths are trapped inside the tunnel, which warms the air.

On a sunny day, the air temperature inside a tunnel can quickly increase to tens of degrees warmer than it is outside. On a cloudy day the difference may only be a few degrees. After the sun goes down, the tunnel loses heat through the plastic covering and through gaps in the covering. The rate of heat loss depends on how much colder it is outside than inside and how windy it is. The greater the temperature difference between the inside and outside of the structure, the faster the inside temperature will drop. The windier it is, the faster the tunnel will lose heat.

The tunnel's surface area compared to its volume also makes a difference. The more surface area for a given volume, the faster the heat loss. A long, narrow tunnel has more surface area per cubic foot of space, which will cause it to cool down more quickly than a wider tunnel that encloses the same cubic feet.

Some of the daytime radiation that hits the soil and other objects in the tunnel gets directly absorbed by (and warms) those objects. After the sun goes down and the air starts to cool, the soil also cools and loses its heat to the air. In this way, the soil acts as a heat storage system, or heat "sink." The heat that the soil releases overnight can keep the air temperature inside the tunnel higher than the outside when there is a layer of insulating material.

A single layer of plastic does not insulate well. The overnight low temperature inside a tunnel covered with just one layer of plastic can easily drop to the outside temperature. Row covers and/or inflated double layers of plastic are better insulators and will increase air temperature in the high tunnel on cold nights.

On sunny days in spring and fall and on most days in the summer, the air temperature inside the high tunnel gets too high for optimal plant growth. The solution is to ventilate — let cooler outside air pass through the tunnel. Depending on the structure, this may mean rolling up sidewalls, opening end wall doors or vents, opening roof vents, or moving plastic to create openings.

In spring and fall, you may need to do this daily. In summer, the vents often are open all the time except during severe weather. You can install thermostatically controlled motors to open and close vents and sidewalls. However, whether the expense is worth the savings in time will be different for each farm operation.

In greenhouses, thermostatically controlled vents in end walls are often paired with fans in the opposite end wall to increase airflow. Some high tunnels also have this option, and it can reduce the need to manage sidewalls early and late in the season.

It's important to note that ventilation alone (with or without fans) will not reduce the temperature inside the tunnel below what it is outside. It will always be a few degrees warmer inside the tunnel.

In locations with warm, sunny summers, farmers also use shade cloth for temperature management. The cloth reduces the amount of sunlight that enters the tunnel, which reduces the temperature. But the shade also reduces the light that plants need for photosynthesis, so there is a trade-off. For tomatoes in Indiana, 30 percent shade is typical, and this is likely a good level for other summer crops as well.

Another strategy for reducing summer temperatures is to reduce the number of objects in the structure that absorb heat. Light-colored mulches and ground covers reflect more radiation, and heat up less, than dark-colored mulches and ground covers. Thus, light-colored mulches can reduce heat buildup in the summer. Because many summer crops benefit from soil warming early in the season, many growers use a dark-colored or IRT plastic mulch in the row to warm soil near crop roots, and a light-colored mulch or ground cloth between rows. As the plants grow, they shade the dark mulch and reduce its warming effect.

In spring and fall, temperatures in the tunnel drop below optimum, and in winter they may remain below optimum for weeks at a time. At these times, the strategy is to maximize heat storage in the tunnel and reduce heat loss. Common practices include using row covers and additional insulation around the base of the tunnel. A double plastic covering is helpful but not essential.

Row Covers

Spun-bonded, lightweight fabric insulates better than a single layer of plastic. This material is used just above the crop to provide an insulation layer that traps heat from the soil near the crop and slows heat loss from the tunnel. You may place the fabric over individual rows or beds, over multiple rows, or over the entire width of the tunnel. You can support the fabric with wires or small hoops, or in some cases, you can drape it over the crop like a blanket.

Fabrics are available in different weights. Heavier weights provide more insulation but also block more light. Most growers use a mid-weight cover and double it when temperatures get very cold, but growers have had success using lightweight covers, too.

You can remove the cover during the day and put it on as temperatures drop in the evening. This allows the most light to plants and the most soil warming. Growers also have success leaving covers on both day and night during the coldest weather.

Experienced growers follow guidelines for placement. For example, if the temperature is below 25°F, they use one layer; if is below 20°F, they use two layers, depending on the crops. For cold-tolerant crops in winter production, row covers are not meant to prevent crops from freezing. Crops adapted to this production system can withstand freezing, thawing, and refreezing. It is important not to handle, harvest, or jostle crops while they are frozen because that will injure them and reduce their marketability.

The previous discussion has been about using row covers on cold-hardy crops growing in the winter. For frost-sensitive warm-season crops, row covers also protect against cool temperatures and freezing. For warm-season crops, temperatures should not fall below 50°F for any length of time. The longer there are low temperatures and the lower the temperature, the greater the likelihood of chilling injury, a physiological injury that slows growth and sets the plant back. Frost injury can occur if the temperature drops below 32°F in the tunnel. When protecting crops from frost, it is best to support the cover above the crop, rather than to rest it on the crop. If you were to rest the cover directly on the crop, the plant is likely to freeze at the points it contacts the cover.

Growers also use clear plastic that is supported on rebar, conduit, or another structure to create tunnels within tunnels. When left in place during the day, this mini-tunnel traps additional heat, and the air above the small tunnel acts as an insulating layer. Temperatures inside the smaller tunnel can rise quickly on a sunny day, so it is important to monitor and open them if it gets too hot. Some growers use clear plastic over-row covers on the coldest nights.

Row covers protect crops from low temperatures inside the high tunnel. They can be supported above crops on wire hoops or other lightweight supports, or, if it won't damage the plants, laid over the crop like a blanket.

Controlling Humidity

Relative humidity greatly influences plant diseases. High humidity promotes many fungal diseases, and when humidity is high enough that water drops condense and remain on leaves, certain diseases are even more likely.

Relative humidity depends on the amount of moisture in the air and the temperature. For a given amount of water vapor in the air, as temperature drops, relative humidity increases; as temperature rises, relative humidity decreases. A 24-hour graph of relative humidity in a high tunnel illustrates this: it drops as the sun rises and temperature goes up, then increases again at night as the temperature drops.

Ventilation is the primary means of reducing relative humidity in a high tunnel. Row covers can trap moisture close to the plants, so removing them periodically can reduce humidity near crops in the winter.

Supplemental Heat

Although the definition of a high tunnel usually includes the word "unheated," some producers provide heat for emergencies to prevent freezing warm-season crops, or to minimally heat the structure to increase crop production during the winter.

A complete discussion of heating greenhouse structures belongs in another publication, but we will briefly consider it here.

Growers report using portable, unvented propane heaters that "burn clean" for emergency heat. We don't recommend these because exhaust fumes from these heaters contain materials that are toxic to plants and humans and may build up to harmful concentrations if the heater is not exhausted out of the tunnel. Without a fresh air supply, the burners may use oxygen fast enough to deplete the supply in the tunnel to dangerous levels.

Propane and natural gas-fired unit heaters are common in standard greenhouses, and in high tunnels where they are used for minimal heating in the winter. Growers also use furnaces that burn wood or corn. Few Indiana growers use geothermal heating systems.

Minimally heated structures are typically kept above 28-32°F. This speeds cool-season crop growth in the dead of winter, and it allows less hardy crops (like lettuce) to survive, which increases yield. Growers also supply heat to get a jump-start on warm-season crops. Heating the soil is an efficient way to provide heat in a high tunnel for winter crops or in the early season for spring crops.

There are a variety of systems you may use: you can bury water tubes below tillage depth, and pump water through them to heat the soil; you can add perforated pipes in the soil and force warm air through them; or you can add heating cables in or on the soil. Roots grow faster in warmer soil, the soil heats the air, and the tops grow faster because of both improved root growth and increased air temperature.

Learn from a Farmer: Silverthorn Farm

Silverthorn Farm is a small, diversified vegetable and small animal farm on 120 acres in northern Clinton County, near Rossville, Indiana. The farm is owned and operated by Nate and Emily Parks and has been in Emily's family for generations. Nate was also lucky enough to grow up on a highly diversified farm. Today, they farm on about 20 acres of the family property to produce meat, eggs, and more than 40 different types of vegetables with more than 200 varieties.

Overall Management Strategy

High tunnels are at the center of Silverthorn Farm's business. They rotate summer fruiting crops, herbs, and winter greens crops through five tunnels. They plant summer fruiting crops in early April, harvest them through September, and plant and seed winter crops in mid-September.

They recently invested in a very large structure that was designed for a commercial greenhouse and will provide 20,000 square feet of growing space! This structure will be heated, which will allow them to raise seedlings, create a retail space for on-farm sales, and grow potted herbs in addition to succession plantings of winter greens and herbs. The gas heater will allow them to plant as early as February to get a head start on summer fruiting crops.

They say that using organic growing methods and extensive rotations between five tunnels helps them keep pest and weed pressure to a minimum. In addition, their emphasis on diversity provides an impressive array of produce year-round that has increased their customer base and reputation with area restaurants. Finally, their success derives from an innovative, flexible, customer-focused, and web-based CSA model to distribute their products.

This is a gutter-connected structure from Silverthorn Farm — there are three high tunnels coupled together. Emily and Nate Parks grow lettuce, chard, onions, mixed greens, spinach, and several other crops in this structure. They also have planting tables for starts.

8. Soil Management

Well-managed soil in high tunnels will provide an environment where roots grow easily; plants benefit from interactions with soil microorganisms; mineral nutrients are present and available in sufficient supply for healthy plant growth; and crop pathogens, weed seeds, and invertebrate pests don't reduce yield or quality.

Roots need soil with plenty of pore space for air and with little compaction. Intensively cultivated soils in high tunnels are prone to compaction because of repeated traffic — from feet or machines. In addition, tillage that creates smooth, uniform seedbeds for direct-seeded crops can beat the soil into small particles, which destroys the mix of larger and smaller particles that form the basis of good soil structure. Even before crops are grown, the soils in many high tunnels were already compacted during construction when machinery may have graded the soil or moved parts into place.

You can reduce soil compaction in the crop root zone by planting on beds and limiting traffic to alleys between beds. The beds may be raised or flat and they may be kept from season to season or remade periodically.

You can also create a compacted layer if you repeatedly till to the same depth, especially with an implement like a rototiller. Some growers use broadforks, power harrows, or spaders to avoid this problem. Another solution is to break up the compacted layer with a deep shank that you pull through the soil.

You can also help to reduce the negative effects of compaction by maintaining or increasing soil organic matter. Deep rooting cover crops can also help alleviate compaction. You can add organic matter in the form of: mulches for weed control that you work into the soil (such as straw, dead leaves); composts that supply nutrients; cover crops; and crop residue if you do not remove it from the tunnel as a disease management practice.

Managing soil nutrients in a high tunnel is similar to managing nutrients in the field in a dry climate: minerals added to the soil are either taken up by plants or stay in the soil unless you irrigate beyond what the crop needs to leach the minerals out. Over time, minerals can build up high enough that crop growth suffers.

You may be adding minerals through fertilizers, composts, mulches, or other soil amendments. You can also add minerals with your irrigation. If you irrigate with hard well water, the minerals in the water include calcium and magnesium. Over time, these minerals increase soil pH. As soil pH increases greater than 7, some plant nutrients become unavailable for crop uptake and deficiency may occur.

This image shows the previous season's tomato remnants (left) and a well-established cover crop. These tunnels will be flipped to cover the center areas that are currently not under cover.

Soil Testing

Annual soil tests that indicate nutrient content, pH, soluble salts, and organic matter will help you determine whether minerals are building up. You can also use the results to estimate how much and which nutrients you should add to ensure a healthy crop.

Irrigation water tests that determine the mineral content of your irrigation water are also helpful. From these tests you can determine how much of what minerals are added with each inch (or gallon) of irrigation, and these values can go into the tunnel's nutrient budget. The tests will also alert you to high alkalinity or sodium levels in the water that, if not addressed, can reduce soil quality over time.

Usually, growers add nutrient sources and mix them into the soil when they prepare for planting. For crops that will be grown for three months or more in the summer (like tomatoes or peppers), growers often supply additional nutrients several times during the season (especially nitrogen and sometimes potassium).

When growers use drip irrigation and soluble fertilizers, it is common to supply a little fertilizer through the drip irrigation system a few times a week or even with every watering. With a fertigation system like that, it is important to tally up all the added nutrients over

the course of the season and to confirm that the total matches what the crop needs. Otherwise, it is easy to over-apply and build nutrient levels up so high that they limit plant growth.

If the soil has adequate nutrients to support a crop, then you can maintain fertility by adding nutrients each crop cycle to replace what the crop will remove when it is harvested. Table 2 provides estimates of major nutrients contained in each 100 pounds of a crop harvest. This represents the nutrients that you would need to add in order not to deplete the soil.

If you remove the entire plant from the tunnel as well as the harvested portion of the crop (for example, tomato plants), then you should also consider the nutrients contained in the plant. As soil fertility builds up over years by adding organic matter, the soil will be able to supply more nitrogen each year, and the need for amendments with large amounts of nitrogen should decrease.

Table 2 also estimates the amount of nitrogen per 1,000 square feet that crops typically need from fertilizers and soil amendments (if the soil does not have a build-up of nitrogen-supplying potential).

Determining how much of what soil amendment or fertilizer to apply in a high tunnel involves estimating how much the crop will need, how much the soil will supply, and how much the harvested crop will remove. You can use leguminous green manures to supply nitrogen to the next crop, and you should include their contribution when you figure out what amendments your soil needs. Soil testing for major plant nutrients, pH, and organic matter is an important tool for maintaining soil fertility.

You can mitigate nutrient buildup in a high tunnel by repeated heavy irrigation to leach away soluble nutrients. Or, you can remove the plastic covering and leave it off long enough to allow several inches of rain to leach excess nutrients. Tunnels that are designed to easily move from one spot to another provide another way to avoid nutrient buildup.

In our survey of Indiana high tunnel growers, high soil phosphorus levels were a common problem. This doesn't usually harm plants, but it can lead to environmental pollution if the phosphorus leaches or moves away on soil particles.

You can test soils for the level of soluble salts, which measures the quantity of dissolved salts that can inhibit plant growth if too high. Many of the salts come from fertilizers or irrigation water and can build up if nutrient applications are excessive. A white crust may be visible on the soil surface, which raises concern that salts might be injuring plants. Other researchers have measured soluble salt levels associated with this crust in high tunnels and found it does not indicate a build-up of salts that will harm plant growth. In the soil samples we took from 20 Indiana high tunnels, high salts were not a problem.

Managing the biological component of soil is the area where we have the least research-based knowledge. In general, biological activity in the soil indicates soil health, and you can promote biological activity by adding organic matter and maintaining aeration and good drainage. Some labs offer soil tests that measure the biological aspects of soil health. Conducted over a period of years, these tests help you monitor trends in biological activity.

Indiana Soil and Water: How to Understand and Interpret Soil Health Tests (Purdue Extension publication AY-366-W) describes the tests and discusses their use in agronomic crops. It's available from the Education Store, edustore.purdue.edu.

The most specific recommendations about managing the biological components of soil relate to managing plant diseases that survive in the soil. These diseases can be especially problematic in high tunnels, because growers often plant the same susceptible crop there year after year due to its high value (such as tomatoes). This practice provides no chance for the pathogen to die off and break the disease cycle.

Managing diseases that survive on crop debris or in the soil involves accurately diagnosing diseases, rotating to crops not affected by that disease, and following strict sanitation practices. A soil may become so infested with disease that you cannot profitably grow a crop. In these cases, some growers choose to grow crops in containers of growing media and discard the media after a season or two. The disadvantage of growing in containers is that the system does not take advantage of the biological, chemical, physical relationships that can develop between plant and soil — and this method does not qualify for USDA-NRCS High Tunnel Initiative programs.

Indiana high tunnel growers who responded to our survey said that adding compost was the most widely used soil fertility practice (61 percent), followed by organic fertilizers (52 percent). These soil amendments are probably why soil phosphorus was very high in several tunnels. Composts and many organic soil amendments have a higher proportion of phosphorus to nitrogen than plants require. If you apply the

amendments to supply enough nitrogen, you will also add more phosphorus than the crop can use.

The survey also found that 30 to 40 percent of respondents used foliar feeding, cover crops, and synthetic fertilizers to supply nutrients. Not quite a quarter of respondents used fertigation and other methods. Several who used fertigation mentioned it was an easy way to evenly distribute nutrients in the cropped area.

An example of a fertilizer application system that has been integrated with a drip irrigation system that is commonly used in high tunnels.

Source: Adapted from D. Warncke, J. Dahl, and B. Zandstra. 2004. Nutrient Recommendations for Vegetable Crops in Michigan. E2934. Michigan State University Extension, Lansing.

Table 2. Estimated nitrogen requirement and amounts of nitrogen, phosphorus (as P2O5), and potassium (as K2O) removed in harvested portion of selected vegetable crops.

	Crop Nitrogen Requirement	Nutrients Removed in Harvested Portion of Crop		
Crop	**N** (lbs. per 1,000 ft^2)	**N** (lbs. per100 lbs. of crop)	**P_2O_5** (lbs. per 100 lbs. of crop)	**K_2O** (lbs. per 100 lbs. of crop)
beans, snap	0.92	1.20	0.12	0.55
beets, red	2.30	0.18	0.11	0.39
broccoli	3.21	0.20	0.06	0.55
cabbage, Chinese	2.75	0.35	0.08	0.34
cabbage	3.21	0.35	0.08	0.34
carrots	2.30	0.17	0.09	0.34
cauliflower	3.21	0.33	0.13	0.33
celeriac	3.44	0.20	0.13	0.33
cucumber, slicers	1.84	0.10	0.06	0.18
eggplant	2.75	0.22	0.08	0.26
greens, leafy	2.30	0.24	0.10	0.30
kohlrabi	3.21	0.30	0.13	0.33
leek	3.44	0.20	0.13	0.24
lettuce, leaf, or bib	2.30	0.24	0.10	0.45
lettuce, romaine	3.21	0.24	0.10	0.45
market garden	3.21	0.32	0.14	0.28
muskmelon	2.30	0.42	0.10	0.55
onion, green	2.98	0.25	0.13	0.24
pak choi	2.75	0.35	0.08	0.34
parsley	2.30	0.24	0.09	0.64
parsnip	2.30	0.17	0.16	0.45
pea	0.92	1.00	0.23	0.50
pepper	2.30	0.20	0.07	0.28
potato	4.13	0.33	0.13	0.63
radish	1.15	0.15	0.04	0.28
spinach	3.90	0.50	0.14	0.60
squash, summer	1.84	0.18	0.11	0.33
sweet potato	1.38	0.265	0.12	0.64
Swiss chard	2.30	0.18	0.06	0.44
tomato	2.75	0.20	0.04	0.35
turnip	2.07	0.17	0.06	0.23

9. Pest and Weed Management

To effectively manage pests, you need to be aware of likely pests, correctly identify pest organisms, understand pest life cycles, learn to efficiently scout for problems, and use a variety of management strategies to reduce damage to acceptable levels.

Insect and Disease Management

Plan your insect and disease management before planting the crop. Learn what problems are likely by reading and talking with others. Choose management practices that you want to use and prepare to implement them. Develop a plan for weekly crop scouting and a way to record what you find. If unknown pests or diseases show up, identify them and learn about management practices. When pest pressure is high enough to warrant action, implement your control strategies. Then, note how well they work so you can make adjust them in the future.

As one grower notes:

> "I always anticipate the arrival of aphids on certain high tunnel crops in the late winter and early spring. So, I order ladybugs and parasitic wasps by mid- February to get on top of an outbreak before it gets critical."

Cultural pest management practices may also help in high tunnel production. Of the common cultural practices, crop rotation might be less effective in tunnel production because there are just a few crops that produce the biggest profits. Moveable high tunnels or structures that you can move to another location may help.

Managing the environment can be important for reducing disease pressure. It is important to vent the tunnel to bring in outside air, dry off leaves, and reduce humidity — even in winter. It also helps to remove row covers in winter (when possible) or consider planting arrangements that promote good airflow to reduce humidity.

You should also assure the tunnel has proper drainage so rainwater doesn't seep into the tunnel and keep the soil saturated. Adequate drainage will reduce humidity and diseases caused by soil organisms that proliferate in wet soils.

Devote your attention to sanitation. Remove crop residue from the structure, clean and sanitize hardware and materials that contact plants, and keep weed mats free of plant residue. All these practices can reduce inoculum that starts new disease cycles.

To help manage insects, provide habitat for the natural enemies of pests. To do this, plant appropriate plants inside and/or outside the structure. In particular instances, you can purchase and release natural enemies.

Natural pest enemies include parasitic wasps, ladybug larvae and adults, lacewing larvae, minute pirate bugs, and predatory mites. Remember that the effective use of natural enemies requires understanding when and how to use them — a thorough discussion is beyond the scope of this publication, so consult knowledgeable practitioners and be prepared to learn as you go. About 40 percent of Indiana growers remove insects by hand to control them.

You may need to resort to pesticides to control diseases and insects in high tunnels in both conventional and organic production systems. For current, crop-specific pest control information, refer to the *Midwest Vegetable Production Guide for Commercial Growers* (Purdue Extension publication ID-56) available at mwveguide.org, or contact your local university extension specialist.

In some situations, you can protect crops from insects by using row covers or netting. Research underway at Purdue and elsewhere is investigating how netting can exclude insects from the entire tunnel or keep beneficial insects inside the structure.

Rodents have proven to be serious problems in high tunnel production. They may eat seeds, leafy greens, or root systems underground. They can destroy entire plantings of winter or spring crops.

Mice and voles seem to be the most common. Current control practices include trapping and killing and using bait stations. Bait stations are regulated as pesticides, so you must use them following the instructions on the product label. If you use bait stations around a crop, the label must explicitly state that the product may be used in that crop.

You should also manage the habitat outside of the structure to make it unfavorable to these creatures and try to discourage them from setting up home in your tunnel. It has been suggested that you should construct the tunnel so rodents cannot enter. One researcher from Connecticut suggests burying hardware cloth 18 inches below the soil line around the edge of the tunnel to prevent voles from entering.

Weed Management

Planning to manage weeds begins before you build the tunnel. Choose a site without perennial weeds like Canada thistle, horsenettle, or quackgrass; or manage those weeds before you construct the tunnel. Refer to weed management guidelines for the particular perennial weed problem.

Take care when you bring in soil, compost, mulch, or cover crop seed. You must avoid importing weed seeds and perennial plant parts such as underground stems, rhizomes, stolons (as from quackgrass), or roots (as from Canada thistle). All these parts and seeds have the ability to sprout new plants.

Create a stale seedbed before planting by preparing the soil, wetting it, and allowing a flush of weed seedlings to emerge. Kill those seedlings while they are small with very shallow cultivation, flaming, silage tarps, or another method that does not disturb the soil much — that way you will not bring new weed seeds to the soil surface. Be careful with flame weeding near polyethylene, straw, silage tarps, and other flammable materials.

Use dense crop plantings to out-compete weeds. This will help to keep weeds small.

Use drip or targeted overhead irrigation to wet soil only near crops; fewer weeds will grow in areas that are not irrigated.

Remove weeds when they are small to minimize competition with the crop. Don't let weeds go to seed or that seed will provide weed problems for years to come. If weeds do flower, remove them from the structure before seeds can mature.

Design your bed's shape, size, and planting arrangements so you can efficiently use your weeding tools. You should explore the weeding implements that are available, learn and/or teach workers how to use them, and keep them sharpened. In our grower survey, 20 percent said they used machine cultivation, 70 percent used hand hoeing, and more than 80 percent used hand-pulling. Around 10 percent used flaming implements.

Many growers use mulches to control weeds. In the planted row, opaque plastic mulches or woven weed mats are common. Between rows, woven weed mats or organic materials (like straw, leaves, wood chips, and cardboard) are used. Mulches also help maintain soil moisture and shade the soil in the summer.

Pay attention to the source of the mulch, and avoid materials that:

- Could present food safety hazards (including improperly composted materials)
- Be a source of weed seed (such as weedy straw)
- Contain damaging herbicide residues (such as grass clippings from areas treated with broadleaf herbicides)

Under certain conditions, you may apply herbicides inside a high tunnel. About 10 percent of surveyed growers use herbicides. A thorough discussion of herbicides is more involved than we will provide in this document. To learn more about herbicide options, contact a horticultural weed scientist from your state's extension service.

10. Irrigation

An irrigation system is necessary for high tunnel production. During the summer, full-size crops will require more than 1 inch of water per week — or more than 1,800 gallons in a 30 x 96-foot structure. Crops require less in winter.

Growers commonly use well water, but some use a municipal or other public water supply, surface water from a pond or stream, or runoff from the high tunnel roof. Always test water sources to ensure they are suitable for irrigation. Depending on the crops you grow, the size and nature of your business, and the irrigation system you use, food safety regulations may require specific tests for microbial quality.

Farmers often use drip irrigation in high tunnels — more than 75 percent of the Indiana growers we surveyed used it. Hand-watering is also common (used by about 33 percent of surveyed growers), and sprinklers (about 20 percent).

It's not unusual to have more than one irrigation system. That said, the most effective irrigation system is one that's designed for your structure, planting arrangement, crops, soil type, and water supply.

For example, in a sandy soil, a tomato crop may need two drip lines per bed. In a clay soil, the same crop may only need one drip line.

For a spinach crop, you may use overhead sprinklers to get the soil to the desired moisture content before you seed, and then maintain soil moisture during emergence. During crop growth, you may continue to irrigate with the sprinklers, or switch to several lines of drip tape.

Those who supply professional irrigation equipment often can advise on design. Your state extension service may have staff with irrigation expertise.

Irrigation schedules (when to irrigate and how much water to put on) depend on the crop and its growth stage, weather, soil type, and irrigation system. Your goal is to provide adequate water for crop production and quality — you do not want to apply so much water that the soil remains saturated or that excessive nutrients leach below the rooting zone. You can often track tomato fruit disorders (such as blossom end rot and cracking or splitting) back to inadequate irrigation management.

Each operation will need to develop its own irrigation schedule. Just because another tomato grower runs drip irrigation twice a day for an hour each time, it doesn't mean that schedule is appropriate in your system.

If your irrigation schedule requires frequent irrigation for regular periods, automating the system (even partially) can save lots of time. For instance, we spoke with a tomato crop producer who runs drip irrigation three to four hours a day that turns on and off automatically. About 10 percent of surveyed growers use irrigation controllers that turn on and off. These controllers may be set for timed irrigation (that is, they start at a particular time of day and run for a specified time). While timing is probably most common, you can get controllers that turn on and off based on soil moisture or other environmental measurements.

Table 3 describes the pros and cons of common irrigation systems.

Table 3. *Pros and cons of select irrigation systems.*

Irrigation System					
Drip		*Sprinkler*		*Hand*	
Pros	**Cons**	**Pros**	**Cons**	**Pros**	**Cons**
Makes localized water application	Drip lines get in the way of tillage, cultivation	Easy to wet a large area (especially before or after seeding)	Wets leaves	Makes very localized water application	Is labor intensive
Doesn't wet leaves as much, which reduces disease pressure	Must spend time laying out and picking up drip lines	Parts last longer; depending on system, maybe not as many	May wet alleyways	Easy to tailor quantity	May provide less uniform application
Requires only low pressure		Easy to automate	May wet people	No special set-up needed	
Easy to apply soluble fertilizers		May not get in the way of tillage, cultivation	Uses water less efficiently if soil is covered with impermeable mulch		
Can be used under mulches					
Easy to automate					

***A.** A drip tape. **B.** A lay-flat header line with drip tape lines. **C.** A drip tape in a larger tunnel. **D.** A sprinkler irrigation system. **E.** A header for drip tape attached to a garden hose. **F.** An irrigation water storage tank with a gravity feed to drip irrigation lines. **G.** A storage tank for collecting water from a high tunnel roof.*

11. Summary

Overall, our research found that Indiana farmers have had a positive experience with integrating high tunnels into their farm operations. The most important opportunities growers reported are the higher quality and shelf life of their high tunnel crops, the price premium they can obtain for having crops earlier in the season, and the higher yield of their high tunnel crops.

Farmers also told us they valued the opportunity to earn an income in the fall and winter months, the ability to attract and keep employees by offering employment for more (or all) months of the year, and the opportunity to grow crops that complement their farm business and that they would not otherwise be able to offer. These crops include greens and root crops to complement fall crops or agritourism, early berry crops to extend the time they can sell berries at the farmers' market, or varieties of delicate flowers or other crops they would not otherwise be able to offer their customers.

While high tunnels present many opportunities for growers, they are also time-consuming and labor-intensive to manage. Successful high tunnel production requires advanced planning and monitoring, including well-conceived business planning and site preparation, plus continued attention and monitoring of soil health, weed problems, pest changes, and disease management. Ultimately, as one grower said: "you get out what you put into it," because the benefits you gain will partly depend on the time and attention you are able to give to your high tunnel crops.

In this guide, we have shared important points and questions that other growers wish they had known or considered before investing in their high tunnels. We thank them for sharing their experiences with us, and now with you. We hope this handbook has been helpful and wish you success with your high tunnel production!

12. Resources

There are lots of resources out there to help you with high tunnels. We encourage you to browse these suggestions and find the information suited to your unique goals and needs.

Purdue Extension

extension.purdue.edu

Find your county office at extension.purdue.edu/Pages/countyoffices.aspx or (888) EXT-INFO.

Books

Coleman, Eliot. *Four-Season Harvest: Organic Vegetables from Your Home Garden All Year Long*. Chelsea Green Publishing, 2012.

Coleman, Eliot. *The New Organic Grower: A Master's Manual of Tools and Techniques for the Home and Market Gardener*. Chelsea Green Publishing, 1995.

Fortier, Jean-Martin, and Marie Bilodeau. *The Market Gardener: A Successful Grower's Handbook for Small-scale Organic Farming*. New Society Publishers, 2014.

Hartman, Ben. The Lean Farm: How to Minimize Waste, Increase Efficiency, and Maximize Value and Profits with Less Work. Chelsea Green Publishing, 2015.

Mefferd, Andrew. *The Greenhouse and Hoophouse Grower's Handbook*. Chelsea Green Publishing, 2017.

Solomon, Steve and Erica Reinheimer. *The Intelligent Gardener; Growing Nutrient-dense Food*. New Society Publishers, 2012.

Stone, Curtis. *The Urban Farmer: Growing Food for Profit on Leased and Borrowed Land*. New Society Publishers, 2015.

General High Tunnel Websites

eXtension "Introduction to High Tunnels"
articles.extension.org/pages/18358/introduction-to-high-tunnels

HighTunnels.org
hightunnels.org

University of Kentucky High Tunnel Research Facility
ukhtrf.webs.com/production

Rutgers University: Sustainable Farming on the Urban Fringe website ("High Tunnels in New Jersey")
sustainable-farming.rutgers.edu/high-tunnels-in-new-jersey

USDA-Sustainable Agriculture Research and Education (SARE). Season Extension: "Types and Construction"
www.sare.org/Learning-Center/Topic-Rooms/High-Tunnels-and-Other-Season-Extension-Techniques/Season-Extension-Types-and-Construction

Handbooks

Bachmann, Janet. *Season Extension Techniques for Market Gardeners*, ATTRA 2005. attra.ncat.org/attra-pub/summaries/summary.php?pub=366.

Blomgren, Ted and Tracy Frisch. *High Tunnels: Using Low-Cost Technology to Increase Yields, Improve Quality and Extend the Season*. University of Vermont Center for Sustainable Agriculture, May 2007. www.sare.org/Learning-Center/SARE-Project-Products/Northeast-SARE-Project-Products/High-Tunnels.

Hannan, Joe, et al. *Iowa High Tunnel Fruit and Vegetable Production Manual*, Iowa State University Extension publication HORT 3060. store.extension.iastate.edu/product/13342.

Thompson, Collin. "Planning and Siting for Hoophouses." The North Farm, Michigan State University Extension. www.msunorthfarm.org/uploads/3/8/2/8/38288527/the_north_farm_planning_and_siting_for_hoophouses.compressed.pdf.

Thompson, Collin. "Keeping Your Hoophouse Busy." The North Farm, Michigan State University Extension. www.msunorthfarm.org/uploads/3/8/2/8/38288527/keeping_your_hoophouse_busy_-_miffs.compressed.pdf.

Jim French, Kimberly Oxley, Tom Buller, and Cary Rivard. 2018. Growing Under Cover: A Guide to Polytunnel Options for Kansas Growers. A Kansas Rural Center Publication. kansasruralcenter.org/growing-under-cover.

Select High Tunnel Suppliers

Atlas Greenhouse
www.atlasgreenhouse.com/

Farmtek
www.farmtek.com

Farmer's Friend, LLC
farmersfriendllc.com

Four Season Tools
www.smallfarmtools.com

Nifty Hoops
www.niftyhoops.com

Rimol Greenhouse Systems
www.rimolgreenhouses.com

Rough Brothers, Inc.
www.roughbros.com

Stuppy Greenhouse
www.stuppy.com

Zimmerman High Tunnels & Greenhouses
www.zimmermanshightunnels.com

How to Build High Tunnels

"How to Build High Tunnels" video from Utah State University Extension
www.youtube.com/watch?v=RytuhqGBxZA

"Resources" page from The North Farm, Michigan State University
www.msunorthfarm.org

"Rainwater Catchment from a High Tunnel for Irrigation Use" video from Iowa State Extension
www.youtube.com/watch?v=XsxRZQR_7VU

Planting Guides

"Winter Growing Guide" from Johnny's Selected Seeds
www.johnnyseeds.com/growers-library/vegetables/winter-growing-guide-high-tunnel-scheduling.html

Plant Disease and Insect Identification

Caldwell, Brian, Eric Sideman, Abby Seaman, Anthony Shelton, and Christine Smart. Resource Guide for Organic Insect and Disease Management. New York State Agricultural Experiment Station, Cornell University.
cvp.cce.cornell.edu/submission.php?id=37.

"Natural Enemy Field Guide" from Ohio State University Extension
u.osu.edu/pestmanagement/files/2017/02/Final-NE-Guide-for-GLVWG2022017-rpiftt.pdf

Egel, Dan, and Shubin Saha. *Vegetable Diseases: Tomato Disease Management in Greenhouses*. Purdue Extension publication BP-197-W.
edustore.purdue.edu/item.asp?Item_Number=BP-197-W.

Foster, Ricky E., and John L. Obermeyer. *Vegetable Insect Identification*. Purdue Extension publication E-65-W.
edustore.purdue.edu/item.asp?Item_Number=E-65-W.

Vegetable Management

Midwest Vegetable Production Guide for Commercial Growers
mwveguide.org

PURDUE UNIVERSITY | Extension purdue.edu/extension

Find out more at THE EDUCATION STORE edustore.purdue.edu

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