HIGH TUNNEL PRODUCTION GUIDE

FOR ARKANSAS AND THE SOUTHEAST

High Tunnel Production Guide for Arkansas and the Southeast

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RESEARCH & EXTENSION
University of Arkansas System

HIGH TUNNEL
AND URBAN AGRICULTURE

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CHAPTER 1

Introduction to High Tunnel Production in the Southeast

Specialty crop production in high tunnels has grown considerably over the past decade because tunnels offer cost-effective ways of extending growing seasons and protecting plants from damaging weather. The incorporation of high tunnel production on farms in the warmer southeastern United States, however, has been slower than in cooler climates. This lag is often attributed to the milder and shorter winter season experienced in many warm southern states, such as Arkansas. More frequent adverse weather conditions and the availability of cost share programs through the NRCS (see Chapter 11 – Financial Assistance for Purchasing a High Tunnel - The Environmental Quality Incentives Program) has led to greater interest in adapting these structures for warmer climates.

Image 1.1. A Quonset style high tunnel.

While resembling greenhouses in look and design, high tunnels are used and managed differently. In their purest and simplest form, high tunnels are constructed by stretching a single layer of plastic over metal or PVC hoops and contain no heating or automated venting systems (Image 1.1). Instead, high tunnels are warmed through passive solar radiation and are typically cooled by manually opening endwalls, vents and rolling up/down sidewalls. While this passive approach to temperature management offers less climate control than a greenhouse, when managed correctly high tunnels can successfully extend growing seasons, improve yield and quality for many high-value specialty crops, for a more affordable price, compared to a greenhouse.

In a high tunnel, plants are most often grown directly in the existing soil and irrigated using drip systems (Image 1.2). The integration of fertigation into the drip irrigation system can also give growers precise control of fertility programs (see Chapter 9 – Irrigation Strategies and Chapter 10 – Soil Management and Fertility). Vegetables are the most common high tunnel crops, with early season tomatoes

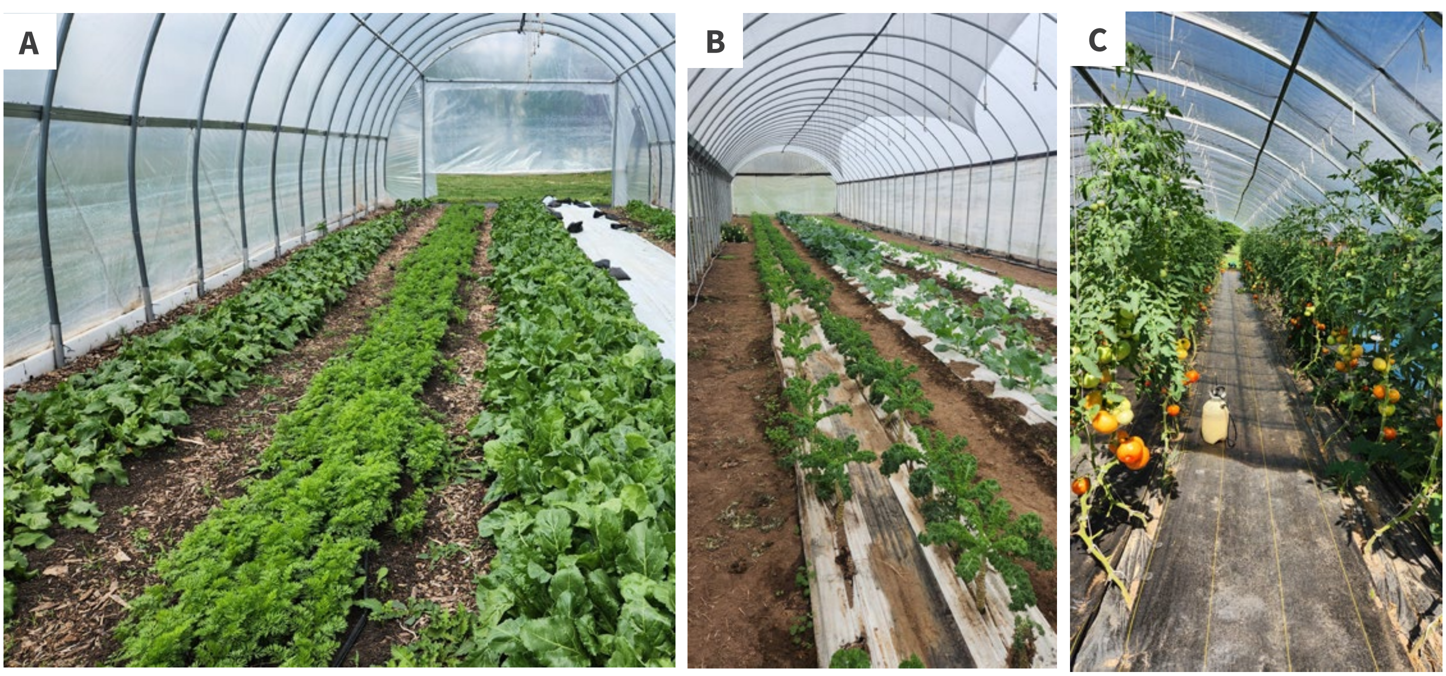

Image 1.2. Leafy crops (A and B) and indeterminate tomatoes (C) growing in the existing soil inside high tunnels. All of these tunnels were irrigated using drip irrigation.

easily being the most popular and profitable nationwide. Winter-grown lettuces, however, are quickly moving up the list of profitable high tunnel crops. Other vegetable crops that have performed well and been profitable in Arkansas and the Southeast include bell pepper, cucumber, summer squash, eggplant, okra and a mix of leafy greens. In some instances, annual strawberries have also been profitably produced within a tunnel. In more recent years, production of perennial fruiting crops, such as blackberries and grapes, have been trialed in high tunnels in Arkansas and the cost-effectiveness of growing these larger fruiting crops is still being evaluated. Cut flower production in high tunnels is also increasing and has proved to be very profitable.

When compared to field production, high tunnel production often requires more attention to pest management, irrigation and fertility programs, and soil health. Despite needing more focused management, high tunnel production offers growers a wide variety of advantages and new opportunities.

Advantages of High Tunnel Production

- **Season Extension:** Within a high tunnel air and soil temperatures warm more quickly in the spring and stay warmer longer in the fall. This allows for earlier crop establishment, accelerated growth, and earlier harvests in the spring and extends harvest later into the fall. Favorable growing environments can also be maintained within a high tunnel through the winter months to support out-of-season production of many cold hardy crops. Depending on crop selection and grower preference, tunnels can be used to produce year-round.

- **Weather Protection:** Poor crop performance and reduced marketable yields due to weather stress in the open field can be significant. A high tunnel's plastic cover can protect plants from environmental stresses including late spring frosts, hail, heavy rain (particularly during vulnerable growing stages), and wind. High tunnels also allow for crop maintenance and harvests despite weather conditions, such as rain.

- **Environment Moderation:** In addition to temperature management, a high tunnel can provide growers the ability to influence other growing conditions. For example, the tunnel's plastic cover blocks rainfall, essentially creating desert-like conditions inside the tunnel. This means the grower has absolute control over irrigation management and can potentially prevent plants from experiencing any water stress.

- **Improved Yields and Crop Quality:** In a well-managed high tunnel, the protected microclimate of the tunnel tends to produce greater yields of higher quality produce. Production research in high tunnels continually shows yield and quality improvement for many specialty crops. One study conducted at the Kansas State University Olathe Horticultural Research and Extension Center achieved 126-528 percent higher marketable yields on high tunnel lettuce compared to open field, while other studies showed a 47-50 percent increase in high tunnel tomato yields compared to the open field. It is important to note that sound horticultural practices such as variety selection, proper soil preparation, irrigation, fertility, and pest management are required to achieve these results.

- **Improved Farm Revenue:** The potential for higher yields of better-quality produce, coupled with the premium prices out-of-season produce can demand when well marketed, means high tunnel production can improve total farm revenues, improve economic stability in the off season, and potentially generate year-round income.

- **Reduced Incidences of Certain Diseases:** The exclusion of rainfall and the use of drip irrigation within a well-designed and properly managed high tunnel can reduce the occurrence of certain diseases, more specifically diseases dispersed by splashing water. Anthracnose, for example, is an economically damaging fungal disease on strawberries and, in the open field, is quickly spread by splashing rainfall. The incidence of anthracnose is greatly reduced on drip irrigated high tunnel strawberries, even without the use of fungicides. It is important to mention that diseases dispersed by other methods occur often inside a high tunnel, particularly diseases that thrive and spread in high humidity conditions. Botrytis gray mold, leaf mold, and powdery mildew are common and potentially devastating fungal diseases in high tunnels (Image 1.3). Damaging levels of powdery mildew have been reported in high tunnels in Arkansas due to conducive environmental conditions often as a result of poor climate management.

- **Increased Diversification:** High tunnels can be used to extend the growing season for crops that are normally grown in an area, or they can be used to grow crops that generally cannot be grown due to weather constraints. This allows growers to use high tunnels to augment the selection of their field crops, increasing the assortment of crops they can offer customers.

While high tunnels offer many possibilities and new opportunities, they also present both new and familiar challenges. The warm and humid climate in the southeastern United States presents some unique challenges to high tunnel production, particularly when summer temperatures reach above 90°F for long stretches.

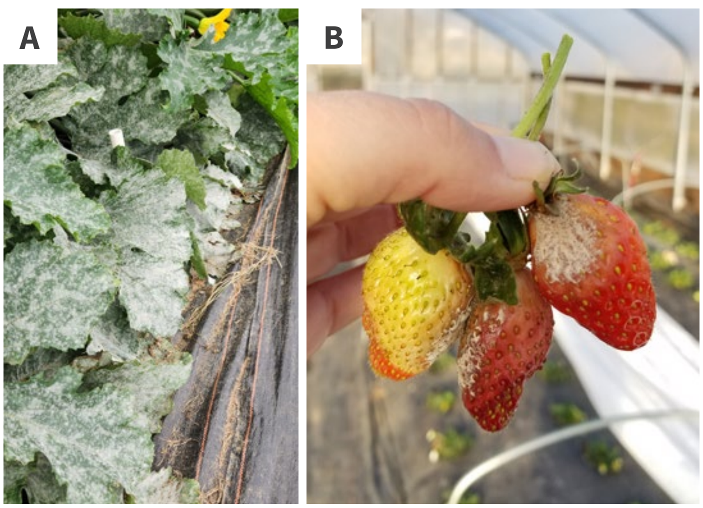

Image 1.3. Powdery mildew on high tunnel zucchini plants (A) and botrytis fruit rot growing on high tunnel strawberries (B).

Limitations to High Tunnel Production

- **Extreme Summer Temperatures:** On a sunny day, the air temperature inside a tunnel will always be warmer than the outside temperature. Summer temperatures in the southeastern United States can regularly exceed 90°F, with heat indexes above 100°F, for several consecutive days or weeks. During these summer months, a well-designed and fully ventilated tunnel with a shade cloth may still experience temperatures above the optimal growing conditions for many warm season crops. These extreme temperatures cause plant growth to stall, flowers to drop, fruit set to fail, and increase certain abiotic disorders (such as blossom end rot) all of which can result in lower yields and poor fruit quality. This issue can be compounded in a poorly designed tunnel that lacks adequate ventilation.

- **Higher Labor Needs:** Monitoring and managing the high tunnel climate will require labor not needed in open field production. Climate management often requires someone to be onsite or nearby every day, including weekends and holidays. This is especially true in the spring and fall when temperature management could be a twice-daily task. The use of secondary covers may also be necessary during the winter and shoulder seasons, requiring additional labor hours to cover/uncover plants. On average, it can take one person 5 – 10 minutes a day to open or close the side/endwalls of a high tunnel. When secondary covers are used, this could increase to 20 – 40 minutes per day, depending on the size of the tunnel and the way the secondary covers are laid out. Remember that opening/closing a tunnel and covering/uncovering with secondary covers may need to be done twice a day — uncovering in the morning as temperatures increase and covering in the evening as temperatures drop. This means high tunnel climate management could require a daily time commitment of an hour or more.

- **New Pest Problems:** The microclimate created within a high tunnel may also provide the optimal environment for pests to flourish. For example, aphids and white flies can reach higher population densities inside a high tunnel compared to open fields nearby. Mites, such as the two-spotted spider mite, also thrive in the warm, dry high tunnel environment and have become a persistent and harmful high tunnel pest (Image 1.4).

- **Construction and Maintenance Costs:** While less expensive than a greenhouse, construction costs for a high tunnel are increasing. Crop selection and market demand will heavily influence how quickly the initial cost of the tunnel can be recuperated, with reports averaging between two and five years. Secondary covers will need to be purchased for winter production, and a shade cloth for summer production. Structure maintenance, such as the replacement of the plastic cover, should be included in farm overhead budget plans.

Image 1.4. A population of two-spotted spider mites that quickly grew out of control inside an organic strawberry high tunnel.

Because the internal climate of a high tunnel is largely governed by the surrounding environment, success will depend on the selection of a structural design that is well suited for that location's specific climate. A tunnel design that compliments the environment will not only improve crop quality but also limit many temperature management headaches and frustrations (see Chapter 4 - High Tunnel Design). Crop selection, planting date, and high tunnel management strategies are also influenced by climate. Many production guides and research done in high tunnels have focused on cooler climates. The purpose of this production guide is to provide growers in Arkansas and other warmer southeastern states, with information to help adapt this valuable resource to a warm humid environment.

Additional Resources

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Notes

CHAPTER 2

Should You Invest in a High Tunnel?

While high tunnels offer many possibilities and new opportunities, they also present new challenges. Anyone interested in investing in a high tunnel should understand the potential limitations and requirements that accompany high tunnel production. Before purchasing a high tunnel consider the following questions:

1. Can you afford a high tunnel?

One supplier of prefabricated high tunnel kits quoted a price range from $8,765 to $11,585 for a very simple 30 ft by 96 ft tunnel (prices obtained in spring of 2024). These kits did not include the cost of the plastic, hip/baseboards, endwalls or supplementary structural supports necessary for areas with high winds (Image 2.1). Installation or construction costs are also not included. Other costs include plastic replacement, which will need to be done every three to five years, shade cloth (necessary for summer production in Arkansas), irrigation systems and labor to install these coverings. High tunnel construction and repair requires skilled labor. In rural areas, growers may have to pay travel expenses for skilled technicians to construct the tunnel. Learning how to install plastic and other coverings as well as basic structure maintenance will help save money that would otherwise be spent on hiring labor. For example, replacing the plastic covering on the tunnel requires multiple people. With proper skill and know-how, plastic can be replaced with just three or four people — but inexperience may make it necessary to hire additional help. While cost share programs through the NRCS are available to help cover the initial cost of a tunnel, growers should seriously consider the ongoing and recurring costs associated with high tunnel production before considering these programs. For more information on the NRCS cost share program see Chapter 11 – Financial Assistance for Purchasing a High Tunnel - The Environmental Quality Incentives Program.

2. Do you have space and land that can support a high tunnel?

Image 2.2. Clay soils and low-lying ground made this tunnel very susceptible to flooding after rainstorms.

Placement of the high tunnel in a suitable location can be the difference between success and failure. Soil conditions, weed pressure, water drainage, air movement and sunlight are just a few important factors that should be considered when choosing a location for a high tunnel. It is important to note that a high tunnel needs more space than just the ground it covers. Tunnels located in an open area where air movement and sunlight are unrestricted are better situated to obtain high yields of good quality produce. Crop quality and marketable yields will also be impacted by soil conditions. Locations with preexisting soil issues such as poor drainage, soil-borne disease(s) or compaction should be avoided (Image 2.2). High tunnel production tends to amplify any preexisting issues of the site location which can result in declining profits and make it necessary to relocate

A

B

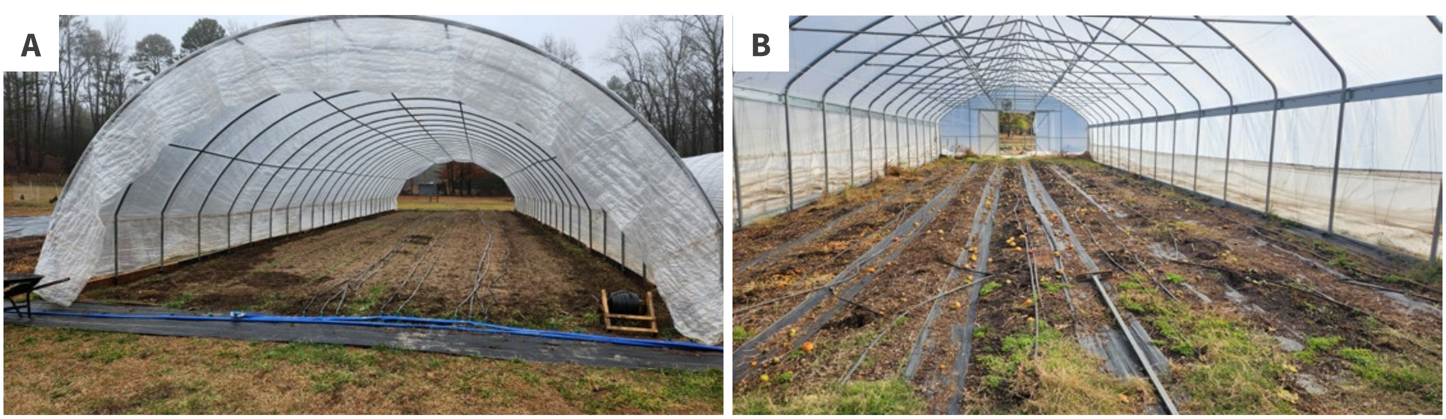

Image 2.1. A simple high tunnel design with minimal structural support (A). This simple high tunnel does have raised sidewalls which will be an added cost (A). A high tunnel design with additional structural support (trusses) and endwalls (B).

a tunnel. For more information on selecting an optimal location for a high tunnel see Chapter 3 - Site Selection.

3. Do you have the time and/or money to operate a tunnel?

When compared to field production, high tunnels have a higher demand for labor and time for crop management. Good climate control, which is essential not only for crop growth but also pest management inside a tunnel, can be a twice daily (or more) activity (Image 2.3), including weekends and holidays. Consequently, a high tunnel grower must either be onsite, or near the site, daily or pay someone to be on/near the site daily while a tunnel is in production. The need for daily climate management is more prominent during the shoulder seasons (spring and fall) and winter months, when large day to night temperature fluctuations can occur. Pest monitoring is often more time intensive inside a high tunnel as well. The microclimate created by the tunnel can promote rapid pest outbreaks. Successful high tunnel production and higher returns are achieved by growers who are able and willing to invest the time and labor needed to tend to the crop.

Image 2.3. Secondary covers are often needed during the off-season for additional frost protection on particularly cold nights. Covering and removing secondary covers will require extra labor hours.

4. Are the crops you plan to grow profitable in a high tunnel, and in your area?

Crop production in a high tunnel is expensive once you consider the irrigation equipment, plant material, fertilizer, labor, and cost of the structure. As such, crop selection should be done carefully to ensure maximum return per sq ft of the space is achieved. While it is possible to produce most common fruits or vegetables in a tunnel, not all will be profitable. If generating revenue is the tunnel's purpose, then crop selection will be key. For example, consider the economics of a single high tunnel that produces either a perennial fruit crop (like grapes) or an annual crop (like lettuce) that is produced year-round. Both crops will utilize all available production space in the tunnel year-round and require care year-round. The perennial grape crop, however, will only produce fruit for a few weeks each year while the lettuce crop could be harvested nearly continuously. Which cropping system is more desirable and profitable will be determined by the farm goals and market demands. For more information on crop selection and rotation see Chapter 6 – Crop Selection and Planting Dates.

5. Is there a market for your produce?

High tunnels make it possible to produce fruits and vegetables outside their normal production window. However, being able to supply the produce does not guarantee a market demand for that produce at that time. This is of particular concern in more rural areas. Some farmers markets are only open for five to six months out of the year. Before investing in a high tunnel, it is vital to explore retail avenues that can be utilized or developed in the surrounding area for out of season produce.

Additional Resources:

Bruce, A. Maynard, E., Farmer, J. and J. Carpenter. 2018. Indiana High Tunnel Handbook. Perdue Extension. Publication HO-296. www.extension.purdue.edu/extmedia/ho/ho-296.pdf

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Question & Answer Sheet

1. Can you afford the upfront cost to construct a high tunnel?

2. Do you have the space to support a high tunnel?

3. Do you have the time and/or money to operate a tunnel?

4. Are the crops you plan to grow profitable in a high tunnel, and in your area?

5. Is there a market for your produce?

CHAPTER 3
Site Selection

Introduction

Successful high tunnel production begins with deliberate and careful selection of a suitable location to construct the tunnel. A poor site can cause production issues such as higher soilborne disease pressure and low plant vigor. Climate management could also become problematic if there is poor air movement or air drainage at the site. Crop production at a less than ideal site may be able to limp through a season or two but unaddressed issues could eventually make relocating the tunnel necessary. This chapter outlines several key considerations when evaluating a potential location for placing a high tunnel.

Accessibility

High tunnel management requires daily monitoring and labor, and easy access to the tunnel can be a determining factor in a tunnel's success. Place the tunnel in a location that makes daily year-round access easy, such as near a farmhouse or other farm buildings (Image 3.1). The adage, "out of sight out of mind" often holds true with high tunnel management and the more conveniently located a tunnel is to daily farm activity the better. Additionally, keep crop harvest and storage facilities in mind when selecting a location. It should be easy to move produce from the high tunnel to washing and cooling facilities. Easy access to irrigation must also be considered.

Soil Conditions

High tunnel production is intensive and can be hard on the health of the soil. Any preexisting issue with the soil can be compounded after several years of high tunnel production. For example, after just three or four years of production, excess salts or fertilizers can build up to toxic levels in tunnel soils due to the lack of rainfall leaching that open field soils experience. High tunnel soils are also at a higher risk for compaction, loss of organic matter and destruction of soil structure. For more information on maintaining healthy soils inside a high tunnel see Chapter 10 - Soil Health and Fertility Management. Ensuring soil conditions are suitable from the start at a potential site will help achieve the high yields of good quality produce associated with high tunnel production.

The soil depth above bedrock must be considered. Not only do crops need a minimum of 10-12 inches of rooting depth to achieve the best production, but the ground posts that anchor the high tunnel should be driven three to four feet into the ground. Shallow soils overlaying bedrock can also be prone to poor water drainage.

Soil type

Soil texture (sand, silt or clay) impacts water and nutrient movement through the soil which can impact fertility and irrigation management at a site. Soil texture cannot be changed but the addition of organic matter and other soil

Image 3.1. High tunnels located near farm buildings and a frequently used lane for easy access.

Collecting a Soil Sample

When:
Soil samples can be collected any time throughout the year. But avoid collecting when the soil is extremely wet.

Tools needed:
- ☐ A soil probe or hand trowel
- ☐ One five-gallon bucket (or something similar)
- ☐ Soil sample box (from your local extension office) or sealable bag

How:
- Using the soil probe or hand trowel, dig a hole 6-8" deep and as wide as the probe or trowel blade
- Place this soil into the five-gallon bucket
- Repeat this sample process at random areas throughout your tunnel, placing all samples into the five-gallon bucket
- Collect between 6-10 samples for a 1,000 sq ft tunnel
- Once all samples are in the bucket, mix thoroughly
- Remove about 2 cups of soil from the five-gallon bucket and place it in the soil sample box or sealable bag

What to do with the sample:
- Fill out the soil sample submission form (your local extension agent can help you)
- Drop the soil sample box or bag at your local extension office
- Wait for the soil report to show up in your email!

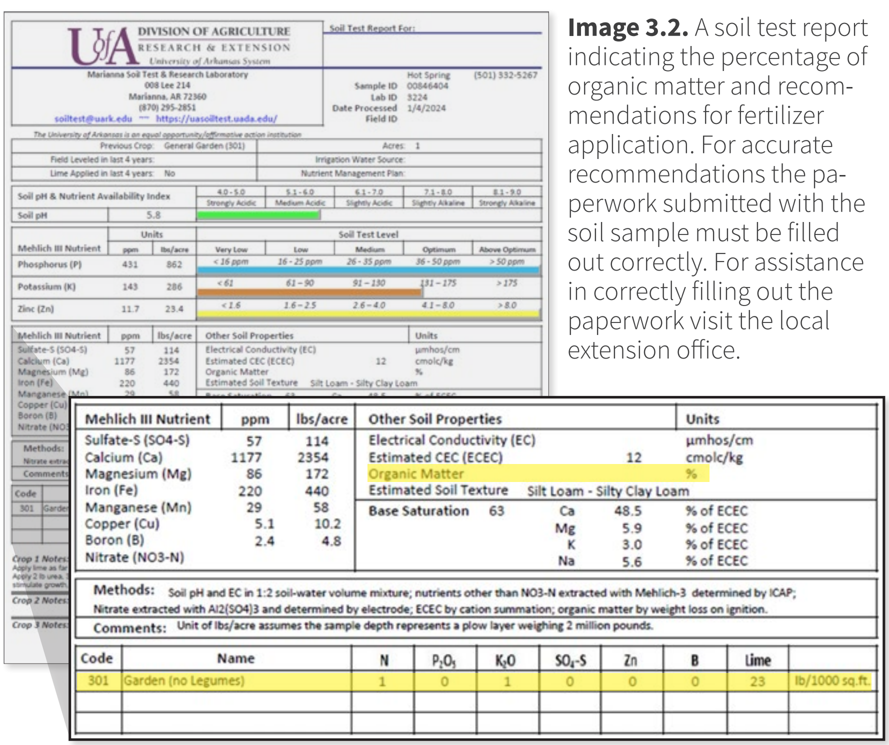
amending and building practices can improve many soil characteristics to improve high tunnel production. Soils with high clay content, for example, may struggle with poor water infiltration and drainage making them more prone to harbor soilborne diseases and salt build-up. Using raised soil beds can improve water infiltration and drainage in this situation. However, if you are participating in the NRCS High Tunnel EQIP program there could be restrictions on using raised beds inside a high tunnel. When possible, select a site with a lighter-textured soil, such as a sandy loam. Sandy soils work well for out-of-season production because they warm quickly and experience better water drainage. However, they also have lower natural soil fertility and may require more regular irrigation.

Soil health

Soil health is an indicator of a soil's ability to promote and sustain plant growth. Soils with high organic matter tend to have better soil health. Nearly all soils in the Southeast United States have only 1-2 percent organic matter. Adding high-quality compost or mulch to the soil before planting (as well as between plantings when needed) can increase organic matter over time. While cover cropping will require more advanced planning it can also contribute to increasing soil organic matter (see Chapter 7 - Cover Cropping and Crop Rotation). While poor soil can be amended and healthy soil developed, this takes dedicated effort over many years. A tunnel constructed over poor soil will likely experience lower yields and poor crop vigor. Understanding Soil Health (www.uaex.uada.edu/publications/pdf/FSA2202.pdf) is a good resource for building and maintaining soil health.

Soil Fertility

Soil fertility is a single facet of soil health. A soil test will indicate pH and fertility levels currently present in the soil and what amendments, if any, need to be incorporated before high tunnel construction (Image 3.2). Soil tests can be obtained from the Marianna Soil Testing Laboratory (aaes.uada.edu/technical-services/soil-testing-and-research-laboratory/). Incorporating the recommended rates of lime



Mehlich III Nutrient	ppm	lbs/acre
Sulfate-S (SO4-S)	57	114
Calcium (Ca)	1177	2354
Magnesium (Mg)	86	172
Iron (Fe)	220	440
Manganese (Mn)	29	58
Copper (Cu)	5.1	10.2
Boron (B)	2.4	4.8
Nitrate (NO3-N)		

Other Soil Properties				Units
Electrical Conductivity (EC)				µmhos/cm
Estimated CEC (ECEC)			12	cmolc/kg
Organic Matter				%
Estimated Soil Texture	Silt Loam - Silty Clay Loam			
Base Saturation	63	Ca	48.5	% of ECEC
		Mg	5.9	% of ECEC
		K	3.0	% of ECEC
		Na	5.6	% of ECEC

Methods: Soil pH and EC in 1:2 soil-water volume mixture; nutrients other than NO3-N extracted with Mehlich-3 determined by ICAP; Nitrate extracted with Al2(SO4)3 and determined by electrode; ECEC by cation summation; organic matter by weight loss on ignition.

Comments: Unit of lbs/acre assumes the sample depth represents a plow layer weighing 2 million pounds.

Code	Name	N	P_2O_5	K_2O	SO_4-S	Zn	B	Lime	
301	Garden (no Legumes)	1	0	1	0	0	0	23	lb/1000 sq.ft.

Image 3.2. A soil test report indicating the percentage of organic matter and recommendations for fertilizer application. For accurate recommendations the paperwork submitted with the soil sample must be filled out correctly. For assistance in correctly filling out the paperwork visit the local extension office.

(raise soil pH), phosphorus or potassium is best done before tunnel construction. This not only allows larger equipment to be used but also gives lime the time needed to raise the soil pH. It takes six months or more for lime to have any significant effect on soil pH. If the proposed high tunnel site has an extended history of crop production, testing the level of organic matter and soil salinity can provide valuable information on the site's soil health. For more information on interpreting soil test reports (Image 3.2) see Chapter 10 on Soil Health and Fertility Management.

Soil compaction

Soils become compacted when soil particles are pressed or compressed together, reducing the space (pore space) between them. This smaller pore space decreases a soil's capacity for water infiltration, drainage, and gas exchange (Image 3.3). Roots growing in compacted soils often struggle to expand and thrive which can lead to nutritional deficiencies and poor plant vigor. Additionally, compacted soil can easily become waterlogged which can cause them to harbor soilborne diseases. Locations with compaction issues should be avoided or efforts should be made to reduce compaction before tunnel construction, which requires time and dedicated effort. Remember that soil can become compacted by anything that supplies sufficient compressive force to a soil such as heavy farming equipment (mowers, seeders, etc.) and high foot traffic (human or animal). Excessive tillage is often cited as a big contributor to soil compaction in agricultural land. High tunnels are likely to experience many of these factors, including repeat tillage and high foot traffic, which could compound a preexisting compaction issue or introduce one. Cover cropping, mulching, and incorporating organic matter can help mitigate soil compaction and should be part of all long-term high tunnel soil management plans.

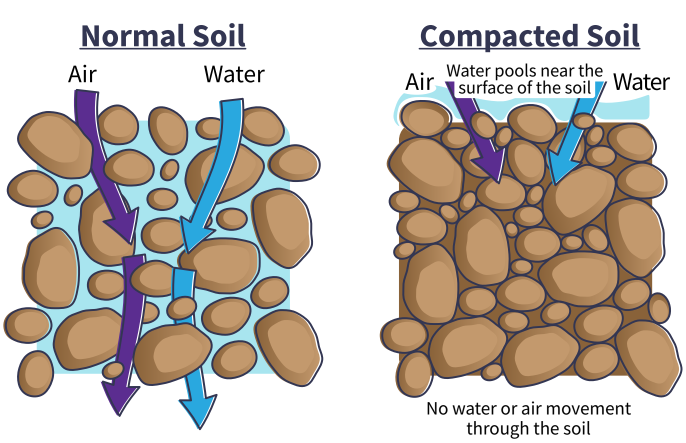


Image 3.3. Movement of air and water through normal or healthy soils and the effect soil compaction has on this movement.

History

Knowledge of a site's history can provide insight into potential issues that might be hiding in the soil. For example, land previously used as pastureland may have herbicide residue that can persist in the soil for several years, harming specialty crops planted in a high tunnel; or land used for tomato production for multiple years may have soilborne pathogens such as fusarium, timber rot or bacterial wilt; and areas that had been regularly tilled in the past could be highly compacted. Knowing this history could prevent constructing a tunnel in a problematic area and help avoid unnecessary stress and frustration.

Knowledge of a site's neighboring area can also help you avoid installing a tunnel in a problematic area. For example, spray drift from neighboring fields where pesticide applications occur is a concern. Herbicides used in row crop and pastures may drift across property lines and stunt or kill specialty crops — even crops growing inside a tunnel. Because tunnels must be vented regularly, they do not provide protection from herbicide drift. Growers, specifically organic growers, should consider using tools such as driftwatch.org to help protect their crops from spray drift.

DriftWatch.org is a website that allows specialty crop growers to voluntarily register their operations so growers and pesticide applicators can be aware of each other and work together to protect specialty crops. Additionally, surrounding crop production could introduce damaging pests to a tunnel environment or affect a grower's ability to obtain organic certification. Building relationships with neighbors and making pesticide applicators aware of your operation are good steps to limit potential issues.

Soilborne pathogens and plant-parasitic nematodes

Areas with known soilborne pathogens and plant-parasitic nematode issues should be avoided. Soilborne pests can be difficult to manage once established in the soil and require a combination of pesticide intervention, soil solarization, soil fumigation or several years of crop rotation to control (Image 3.4). It may even become necessary to move the tunnel to a new location. To check for plant-parasitic nematode populations, soil samples can be sent to the Arkansas Nematode Diagnostic Lab (https://www.uaex.uada.edu/farm-ranch/pest-management/plant-disease/nematodes.aspx). It is more difficult to ascertain what bacterial or fungal diseases are currently present in the soil. Knowing the history of the location can help determine potential issues.

Image 3.4. A planting of tomatoes dying from bacterial wilt, a soilborne disease (A). Roots infected with root knot nematodes (B). Image B from Gerald Holmes, Strawberry Center, Cal Poly San Luis Obispo, Bugwood.org.

Slope

A potential high tunnel site should be nearly level. A terrain that is too uneven or that has a slope greater than 5 percent could cause structural stress and pose issues for drip irrigation and fertilizer systems. If leveling the ground is an option, avoid removing the topsoil as much as possible. If the ground cannot be leveled, and another site is unavailable, smaller tunnels or tunnels with a simpler design, like a caterpillar tunnel, may be more accommodating to a sloped site, while more complex designs will be less adaptable. Keep in mind that a more basic tunnel design, while easier to adapt to an uneven slope, will be more susceptible to structural damage caused by weather such as wind or snow (Image 3.5).

Image 3.5. The hoops of a caterpillar tunnel partly collapsed under the weight of a snow load.

Drainage

Areas with soggy soils or soils that drain poorly and remain wet for an extended time after heavy rains should be avoided. Tunnels built in low-lying areas or areas that are slow to dry can experience a higher incidence of soilborne diseases and poor crop growth. Most fruit and vegetable crops require well-drained soil and will struggle if standing water is a regular occurrence. Positioning a high tunnel on ground slightly elevated above the surrounding area can help guarantee that stormwater runoff or snow melt flows away from the tunnel instead of through it.

Keep in mind that the addition of a high tunnel can intensify even small drainage issues. A 30 ft by 96 ft high tunnel can shed 1,728 gallons of water with just an inch of rainfall. If this water does not flow away from the high tunnel, flooding inside the tunnel will occur and negatively affect crop quality and yields.

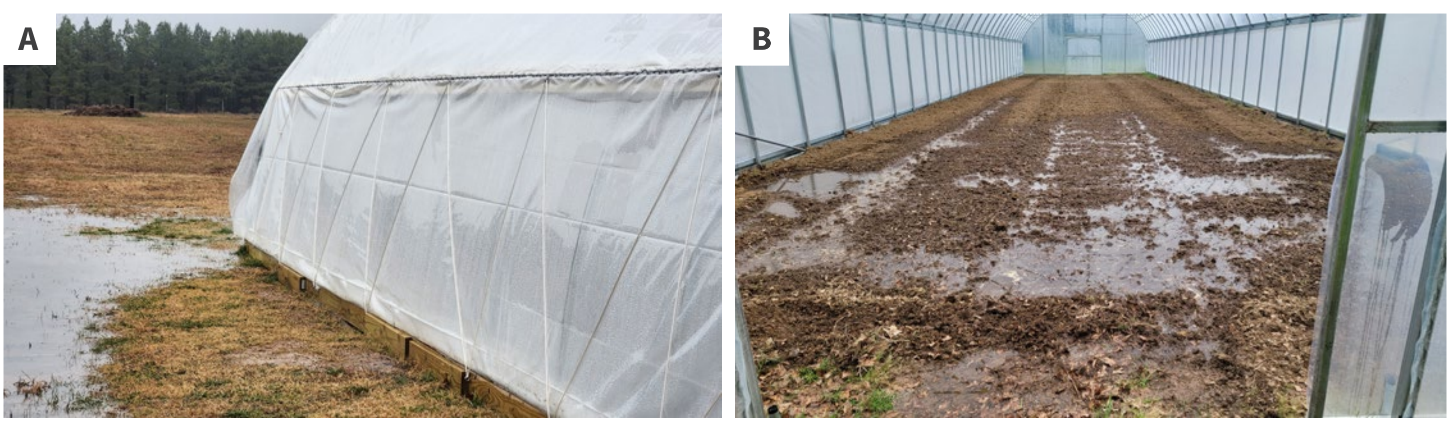


Image 3.6. Heavy rains flood a field outside a tunnel (A). Storm water flowing into and flooding a tunnel (B). Image B provided by Sarah Shelton-James with BWG Herbal Tea.

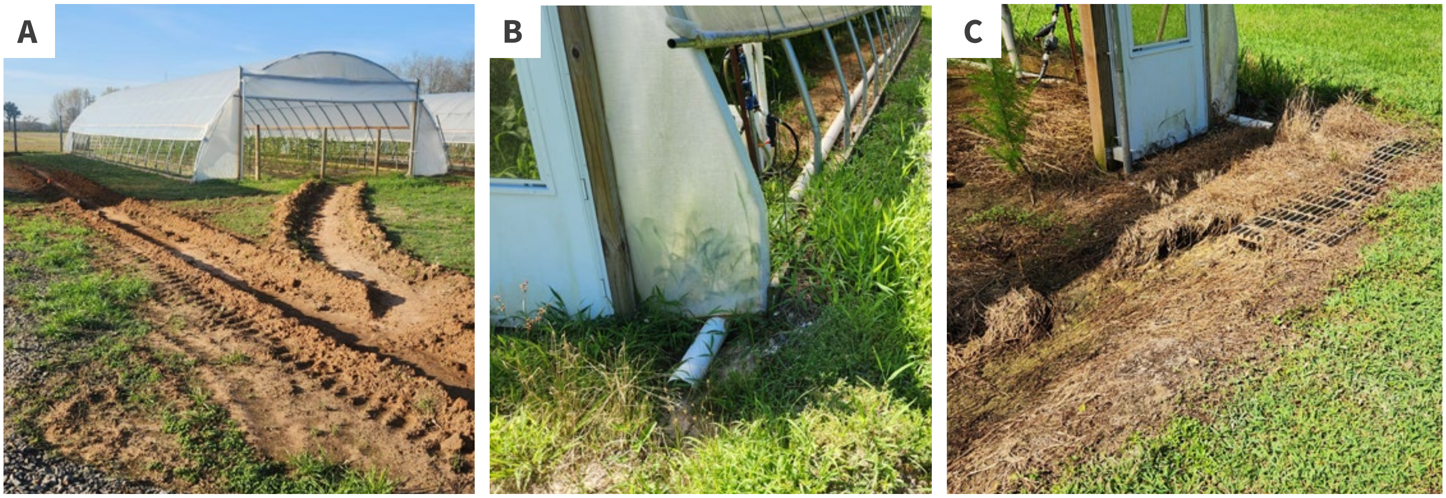


Image 3.7. Open drainage ditches to help divert water away from a group of high tunnels (A). A modified French drain installed inside a tunnel to help direct water out of the tunnel (B and C).

Arkansas is among the 10 wettest states in the United States, averaging 50 or more inches of rainfall a year. Because of this, inadequate drainage and flooding are among the most common issues experienced by high tunnel growers in Arkansas (Image 3.6). Many tunnel growers must install drainage systems, such as French drains or open ditches, around their tunnels after construction to divert water and prevent flooding (Image 3.7).

Sunlight

Optimizing sunlight entering the tunnel is important. In addition to a plant's need for sunlight to grow, high tunnel production relies on the sun for warmth during out-of-season production.

Select a site where the high tunnel will receive full direct sunlight more than eight hours per day. Place the tunnel where it will not be shaded by surrounding structures or trees. Full sun may seem unnecessary in the long hot summer days in Arkansas, but tunnels provide the greatest benefit in the winter, spring, and fall seasons when days are shorter and often overcast. Shade from trees or other surrounding structures will limit the amount of sunlight reaching the tunnel, slowing plant growth, causing harvest delays and potentially lower fruit quality.

Keep in mind the lower sun angle during the cooler months will cause structures to cast longer shadows. Structures or trees that pose no shading risk during summer could shade a tunnel during winter (Image 3.8). If there are trees or structures to the south or west of a tunnel's proposed location, set the tunnel back a distance of 2 to 2.5 times the height of the tree or structure to avoid potential shading issues. For example, if an adjacent building is 25 ft. tall, the high tunnel should be set at least 50 feet away from that building. Another thing to remember when evaluating the shading potential of a site are young trees with the potential to grow larger. While tunnels are generally considered temporary structures, they regularly remain in place for many years. During those years, a small tree can eventually become a shading risk as it grows.

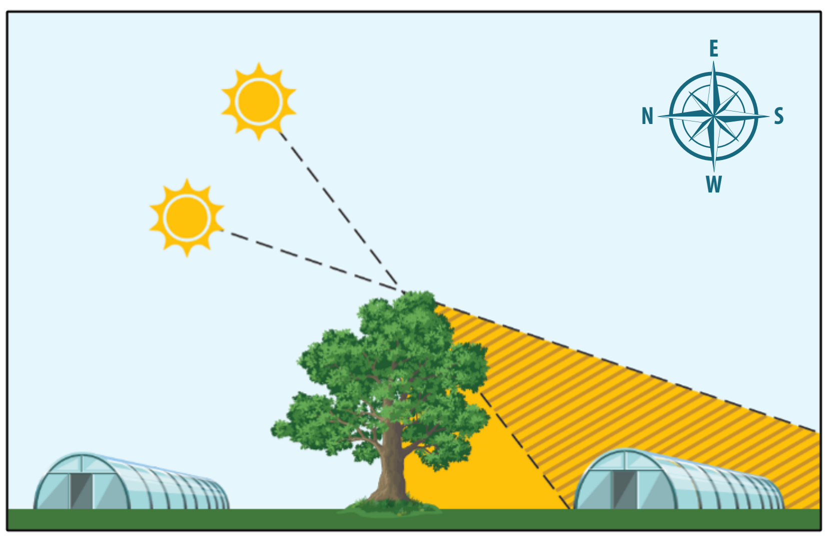


Image 3.8. The shaded orange area indicates the shading potential of a tree growing near a high tunnel. The area shaded orange and black indicates the increased shading potential of the same tree during the winter months when the sun angle is lower. While this tree does not shade the tunnel during the summer, it will shade the tunnel during the off season. A tunnel situated north of this tree will not be at risk of shading during the off season.

Wind

Ideally, high tunnels should be in an open area where air movement is good. Wind moving through the tunnel is the primary method of reducing air temperature and humidity within the structure. Restrictions in air movement can lead to overheating and higher pest and disease pressures inside the tunnel. Areas with high winds, however, should be avoided. High winds can cause a significant amount of damage to tunnel structures, leading to costly repairs (Image 3.9). Windbreaks can be used in areas that experience high winds but be mindful of potential shading issues. Additional structural support, or cementing ground posts, may also be necessary in areas with high winds (Image 3.9). Because endwalls typically have more structural hardware they are usually stronger and more capable of withstanding higher wind forces. So, orienting a tunnel so endwalls are perpendicular to the dominant wind flow could improve a tunnel's ability to withstand wind.

Orientation

Historically, a lot of emphasis has been put on the correct orientation of a high tunnel for light capture. Generally, for areas north of the 40th parallel, where growing seasons are shorter and winter sun angles lower, an east/west orientation is recommended for better light capture during winter months. For areas south of the 40th parallel, which includes the entire state of Arkansas, a north/south orientation is generally recommended to capture more light. In Arkansas (and other southern states), however, orienting a tunnel for light capture is usually less important than positioning a tunnel for better airflow. Because tunnels are cooled passively by wind blowing cooler air into the tunnel, restricting that airflow could cause excessive heat build-up inside the tunnel and thwart pest management plans. Situating a tunnel so major openings are perpendicular to the dominant wind flow can help improve air movement within the tunnel. Keep in mind that high winds can damage a tunnel. Orienting a tunnel so endwalls are perpendicular to the dominant wind flow may be needed in high wind areas.

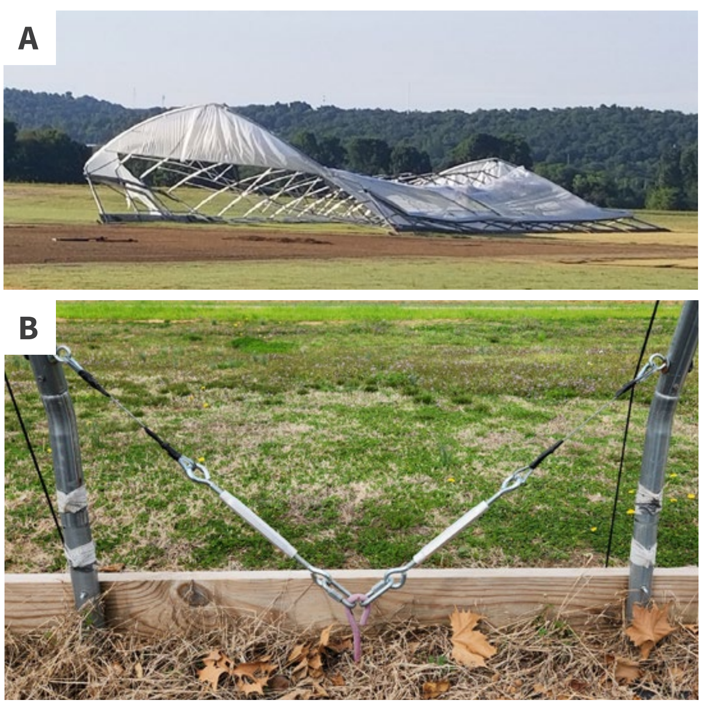


Image 3.9. High tunnel damaged by high winds (A) and a high tunnel with additional anchoring (B).

The height of the planned crop(s) should also be considered when determining a tunnel's position. Taller or trellised crops can act as a wind or sun block to neighboring rows. Inside a tunnel, plant rows will typically run parallel to the sidewalls. If this is the case, then orienting a tunnel north/south can prevent taller crops from shading neighboring rows, particularly during winter months. Positioning a tunnel so the dominant wind flow moves down plant rows (endwall to endwall) instead of across the rows (sidewall to sidewall) may also help avoid wind restrictions caused by taller crops.

Weeds

Perennial weeds can become a persistent problem for high tunnel growers. When possible, select a site with a low population of noxious perennial weeds such as nutsedge

Image 3.10. Perennial nutsedge growing through plastic mulch. Nutsedge can be a chronic problem for high tunnel growers, even growers utilizing plastic or fabric mulches for weed control.

(Image 3.10). Large weed populations can make crop management more difficult and increase pest pressure inside a high tunnel. If the proposed site has a dense population of perennial weeds, before constructing the tunnel consider weed removal strategies that will eliminate or reduce the presence of these weeds.

A broad-spectrum herbicide can kill perennial weeds before the tunnel is constructed. Before applying any herbicide be sure to read the pesticide label carefully as some herbicides can linger within soils for several years, killing or stunting future fruit or vegetable plants grown in those treated soils. Another weed control method often employed in high tunnel production is solarization or tarping. Both methods have been used successfully to manage annual weeds and, to a lesser extent, some perennial weeds.

Nutsedge, a potentially devastating perennial weed has shown considerable resistance to solarization/tarping. The effectiveness of solarization/tarping will depend on the temperature achieved beneath the cover (the warmer the better), and how long high temperatures are maintained (see Chapter 8 - Pest and Disease Management Strategies). Weed management options become more limited once the tunnel is constructed.

Utilities

A high tunnel excludes rainfall, so to ensure a crop's success, all irrigation water must be supplied to the crop from a reliable year-round water source. Ponds, creeks, wells and municipal water are all viable sources for irrigation water.

Before constructing a tunnel be aware of the availability, quality and cost of a water source. Municipal water sources are reliable and usually of high quality but can be costly. Ponds or other surface water sources can vary in quality and may be unreliable during dry periods. Have the water source tested to make sure it is safe to use on food crops. A feasible method of getting the water from the source to the high tunnel should also be in place before planting in the tunnel. During the colder months, a frost-free water source will be needed for irrigation (Image 3.11).

For more information on water sources and setting up an irrigation system, see the extension factsheet Basics of Drip Irrigation and Fertigation for Specialty Crops (www.uaex.uada.edu/publications/PDF/FSA6160.pdf).

Consider constructing a high tunnel near an electrical source or running electricity to the tunnel. While high tunnels are generally passively heated and require no electrical input, situations may arise where access to electricity may be desirable. Automated ventilation, electric heaters, fans and the addition of artificial lighting are common modifications growers have made to high tunnels (Image 3.12).

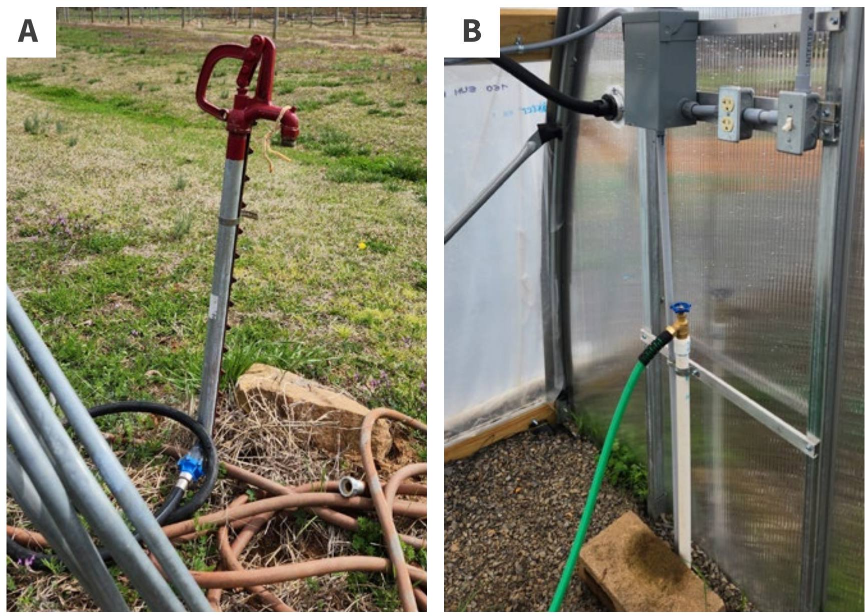


Image 3.11. A frost-free spigot located just outside a high tunnel (A) and a spigot located inside a tunnel, near an electrical source (B).

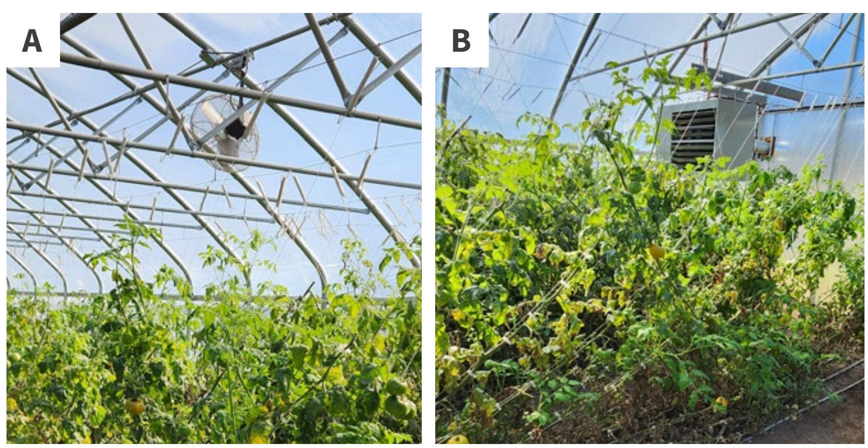


Image 3.12. An electric fan used to improve air movement throughout a high tunnel (A) and a heater (B) installed inside a high tunnel.

Zoning codes and regulations

Because high tunnels are generally considered nonpermanent structures, zoning restrictions for high tunnels are not common in rural areas of Arkansas. Urban areas, however, may have more restrictions and zoning regulations. Zoning regulations can vary from city to city and change over time. Before erecting a high tunnel become familiar with the zoning regulations for a proposed location and contact the planning department in your community for guidance.

Image 3.13. A farm in Northwest Arkansas with multiple high tunnels and low tunnels.

Plan for the future

Some high tunnel growers express regret that they did not consider possibilities for expansion when selecting a tunnel site. One Arkansas grower even mentioned dismantling their tunnel so it could be moved to a new site where multiple tunnels could be constructed near each other. If high tunnel production proves beneficial and profitable for your farm, acquiring more tunnels may be desirable in the long-term. Consider selecting a location that can accommodate expansion, including additional high tunnel structures or harvesting, packing and storage facilities (Image 3.13).

Conclusion

It is unlikely that a single site will meet all the ideal considerations for a high tunnel described in this chapter. When selecting a site, take the time to carefully consider which factors are most important for the success of your high tunnel production and best support your farm goals. Focus on the considerations with the highest potential to mitigate potential issues for high tunnel crop production at that site.

Additional Resources

Adams, S. A. and K. A. Todd. 2015. High Tunnel Design, Site Development, and Construction. Nebraska Extension. Publication EC308. extensionpubs.unl.edu/publication/ec308/pdf/view/ec308-2015.pdf

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Birthisel, S. K., Gallandt, E. R. and A. E. S. Cunha. 2018. Solarization and Tarping for Weed Management on Organic Vegetable Farms in Northeast USA. eOrganic. eorganic.org/node/25440

Bruce, A. Maynard, E., Farmer, J. and J. Carpenter. 2018. Indiana High Tunnel Handbook. Purdue Extension. Publication HO-296. www.extension.purdue.edu/extmedia/ho/ho-296.pdf

Buck, E. 2014. Best Management Practices in High Tunnel Production. Cornell University Cooperative Extension. bpb-us-e1.wpmucdn.com/blogs.cornell.edu/dist/5/91/files/2016/04/BMP-in-High-Tunnel-Production-Site-Selection-rd0dwu.pdf

Fryer, M., McWhirt, A., Daniels, M., Robertson, B., Roberts, T., Mahmud, K., Brye, K. and M. Savin. Retrieved 2024. Understanding Soil Health. University of Arkansas Division of Agriculture Research and Extension. Publication FSA2202. www.uaex.uada.edu/publications/pdf/FSA2202.pdf

Maughan, T., Drost, D. and B. Black. 2019. High Tunnel Site Selection. Utah State University Extension. digitalcommons.usu.edu/cgi/viewcontent.cgi?article=3083&context=extension_curall

Videos:
PennState Extension: Video series on High Tunnels: extension.psu.edu/high-tunnel-structures-the-basics

Begin evaluating a potential site:



CHAPTER 4
High Tunnel Design

Introduction

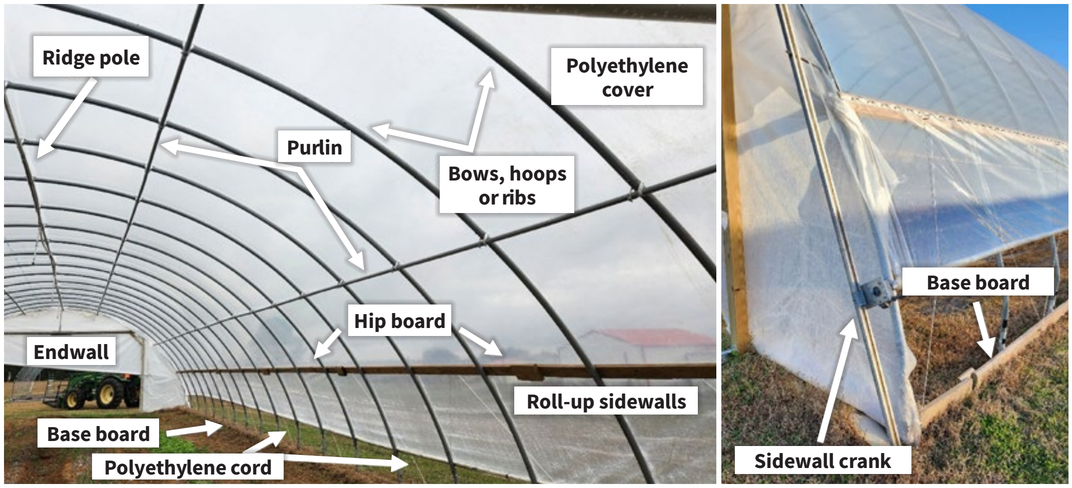

Image 4.1. Main structural components of a high tunnel. Some alternative terminology has been used by different high tunnel manufactures.

While all high tunnels are similar in their basic structural components (Image 4.1) they can differ in size, shape, degree of structural integrity, and ventilation capacity. These structural differences will influence the degree to which climate can be managed within the tunnel. They will also affect the structure's longevity and can even impact disease pressure in the structure. A poorly thought-out tunnel design can cause management headaches and significant crop production issues. Because of this, it is important to become familiar with how different design elements may influence climate management and select a tunnel design that best fits your farm and crop production goals. A high tunnel that is designed thoughtfully can last more than 20 years.

Single Bay High Tunnels

Single bay high tunnels are regularly categorized by the shape of the hoops that form the structure of the roof. There are two main hoop shapes: Quonset and gothic.

Quonset Style: A Quonset-styled tunnel has rounded hoops, giving the tunnel a semi-circular or dome shape (Image 4.2). A simple Quonset tunnel has fewer structural parts, making them less expensive and often easier to construct. However, they are more susceptible to wind and snow load damage. While it will increase the cost of the tunnel, additional structural support can be included in the design to make it more durable (Image 4.2).

The domed roof of a Quonset tunnel can struggle to shed snow, and it is often necessary to manually remove snow from the structure before the weight damages the plastic or hoops. The curved sidewalls on a Quonset tunnel can also be limiting. Larger farm equipment will struggle to fit near the curved sidewalls, making soil preparation and other tasks more difficult.

Curved tunnel walls can also impact crop selection and management. Taller crops, such as tomatoes, must be set further back from the sidewalls in order to have enough canopy height. Any plants growing near the sidewalls will

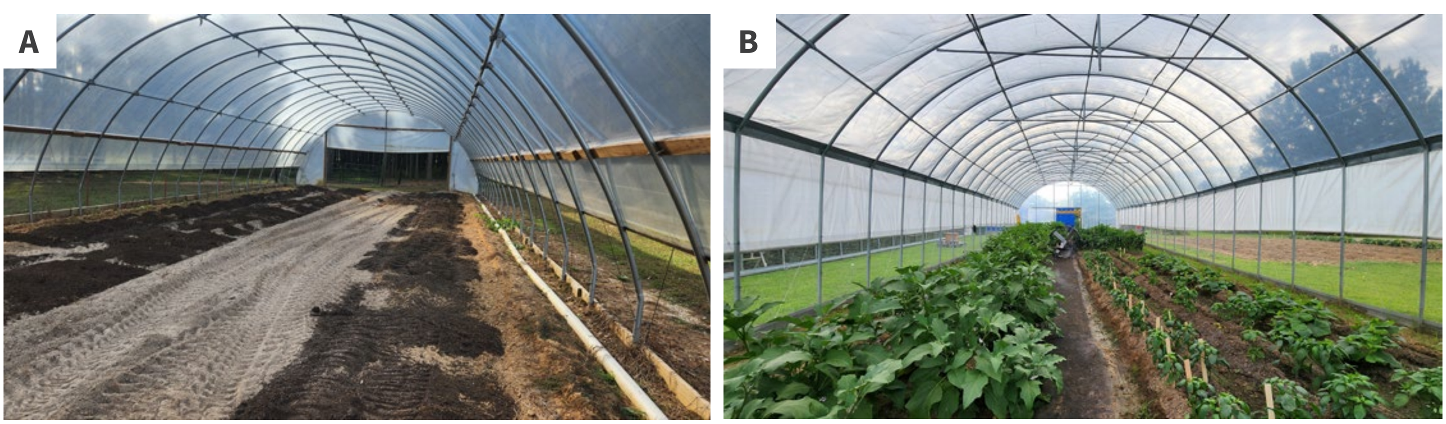

Image 4.2. A simple Quonset tunnel with no added structural support (A) and a Quonset tunnel with trusses for added structural stability (B).

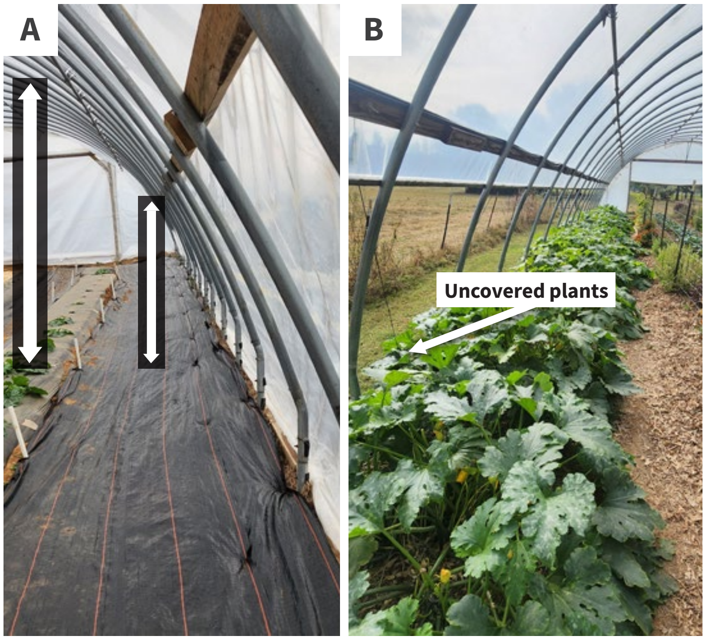

Image 4.3. Crop height is limited near the curved sidewalls of a Quonset styled high tunnel (A) and plants grown near the sidewalls are exposed to rain when the tunnel walls are open to vent (B).

Image 4.4. Two Quonset styled high tunnels with extended ground posts. The sidewalls on the tunnel in Image A were extended 2 ft while the tunnel in Image B was extended 5 ft. This offers more protection for plants grown near the sidewalls in both tunnels as well as increases canopy space for taller crops.

be exposed to rain or hail when the sidewalls are opened for ventilation (Image 4.3). When the sidewalls are closed, workers may struggle to access the sidewall-facing side of a plant for crop management and harvest. This can limit the type or quantity of plants grown in a Quonset tunnel.

It is becoming more common to place Quonset hoops on extended ground posts to create straight sidewalls on these tunnels (Image 4.4). While extending the sidewall height will increase the cost of a tunnel, the added height offers several advantages including more overhead space for taller crops near the sidewalls and more protection for plants when the tunnel walls are open. Equipment and workers will also have more space to maneuver near these walls. Taller sidewalls can also improve air circulation into the tunnel when walls are open for ventilation. Extended sidewall height can vary and should be determined by farm goals, such as the height of the planned crop(s), tunnel ventilation needs and cost.

Gothic Style: Hoops on a gothic-styled tunnel come to a peak and are always placed on straight sidewalls (Image 4.5). These peaked hoops offer many advantages for both structure and crop management. For example, snow will shed more easily, often eliminating the need for manu-

Image 4.5. Gothic styled high tunnels.

al snow removal, and dripping condensation is regularly diverted away from plants. Limiting the amount of condensation dripping onto plants can help curtail the spread of some diseases inside the tunnel.

The straight sidewalls on a gothic tunnel will accommodate taller crops and improve air movement within the tunnel. These tunnels usually have more structural support, even in a gothic tunnel with a simpler design. This often makes them more durable and better suited for areas with high winds or heavy snow. The additional structural components in a gothic-styled tunnel design generally make them more expensive than a Quonset tunnel.

While gothic tunnels tend to handle harsh weather conditions better than a Quonset tunnel, this may not always be the case. If purchasing a prefabricated tunnel, pay attention to the wind and snow load ratings provided by the manufacturer and select a design that can best withstand the weather in your area. The durability of a gothic DIY high tunnel will depend on the materials used for construction and the level of structural support included in the design (see the sections on wind support and construction material below).

Single bay tunnel size

High tunnels vary widely in their dimensions. The width, height, and to some degree, length of a high tunnel will have a notable effect on a tunnel's internal environment.

Width: Air flow into and throughout a tunnel is the main driving force in temperature and humidity management inside a high tunnel. The width of the tunnel will affect how well air flows into and moves throughout the tunnel. Narrower tunnels, regardless of their length, will experience better air movement throughout the entire tunnel. This makes them easier to cool and more capable of avoiding humid hotspots. This can be an advantage in the shoulder seasons (spring and fall) when temperatures may spike when the sun suddenly appears on an overcast day. On the other hand, wider tunnels will retain heat longer on cold winter nights, a key benefit if winter crop production is the main purpose of the tunnel. However, tunnels wider than 30 feet will have a noticeable reduction in lateral airflow across the tunnel and will likely struggle with overheating issues and higher disease pressure.

Height: Tunnel height will not have the same degree of influence over the internal environment as tunnel width. However, a taller, wider tunnel will retain accumulated heat longer throughout cold winter nights than a shorter, narrower tunnel. In general, a smaller more compact tunnel will heat up and cool down more quickly than a larger, bulkier tunnel.

Length: Compared to width and height, the length of the tunnel is less important for climate control in a single bay tunnel. Tunnel length is largely determined by grower preference, with many growers choosing not to exceed 96 ft, keeping maintenance and management simpler. When describing some of the management struggles of his four 150 ft high tunnels, one experienced high tunnel grower in northeast Arkansas said he wished he had selected a shorter tunnel. One of his chief criticisms was the added difficulty of handling and replacing such a large piece of plastic, and the added labor needed to accomplish the task. Multi-bay high tunnels (see below) experience a measurable reduction in airflow when their length exceeds 96 ft.

In addition to climate management, the size of a tunnel will also impact other key management aspects, including the size and number of beds that can be planted, the subsequent yield potential of the tunnel and the size and type of equipment that can be used inside the tunnel.

When sizing a high tunnel, consider the following questions:

- When will the tunnel be in production (winter, summer, all year)?
- How much time or labor can be dedicated to tunnel management (daily monitoring of tunnel temperature and crop production practices)?
- What is the desired bed width and how many beds must fit within the tunnel?
- What kind of maneuverable space is needed around the beds for workers to accomplish crop management tasks and harvest?
- What equipment, such as tractors or trellising hardware, will be used inside the tunnel?
- What size tunnel can fit within the space available?
- Is the tunnel for personal or commercial use?
- What is the high tunnel construction budget?

Prefabricated kits can be purchased in a variety of sizes, and it is often more economical to purchase a manufac-

Image 4.6. Two sled frame tunnels routinely rotated between three plots of ground. This allows the grower to rotate between cover and cash crops and for rain to leach excess nutrients (salts) from the soil.

tured kit as they are designed to fit current industry standard sizes for plastic and shade cloth. Arkansas residents should note that a manufactured kit is required for any tunnel funded by the NRCS EQIP high tunnel grant.

Hoop Spacing

The distance between hoops will impact a tunnel's structural strength. High tunnel hoops are generally spaced either 4, 5 or 6 ft apart. The spacing of hoops in a tunnel design is largely determined by climatic conditions and the size and material used for the hoops. Closer hoop spacing will improve structural integrity and durability during snowfall or high winds. A closer hoop spacing (4 ft) is recommended for areas that experience high winds or heavy snowfall. While larger diameter hoops (steel or PVC) cost more they can usually be spaced further apart, without compromising structural integrity, making fewer hoops necessary. However, hoops spaced further apart will put plastic at a higher risk of damage caused by snow loads.

Moveable tunnels

While high tunnels are considered temporary structures, relocating a tunnel is laborious and growers often choose to leave a tunnel in the same location. Moveable tunnels, as the name suggests, are single-bay tunnels designed to move easily from one plot of ground to another (Image 4.6). Shifting a tunnel to a new location offers growers several advantages, including:

- Simplifying and encouraging the rotation of crops, particularly when there is only one tunnel available.
- Avoiding the buildup of excess nutrients (salts) in the soil, a common issue in high tunnel production (see Chapter 10 – Soil Health and Fertility).
- Eliminating the need to purchase new equipment to fit inside a high tunnel. Soil preparation and bed laying can be done outside the tunnel and then the tunnel moved into place (Image 4.7).

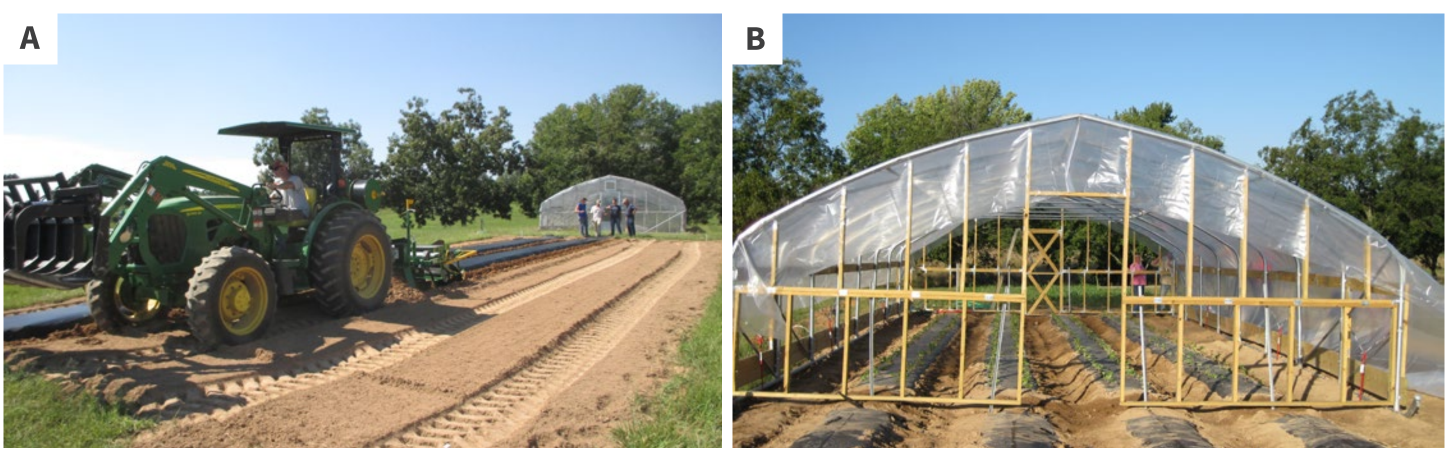

Image 4.7. Ground preparation and bed formation was done outside this sled high tunnel (A). Once completed the high tunnel was pulled over the beds, and strawberries planted (B).

- Allow overlapping plantings of cool- and warm-season crops in the fall and spring. For example, fall cabbage could be planted outside while the tunnel continues to house and protect a planting of tomatoes. Once the tomatoes are finished, the tunnel can be moved over the cabbage for the winter. The tomatoes can then be replaced by a winter cover crop to aid soil health without losing production time inside the high tunnel. A similar method can be used in the spring.

Moveable tunnels can usually be grouped into two main designs: the sled frame system and the rail frame system. In a sled frame design, hoops are attached to a sled instead of ground posts (Image 4.8). This allows the tunnel to be pulled, like a sled, to a new location. In a rail frame design, hoops are attached to wheels that rest on a rail. The tunnel can then be rolled along the rail to a new location (Image 4.9). Because a rail framed tunnel must remain on its rail, they are more limited in their ability to move. Often, they are limited to rotating between two or three plots of ground. On the other hand, a sled frame tunnel is more flexible, and can more easily be moved to any area in a field. To view the process of moving both a rail and sled frame high tunnel, visit youtube.com/watch?v=dMfwgkBP9-U.

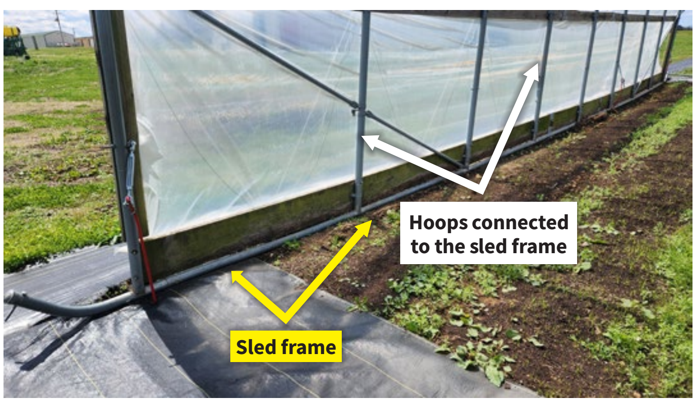

Image 4.8. A high tunnel built on a sled frame. The hoops are connected to a sled so the tunnel can be pulled to a new plot.

Image 4.9. A high tunnel rail system. Hoops attached to wheels resting on a rail.

There are a few drawbacks to moveable tunnels. Most notably, the removal of ground posts from the tunnel design. This makes movable tunnels less stable and more prone to wind damage. An adequate anchoring system is mandatory and can help improve the structure's ability to withstand wind (Image 4.10). Additionally, the process of moving the tunnel can add more wear to structural components, particularly if the tunnel is moved carelessly or incorrectly. It can require more frequent maintenance, possibly reducing the lifespan of the tunnel. And finally, a movable tunnel does not seal as well as a fixed tunnel (Image 4.11). This can result in trapped heat leaking from the tunnel on cold days/nights. It should also be noted that moveable tunnels are generally more expensive, and cost-share programs, such as NRCS-EQIP, may not help cover the cost of a moveable tunnel.

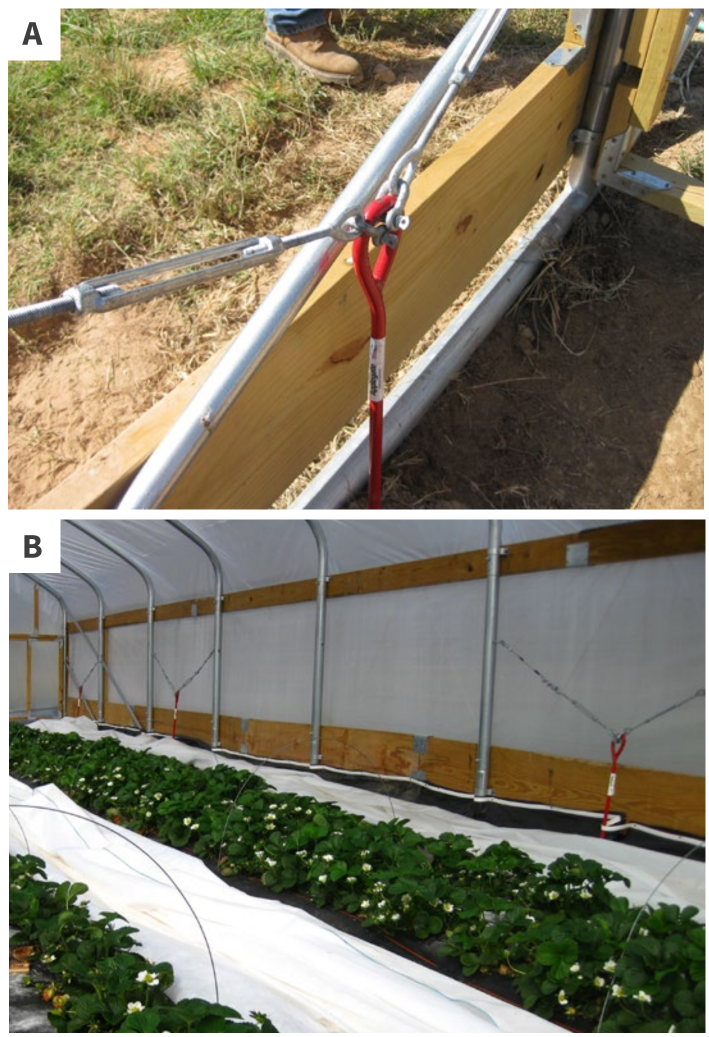

Image 4.10. Additional anchors on a moveable sled system (A and B). Multiple anchors needed along one sidewall (B)

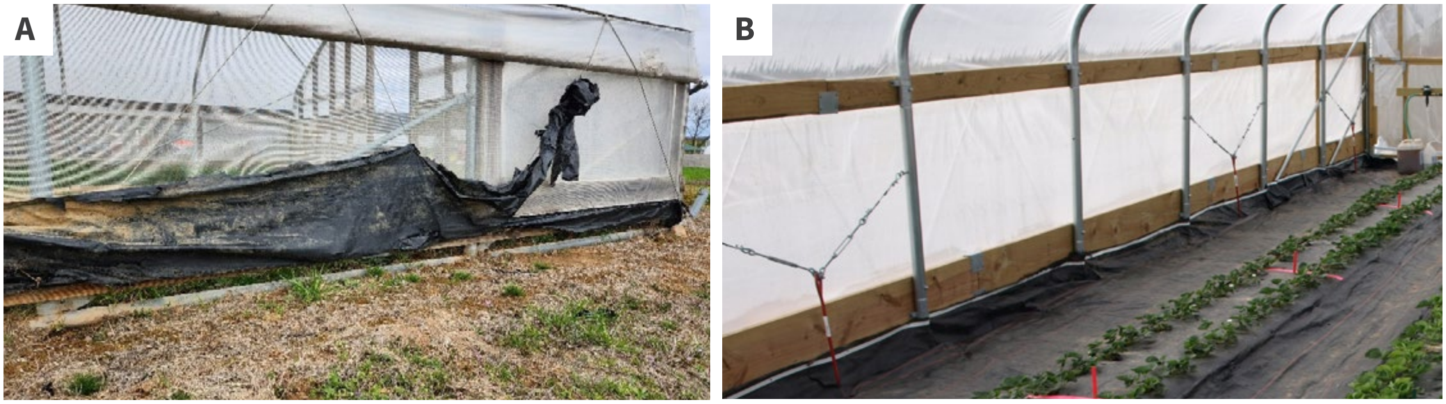

Image 4.11. Two methods growers used to seal the gaps on a sled tunnel. The black plastic visible in Image A was stretched between the baseboard and ground to help seal the tunnel. The woven plastic used to cover the walkways in the tunnel in Image B is attached to the baseboard along the whole length of the sidewall to seal the tunnel and prevent trapped heat from escaping too quickly at night.

Caterpillar tunnels

Caterpillar tunnels have a similar look and function as a high tunnel. However, their structural design is much simpler, making them more affordable than a high tunnel. They usually consist of PVC or metal hoops slipped over rebar (or something similar) that has been driven into the ground. Caterpillar tunnels have no hip or baseboards (plastic is held in place using rope) and only a single ridge purlin. They are also shorter (usually between 6 – 10 ft tall) and narrower (between 10 – 15 ft) than a typical high tunnel (Image 4.12). The simple design of a caterpillar tunnel makes them more affordable and easier to move. This has led growers to use caterpillar tunnels as moveable tunnels to help prevent soil-related issues (Image 4.13). While caterpillar tunnels are often considered three-season structures, and are usually less permanent than a high tunnel, it is not uncommon for growers to use these structures for year-round crop production.

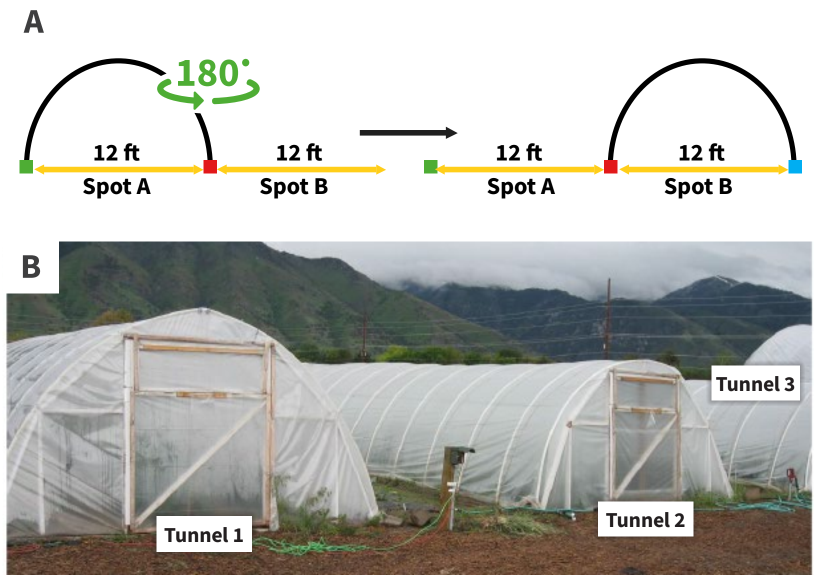

Image 4.13. Caterpillar tunnels can be used as a movable tunnel by lifting one end of each hoop (highlighted in green), rotating it 180° and re-anchoring it (highlighted in blue) (Image A). A new section of ground is now protected by the tunnel. This can help prevent many soil issues that are common in high tunnel production. In Image B a row of caterpillar tunnels spaced so when the PVC hoops from tunnel 1 are rotated 180° they can easily be slid over the rebar used for the near wall of tunnel 2. The now displaced hoops from tunnel 2 are then rotated 180° and slid over the rebar of tunnel 3, etc.

Image 4.12. Two caterpillar tunnels situated side by side.

Multi-bay high tunnels

Multi-bay high tunnels are Quonset-styled tunnels connected by a common "gutter" near where the hip board would normally be (Image 4.14). These structures are a comparably low-cost way to cover large areas of ground. Multi-bay tunnels are popular in areas with milder climates where they are used more for rain exclusion and shade structures rather than for out-of-season production. And it is not uncommon for multi-bay tunnels to be left uncovered and empty during winter months. For this reason, multi-bay tunnels are sometimes referred to as "three-season tunnels." Because multi-bay tunnels often lack purlins and brace or truss supports, they are more likely to be damaged by high winds or snow loads than a single-bay tunnel.

Construction materials

A high tunnel can be constructed using materials that vary in quality, durability and cost. Common materials include galvanized steel greenhouse grade tubing, PVC, wood and corrugated or twine-walled polycarbonate sheeting. The structural stability and longevity of a tunnel will depend on the type of materials used for construction.

PVC is commonly used for hoops and purlins in Caterpillar tunnels or small high tunnels. Larger, more robust tunnels will use some kind of metal, often steel, for their hoops, purlins, trusses, and angular braces. Though more expensive, steel hoops are more capable of withstanding snow loads and high winds and generally have a longer lifespan. Hoops made with galvanized steel greenhouse-grade tubing will last longer and usually require less maintenance.

While using steel for hip and baseboards is generally recommended for longevity, wood is also a common material used for these features as well as endwall framing. Treated lumber is not recommended for high tunnel construction for a few reasons:

- Some chemicals used to treat lumber can cause the polyethylene plastic to degrade more quickly, making it necessary to replace any plastic contacting the wood more often.
- Treated lumber is prohibited in organic certification.
- Certain chemical treatments used on lumber may leach into the soil and be taken up by the plants. While this is not true for all treated lumber, it is advisable to avoid using treated lumber in high tunnel construction as a way to err on the side of caution. For an overview of wood preservation chemicals and their potential safety concerns, visit www.epa.gov/ingredients-used-pesticide-products/overview-wood-preservative-chemicals.

Selecting the right material will require a cost-benefit analysis and finding a balance that will support the goals of the farm and high tunnel design without breaking the budget.

Plastic

The roof and sidewalls (and often endwalls) of a high tunnel are covered with clear greenhouse-grade polyethylene plastic with ultraviolet light (UV) protection. While 6-mil

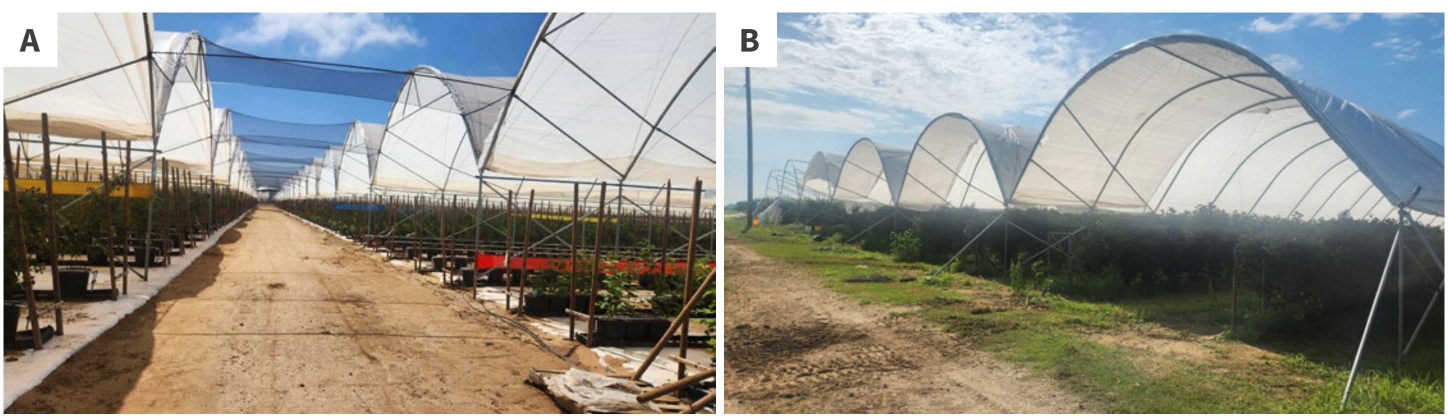

Image 4.14. These multi-bay high tunnels in Mexico are being used to protect caneberries and blueberries from excess sun and rain rather than for season extension (A). A shade cloth can be seen covering the plastic (A). A high tunnel grower in Arkansas recovering a six-bay high tunnel for blackberry production (B). Like the multi-bay tunnels is Mexico, these tunnels will also be used for rain and sun protection. The lack of purlins and truss or brace supports in the tunnel construction is evident in both images.

plastic is most common, greenhouse-grade plastics are available in several thicknesses (4 -10 mil). Thicker plastic will be more durable during harsh weather conditions, such as hail, but will also be more expensive and could lower the amount of light transmitted to the plants inside the tunnel. A new 6 or 8-mil plastic will transmit about 88-92 percent of the available light and should last four to five years (barring any physical damage). Constant exposure to sunlight and UV radiation will degrade the plastic over time, reducing the amount of light transmitted after a few years. Due to this degradation, it is recommended that plastic be replaced every four to five years, even when there is no visible damage.

Infrared radiation (IR or “thermic”) plastics and anti-condensate plastics cost more but can limit heat loss at night, reduce the spread of diseases and improve daytime light quality. Do not use the construction-grade plastics easily found at local convenience or hardware stores. These plastics lack the UV polymer resin that allows greenhouse plastics to hold up under constant sunlight and UV exposure.

Image 4.15. Multi-bay high tunnel structures in the process of being covered by a white greenhouse plastic (A). The plastic was used to protect ripening blackberry fruit from rain and heat related quality issues. Once harvest was concluded the plastic was removed and stored (B).

Image 4.16. Hail damage on 6 mil greenhouse grade plastic. A tunnel covered with a woven plastic received no visible damage from the same hailstorm. Images provided by Kyle Manning from Fat Rabbit Farms.

White greenhouse plastic is also available. In addition to protecting plants from rain or hail, white plastic can also lower temperatures inside a tunnel by blocking light. While this would cause growth and production issues for out-of-season production, it could be a good option for tunnel structures used solely for rain exclusion during the hot summer months. This opaque plastic may even cool temperatures better than a shade cloth by lowering light transmission by 45 percent. When used for this purpose, the white plastic is typically pulled over the tunnel sometime during the late spring or early summer (depending on the crop and farm goals), protecting plants from potentially damaging summer conditions such as heat, rain and hail. The plastic is then removed after harvest (Image 4.15).

Recently, string-reinforced or woven plastics have become available. Usually ranging from 10–11 mil in thickness, these plastics have a longer life expectancy and can better withstand damaging events such as hail (Image 4.16). However, these woven plastics further reduce light transmittance (about 80-85 percent of light transmitted through a new sheet) and are very expensive. Not much research has been done on their impacts on crop production. Because of the increased durability of these plastics, it is becoming more common to see woven plastic used on endwalls (Image 4.17).

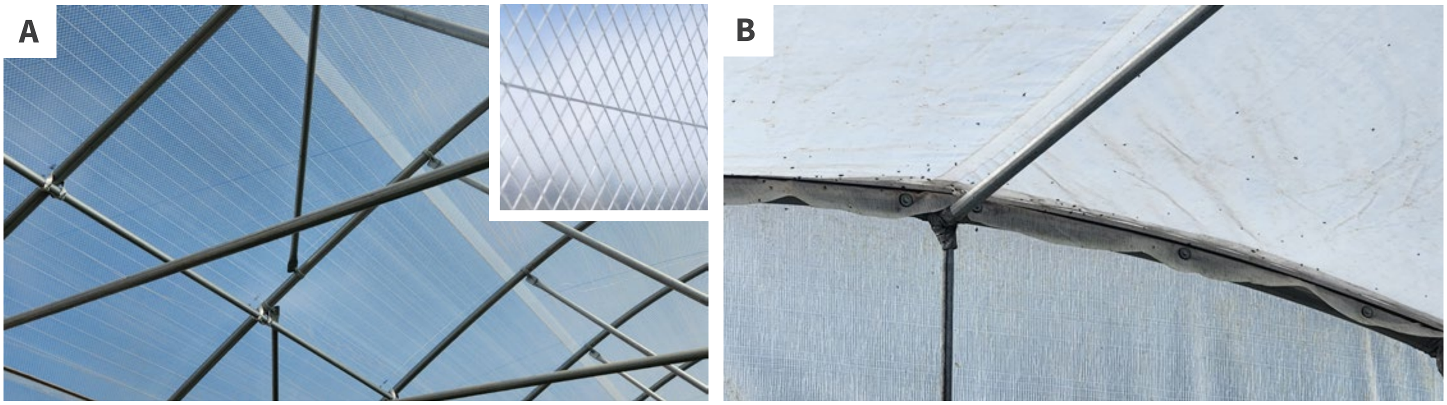

Image 4.17. A high tunnel covered with a string reinforced plastic (A). A Quonset tunnel with 6-mil greenhouse grade plastic on its roof and a woven plastic on its endwalls (B).

Sidewalls

Sidewalls can vary in height and ventilation method. The height of a sidewall will have a substantial impact on humidity and temperature management within the high tunnel. Higher sidewalls will improve airflow into and within the tunnel and make it easier to avoid excess heat and humidity. Better air movement within a tunnel can also help prevent disease and pest "hotspots." (See Chapter 8 –Pest and Disease Management Strategies). Higher sidewalls will also accommodate taller crops more comfortably. Indeterminate tomatoes, for example, trellised using the lean and lower training method will need more sidewall height to accommodate their canopies compared to a determinate tomato on a Florida weave trellis.

Sidewall height can vary anywhere from 1 – 8 ft (or higher) (Image 4.18). Determining the best height for a sidewall will depend on other design aspects of the tunnel (such as tunnel width and endwall design) and site conditions (degree of wind flow), and crop selection. The endwall design of the tunnel in Image 4.18A allowed little air movement into the tunnel and the 4 ft sidewalls were unable to supply enough ventilation across the tunnel when a taller crop, such as tomatoes, was planted. The height of the taller crop, which reached above the height of the hip board, impeded air flowing into the tunnel through the sidewalls. This caused damaging high temperatures and humid hotspots inside the tunnel in the late spring and early summer. This tunnel would have benefited from higher sidewalls, or a more open endwall design.

Sidewalls open in one of two ways; they can be rolled up (Image 4.19) or dropped down (Image 4.20).

Image 4.18. Sidewalls with different heights. Sidewall height will have an impact on air flow inside the tunnel which will impact climate and disease management within the tunnel.

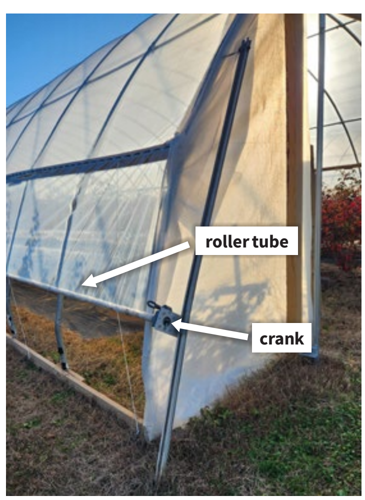

Image 4.19. Roll-up sidewalls on a Quonset high tunnel.

Image 4.20. Drop-down sidewalls on a gothic styled high tunnel.

Roll-up sidewalls: Currently this is the most common type of sidewall. This is likely because they tend to be less expensive and easier to install. In this system, one end of a length of greenhouse-grade plastic is secured to the hip board at the eave of the tunnel. The other end of the plastic is attached to a metal tube, often called a roller tube, that runs the length of the high tunnel (Image 4.19). A hand crank attached to one end of the roller tube is then used to raise the plastic. This allows the plastic to be raised to the height of the hip board (Image 4.19). Most hand cranks come with a locking mechanism allowing the wall to be opened to different degrees, giving more control over climate management.

Drop-down sidewalls: Despite being more difficult to install, this method is becoming more common. In this system, a length of greenhouse grade plastic is attached to the bottom of a tube running the length of the tunnel. Through a series of cables attached to the top of this tube, the plastic is lowered from the eave of the tunnel to the ground by a hand winch (Image 4.20). One advantage to this system is when sidewalls are opened, the cooler outside air enters the tunnel above the plant canopy, preventing cold air from blowing directly on the plants. This can make climate control easier in the early spring and late fall, when large temperature swings are common. One Arkansas grower with experience managing tunnels with both roll-up and drop-down sidewalls commented that while drop-down sidewalls are harder for maintenance, they are better for crop management. Another grower mentioned that the maintenance costs and issues they experienced with drop-down sidewalls outweighed the benefits to crop management.

Both methods for opening sidewalls can be automated. This, of course, will increase the initial cost of the tunnel, but could reduce labor later. It should be noted that caterpillar tunnels do not have sidewalls. Instead, the plastic roof extends all the way to the ground and when the tunnel needs to be ventilated the plastic is pushed up and held in place using various methods (Image 4.21).

Endwall Design

Endwalls can vary considerably in design and construction material. Greenhouse plastic is probably the most common material used to cover an endwall. This is likely because growers can save money by purchasing a single roll of plastic to cover both the top of the tunnel and both endwalls. Woven plastics, corrugated or twine-walled polycarbonate sheeting are also commonly used for sidewalls. While these materials cost more upfront, they are more durable and last longer (Image 4.17). Avoid using construction-grade plastic.

Image 4.21. Caterpillar tunnel with plastic sidewalls pushed up to ventilate.

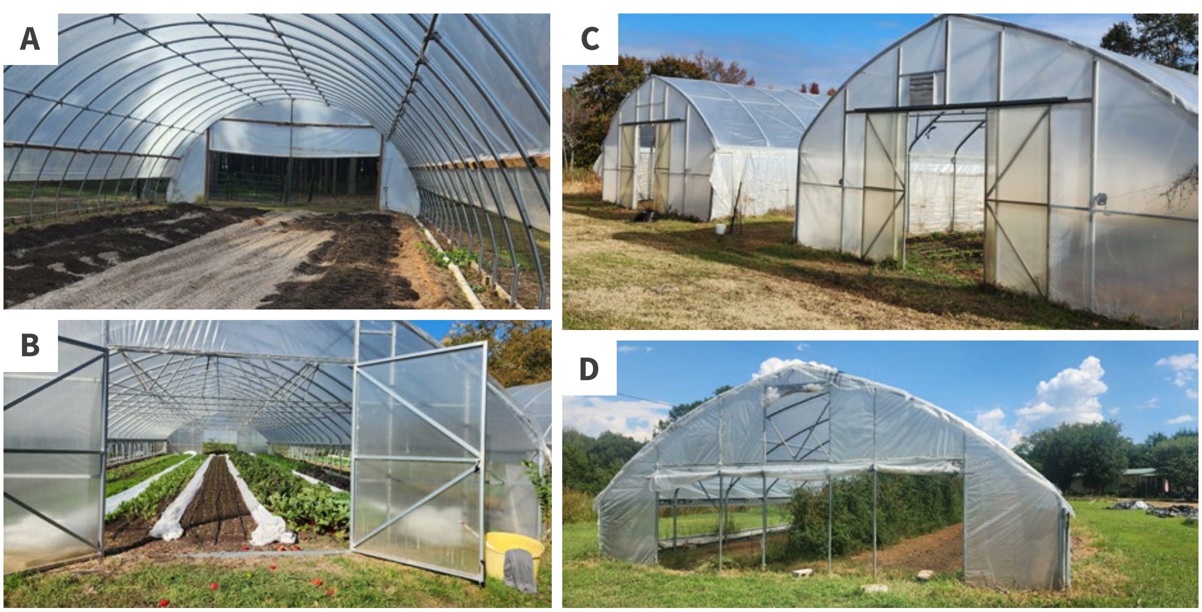

Image 4.22. Various endwall designs for high tunnels. Roll-up/down walls made with a woven plastic (A), hinged doors made with polycarbonate sheeting that swing open (B), sliding doors also made from polycarbonate sheeting (C) and a roll-up door with added structural support (D).

The type of material used will influence the final endwall design. Plastic endwalls are often designed to simply roll up and down or have wide doors that swing open. Woven plastic endwalls can also roll up and down or they can include things like Zipper doors or flaps. Heavier sheeting material can be used to build sliding or hinged doors (Image 4.22).

Larger tunnels usually have endwalls with some level of wood or metal framing to help with structural stability and durability against wind. While smaller tunnels can also have framed endwalls, it is not uncommon to find them simply covered with a plastic curtain that can be raised/lowered or parted.

Consider the following when designing or selecting an endwall design:

- Tunnel size. Wider tunnels, for example, may need more open endwalls to improve airflow inside the tunnel.
- Ventilation capacity. A more open endwall design will improve air movement within a tunnel.
- The size of equipment that needs to fit inside the tunnel. A more open endwall design will accommodate larger farm equipment.
- The budget (material cost and what level of framing can be afforded).
- Weather conditions at the high tunnel site. Sites that receive a lot of high wind may need a more robust endwall.
- Grower preference.

Endwall designs that have worked well for Arkansas high tunnel growers typically have large doors for improved air flow and can accommodate tractor entry (Image 4.23). Although the material costs are higher, many Arkansas growers opt for more durable endwall materials, like string-reinforced plastics or polycarbonate sheets, as they perform better in windstorms, require less maintenance, and have longer lifespans. Remember that some prefabricated high tunnel kits do not come with materials for endwalls, and any design will be an additional cost.

Both endwalls on a tunnel need to be able to open for airflow and climate management. Tunnel designs that leave one endwall closed and unable to open experience poor airflow and struggle with high temperatures. Most growers will use their selected endwall design on both ends of the tunnel.

Wind support

Wind can do a lot of damage to a high tunnel, especially if a tunnel is inadequately braced (Image 4.24). Every high tunnel design should include angular wind braces (Image 4.25). At a minimum, angular braces should be positioned between the end hoops and the baseboard at each corner of the tunnel. More angular braces between other hoops will improve the structural strength of a tunnel. Additional support can be included by running braces from the endwalls to the roof purlins.

Image 4.23. An example of a popular endwall design in Arkansas. The wide door allows access for farm equipment, including small tractors, and promotes air flow into the tunnel.

Image 4.24. Minor wind damage to a single hoop on a Quonset high tunnel.

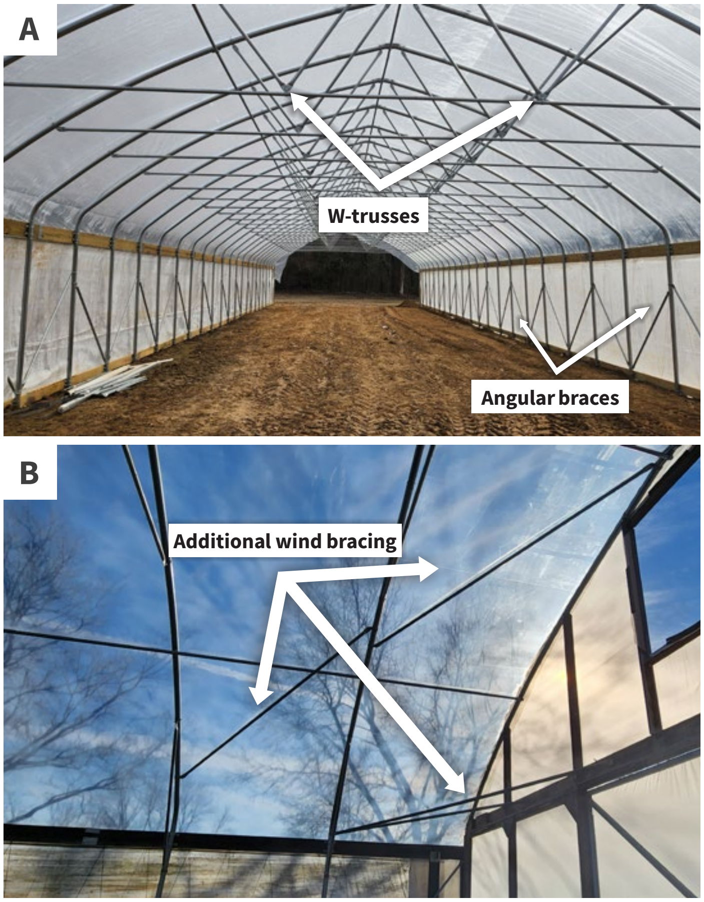

Image 4.25. A gothic styled high tunnel with W-trusses and angular braces along the full length of the sidewalls (A). A tunnel with additional peak and endwall bracing (B).

Trusses will also improve the structure's sturdiness. The most basic (and cheapest) tunnel designs often include no truss support, but more robust designs will contain some level of truss bracing (Image 4.25). In addition to helping resist wind damage, hoops with trusses will hold up better under snow loads and could help support a roller hook or line trellising system for crops such as indeterminate tomatoes or cucumbers.

Ventilation

Image 4.26. A fan installed inside a high tunnel to help improve air flow throughout the structure.

Adequate ventilation inside a high tunnel is important no matter what climate or state the tunnel is located in. In Arkansas' humid climate, where pest pressure is high and summers are long and hot, good ventilation is a requisite for healthy, high-yielding plants. Adequate ventilation improves temperature and humidity management, which in turn helps lower the incidence of certain diseases inside a tunnel. As mentioned earlier, a tunnel's width, height, endwall design, and sidewall height will all influence wind and airflow into and throughout a tunnel. However, even in a well-designed tunnel, many growers in Arkansas have seen an advantage in including supplemental vents or fans to help move air more efficiently throughout a tunnel (Image 4.26).

Possible venting alternatives include:

Gable vents: Located near the peak on the endwall(s), these vents work well for winter or shoulder season production, especially on tunnels with roll-up sidewalls (Image 4.27). Gable vents can lower temperatures or humidity within a tunnel without directly exposing plants to cold winter air.

Roof vents: Also called ridge vents, they allow trapped heat to escape through openings in the roof, usually near the peak (Image 4.28). Roof vents are particularly helpful for summer production of taller crops such as tomatoes or peppers.

Image 4.27. Gable vents of different styles located near the peak on two gothic styled high tunnels.

Image 4.28. A roof vent running the length of this tunnel.

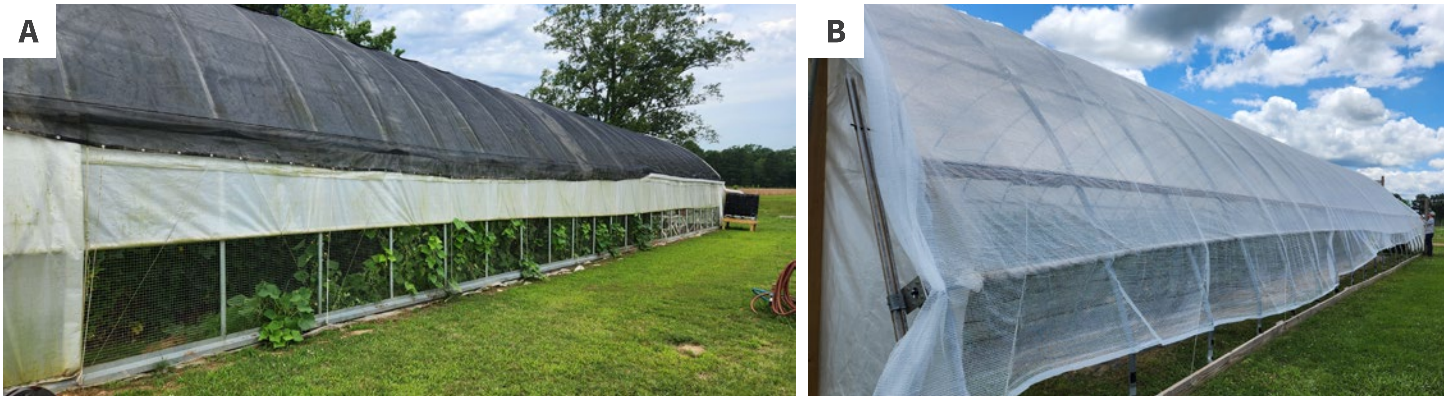

Image 4.29. A Quonset styled high tunnel covered with a 40 percent black shade cloth (A). This shade cloth was used for high tunnel cucumber, eggplant, tomato, and pepper production. A Quonset styled high tunnel in the process of being covered with a 30 percent white shade cloth (B).

Exhaust fans: Exhaust fans can speed up air exchange inside a tunnel when they are paired with a vent(s) on the opposite wall.

Sidewalls (roll-up or drop-down), gable vents and roof vents can all be automated or controlled thermostatically to ease labor demands. Without automation, proper temperature and humidity management in a high tunnel will require someone to be onsite, or close by, every day. This includes weekends and holidays. During the shoulder seasons, temperatures can fluctuate throughout the day, most notably on cloudy days when the sun can unexpectedly appear and cause temperatures to spike. This requires someone to open or close tunnel vents, which can be disruptive to other farm tasks.

Shade Cloth

High tunnels are a valuable season extension tool because they do such a great job of increasing their internal temperature and protecting plants from the cold. Many growers leave the tunnel's plastic cover on during the summer for rain exclusion. During these months, the heat retained in the tunnel will become a limitation to production. Even a well-designed and fully ventilated high tunnel will be a few degrees warmer than the outside air temperature. Any tunnel that will be used during the summer in Arkansas will need a shade cloth to help prevent heat-related disorders and yield losses.

Shade cloth is made from UV-stabilized polyethylene strands kitted together and is rated by the percentage of shade it offers (ranging from 20-90 percent shade). Depending on the shade provided, a shade cloth can lower the temperature inside a tunnel by 5°F or more. While black is the most common color for shade cloth, several other colors are available (Image 4.29). These alternate colors may reduce temperature further but could also affect crop physiology and quality. Despite their higher cost, white shade cloths are gaining popularity in the warmer climates due to their ability to decrease temperatures inside the tunnel more than a black cloth.

The degree of shade needed will depend on the crop, shade cloth color, farm location, and other tunnel design elements that influence ventilation capacity. While some Arkansas growers go as high as 50 percent, a 30 – 40 percent black shade cloth works well for many warm-weather crops in Arkansas (Image 4.29).

Supplemental Heating

While winters tend to be mild in many southern states, supplemental heating may still be necessary on cold nights. At the very least, high tunnel growers in Arkansas should have a secondary cover on hand for cold nights to provide extra frost protection (see Chapter 5 – Climate Management Strategies). In addition to secondary covers, several types of supplemental heating systems have been used successfully inside a high tunnel.

Temporary systems, such as portable propane heaters, can be used to warm the air inside the high tunnel when needed and removed once the danger has passed. More permanent systems, such as unit heaters or wood-burning stoves, are also available and have been used successfully inside high tunnels (Image 4.30).

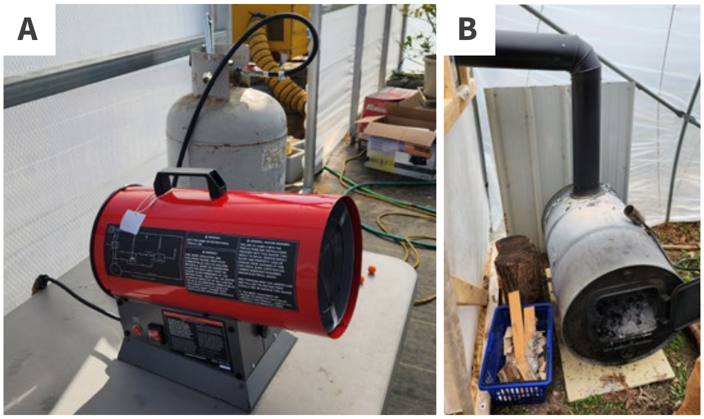

Image 4.30. A propane heater (A) and a wood burning stove (B) installed inside a high tunnel to protect crops from damaging freezing temperatures.

Whether using a temporary or permanent heating system, exhaust fumes must be vented out of the tunnel. Common combustion byproducts from heating systems include carbon dioxide, sulfur dioxide and ethylene gas. Even at low levels sulfur dioxide can cause leaf burn and chlorosis, while ethylene gas can cause malformation of leaves and flowers, stunted growth, bud abscission and flower senescence. Water vapor is also a byproduct of many heating systems that, if not vented out of the tunnel, can increase humidity, which in turn could increase the incidence of diseases.

Image 4.31. Installing soil heating cables in a spinach bed inside a high tunnel.

While less common, soil heating systems are also available. Two examples include the installation of in-ground tubing that can circulate hot water or burying soil heating cables a few inches into the soil near a plant's root zone (Image 4.31). To use either of these heating methods, advanced planning will be needed as neither system can be installed after plants are in the ground. Whatever heating system is used, either electricity or fuel will be necessary. This will be an added cost and should be considered during the planning stages.

Who should install the high tunnel

Once a high tunnel kit has been selected, the next big question is who will construct the tunnel. It may be tempting to erect a tunnel yourself, mostly to avoid installation costs. Before deciding who should construct the high tunnel consider the following questions:

- Do you have all the necessary tools? Installation may require access to tools an average homeowner may not have, especially if installing a larger, more complex tunnel design.
- Do you have the skills needed for construction? Understanding how something is done and having the skill to do it are two different things. Possessing some degree of mechanical knowledge and proficiency will generally produce a better final product. Physical ability is also very important. Even with the assistance of a tractor, lifting and setting hoops is a physically demanding task.
- Do you have the time and additional help needed for the duration of construction? The USDA-NRCS estimates a 30 ft by 72 ft high tunnel will take about 80 man-hours of labor to construct. And several tasks, such as setting hoops and pulling plastic, will require multiple people.
- Can the installation be completed in time to plant the crop without sacrificing other necessary tasks/projects?
- Did you receive any grants or financial assistance? Any financial assistance or grant program will have qualifications and requirements that must be met before payment. Some financial assistance programs may require professional installation to prevent voiding any warranties. The NRCS EQIP high tunnel grant requires construction to be completed before reimbursement of the tunnel's cost. A professional installation could accelerate the compilation of the high tunnel and, therefore, the reimbursement.

Remember that instruction manuals can be challenging to decipher. A common complaint among first time high tunnel builders is that manuals often appear to "skip steps" or assume the reader has a high degree of construction knowledge or experience. Some manufactured designs are more complicated and less beginner-friendly than others. A list of high tunnel suppliers can be found at www.uaex.uada.edu/farm-ranch/crops-commercial-horticulture/horticulture/high-tunnel-production.aspx

Some common tools used in tunnel construction:

- ☐ Tractor with a loader
- ☐ Post pounder, post leveler, and post puller
- ☐ Cordless drills or drivers
- ☐ Various drill bits
- ☐ Reciprocating saw
- ☐ Circular saw
- ☐ Clamps
- ☐ Measuring tapes
- ☐ Ropes and tennis balls (pulling plastic)
- ☐ Adjustable wrenches
- ☐ Pliers
- ☐ Shovels
- ☐ Tall adjustable ladders
- ☐ Wire cutters
- ☐ Mattocks
- ☐ Wooden stakes (or marking flags)
- ☐ Manpower

Conclusion

The high tunnel features described in this chapter will impact the structure's stability, longevity, degree of climate control, crop productivity and pest management. When selecting a tunnel design, keep these things in mind and select a design that best fits farm and crop production goals. Remember, a high tunnel that is designed thoughtfully could last more than 20 years.

Additional Resources

Adams, S. A. and K. A. Todd. 2015. High Tunnel Design, Site Development, and Construction. EC308. Institute of Agriculture and Natural Resources, University of Nebraska Extension. Available: extensionpubs.unl.edu/publication/ec308/pdf/view/ec308-2015.pdf

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Jacobsen, K., Wolff, B. and T. Coolong. 2019. Moveable High Tunnels: Opportunities and Challenges for Producers. University of Kentucky College of Agriculture, Food and Environment. CCD-SP-15. Available: https://ccd.uky.edu/resources/systems/hightunnel

Kaiser, C. and M. Ernst. 2021. High Tunnel Overview. CCD-SP-2. Lexington, KY: Center for Crop Diversification, University of Kentucky College of Agriculture, Food and Environment. Available: https://ccd.uky.edu/resources/systems/hightunnel

Maughan, T., Drost, D. and B. Black. 2014. Supplemental Heating in a High Tunnel. Utah State University Extension. Available: digitalcommons.usu.edu/cgi/viewcontent.cgi?article=1678&context=extension_curall

United State Department of Agriculture. 2014. Controlling the High Tunnel Environment. Produced by the Natural Resources Conservation Service. www.nrcs.usda.gov/sites/default/files/2022-10/Controlling-High-Tunnel-Environment.pdf

Begin designing your high tunnel:

1. What type of tunnel: Single bay? Movable tunnel? Gothic?

2. Tunnel size:

3. Sidewalls: Drop down? Height?

4. Endwalls: Door size? Material?

5. Truss and wind support:

6. Additional ventilation: Gable vents? Fans?

7. Type of material: Metal hipboard? Woven plastic?

Notes



CHAPTER 5
Climate Management Strategies

Introduction

In Arkansas, high tunnels have successfully extended the production season for many fruit and vegetable crops. A high tunnel allows growers to modify environmental conditions to favor plant growth. By manipulating the internal climate of these structures, growers are able to plant earlier in the spring, extend harvest later in the fall, and grow and harvest throughout the winter months.

While similar in structure to a greenhouse, climate management in a high tunnel is not automated. For example, both air and soil temperature increase inside a high tunnel when solar radiation is trapped beneath the tunnel's plastic cover (Image 5.1). When the sun is out, this passive heating is very effective. On a cold sunny day, the air temperature inside a closed high tunnel can be more than 30°F warmer than the outside ambient air temperature (Image 5.2). This temperature difference can be even greater on a warm sunny day, or slightly mollified on a cloudy or partly cloudy day. A tunnel is cooled by manually opening doors, endwalls, sidewalls or vents to allow cooler outside air to blow into the tunnel (Image 5.3).

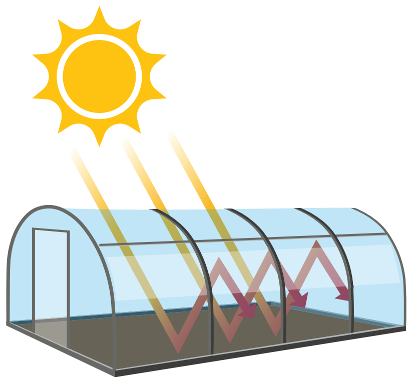

Image 5.1. Solar radiation is trapped under the high tunnel's plastic cover. This warms the air and soil inside the high tunnel.

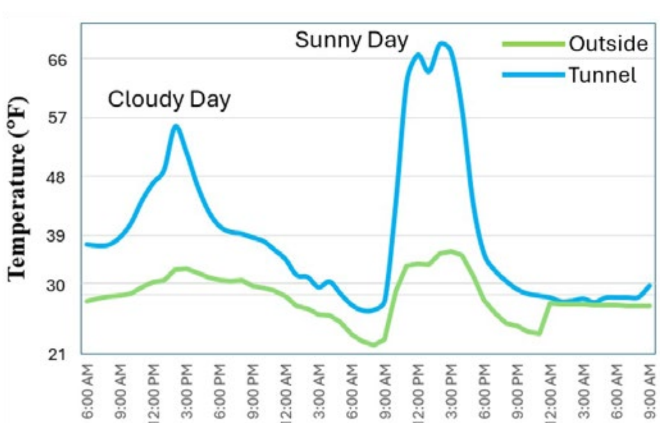

Image 5.2. The change in temperature both inside (blue line) and outside (green line) a high tunnel over a two-day period. While the tunnel was warmer on the cloudy day the temperature increase was not as extreme as it was on the following sunny day with a similar outside temperature.

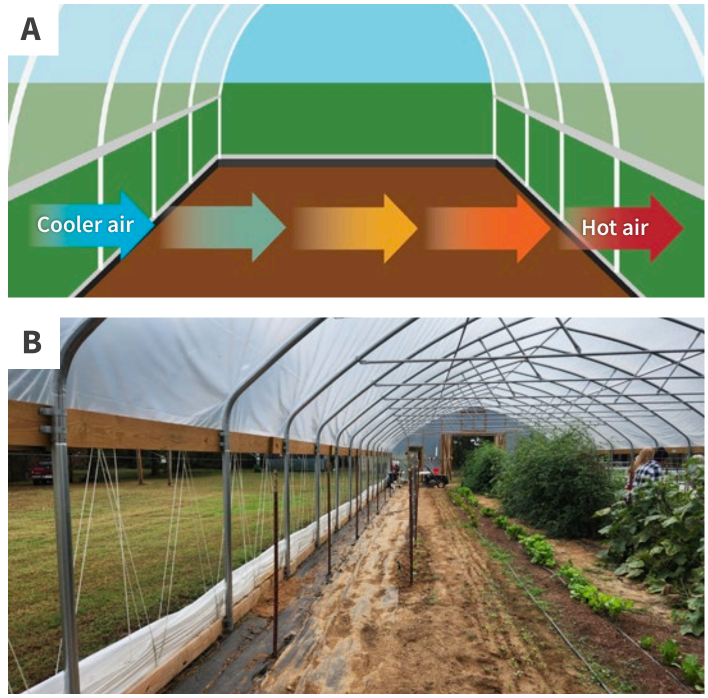

Image 5.3. Opening the sidewalls and endwalls of a high tunnel allows cooler outside air to enter and push out the trapped hot, humid air (A). A tunnel with sidewalls opened to help cool the internal environment (B).

The many benefits associated with high tunnel crop production, including higher marketable yields and season extension, are only possible with good management of the tunnel's climate. If the tunnel climate is managed poorly, plants grown inside a high tunnel can experience damaging extreme temperatures (both high and low) and prolonged periods of high humidity. When developing environment control strategies for a high tunnel it can help to understand how temperature, humidity and light influence plant growth. Understanding how a plant responds to changes in these three environmental conditions can help with the development of appropriate climate management strategies.

Plant growth and temperature

The rate at which a plant grows is greatly influenced by temperature. Every crop has a preferred temperature range for peak plant growth. When grown at this "optimal" temperature the plant will experience its most rapid growth rate (if all other growing conditions are favorable). When temperatures begin to drop below this optimum, plant growth slows. If temperatures continue to drop, reaching the crop's minimum or "baseline" temperature, growth will cease. Typically crop injury is not observed at this baseline temperature. However, if the temperature continues to

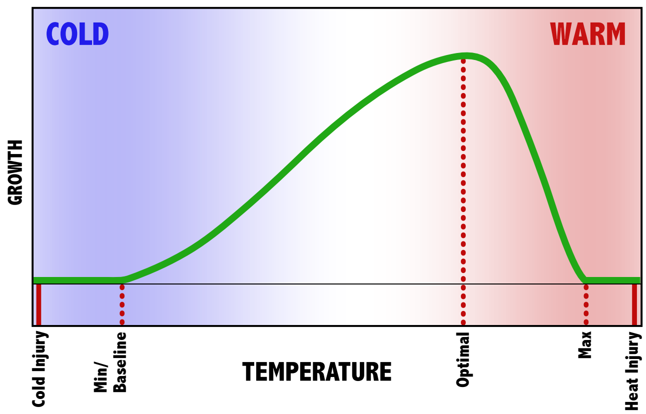

Image 5.4. The effect of temperature on plant growth rate. Image modified from Black and Drost 2010.

drop plant injury or death will occur. A similar growth response happens as temperatures rise above the optimal range. Growth rates will slow until a critical maximum temperature is reached, at which point growth stops. When exposed to temperatures above this critical maximum temperature plants will experience injury or death (Image 5.4).

The optimal and critical temperatures that form this growth response curve will differ for each crop. Cool season crops such as lettuce, broccoli and kale have baseline temperatures much lower than warm season crops like tomatoes and peppers. This allows these cool season crops to survive and even thrive at much cooler temperatures, temperatures that would stunt or damage a tomato plant.

Table 5.1. Critical air temperatures for some common high tunnel vegetable crops and strawberry.

Crop	Min or Baseline*	Optimal Range	Max*
Spinach, collards, broccoli, radish, kale, beet	40°F	60-65°F	75°F
Lettuce, pea, cauliflower, carrot	45°F	60-65°F	75°F
Tomato, squash	50°F	65-75°F	90°F
Cucumber	60°F	65-75°F	90°F
Sweet pepper	65°F	70-75°F	80°F
Hot pepper, eggplant, okra	65°F	70-85°F	95°F
Strawberry	40°F	65-75°F	85°F

*Hardening, or acclimating, a plant to cooler conditions can shift that plant's baseline temperature lower (see section on Hardening Plants).
*A plant's growth stage may also influence baseline and maximum temperatures. Broccoli, for example, has a "window of sensitivity" of about 10 days during which they are more vulnerable to heat injury.

On the other hand, a tomato plant can grow and thrive in warmer temperatures that would cause a lettuce plant to bolt prematurely. Table 5.1 lists optimal and critical temperatures for several common high tunnel vegetable crops.

The visual symptoms of plant injury caused by extreme temperatures can vary depending on the crop and the plant's growth stage when exposed to extreme temperatures. Strawberry flowers exposed to temperatures below their baseline temperature will turn black in the center and fail to develop fruit, while exposed fruit can be deformed and/or have an altered taste (Image 5.5). Tomato flowers

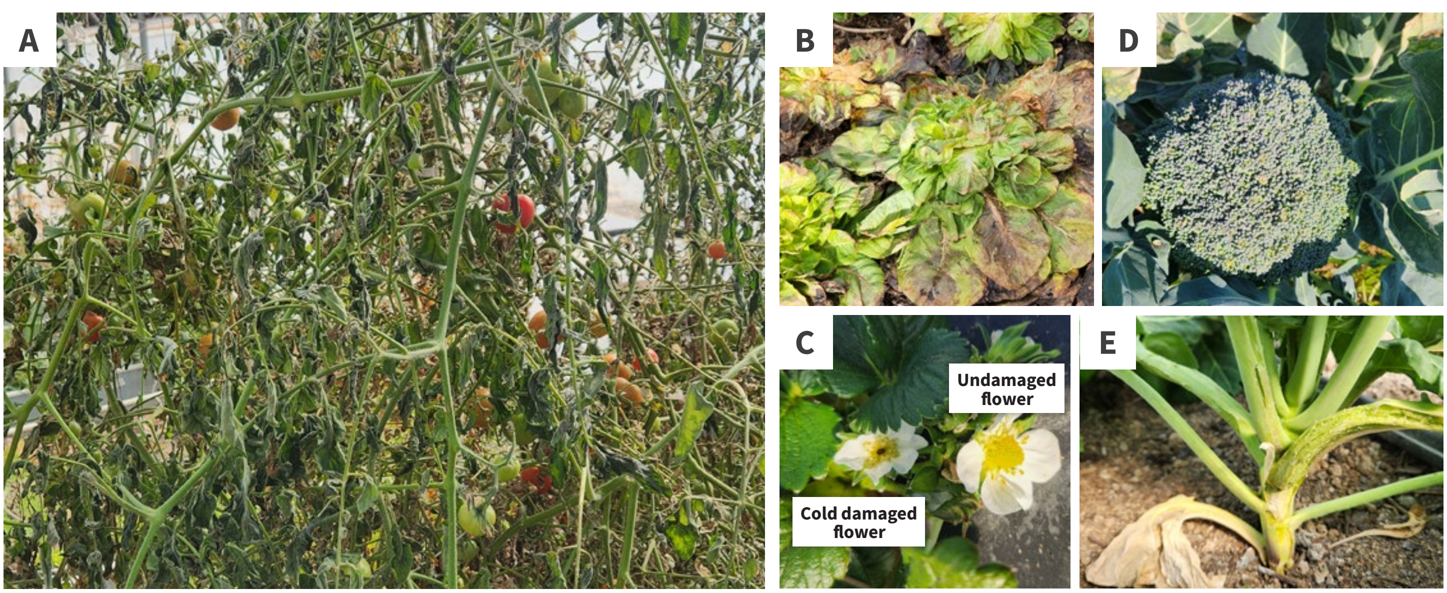

Image 5.5. Cold injury on some common high tunnel crops. Leaf wilting on tomato plants (A). Soggy, brown and wilting leaves on lettuce plants (B). Blackened center on strawberry flowers (C). Buttoning on broccoli (D). Cracked and split petioles on collard leaves (E).

will abort and drop when grown at temperatures above their maximum. Sunscald, cracking, yellow shoulder, or increased incidence of blossom end rot are common symptoms of heat stress on tomato fruit (Image 5.6). Table 5.2 outlines common symptoms of heat and cold stress for different vegetable crops.

Vernalization

Vernalization is a natural process in which plants are triggered to transition from vegetative growth (leaves) to reproductive growth (flowers) after being exposed to a period of cold temperatures. Under normal field conditions, vernalization allows plants to distinguish between the winter and summer seasons, preventing plants from flowering when conditions are not optimal. In high tunnel fall, winter and spring production, however, prolonged exposure to cold, or rapid and large shifts in temperature, can trigger vernalization in many cool-season crops, causing them to flower (bolt) prematurely. This can cause fall or early spring planted leafy green crops like lettuce to bolt early, rendering them unmarketable before harvest is complete (Image 5.7). Common high tunnel crops susceptible to bolting include kale, cabbages, mustards, bok choy, radishes, carrots, beets and turnips.

Image 5.7. An early spring planted spinach plant bolting before reaching harvestable size.

Table 5.2. Visible symptoms of heat or cold stress on common high tunnel vegetable crops. Symptoms may vary depending on the crop's growth stage when exposed to extreme temperatures.

Crop	Symptoms of heat stress or injury	Symptoms of cold stress or injury
Broccoli & cauliflower	Bracting, brown head, "cat eye", uneven bead sizes, poorly shaped heads, or loose heads	Water soaked or discolored tissue, head yellowing, blindness
Beans	Poor pollination, flower buds abort, short misshapen pods with fewer seeds	Pitting and russeting, stunted root system
Lettuce	Bolting, tip burn, abnormal head development, bitterness	Russeting, water-soaked tissue and discolored leaves
Peas	Poor pollination, cease producing flowers and pods	
Cabbage	Loose and/or small heads, tipburn	Blindness (when exposed to cold shortly after transplanting)
Spinach	Lower yields, bolting	Very cold tolerant – bleaching of leaf tips
Tomato	Sunscald, aborted flowers, cracking, blossom end rot, yellow shoulders	Water-soaked tissue, cat facing, decay, poor color when fruit ripens
Cucumber	Poor pollination, misshapen fruit, flower/fruit drop, sunscald	Browning, vein bleaching or upward curling of leaves, stem or fruit splitting or discoloring
Capsicum (peppers)	Poor pollination and fruit set, sunscald, blossom drop	Misshapen fruit, leaf curl, blossom drop
Eggplant	Sunscald, poor pollination, flower drop and reduced fruit quality	Fruit splitting, uneven ripening, off-flavor, discolored flesh or skin, or water-soaked fruit

Image 5.6. Symptoms of heat stress on tomato and pepper plants and fruit. Tomato fruit with yellow shoulders due to continual exposure to temperatures above 95°F (A). Heat stress causing tomato flowers to abort (B) and bell pepper fruit with sun scald (C).

Soil Temperature

Soil temperature is also important for plant growth and seed germination. Warmer soils generally support faster plant growth. Just like air temperature, soils that are too warm or cold will have detrimental effects on plant growth. Frozen, or nearly frozen soils, a potential occurrence in winter high tunnels, can restrict water movement to a plant's roots. Because air temperature will warm more quickly inside a tunnel than the soil temperature, plants can experience water stress on sunny days when warmer air temperatures support growth, but the soil remains cool or cold. As with air temperature, cooler season crops will prefer cooler soil conditions while warmer season crops will prefer warmer soils.

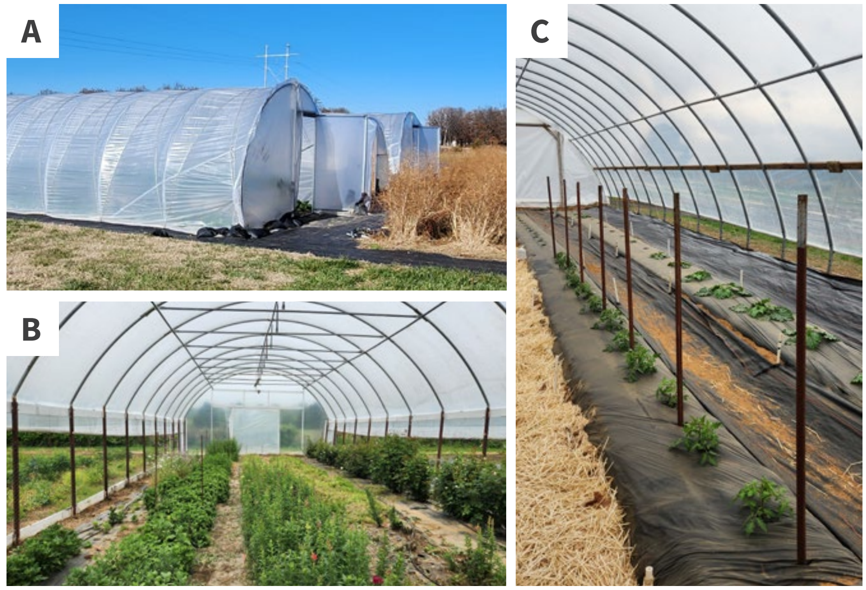

Image 5.8. High tunnels opened to various degrees. Endwall doors opened to allow for moderate cooling while sidewalls remain closed (A). Sidewalls fully open while endwalls doors and vents remain closed (B). Sidewalls cracked a few inches while endwalls and doors remain closed (C).

Conditioning Plants

Plants can be conditioned to grow in temperatures slightly outside their normal optimal range. Often referred to as "hardening off" or acclimating, conditioning occurs when plants are exposed to, and grown in cooler temperatures for at least one week before being transplanted. This triggers plants to produce compounds that act like antifreeze, allowing them to protect themselves when exposed to cold temperatures that would normally damage them. When grown in a high tunnel, well-conditioned lettuce plants have survived temperatures as low as 20°F, while well-conditioned tomato plants survived temperatures as low as 27°F without significant damage. Even though conditioned plants can survive temperatures below their normal critical low, exposing plants to these conditions should be avoided whenever possible. Secondary covers (see below) or heaters can offer additional frost protection.

Temperature control inside a high tunnel

Compared to other key climate conditions, like humidity, temperature management often gets more attention and emphasis in discussions of high tunnel climate control, and for good reason. Temperature is often the limiting factor in plant growth and health in tunnel production, and factors into how much water the air can hold (humidity) and how much sunlight plants can use (see sections on plant growth and humidity and plant growth and sunlight). Because of this, to protect plants from temperatures that could cause injury or death, high tunnel growers may choose to expose plants to suboptimal humidity or light conditions for short periods (see section on Secondary Covers).

As described earlier, the temperature inside a high tunnel is adjusted manually by opening and closing sidewalls, endwalls and vents. High tunnels are designed to be opened or vented incrementally. Sidewalls, for example, can be partly opened, or doors and vents can be opened while side/endwalls remain sealed (Image 5.8). This allows for more precise temperature regulation. A closed high tunnel can warm rapidly on a cold, sunny day while outside weather conditions remain cold. Fully opening sidewalls could quickly lower temperatures too much, potentially injuring plants. Raising (or lowering) the sidewalls a few inches could cool the environment enough to prevent damaging high temperatures without overcooling.

Retaining some trapped heat inside the high tunnel through the night is crucial to protect plants during cold nights. On its own, a high tunnel will retain very little of its trapped heat into the night. Even when managed correctly, a tunnel may only be 4 – 7°F warmer than the outside air temperature. Sometimes, under the right climate conditions, night temperatures could even be a few degrees colder inside the tunnel than outside the tunnel. Growers have developed several methods to help build-up and retain more heat inside the tunnel after the sun sets. These include the use of secondary covers, heat sinks, plastic mulches and soil moisture.

If a tunnel is open during the day, closing it in the late afternoon or early evening, while the sun is still shining, can help build up heat inside the tunnel before the sun sets. Closing the tunnel before the sun sets will not only warm the air but will also heat any "heat sinks" placed inside the tunnel. Heat sinks are objects situated inside a tunnel that can absorb heat throughout the day and slowly release it throughout the night. Soil, particularly moist soil, is the largest heat sink inside a tunnel, but any object that can absorb and release heat could potentially be used (be weary of objects large enough to restrict air movement within the tunnel or shade plants). As one example, some growers have tried using black tubes/pipes or barrels filled with water as heat sinks. The effectiveness of these tricks varies, and growers should closely monitor the nighttime temperature lows, using sensors, and modify temperature management strategies accordingly. A supplemental heating system may be necessary on extremely cold winter nights (see Chapter 4 – High Tunnel Design).

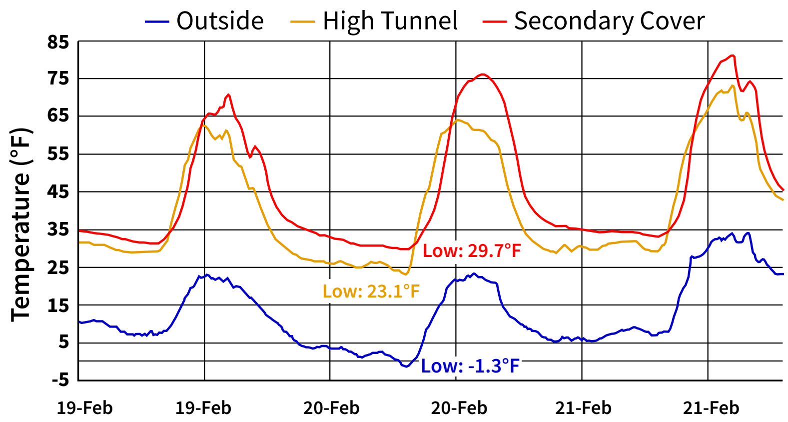

Image 5.9. The effect of a secondary cover on air temperature. It is important to note the effect the secondary cover had on air temperature at night. The secondary cover was suspended above the plant using metal hoops. Data collected in Northwest Arkansas by Taunya Ernst

Secondary Covers

A secondary cover, often called a row cover or frost blanket, is made from lightweight material and placed over a row (or multiple rows) of plants. Mimicking the high tunnel's ability to capture heat, the air beneath a secondary cover can be a few degrees (~2-5°F) warmer than the ambient air inside the high tunnel. A secondary cover can also trap heat radiating from sun-warmed soil throughout the night. Combined, these attributes of secondary covers offer a few degrees of additional frost protection to plants (Image 5.9). While this may not sound like much, a few degrees could be the difference between 32°F and 35°F, which could prevent cold damage or potentially damaging freezing conditions.

The type of material used for a secondary cover varies, but a spun-bonded agricultural fabric (often called row cover or frost cloth) is the most common (Image 5.10). Clear or slightly opaque construction-grade plastic has also been

Image 5.10. Covering strawberry plants with frost cloth to help protect them during a cold night.

Image 5.11. Secondary covers made with different materials. Construction grade plastic is suspended over plants using hoops while a frost cloth is resting directly on plants.

used successfully by growers in Arkansas. Row covers can come in different thicknesses (0.5 – 2.0 oz/sq. yd), with thicker covers offering more frost protection than a thinner fabric. Row covers are often suspended above the plants using hoops or other means, but they can also be placed directly on the plants (Image 5.11). While both methods work, many growers choose to suspend the cover above the plant to avoid possibly damaging plants during the covering and removal process. Under extremely cold temperatures, row covers placed directly on top of plants can freeze to the plants. Removing these row covers while they are still frozen to the plants can cause significant damage as well.

One concern about using row covers is their shading effect when used during the day. To reduce labor, growers sometimes choose to leave secondary covers in place on cool, overcast days. Any secondary cover will reduce the amount of light available to plants with heavier fabrics reducing light more than a lighter fabric. A thicker frost cloth can reduce available light by 50 percent or more. For that reason, despite offering less temperature protection, some growers may choose to use a lighter-weight frost cloth as it allows more light to reach plants. On especially cold nights, these growers may add a second layer of the lightweight cloth for added frost protection. Remember that the second layer of row cover will not double the protection achieved by the first cover, but will provide an additional degree or two of heat retention at the canopy level. And remember that while temperature management usually takes precedence over light management, both are essential for plant health and growth.

To avoid excessive heat build-up around the canopy, secondary covers will need to be removed on sunny days. This removal of secondary covers in the morning and re-application in the evening is a labor consideration growers must be aware of. It should also be noted that removal and re-application of secondary covers may be necessary multiple times a week during spring, fall and winter production.

Humidity build-up under secondary covers can also be a concern. Removing them during the day will lower humidity levels underneath the cover. If secondary covers are left in place for several days (due to overcast, cooler weather conditions), it may be necessary to remove the covers, even briefly, to lower humidity and prevent potential disease outbreaks (Image 5.12).

Image 5.12. Venting a secondary cover inside a high tunnel. A greenhouse grade plastic was used for this secondary cover.

Plant growth and humidity

Humidity, specifically relative humidity (RH), influences water movement into and throughout a plant. Water movement through the plant is crucial for several essential plant functions including photosynthesis, nutrient transportation, and plant rigidity. Water movement out of the plant, specifically transpiration, is also how plants cool themselves. When water movement within a plant is restricted or slowed, plant growth and crop quality will be affected. To understand how RH influences water movement and plant growth it is important to be aware of a few things:

- RH is a measurement of how much water vapor air can hold at a certain temperature.
- Warmer air holds more water.
- The drier the air (lower RH) surrounding a plant the faster a plant will transpire (lose water to the air) and absorb nutrients.
- The wetter the air (higher RH) surrounding a plant the slower a plant will transpire (lose water to the air) and absorb nutrients.
- Plant transpiration slows, or even stops, when the air is too wet (high RH).

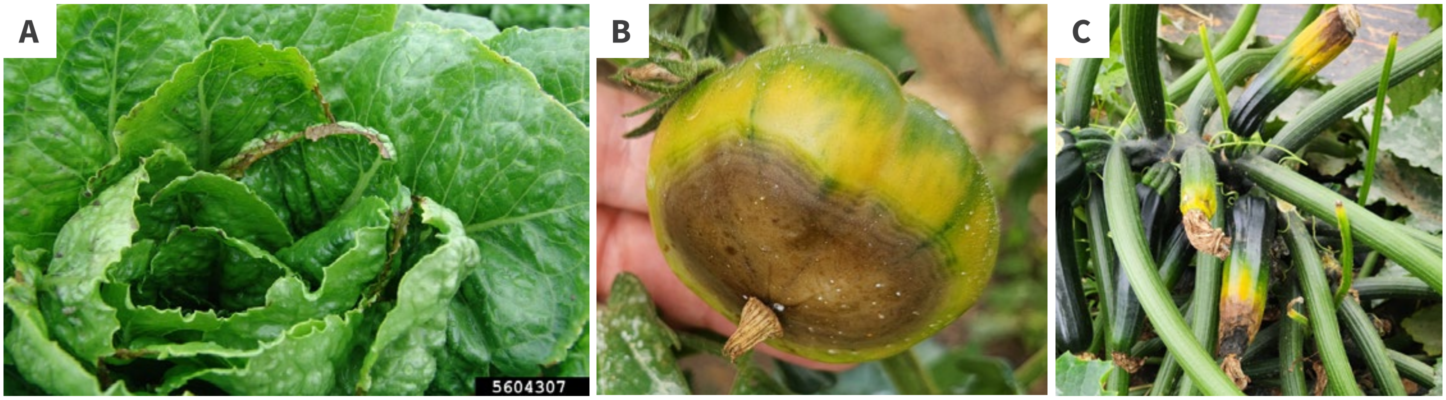

Image 5.13. Calcium deficiencies on lettuce (A) tomato (B) and zucchini (C). When calcium up-take from the soil is restricted leaf and fruit tissue fails to develop correctly. Image A from Gerald Holmes, Strawberry Center, Cal Poly San Luis Obispo, Bugwood.org.

High Relative Humidity: Plants grown in persistently high RH may become overheated, particularly on warm or sunny days, due to reduced transpiration rates. These overheated plants will exhibit symptoms of heat stress or injury if humidity remains high. Certain physiological disorders caused by nutritional deficiencies can become more common under high RH. Tipburn on lettuce, or blossom end rot on tomatoes and peppers, for example, are caused by calcium deficiencies (Image 5.13). High RH can hinder a plant's uptake of calcium from the soil, causing an increase in incidences of these disorders.

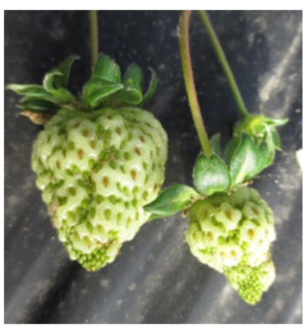

Image 5.14. Strawberry fruit misshaped by inadequate pollination.

High RH can also impede pollination. While this may not be an issue for many fall crops such as lettuces that do not depend on pollenated flowers for harvest, many high tunnel spring crops, such as tomatoes, cucurbits and strawberries, do require pollination for fruit development. If pollination is hampered by high RH, yield or fruit quality of these spring crops could be negatively impacted (Image 5.14). It should also be noted that many fungal diseases, such as powdery mildew and botrytis, prefer humid conditions and will spread and develop more quickly when RH is high (see Chapter 8 – Pest and Disease Management Strategies).

Low Relative Humidity: When RH is low plants can become more vulnerable to temperature-related injuries or death, particularly when soil moisture is also low. It is rare to experience prolonged low RH conditions in high tunnels in the southeast United States due to the humid climate.

Humidity control inside a high tunnel

Arguably the two most important things to remember for humidity control are:

1. Cooler air is drier air
2. Still air is humid air (at least in high tunnel production)

The simplest and quickest way to lower humidity inside a high tunnel is to open the side/endwalls or vents to allow cooler and drier outside air to enter. Wind (air movement) is needed for the cooler air to push the warm humid air out of the tunnel. Without wind, a fully opened high tunnel can experience inadequate air movement, especially if a tunnel was designed without sufficient ventilation capacity. Still air can create or compound humidity issues and cause humid "hotspots" to develop around plant canopies. These humid hotspots can become pockets where fungal diseases can develop and spread to surrounding plants. If insufficient wind movement into and throughout the tunnel is a chronic issue, it may be necessary to install fans to help move air into and throughout a tunnel.

Humidity can rise more quickly in the smaller air space beneath a secondary cover. If using a secondary cover for frost protection, removing or venting it in the morning as soon as temperatures warm will help keep humidity low (Image 5.12).

Plant growth and sunlight

Sunlight is the energy that powers photosynthesis and drives plant growth. The more sunlight that reaches a plant the higher its rate of photosynthesis. In other words, more light equals faster plant growth, at least up to a point. Eventually, adding more light will have no corresponding increase in photosynthesis. Once this "light saturation point" is reached, the rate of photosynthesis plateaus (Image 5.15). The more time a plant maintains its maximum photosynthesis rate the faster it grows (if all other growing conditions are favorable).

Long, sunny summer days in Arkansas have plenty of light and daylength for plants to maintain high photosynthesis rates for many hours. Winter days in the Southeast, however, are shorter and the sun sits lower in the sky, reducing the amount of light reaching plants. The tunnel's plastic cover will also reduce the amount of light reaching plants. A single layer of 6-mil greenhouse-grade polyethylene plastic only transmits about 88-92 percent of available light. The use of secondary covers further lessens the amount of light reaching plants, with some common covers only transmitting about 48 percent of available light (see section on secondary covers). Reducing sunlight too much for an extended period may slow plant growth and affect plant architecture. A study conducted at Utah State University evaluated the impact of different secondary covers on winter grown high tunnel spinach plants. While light reduction was not the focus of this study, it was observed that when compared to plants grown without a secondary cover, plants grown under an opaque plastic secondary cover had smaller, lighter green leaves with elongated petioles despite more optimal growing temperatures. The architecture of these plants mimicked plants grown under lower light conditions (Image 5.16).

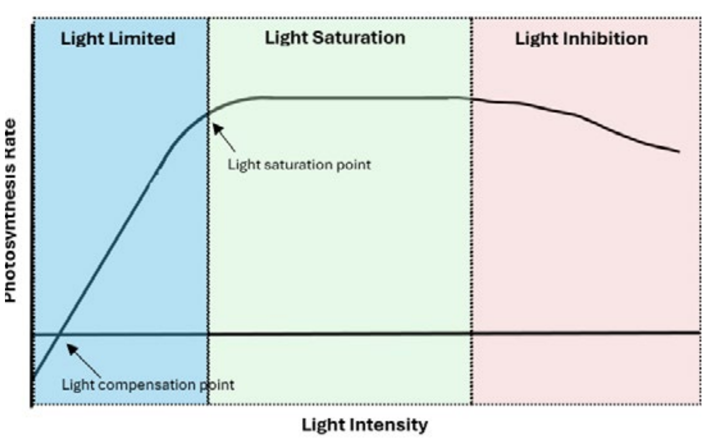

Image 5.15. The rate of photosynthesis in response to changes in light intensity.

Image 5.16. High tunnel winter grown spinach plants in Northern Utah. While the plants on the top right were left uncovered the plants in the bottom left were covered with a semi-opaque plastic for added frost protection. These plants had smaller, lighter green leaves with elongated petioles.

Too much light can also lower photosynthesis rates and cause plant injury. Crop type and temperature will determine how much sunlight is too much light. Light damage to photosynthetic system in plants can occur under lower light conditions when temperatures are cool or cold. For this reason, on cold sunny winter (or fall/spring) mornings, when there is plenty of sunlight for photosynthesis, but the temperatures are below critical baseline temperatures plants are vulnerable to light injury. The most common visible symptom of too much light is dry, browning leaves (usually beginning at the leaf edges) or leaf burn. For optimal plant growth, both light and temperature need to be within favorable ranges.

Climate Management Strategies

Planning for climate management in a tunnel should begin before the tunnel is purchased. Features of the tunnel's design should be chosen with climate management in mind. A poorly designed tunnel can struggle with heat accumulation or humidity hotspots that will negatively affect crop quality and yields. For more information on high tunnel design see Chapter 4 - High Tunnel Design.

Make a plan:

After the tunnel is constructed, but before planting, begin developing a climate management plan. These early plans can be general and simple but should include things like:

1. Critical temperatures for planned crops. Knowing these temperatures can help determine when the tunnel should be vented, or secondary covers applied.
   Example: If tomatoes are the planned crop:
   It could be determined to:

Baseline	Optimal Range	Maximum
50°F	60-75°F	90°F

   - Vent the tunnel when internal temperatures rise above 75°F.
   - If the tunnel was vented during the day, and night temperatures are forecast to drop below 50°F, plan to close all vents and doors in the late afternoon to trap some heat for the night.
   - Apply secondary covers if night temperatures are forecast to drop below 40°F.
   - When outside temperatures are consistently above 85°F every day, cover the tunnel with a shade cloth.

2. Have a means to monitor climate conditions inside the tunnel. Climate data should be monitored and recorded in a way that makes using and interpreting the data simple and easy (Image 5.17).
3. Have a plan to deal with extreme temperatures. In high tunnels, temperatures can drop below or rise above injury thresholds. When this happens, it may be necessary to supply extra heat, install fans or add frost or shade cloth to prevent plant injury or death.
4. Have all necessary supplies, such as secondary covers, shade cloth and sensors, on hand.
5. Determine who will be responsible for monitoring weather forecasts and managing the tunnel's climate on a day-to-day basis.

Tips on selecting a sensor and locating it inside a high tunnel

Selecting a sensor:

- Select a sensor that has a reputation for being accurate, reliable and will work for long periods of time.
- Sensors vary in the type of data they record, the frequency they record it and how long they store it. Two common types of sensors are:
  - » Min/Max Sensors: Digital sensors that display the current temperature and humidity, and the 24-hour min/max for both.
  - » Wireless Recording and Accessing Sensors: These sensors communicate with a remote readout device, such as the Bluetooth on a cellular phone. Some of these sensors can record conditions as often as every minute and graph the changes in climate conditions over time.

  Select a sensor type that will provide the information needed to correctly manage the high tunnel climate without overwhelming you with too much data.
- Sensors that monitor and record sunlight and soil temperature are also available.

Locating the sensor

- Place the sensor near the mid portion of the plant's canopy.
- Temperature sensors may read high if placed in direct sunlight. Solar shields (Image 5.17A) can be used to protect sensors.
- Sensors may read high if placed in areas where air movement is restricted, such as the corners of the high tunnel.
- Temperatures may read cooler if placed near side or endwalls.
- Place the sensor where it will be out of the way of crop management activities (harvesting, trellising, row covers etc.)

Image 5.17. Examples of different types of temperature and humidity sensors. Sensor complexity can range from loggers that can record climate conditions every minute and connect to a phone or computer (A, B) to sensors that just shows the current conditions and the 24 hour high/low (C). Temperature sensors can be placed inside solar shields to prevent inaccurate temperature readings (A).

Daily tasks

Once the high tunnel is in production, environmental conditions, both inside and outside the tunnel, will need to be monitored daily, particularly during the winter, fall, and spring months. It is important to remember that the internal climate of a high tunnel is dictated by outside environmental conditions and that a tunnel's climate is manipulated and managed manually. Because external weather conditions (and therefore the tunnel's climate) can fluctuate from day to day or from day to night, someone will need to be near the tunnel every day to monitor and manage it. This includes weekends and holidays.

Reliable weather apps can be used to monitor forecasted weather conditions which can indicate management needs for the coming days. For example, if tomatoes are planted in the tunnel and the next day's weather is forecast to be mild (50°F) but sunny, plan on venting the tunnel. And if night temperatures are forecast to drop below 40°F, plan on closing the tunnel and covering plants with a secondary cover.

While weather forecasts can suggest potential management needs, the actual climate conditions inside the high tunnel should ultimately dictate management decisions. Temperature and humidity sensors placed inside the tunnel should be monitored at least once a day (Image 5.17). The opening/closing of tunnel vents, sidewalls and endwalls should be adjusted based on internal conditions. Inconsistent sun exposure on cloudy or partly cloudy days can make it difficult to predict the temperature inside a tunnel. A sensor placed inside a tunnel will help determine when or if a tunnel should be ventilated on a cloudy day.

For new high tunnel growers, it can be difficult to decide whether to open a tunnel on mild, overcast days, even with a temperature sensor. If you are struggling with this decision, there are a few considerations that can make the decision easier. First, to save on labor, some growers choose to leave tunnels closed as long as internal temperatures remain below the crop's critical maximum temperature. Second, while temperature is usually the deciding factor when venting a high tunnel, humidity is also managed by opening the tunnel. Humidity inside a closed high tunnel can rise quickly and opening (or partly opening) it on a cloudy day can help keep humidity levels down. Finally, it is often better to err on the side of being a little cooler inside the tunnel rather than too warm. Many plants tolerate cooler (but still above the baseline) temperatures better than temperatures above their optimum.

Season-Specific Strategies

Winter

Main climate management goals:

1. Prevent or protect plants from damaging low temperatures.
2. Balance temperature management with light and humidity.

For many winter crops, plant growth is not the only goal when using the high tunnel. Frequently, winter crops are grown to near full maturity during the fall when conditions are more favorable for plant growth. As days become shorter and colder, the tunnel becomes a kind of living cold storage. For these crops temperatures around freezing with higher humidity may be more desirable. Studies have shown that these "cold storage" crops can survive temperatures as low as 25°F (if previously hardened off). Crops with "cold storage" potential include cabbages, carrots, radishes, turnips and head type lettuces.

For other winter crops, continuous plant growth is expected and needed for leafy winter crops such as baby lettuce, spinach, kale, and arugula. While these crops can also survive temperatures below freezing, they do need warmer temperatures that can support growth. Generally, temperatures at or above 40°F can support the growth of these crops.

Approximate Seasons in Arkansas

Arkansas winters are relatively short, with the coldest temperatures generally experienced in January. On cold winter days, it may not be necessary to open the tunnel. Even when it's sunny, temperatures inside a tunnel may not reach levels that could stress or damage plants. Night temperatures can drop below freezing, and plants may need more protection than the high tunnel can provide. In Arkansas, the few degrees of extra protection offered by a secondary cover is often enough to protect hardened plants on frosty nights. Though not common in many areas in Arkansas, sometimes temperatures can become so cold that even secondary covers do not offer enough protection. If this does occur, growers may need to invest in a temporary heating system (see Chapter 4 – High Tunnel Design).

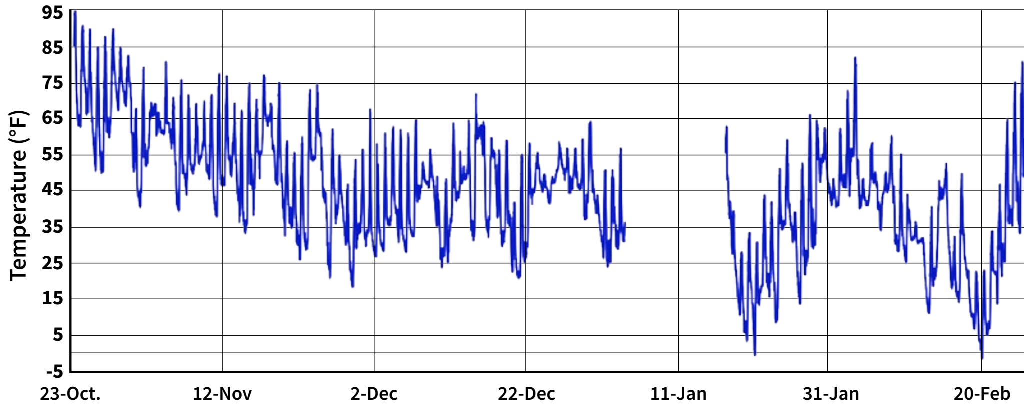

Image 5.18. Daily temperature recorded outside a high tunnel in Northwest Arkansas from October 2024 through February 2025. Data collected and provided by Taunya Ernst.

Winter months can also experience large temperature swings from night to day, particularly on cloudless days/nights (Image 5.18). When this occurs, it will be necessary to open the tunnel during the day to prevent excessively high temperatures and then close the tunnel every afternoon/evening. Remember, crops selected for high tunnel winter production should prefer cooler temperatures. So "excessively high temperatures" could mean 70 - 75°F. Temperatures above this could cause plant tissue damage or a shift in plant growth. Bolting in lettuce and spinach plants, for example, can be triggered by temperatures above 75°F.

High relative humidity inside a high tunnel is common during winter months and can be even higher under a secondary cover. Whenever temperatures allow, the tunnel should be opened to permit humid air to escape. And secondary covers should be removed during the day.

Spring and Fall

Main climate management goals:

1. Prevent damaging high or low temperatures.
2. Avoid long periods of high humidity.
3. Protect plants from sudden temperature drops.

The shoulder seasons have the highest demand for labor when it comes to climate management, especially during the early spring. More drastic daily temperature fluctuations, as well as more extreme day-to-night temperature differences, are common during this time. Days are often mild, or even warm, making it necessary to open tunnel walls or vents to some degree every day to maintain temperatures within the crops' optimal range and vent excess humidity. Mild or warm, sunny days are also common. If a tunnel is not opened on these sunny days, temperatures could become high enough to cause heat stress or injury. Nights, on the other hand, remain cool and regularly drop to just at or below freezing, making it necessary to close the tunnel and apply secondary covers to protect plants at night. Under these weather conditions, temperature adjustment in the tunnel becomes a twice-per-day (or more) task, requiring someone to be onsite or nearby every day.

Another key difference for fall/spring climate strategy goals, compared to winter production, is plant growth. Plants inside a tunnel are actively growing during the fall and spring and warmer temperatures must be maintained. Warm weather crops, such as tomatoes or peppers, are often planted in tunnels in the late winter or early spring. This means it will be important to try and keep temperatures inside the tunnel (or beneath a secondary cover) above 40°F, even at night, to encourage growth. It will also be necessary to maintain these warmer temperatures in the fall if a tunnel is used to extend the harvest of a warm season crop.

Image 5.19. Shade cloth pulled over the plastic roof on a Quonset styled tunnel. Left, shade cloth seen from inside the tunnel, and right, shade cloth seen from outside the tunnel. Fans were installed in the tunnel to improve air movement into, and throughout the tunnel.

As mentioned earlier, spring-planted high tunnel crops are typically warm-season crops growers are trying to start for early local markets. This means more attention and effort may be necessary in the spring to protect these more tender plants from colder temperatures. Fall-planted crops, on the other hand, are most often cool season crops growers are planning on harvesting throughout the winter. While these plants still need warm enough temperatures to support plant growth, they are more capable of handling colder night temperatures, if plants are properly conditioned (see earlier section on conditioning plants). Additionally, allowing fall crops to experience cooler night temperatures will help condition them to survive the winter conditions they will likely be exposed to before harvest.

Whether planting a high tunnel in the fall or spring, be aware of the crops' critical and optimal temperatures. This will help develop effective climate management plans during these months where weather conditions oscillate often.

Summer

High tunnel climate management becomes much easier during the summer months in Arkansas and the Southeast. There is only one goal: To prevent damaging high temperatures. While this sounds easy, it can be difficult to accomplish during a standard hot Arkansas summer, particularly in a poorly designed tunnel (see Chapter 4 - High Tunnel Design). During the summer months, all vents, sidewalls and endwalls on a high tunnel should be opened and remain open day and night. Keeping the tunnel open should allow the cooler drier outside air to continually circulate into the tunnel and push out the hotter, more humid air. Tunnels that do not experience enough air movement will overheat, and disease incidence may increase. It may be necessary to bring in fans to help move air (Image 5.19).

Despite the potential for overheating during the summer, Arkansas growers typically leave the plastic cover on the tunnel for rain exclusion. This means on a sunny summer day, the temperature inside a tunnel will always be a few degrees warmer than outside, even in a well-designed and fully ventilated high tunnel. Because of this, a shade cloth will be necessary to prevent heat stress or injury to high tunnel summer crops. Covering a tunnel with a 30 percent or 40 percent shade cloth can reduce its internal temperature by 5 – 8°F. A few experienced high tunnel growers in Arkansas have opted to use a 50 percent shade cloth for summer tomato production to further lower temperature. While these growers claim there was no notable reduction in yields when they did this, research indicates that tomato plants will yield less if a 50 percent shade cloth is applied too early in the season.

When tunnel daytime temperatures are consistently above 80-85°F, a shade cloth should be placed over the tunnel's roof (Image 5.19). For more information on shade cloth selection see Chapter 4 - High Tunnel Design.

Conclusion

Good climate management strategies are essential for successful high tunnel production. The concepts outlined in this chapter are designed to help a grower develop effective strategies to manage the environment of a high tunnel. Knowing the key climatic requirements for your crop and having clear goals for the crop and farm will make management decisions easier. A tunnel's design will influence the degree to which a tunnel's internal climate can be manipulated. Becoming familiar with the abilities and limitations of a tunnel can take time, but once understood, climate management strategies will become easier to tailor for each unique tunnel and crop.

Additional Resources

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Begin designing your climate management strategy: Desired crops? Critical temperatures?

Notes



CHAPTER 6

Crop Selection and Planting Dates

Introduction

High tunnel production offers specialty crop growers several advantages such as the potential for higher yields of better-quality produce, expanded revenue periods and extended growing seasons. For a tunnel to be profitable and to take full advantage of these benefits, crop selection and planting date determination should be done thoughtfully. Just as in field production, timing when to transplant or direct seed a high tunnel is important, impacting not only harvest windows but final yields. A tunnel's ability to moderate its climate allows growers to plant earlier in the spring or later in the fall. Because of this adjusted season, planting calendars developed for open field production or home gardens in a given region are irrelevant for high tunnels. Information provided in this chapter is designed to help high tunnel growers determine the crops best suited for their production goals and narrow down optimal planting dates.

Image 6.1. Trellised cucumber plants growing inside a high tunnel near Little Rock, AR.

Crop Selection

Just about any common fruit or vegetable crop that can be grown in Arkansas can be successfully grown in a high tunnel, if effort is made to correctly manage the tunnel environment. However, not all crops can be grown profitably in a tunnel. Vegetable crops are the most common, and usually most profitable crops grown in high tunnels nationwide, with early season tomatoes regularly proving to be the most profitable.

When considering the profitability of a crop for high tunnel production consider the following questions:

1. Will there be a market to sell the desired crop during the adjusted harvest window? While this is a question all growers should consider, it is especially important for high tunnel growers in rural areas. Tunnel growers located in more rural areas in Arkansas have experienced some degree of trouble locating markets or achieving premium prices for out-of-season produce. If the crop is not in demand out of seasons this reduces the economic benefit of growing it in a high tunnel.

2. What is the crop's potential productivity per square foot? Some crops, while they grow well in a tunnel, require a sizable amount of space to grow, making them less profitable per square foot. Viny crops such as cucumbers or melons grow well in a tunnel environment, but their viny growth and the limited number of fruit produced per vine limits final yields per square foot.

3. A related question to square foot productivity would be whether a crop could be trellised to better take advantage of both vertical and horizontal space. Trellising crops like cucumbers can increase their yield per square foot, increasing their profitability in high tunnel production (Image 6.1).

4. How long until the crop reaches harvest and how long is the harvest window? Perennial crops, or crops with long establishment periods and short harvest periods may be less profitable for the high-cost real estate inside the high tunnel. Grapes, for example, take two to three years to come into full production in a tunnel and only have a one- to three-week harvest window each year.

In Arkansas, generally profitable high tunnel warm-season crops include early season tomatoes, peppers, eggplant, okra, trellised cucumbers and squash. Potentially profitable cool-season crops for high tunnel production in Arkansas include various lettuces, kale, radishes, spinach, cabbage, beets and turnips, which are grown and harvested throughout the fall and winter. These lists of potentially profitable crops are not exhaustive, and not all these crops will be profitable in all situations. Growers should consider their unique situations to determine what will work best for their farm.

Determining Planting Dates

When to plant or direct seed a high tunnel is largely determined by three key things:

1. Crop-specific growing requirements, most notably temperature and daylength: Crop-specific growing requirements are often readily available and can be found online. Table 6.1 lists the optimal growing temperatures for some common high tunnel crops. Chapter 5 - Climate Management Strategies includes more information on optimal growing conditions and climate management in a high tunnel.

2. What temperatures (soil and air) can be maintained in the tunnel: For new high tunnel growers, this may seem daunting at first, but it will become easier over time. The important thing to remember is that there are climatic limits to high tunnel production. For example, while the high tunnel will generally be warmer than outside conditions during the winter, it is unlikely that optimal temperatures for warm-season crops can be maintained consistently inside the tunnel during the coldest times of the year. Likewise, many cool-season crops will likely struggle in the hot and humid environment of a high tunnel during the summer months.

3. Market goals, demands, and availability: The modified growing environment of a high tunnel will give growers some flexibility on planting dates, allowing them to target harvest periods to align with market needs and availability.

Table 6.1. Critical air temperatures for some common high tunnel vegetable crops and strawberry.

Crop	Min or Baseline*	Optimal Range	Max*
Spinach, collards, broccoli, radish, kale, beet	40°F	60-65°F	75°F
Lettuce, pea, cauliflower, carrot	45°F	60-65°F	75°F
Tomato, squash	50°F	65-75°F	90°F
Cucumber	60°F	65-75°F	90°F
Sweet pepper	65°F	70-75°F	80°F
Hot pepper, eggplant, okra	65°F	70-85°F	95°F
Strawberry	40°F	65-75°F	85°F

*Hardening, or acclimating, a plant to cooler conditions can shift that plant's baseline temperature lower (see section on Hardening Plants).
*A plant's growth stage may also influence baseline and maximum temperatures. Broccoli, for example, has a "window of sensitivity" of about 10 days during which they are more vulnerable to heat injury.

For new high tunnel growers, some general recommendations on planting dates can be beneficial the first year. The following guidelines can help new tunnel growers narrow down planting windows for their high tunnel. As a grower becomes more comfortable and confident with the capabilities of their high tunnel it will be easier to shift crop planting dates to better fit with farm goals and to target available markets.

Warm-Season Crops

For warm-season crops, high tunnels are often used to get a jump start on the season in the early spring. More hardy warm-season crops, such as tomatoes or peppers, can be transplanted into a tunnel four to six weeks before an area's frost-free date (Table 6.2). More tender warm-season crops, such as cucumber or squash, can be transplanted into the tunnel two to three weeks after the hardier crops. It will likely be necessary to provide additional frost protection, particularly for the tender crops, on nights when temperatures drop below baseline temperatures (see Chapter 5 - Climate Management Strategies). While warm season crops could be transplanted into the tunnel even earlier in the spring, these very early plantings will require additional labor to monitor and manage the tunnel's climate when outside temperatures remain cool. These earlier plantings are also at greater risk for frost damage and will experience slower growth rates due to lower light levels and cooler temperatures, which could limit the potential benefits of planting too early.

A second, late summer or early fall planting of warm-season crops is also possible. Late summer plantings will extend the harvest period of warm season crops into the fall (Image 6.2). These fall harvests can interfere with fall plantings of a cool season crop.

Table 6.2. Average last frost date for cities in Arkansas. Data obtained from the National Weather Service.

City	Avg. last frost date
Benton	April 5
Bentonville	April 24
Cabot	April 15
Conway	April 13
El Dorado	April 5
Fayetteville	April 27
Fort Smith	April 8
Hot Springs	April 2
Jonesboro	April 12
Little Rock	April 3
Paragould	April 5
Pine Bluff	March 29
Russellville	April 10
Searcy	April 7
Texarkana	March 29
West Memphis	March 29

It should be emphasized that these early spring planting date suggestions are based on the use of transplants and not direct seeding. Cooler soil conditions can make direct seeding during this time difficult, and it is therefore generally not recommended. It can be challenging to locate transplants this early in the season and it may be necessary for growers to start their own transplants for early spring plantings.

Image 6.2. Some cool season greens planted between rows of fall planted tomatoes.

Cool season crops

Cool-season crops planted inside a tunnel in the late summer or early fall can be harvested throughout the fall, winter and into the early spring months. Harvest method and crop type will influence transplanting or direct seeding dates for winter-harvested cool-season crops.

Harvest methods for winter-harvested cool-season crops:

1. Multi-cut harvests (cut-and-come again): All leaves are cut about one inch above the soil line, leaving the plant's growing point. New leaves develop from the growing point, allowing the plant to be harvested again. This harvest method produces "baby leaf" greens or mixed greens and is often used with mustards, arugula, lettuces and spinach (Image 6.3A).
2. Individual leaf removal: An entire, full-sized leaf is removed when it reaches a desired size. Smaller leaves are left on the plant and allowed to continue growing so they can be harvested later. Leaves harvested this way are often sold in bunches. Kale, spinach, mustard and Swiss chard are often harvested this way (Image 6.3B).
3. Single harvest: The main stem, including the growing point, is cut for harvest which prevents additional harvests. This harvest method produces "heads" or whole plants. Head or Romane lettuces, bok choi, cabbages, and spinach are a few examples of crops harvested using this method (Image 6.3C).
4. Root crops: These crops are harvested at full maturity by removing the entire plant from the soil. Radishes and turnips are popular root crops grown in high tunnels in Arkansas. Carrots and beets have also been grown in tunnels, but their longer growth cycle usually makes them less profitable (Image 6.3D).

Image 6.3. Harvest methods for cool season crops. Cut-and-come again (A), Individual leaf removal (B), Single harvest (C) and root crops (D).

Cool season crops that have a single harvest (head or head-type products, and many root crops) should be planted early enough in the fall or late summer for those crops to reach full or near-full size before environmental conditions become unsuitable for growth. Generally, plants should be at least 75 percent of their full, harvestable size before days become too cold and daylength too short (less than 10 hours) to support growth. While the cold, short winter days may not kill, or even injure these crops, growth will be slower or may even stop. During this time, the high tunnel essentially becomes a living cold storage for these crops. Some cool season crops can be kept in this inactive "cold storage" stage for an extended amount of time allowing fresh produce to be harvested from the tunnel as needed throughout this period. This "cold storage" phase is comparably short in Arkansas, usually spanning parts of December and January.

Certain plants will continue to produce some growth during these short, cold winter days, though growth will be markedly slower. For these crops, multiple harvests of small or individual leaves throughout this period are possible. Spinach, chard, kale and other "baby greens" will all continue to produce some growth throughout the winter months. Often, these crops are planted in succession so a supply of fresh young leaves can be harvested weekly over a longer period (Image 6.4). Remember that later fall plantings will take longer for plants to reach a harvestable size and will likely produce less than earlier fall plantings.

Prolonged exposure to cold, or repeated temperature swings, can cause some crops to flower or bolt early, before reaching their marketable size. For these crops, the harvest potential on either early spring or late fall plantings could be limited. Kale, cabbages, mustards, bok choy, radishes, carrots, beets and turnips are susceptible to this early bolting. More information on this phenomenon can be found in Chapter 5 - Climate Management Strategies.

Just as with early spring plantings of warm-season crops, transplants are often used for cool-season crops planted in the fall, particularly for head-type crops. Direct seeding, however, is common for dense plantings of spinach or salad greens that will be harvested multiple times. When direct seeding, pay close attention to soil temperature. For most cool-season crops, soil temperature must be above 40-45°F for seeds to germinate (Table 6.3). Cooler soil conditions can cause germination rates to slow and be more irregular. Secondary covers can help maintain warmer soil temperatures and improve germination rates.

Table 6.3. Soil temperature requirements for good seed germination and seedling establishment for some common cool season high tunnel crops.

Crop	Minimum Temperature	Optimal Temperature	Maximum Temperature
Cabbage	40°F	85°F	100°F
Cauliflower	40°F	80°F	100°F
Lettuce	35°F	75°F	85°F
Radish	40°F	85°F	95°F
Spinach	35°F	70°F	85°F
Swiss Chard	40°F	85°F	95°F

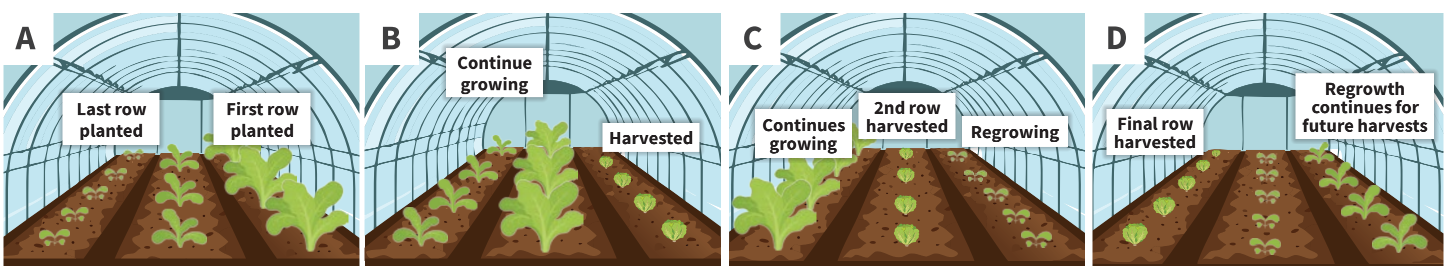

Image 6.4. An example of a simple succession planting and harvest schedule for lettuce inside a high tunnel. Each row of this tunnel was transplanted or direct seeded at a different time, resulting in plantings of different maturities (Image A). Rows can be planted a week or more apart, depending on farm goals and market demands. The row that is planted first will reach harvestable size and can be harvested before the other two rows (Image B). While the first row regrows, or is replanted, the row that was planted second will reach harvestable size and be ready to harvest a week or so after the first row. How soon the second row can be harvested after the first row will depend on time interval between planting dates and climate conditions (Image C). While the first and second rows regrow the third and final row can be harvested. By the time the final row is harvested the first row should be nearing a second harvest (Image D). Growth rates and therefor harvest timing will be determined by climate conditions. Succession planting can help ensure something will be ready to harvest each week (or whatever the desired harvest window). Images developed by Lizzy Herrera.

The shorter days and cooler air and soil temperatures in the fall and spring will slow growth for both cool and warm season crops. This will increase the time it takes for plants to reach harvestable size. When adjusting planting dates to target a specific market window, adjust the days from "seed to harvest" estimates on seed packages by ten or more days, depending on how early you plant.

Considerations for Planting Arrangement and Spacing

The size and arrangement of beds and alleyways inside a high tunnel will influence the amount of plantable space, work efficiency and even crop placement. Beds that run parallel with tunnel sidewalls are easier to prepare when equipment is used for bed preparation, and they generally result in more plantable square feet. The long alleyways also make it easier to move harvest bins and other equipment the length of the tunnel. For these reasons, most tunnels are planted with beds running parallel to tunnel sidewalls (Image 6.5). Crossway beds, however, can be an advantage in some situations. One high tunnel grower in Arkansas experienced chronic flooding issues inside their tunnel. Even minimal water flowing into the tunnel after a rainstorm would become restricted by the long beds, resulting in standing water. By switching to a crossway bed layout, rainwater could flow unhindered through the tunnel, eliminating flooding issues (Image 6.5). For tunnels that are oriented east to west, crossway beds can also reduce shading of northern rows by crops on neighboring rows to the south.

Another thing to remember are the microclimates that often occur inside a high tunnel. Typically, cooler temperatures will be present near the edges of the tunnel, especially during the winter months. Warmer and often more humid conditions are present near the center of the tunnel.

Whenever possible, place crops where they are most adept at growing. For example, place more cold-tolerant crops such as spinach and kale near tunnel walls. The placement of taller crops inside the tunnel should also be given some thought. Taller crops can shade nearby smaller plants and they can restrict airflow into the tunnel. Planting a taller crop on more northern rows can help prevent shading while placing taller crops near the center of the tunnel can help improve air flow into the tunnel. Placing taller crops closer to the center of the tunnel will also allow these crops to take advantage of the higher vertical growing space.

Plant spacing is also an important consideration. Many new high tunnel growers are often tempted to increase plant densities when moving production from the field to a tunnel. These higher densities often restrict airflow throughout the crop's canopy, causing higher intercanopy humidity. This in turn can increase disease pressure. When first planting inside a high tunnel, follow standard plant spacing recommendations. As your understanding and confidence in high tunnel production increases, you can adjust plant spacings if needed.

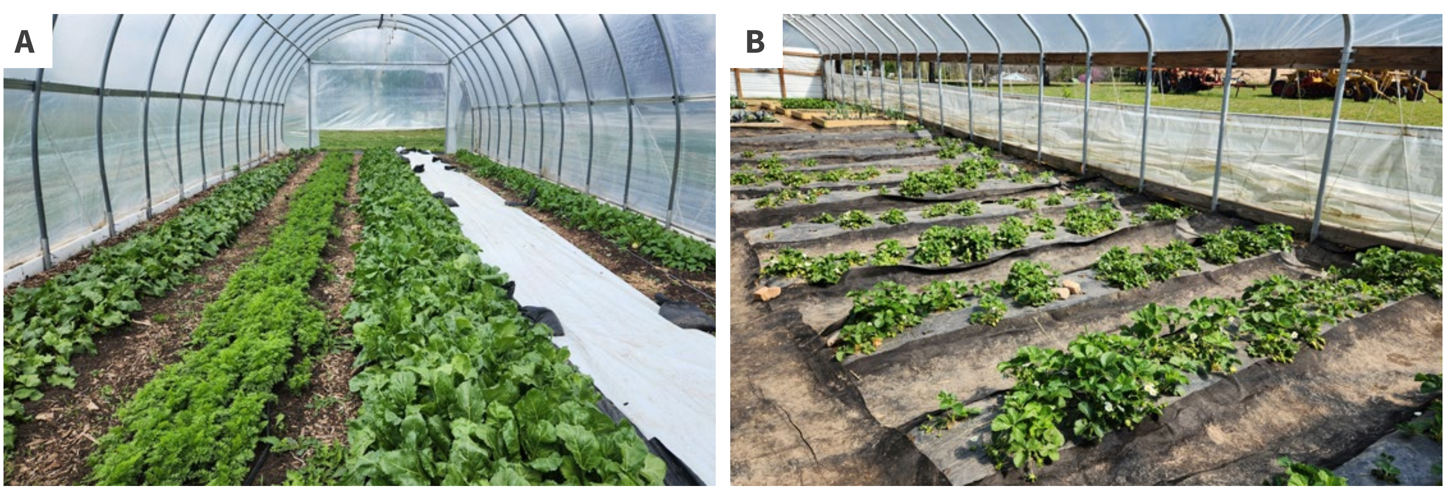

Image 6.5. Planting beds running parallel to the high tunnel's sidewall (A). Crossway beds running perpendicular to the high tunnel's sidewalls (B).

Conclusion

As with field production, planting date and crop selection will have a large impact on the overall productiveness and profitability of a crop when grown inside a high tunnel. Market demand and market windows should be considered when selecting crops for out-of-season production as well as influence planting dates. While the tunnel will modify its internal environment, the degree of climate control inside these structures are limited, and a crop's specific environmental preferences should drive planting dates and influence its placement within the tunnel.

Additional Resources

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What crops do you plan on growing? When do you want to plant those crops?

CHAPTER 7
Cover Cropping and Crop Rotation

Introduction

High tunnel production is intensive and may result in rapid declines in soil health. High tunnel soils often experience an accelerated decline in soil organic matter, nutritional imbalances, soil compaction, and a buildup of soilborne disease. If soil quality issues are not addressed proactively, crop yields and plant health will decline rapidly. A significant cause of declining soil health in high tunnels is a lack of crop rotation inside the tunnel.

Crop rotation is the practice of sequentially rotating plantings of different plant families on the same plot of ground (Image 7.1). Often, crops from the same family are susceptible to the same pests and diseases and tend to use the same nutrients. When crops from the same family are planted in the same ground each year, disease and nutrient imbalances can accumulate in the soil, limiting the profitability of current and future plantings.

While high tunnel production poses a few challenges to crop rotation, at least some degree of crop rotation is possible in most situations. High tunnel growers should thoughtfully design a crop rotation schedule that fits the goals of their operation. Without crop rotation, the soil inside a high tunnel can become unsuitable for crop production in just a few years. The presence and accumulation of soilborne diseases, such as bacterial wilt, may even necessitate moving a tunnel to a new location to continue using it. A well thought out and strategic crop rotation plan can prevent pests and diseases and help maintain the high yields of good quality produce a high tunnel system needs to remain profitable.

Crop Rotation

Designing an effective and profitable crop rotation plan can seem daunting. Following these steps can make developing a crop rotation plan simpler.

Designing a Crop Rotation Plan

1. Identify the goal or purpose of the rotation. Consider what you want to achieve with the crop rotation plan. An example could be maintaining optimum yields by preventing or minimizing the risk of soilborne diseases. Another goal might be crop diversification to spread economic risk over a broader range of crops and across different markets.

2. Create a list of crops you would like to grow and how much of each you plan to grow. If you plan to grow for profit, this crop list should consist of crops that can be grown profitably in the tunnel in your area. Creating a list of profitable crops will require some degree of knowledge about available markets.

3. Group the listed crops by important qualities, such as plant family (Table 7.1) or nutritional needs.

Image 7.1. An example of a simple four-year crop rotation.

Table 7.1. Common vegetable plant families. Rotate successive high tunnel plantings to different plant families to help disrupt disease cycles.

PLANT FAMILY	COMMON CROPS
Composite family (Asteraceae)	Endive, lettuce, sunflower
Goosefoot family (Chenopodiaceae)	Beet, spinach, Swiss chard
Gourd Family (Cucurbitaceae)	Cantaloupe, cucumber, pumpkin, squash, watermelon
Grass family (Poaceae)	Ornamental corn, popcorn, sweetcorn
Lily Family (Alliaceae)	Chives, garlic, leek, onion
Legume Family (Fabaceae)	Bush bean, lima bean, pea, pole bean
Mallow Family (Mavaceae)	Okra
Mustard Family (Brassicaceae)	Broccoli, brussels sprouts, cabbage, cauliflower, collard, kale, mustard greens, radish, rutabaga, turnip
Nightshade Family (Solanaceae)	Eggplant, pepper, potato, tomato
Parsley Family (Apiaceae)	Carrot, celery, parsley, parsnip

4. Consider seasonality and timing. Because crops are adapted to grow best in either a cool or warm environment, it is important to select a crop that will thrive during the season in which you plan to include it in your crop rotation plan. For example, if early spring markets are the target, select crops, such as tomatoes, peppers or eggplant, that fit this window. When growing for a year-round market, include a mix of warm- and cool-season crops in the crop rotation plan. Cover crops (see below) could also be included as part of a crop rotation plan by planting them between production windows.

5. Create a map of the available growing space and divide it into at least three even-sized areas. If only one tunnel is available, divide the tunnel into three or more equally sized sections. To effectively break disease and pest cycles, crops from the same plant family should not be planted in the same ground for at least three years. Dividing the available planting ground into at least three sections will help accommodate a three-year rotation.

6. Plan crop rotation sequences. This will require some knowledge of the crops you plan on growing as some crops will perform better when following a particular crop or crop family. The "Crop Rotation on Organic Farms: A Planning Manual" (https://www.sare.org/publications/crop-rotation-on-organic-farms/a-crop-rotation-planning-procedure/a-complete-step-by-step-rotation-planning-guide/) (Image 7.2) published by the Sustainable Agriculture Research and Education program (SARE) is a good resource for crop rotation planning. The manual includes tables that indicate which plant families are good predecessors for others and which crops should not follow each other. It also includes examples of crop rotation schedules from successful farming operations. While this manual focuses on crop rotation for larger field growers, the concepts and principles discussed are similar for smaller farms, and high tunnel growers.

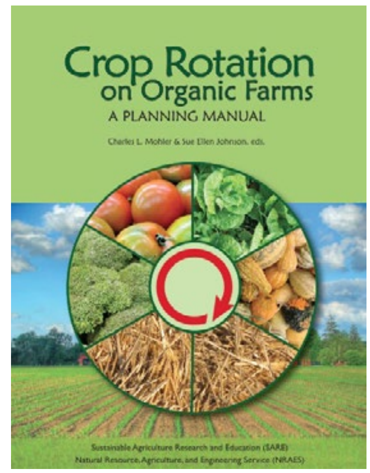


Image 7.2. Crop Rotation on Organic Farms: A planning manual.

7. Evaluate your plan often and refine it as needed to best meet your goals and needs.

As mentioned earlier, high tunnel production does present a few challenges to implementing a good crop rotation plan, particularly when the tunnel crops are being managed for profit. The three biggest constraints are:

- The need to maximize the 'real estate' inside a tunnel to produce the most profitable crop(s) every year to maximize the return on investment of the cost of the high tunnel structure.

- The potentially limited number of crops that can be grown profitably in a tunnel (see Chapter 6 -Crop Selection and Planting Dates) and that fit with your market and farm goals. For example, building a loyal customer base will likely require supplying the same crop at the same time each year, which limits some opportunities for crop rotation.

- Several common and profitable high tunnel vegetable crops fall into the same plant family (Table 7.1). The solanaceae family, for example, includes tomatoes, peppers and eggplant (among others), all common high tunnel vegetable crops. This means that ideally, after a planting of tomatoes, avoid planting not only tomatoes in that ground for at least three years, but peppers and eggplant as well.

When more than one tunnel is available, these limitations become less restrictive. However, with only one tunnel available, implementing a rotation plan can become difficult. One option for growers with a single available tunnel would be to divide the tunnel into three even sections and rotate crop families through these sections. (Image 7.3). This would allow them to grow their most desired crops every year while reducing the risk for disease buildup and other soil health problems. Growers who plan on using the tunnel to grow only one or two specific crops, and have the space and budget, may consider purchasing more than one high tunnel or a single movable tunnel (See Chapter 4 - High Tunnel Design) to make crop rotation planning easier. Having multiple tunnels, or a moveable tunnel, will make it easier to rotate a limited number of crops or grow the same crops annually without risking disease buildup or other soil health problems (Image 7.4).

Growers with a single tunnel should also consider incorporating non-vegetable crops into their rotation. Cut flowers, for example, are becoming more prevalent in high tunnels in Arkansas (Image 7.5). Several cut flowers, when incorporated into a high tunnel crop rotation plan, can help take up excess nutrients in the soil (lower soil EC levels, see Chapter 10 - Soil Health and Fertility Management) and create a physical and temporal break from common pests and diseases that impact a vegetable crop. For example, a University of Kentucky study indicated that following an early spring and sum-

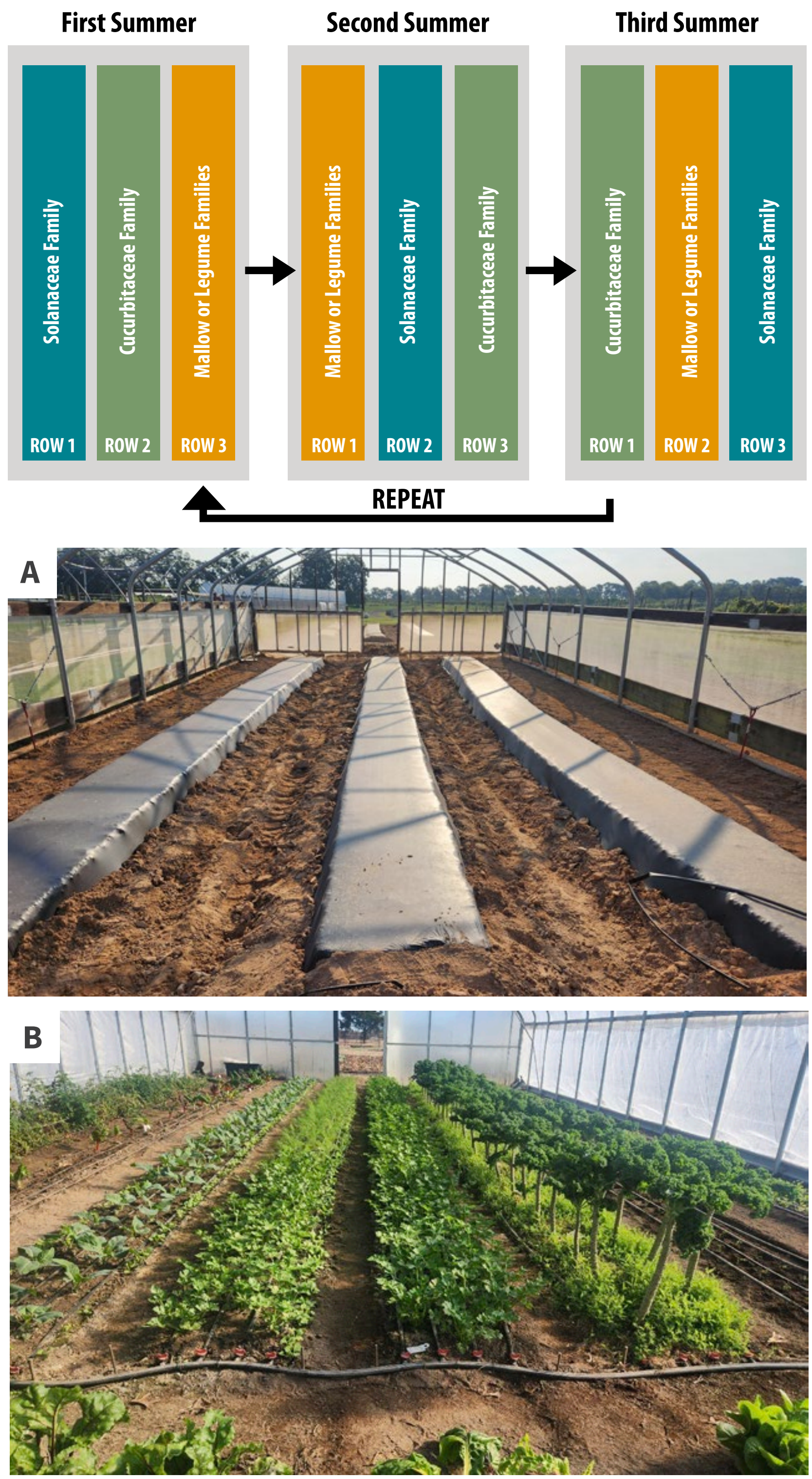


Image 7.3. An example of a spring/summer crop rotation in a single high tunnel. The tunnel was divided into three equally sized production rows. Plant families are rotated between the three rows, ensuring crops from a plant family are not planted in the same ground for three years (A). The Solanaceae family includes crops such as tomato, peppers, potatoes and eggplants. The Cucurbitaceae family includes crops such as cucumber, squash and cantaloupe. The Legume family includes crops such as beans (bush and pole) and peas (A). Image B shows a high tunnel divided into 16 rows. Crops are rotated through these 16 rows.

Image 7.4. Two moveable high tunnels. These tunnels can be moved comparably easily, allowing the tunnel to cover new ground each year. Drastically simplifying crop rotation scheduling.

mer high tunnel tomato crop with a fall cut flower crop could potentially disrupt disease and pest cycles enough to allow annual plantings of spring tomatoes.

Currently, there is little or no data to indicate if rotating cut flowers into a high tunnel rotation plan is economical. As with other profitable high tunnel crops, market demand will determine the economic benefit of high tunnel cut flowers. Possible options for cut flowers in a high tunnel include sunflower, amaranth, zinnia, cosmos and strawflower, with lisianthus, snapdragons and stock as cool season options.

Cover Crops

Cover crops are non-cash crops (not planted for harvest) planted to help maintain or improve soil health (Image 7.6). The benefits of incorporating a cover crop into a crop rotation plan are well documented and include increased soil organic matter, improved soil fertility, weed suppression, decreasing soil compaction and the disruption of pest and disease cycles. Despite their numerous benefits, many high tunnel growers are reluctant to include a cover crop in their planting schedule because they do not want to occupy the valuable space inside a high tunnel with a non-cash crop.

Summer cover crops: Studies conducted in high tunnels in Kentucky, Tennessee and Georgia have determined there is a six- to eight-week window during the summer where temperatures remain too hot inside a high tunnel for most specialty crops. With good crop scheduling this period can fall between the removal of early summer cash crops and the planting of a fall cash crop. This window can provide a great time to incorporate a heat-tolerant summer cover crop into a high tunnel crop rotation. Many warm-season cover crops can tolerate the high soil and air temperatures inside the tunnel during this period as long as they get adequate irrigation. Many of these crops can often reach peak biomass within four weeks and, due to the warm conditions inside the tunnel, will decompose within the remaining two to four weeks after being terminated and incorporated into the soil.

Winter cover crops: Depending on the farm goals for the high tunnel, a cover crop could also be planted in place of a winter cash crop. Because of the warmer soil conditions inside a high tunnel, cool-season cover crops can be planted as much as four weeks later than the recommended planting window in an open field. If the cover crop is planted too late, however, the diminishing light levels and cooler temperatures may prevent it from producing suf-

Image 7.5. Cut flowers growing inside a high tunnel in Arkansas

Image 7.6. A high tunnel with a terminated cover crop.

ficient biomass. Depending on temperatures experienced inside the tunnel, a winter cover crop may not go dormant during the winter months. Growth may be slow, however, and it could take several months for a winter cover crop to reach peak biomass. Take this timing into consideration to ensure a winter cover crop does not interfere with the timing of early spring plantings.

When selecting a cover crop be sure to consider the following:

1. **Desired benefit**. A single cover crop may not provide all the benefits associated with cover cropping. Mustard crops, for example, are great at suppressing diseases but will not fix nitrogen or produce much biomass to suppress weeds. When including a cover crop in a high tunnel crop rotation plan, it is important to select a cover crop that will provide the most benefit to the next cash crop. Table 7.2 lists several summer and winter cover crops that have performed well in high tunnels in several states in the Southeastern United States, as well as the soil and plant health benefits they provide.

2. **The length of the planting window**. A cover crop will not only need time to grow but will also need time to be incorporated into the soil and decompose before the next cash crop is planted. Cover crops with thicker, more ligneous stems or those that produce a lot of biomass, like grasses, will take longer to break down. The cooler soil conditions during winter months or dry soil conditions of mid-summer will slow the decomposition of a cover crop. Cover crop residue that is not sufficiently decomposed can interfere with the planting of the following crop. When limited on time consider selecting a quick-growing cover crop or terminating it earlier, before it reaches peak biomass.

3. **Needed equipment**. Ensure the tunnel can accommodate the equipment needed to establish, terminate and incorporate a cover crop.

4. **Green bridges**. A cover crop could potentially harbor pests and diseases and transfer them to a subsequent cash crop planting (see Chapter 8 – Pest and Disease Management Strategies). To prevent this, wait at least two weeks after terminating a cover crop before planting the next cash crop. It is also a good practice to select a cover crop that is a poor host for plant damaging nematodes and other diseases common to your cash crops. This will help break pest and disease cycles.

Table 7.2. Winter and summer cover crops tested in high tunnels in the Southeast United States. Table modified from Coolong et al. 2021a and b.

Cover Crop	Benefits					
	Nitrogen Fixing	Nitrogen Scavenging	Soil Building	Weed Suppression*	Host for Southern RKN	Quick Growth
Winter Cover Crops						
Annual Ryegrass	No	Good	Good	Good	No	Good
Austrian Winter Pea	Yes	Good	Very good	Excellent	Yes	Very good
Cereal Rye	No	Excellent	Excellent	Excellent	No	Excellent
Crimson Clover	Yes	Good	Good	Very good	Yes	Good
Mustard	No	Excellent	Very good	Good	Yes	Very good
Oilseed Radish	No	Excellent	Very good	Fair -Excellent	No	Very good
Winter oat	No	Very good	Very good	Excellent	No	Excellent
Winter Wheat	No	Very good	Very good	Very good	Variable	Very good
Summer Cover Crops						
Cowpea						
Chinese Red	Yes	Fair	Fair	Fair	Yes	Good
Iron and Clay	Yes	Fair	Good	Fair	No	Good
Millet						
Pearl	No	Good	Good	Good	Variable	Excellent
Japanese	No	Good	Good	Good	Yes	Excellent
Sunn Hemp, various cultivars**	Yes	Very good	Very good	Good	No	Fair
Sorghum-sudangrass	No	Very good	Very good	Excellent	No	Excellent

*Crop stand and the amount of biomass produced will influence weed suppression **Some states restrict the sale of Sunn Hemp seed

5. **Irrigation**. Irrigation will be needed to support cover crop growth and decomposition.

Conclusion

When crop rotation is not regularly practiced in a high tunnel, soil health can suffer and detrimental pests and diseases will increase. Although crop rotation in high tunnel production presents challenges for growers, with careful planning some degree of crop rotation is usually possible. This can disrupt detrimental pest cycles while helping to maintain or improve soil health. To achieve and sustain the high yields and good produce quality associated with high tunnel production, and to keep a high tunnel profitable, growers should put in the necessary time and effort needed to institute an effective crop rotation strategy.

Additional Resources

Crop Rotation

Mohler, C. L. and S. E. Johnson. 2020. Crop Rotation on Organic Farms: A Planning Manual. Sustainable Agricultre Research and Education (SARE) program. www.sare.org/publications/crop-rotation-on-organic-farms/a-crop-rotation-planning-procedure/a-complete-step-by-step-rotation-planning-guide/

Cover cropping

Coolong, T., Gaskin, J., Haramoto, E., Jacobsen, K., Moore, J., Phillips, T., Rudolph, R., & Wszelaki, A. (2021a). Cool-season cover crops for high tunnels in the Southeast (Publication No. CCD-SP-18). University of Kentucky Cooperative Extension Service Center for Crop Diversification.

Coolong, T., Gaskin, J., Haramoto, E., Jacobsen, K., Moore, J., Phillips, T., Rudolph, R., & Wszelaki, A. (2021b). Warm-season cover crops for high tunnels in the Southeast (Publication No. CCD-SP-19). University of Kentucky Cooperative Extension Service Center for Crop Diversification.

Coolong, T., Gaskin, J., Haramoto, E., Jacobsen, K., Moore, J., Phillips, T., Rudolph, R. and A. Wszelaki. 2020. Covers Under Cover: Managing Cover Crops in High Tunnels. CCD-SP-16. Lexington, KY: Center for Crop Diversification, University of Kentucky College of Agriculture, Food and Environment.

Rudolph, R., Larson, J., Sheffield, A., Shepherd, J., Mark, T. and N. Gauthier. 2021. Rotating Cut Flowers Within a Tomato High Tunnel Production System. University of Kentucky College of Agriculture. CCD-FS-23.

Begin thinking through possible crop rotations inside your tunnel:

1. What is the main goal of your crop rotation plan?

2. What crops do you plan to grow in your high tunnel? Group them by plant family.

3. Further group crops by seasonality (cool or warm season crops):

4. Create a map of your high tunnel space and divide it into equal sections:

5. Begin planning your crop rotation sequence:

CHAPTER 8
Pest and Disease Management Strategies

Introduction

When high tunnels first gained popularity in the United States, they were touted as a means to decrease insect and disease pressure. Many early production guides even cited reduced pest pressure as one of the economic benefits of a high tunnel. It was presumed that the tunnel, like a greenhouse, acted as a physical barrier, preventing insects and diseases from reaching the crops. But high tunnels are not greenhouses. While greenhouse producers can seal off the internal growing environment from the pest pressures outside, high tunnel growers cannot. Tunnel producers must open doors, vents and sidewalls to release excess heat and control humidity levels (Image 8.1). This leaves the tunnel open and vulnerable to infestation by several types of pests, especially insects and mites.

While the high tunnel's protected environment can promote faster plant growth and earlier harvests, it also favors rapid population growth of some pest species. The absence of natural mortality events, such as rainfall, coupled with faster reproductive cycles, can quickly lead to damaging pest populations. This is especially true for insects and mites that do well in arid environments. The lack of rainfall can also decrease the impact of entomopathogens (pathogens that grow on or within insects, often killing them) that help suppress soft-bodied insects and many pestiferous mite species in field production.

Studies conducted by several universities have shown that the density of insect pests is often higher inside a high tunnel when compared to nearby field production, necessitating increased pesticide applications to keep insect populations below economic thresholds. Insects and other arthropods that have become common high tunnel pests include aphids, mites, thrips, white flies and several types of lepidoptera. While some insect and mite pest species tend to be more common, the optimal and protected conditions inside a tunnel can cause any unaddressed pest to quickly become an issue. Often small, soft-bodied insects that are common in tunnels also vector, or spread, diseases, making these vectored diseases more prevalent in tunnels than in the field.

While tunnels often increase insects and other pests, they can help reduce pressure from some pathogens, specifically pathogens that rely on rainfall or splashing water to infect or spread throughout a planting. However, the warm and humid environment of a tunnel can be favorable for other disease pathogens such as powdery mildew and grey mold. These diseases can be reduced through effective integration of cultural control strategies such as climate and crop management. Management practices that improve airflow and venting can reduce humidity and temperature and create less favorable conditions for many foliar fungal diseases. Crop rotations and irrigation management can also help reduce disease pressure and buildup. So, while insect pressure is often higher inside a high tunnel than in the field, disease pressure can be lowered with proper management.

Although insects and pathogens are often given priority attention, weeds can also become an issue if not addressed. It's important to prevent weeds from establishing and to remove any weeds present near crops. Weeds compete with crops for resources such as light and nutrients. It's important to prevent weeds from establishing and to remove any weeds present near crops. Weeds also create what entomologists have termed a "Green Bridge," or the movement


Image 8.1. Opened end and sidewalls on high tunnels to vent out excess heat the humidity.

of pests (insect or disease) to any vegetation in or around a field or high tunnel after the crop has been removed. Pests can remain alive and active in this vegetation and quickly infest new transplants or seedlings brought into the tunnel. Essentially, this vegetation creates a bridge for pests to cross from one planting to another. This allows pests to establish earlier, faster and produce more generations in a season (Image 8.2). Earlier establishment also exposes plants to pest pressure when they are young and much more susceptible to damage, which can lead to the loss of entire plantings.

Image 8.2. Weeds growing inside a high tunnel. Left untreated these weeds can harbor disease and insect pests and become a green bridge to infect successive plantings.

Introduction to Integrated Pest Management

Whether organic or conventional production practices are used, a proactive pest management plan is necessary for successful high tunnel production. An integrated pest management, or IPM, program is a sustainable decision-making approach that uses a long term approach paired with a combination of pest managemen practices to manage pests while considering the economic and ecological impact of both the management tactics and the pest. Approaches to pest management can be grouped into four main categories:

Biological Control: This method is based on the impact of natural enemies on plant pests. The most common example of biological control is termed "conservation biological control," or the integration of naturally occurring predators, parasitoids and pathogens that offer free pest control. Another example of biological control is the release of natural predators such as ladybeetles or predatory wasps that target and kill aphids. The partly closed nature of a high tunnel often makes biological methods more effective than under field conditions. However, the release timing of a natural enemy is important for a biological control practice to work successfully, and repeated releases are often necessary.

Cultural Control: Cultural control is the manipulation of the growing environment or plant to reduce the impact from pests. Practices often focus on minimizing the introduction and spread of a pest inside a production system. Good cultural practices are the foundation of a good IPM program. This is particularly true for high tunnel production due to how quickly pest outbreaks can happen once a pest is introduced to the system. Some examples of cultural control practices are good sanitation and crop rotation. Weed control is a sanitation practice that can eliminate green bridges and disrupt insect and disease cycles.

Mechanical and Physical Control: These methods use physical or mechanical means to directly kill or exclude a pest or create environments that are unsuitable for pests. Examples include soil solarization, plastic or fabric mulches, insect netting and proper trellising.

Chemical Control: This is the use of conventional or organic pesticides. In a well designed and researched IPM program, pesticides are used only as needed. Correctly identifying a pest or diseases can improve a pesticides effectiveness and should dictate pesticide selection and application timing. Pest identification can help determine when a pest will be most susceptible to a pesticide application and ensures selected chemicals have a proven efficacy against that pest. In addition, understanding what diseases your plants are at risk for prior to planting will help to dictate which preventative fungicides will yield the most value. Note that organic pesticides work best as preventive sprays and will have little impact on a severe outbreak.

Selecting the correct combination of strategies can not only minimize yield losses to pests but can help lessen the economic cost and ecological impact of an IPM program. IPM programs should always have a long-term and economic approach, focused on how management tactics this crop cycle or year can help minimize impact and increase profitability in subsequent years.

Image 8.3. High tunnels situated in a sunny open area where adequate air flow is achievable.

IPM Strategies for High Tunnel Production

High Tunnel Placement and Design

An effective high tunnel IPM program begins with selecting a location and tunnel design. Sunlight, wind flow and soil drainage capacity at a high tunnel site will influence pest pressures inside a tunnel. A good location will be sunny with adequate wind flow and soil drainage. High tunnels oriented so major vent openings are perpendicular to the prevailing wind will have better air movement within the structure (Image 8.3). Increased air movement will lower humidity levels, which in turn will lessen favorable conditions for diseases. Better air movement within a high tunnel will also make temperature management more effective.

Soilborne pathogens thrive and spread quickly at sites where soil drainage is poor, runoff flows through the tunnel, or puddling often occurs. Properly preparing the soil and installing drainage systems before constructing a high tunnel can prevent pest pressure caused by poor drainage.

When selecting a high tunnel design, consider its ventilation capacity. Taller sidewalls or gable vents may cost more upfront but could improve the success of IPM strategies throughout production. For more information on site selection and tunnel design, see Chapter 3 – Site Selection and Chapter 4 High Tunnel Design.

Have A Plan of Action

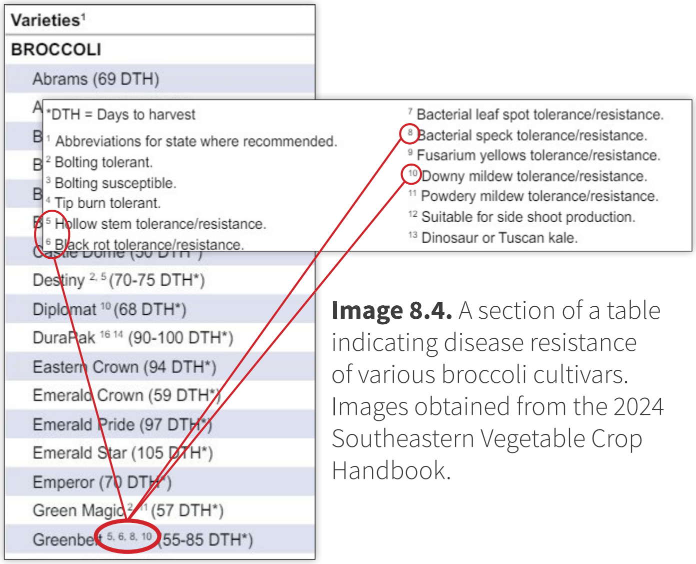
Whether using organic strategies or more conventional agricultural practices, have a response plan prepared before planting the tunnel. Be aware of potential pest issues in the area and be familiar with pests the planned crops are susceptible to. Having a plan of action prepared in advance allows growers to acquire and have on hand any necessary supplies to respond rapidly to a pest situation. It also aides in employing preventive strategies, such as fungicides, necessary to successfully grow crops in warm, humid environments.

A plan of action will prevent or slow down some pest issues, accelerate response time and could head off population explosions that would otherwise reduce yields and profits. Whatever pest issue may arise, be prepared to react fast. Tunnel environments can cause rapid population growth and issues can get out of control quickly. A fast response will prevent severe outbreaks and crop loss. Monitor the effectiveness of implemented strategies and adjust them as needed for future plantings.

Use Resistant Cultivars

For most crops, cultivars have been bred with resistance to many pathogens (fungi, bacteria, virus, nematodes and oomycetes). Using resistant cultivars is an important cultural management strategy that can greatly limit problematic diseases. While there are varying degrees of resistance (ranging from completely resistant to sporadically resistant), selecting a crop and/or cultivar with a level of resistance to many common pathogens will make disease management easier (Image 8.4).

Unfortunately, resistant cultivars have not been developed for all important pathogens. Using resistant cultivars should not be the only IPM strategy employed to control disease inside a tunnel. Most seed catalogs will indicate if a cultivar has shown resistance to any diseases and what those diseases are. The Southeast Vegetable Crop Handbook also contains tables with crop and cultivar disease-resistant information (https://www.uaex.uada.edu/publications/pdf/MP584.pdf).



Varieties[1]
BROCCOLI
Abrams (69 DTH)
Destiny [2, 5] (70-75 DTH*)
Diplomat [10] (68 DTH*)
DuraPak [16 14] (90-100 DTH*)
Eastern Crown (94 DTH*)
Emerald Crown (59 DTH*)
Emerald Pride (97 DTH*)
Emerald Star (105 DTH*)
Emperor (70 DTH*)
Green Magic [2, 11] (57 DTH*)
Greenbelt [5, 6, 8, 10] (55-85 DTH*)

*DTH = Days to harvest
[1] Abbreviations for state where recommended.
[2] Bolting tolerant.
[3] Bolting susceptible.
[4] Tip burn tolerant.
[5] Hollow stem tolerance/resistance.
[6] Black rot tolerance/resistance.
[7] Bacterial leaf spot tolerance/resistance.
[8] Bacterial speck tolerance/resistance.
[9] Fusarium yellows tolerance/resistance.
[10] Downy mildew tolerance/resistance.
[11] Powdery mildew tolerance/resistance.
[12] Suitable for side shoot production.
[13] Dinosaur or Tuscan kale.

Image 8.4. A section of a table indicating disease resistance of various broccoli cultivars. Images obtained from the 2024 Southeastern Vegetable Crop Handbook.

Image 8.5. Strawberry plug plants already infected with Anthracnose, a potentially devastating fungal disease.

Begin With Clean Plants

Pests can be carried into a high tunnel on infected transplants (Image 8.5). Carefully inspect plants for signs of disease or harmful insects and mites before bringing them into a tunnel. If purchasing transplants, acquire them from a nursery that has a reputation for supplying disease- and insect-free plants. Seeds can also carry pathogens. Purchase disease-free seeds from a reputable dealer and consider using treated seeds to lower the risk of introducing a disease from this source.

Scouting and Monitoring

The main purpose of scouting is to detect a pest before it becomes economically damaging. Scouting also provides valuable information such as which pests are present and changes in pest density. This information can be used to determine if action is needed and indicate which management strategies have been most effective. Being familiar with possible insect and mite pests can help determine which parts of the plant should be checked. Spider mites, for example, are usually found on the undersides of leaves, only appearing on the upper surfaces when populations are extremely dense.

General Scouting Tips:

- Scout regularly and often. Scout young plants (new transplants or seedlings) at least once a week, although twice a week is preferable if labor and time allow.
- Set a regular scouting schedule and, when possible, have a designated, trained scout who knows what to watch for and has access to necessary tools. For a list of helpful scouting tools see Additional Resources – IPM Tool Kit.
- For larger summer crops (tomatoes, peppers etc.), check at least five plants/100 ft of row.
- For leafy greens (lettuce, spinach etc.), check at least 10 plants/100 ft of row.
- If more than one crop is present in a single tunnel, check plants from each crop type. Because one crop may be more susceptible to a pest than another, early detection may be missed if only plants from the more resistant crop are checked.
- Similarly, if multiple cultivars of a single crop are present in a tunnel, check plants from each cultivar. Cultivars can vary in their degree of resistance to the same pest and early detection may be missed if only plants from the more resistant cultivar are checked.
- Check plants across the tunnel, from each side of a planting and throughout the row. Avoid just looking at plants from a single area, even if several pests are found that require immediate control.

Even with a good scouting program, some insect pests can be difficult to spot as they hide in the folds and crevasse of plants. Because of this, the damage they cause is often the earliest evidence that they are present. This makes abnormal plant growth a good indicator of the pest's presence. This is particularly true for disease monitoring (Image 8.6). Abnormal growth can include leaf discoloration or cupping. While it is ideal to detect a pest before damage is visible, it is a good practice to ensure anyone working with a crop is familiar with what a healthy plant looks like so abnormal growth can be spotted early and quickly. Additionally, many insects are attracted to plants in decline. Becoming familiar with the early signs and symptoms of common pests can expedite identification and reaction time.

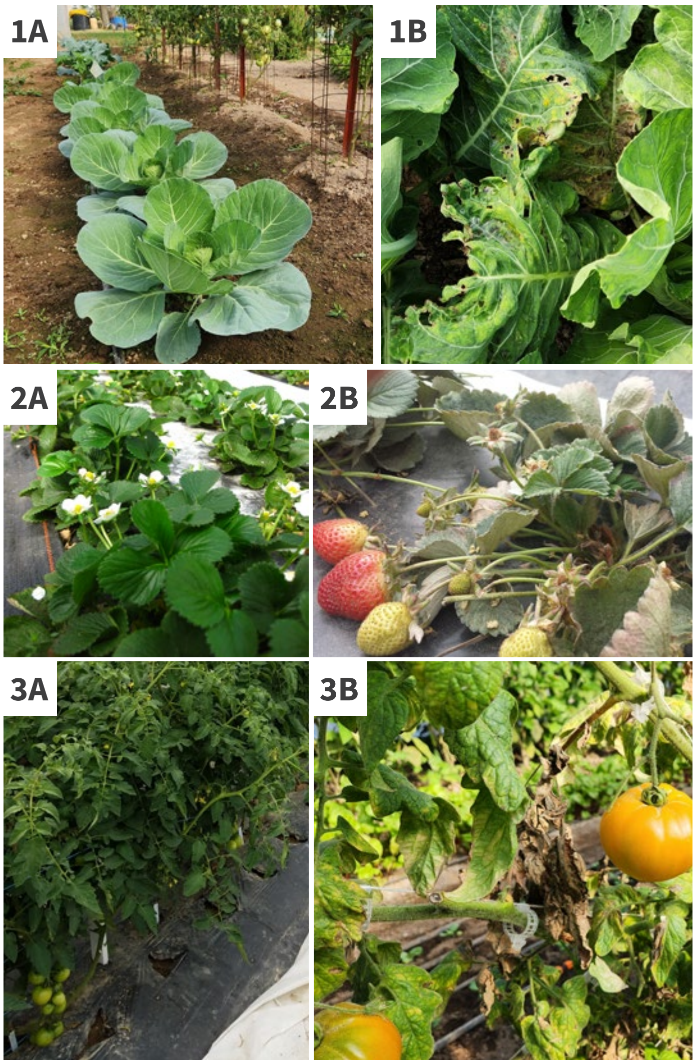


Image 8.6. Examples of healthy and unhealthy plants. Healthy cabbage plants (1A) and cabbage leaves deformed by a plant pathogen (1B). Healthy strawberry plants (2A) and plants infested with two-spotted spider mites (2B). And healthy tomato plants (3A) and tomatoes infected with tomato blight (3B).

Another Scouting Method:

Place a piece of white paper beneath a leaf or plant and gently, but vigorously, shake the leaf/plant. Look for mites, aphids, thrips, or other potential pests on the paper. Or a clear sealable baggie can be placed over the leaf before shaking. Remove and seal the baggie after shaking the plant. Place the baggie over a piece of white paper and look for potential pests. This method would allow samples to be collected in the field and analyzed later if needed.

If abnormal plant growth is apparent but the cause proves difficult to identify, samples can be collected and either submitted to the Arkansas Plant diagnostic lab (uaex.uada.edu/yard-garden/plant-health-clinic/default.aspx) or taken to your local extension office (uaex.uada.edu/counties/) for identification. Both sources can also help determine a good control strategy to prevent further damage.

Sticky cards can be useful in determining the presence of flying insects, such as thrips, white flies and flea beetles. Sticky cards come in different colors, with yellow and blue being the most common (Image 8.7). While yellow is attractive to most insects, blue is often used for thrips. Generally, one sticky card is placed every 100 feet of row, but this spacing can be adjusted as needed. Replace cards as they get dirty or crowded. Remember, sticky cards are only helpful in monitoring flying insects. Visual inspection of plants will still be necessary. Sticky cards and other traps are not effective in reducing pest density and are not an effective form of pest control.

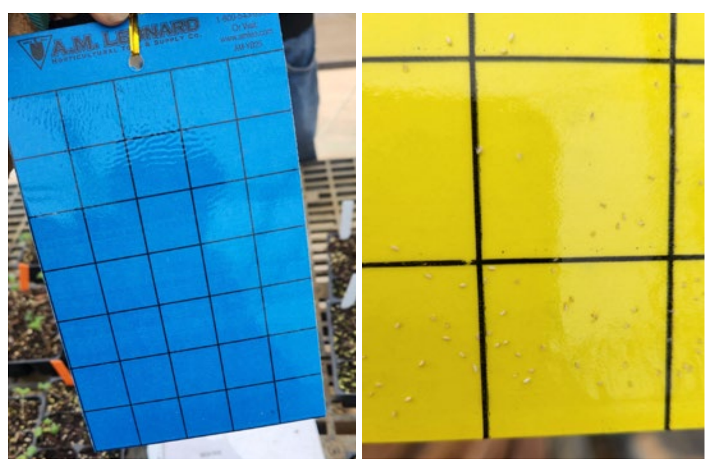


Image 8.7. A blue sticky card and a yellow sticky card with captured white flies.

Keep a Record

Good records can indicate when annual pests are likely to appear each season. This allows growers to be prepared with needed supplies before outbreaks occur. This is particularly beneficial for growers who want to use natural predators to control insect pests. Records can also indicate “hotspots” within a tunnel and whether populations are spreading or getting larger. Good records can show which IPM methods work and help pest management specialists advise on action plans. Helpful information to collect includes dates, crop information (such as growth stage and cultivar), type and severity of pest and presence of natural enemies. For an example of a pest record sheet see Additional Resources – Example of a Scouting Record.

Environment Management

Pests, like the plants they infest, have environmental conditions that they prefer and thrive in. Careful monitoring and management of a tunnel’s environment can restrict the spread and severity of diseases.

While environment management can noticeably lessen disease pressure, insect pests are less affected. The temperatures at which plants thrive are also favorable for many insects. Winter production is a notable exception to this. Plants that have been adequately hardened off to colder temperatures can grow well at much lower temperatures than insects. Restricting the use of row covers to “only when necessary” can help limit insect and mite species from feeding and thriving.

Adequate ventilation and airflow is arguably the most important climate management practice in reducing plant disease. Prolonged periods of high relative humidity will promote the incidence and severity of diseases, such as grey mold and powdery mildew, inside a tunnel. When done correctly, venting a tunnel will maintain air circulation in and around a plant canopy, reducing humidity levels and ultimately reducing leaf wetness.

High tunnels are vented by opening or closing side/endwalls and other vents, allowing the cooler, drier outside air to enter, lowering relative humidity levels (Image 8.8). Even during a humid Arkansas summer, adequate ventilation can help lower relative humidity inside a tunnel. If a

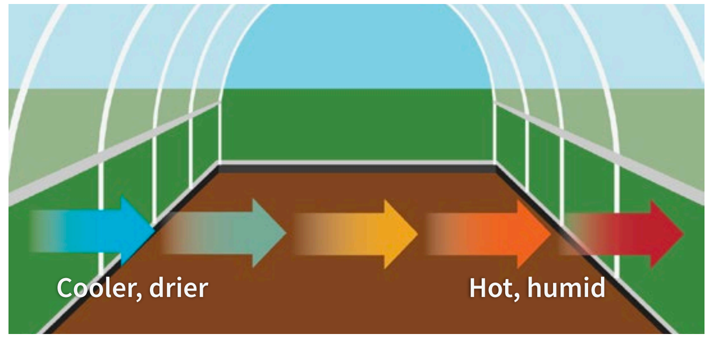


Image 8.8. Cooler, drier air enters a tunnel through open end and sidewalls. Lowering the temperature and relative humidity levels inside the tunnel. This can help ease some disease pressure.

tunnel is situated in an area with poor wind flow, fans may be necessary to help facilitate air movement throughout the tunnel and help reduce humidity. Relative humidity levels between 30-70 percent during the day are usually low enough to inhibit the growth and spread of a pathogen.

Ventilation is also used for temperature management. Plants exposed to temperatures outside their normal growth range or to rapid temperature fluctuations can be more susceptible to pathogens and may become more attractive to insect pests. While temperature and humidity management can be a twice-daily activity in the fall and spring months, the extra labor is worth it as plants will be healthier and pest pressure will be suppressed.

Sanitation

Good sanitation practices are critical for successful high tunnel production, especially organic production. Any surface or tool (such as pruning shears or trellising structures) should be routinely and thoroughly disinfected to reduce the probability of spreading insects or diseases. To help prevent infecting healthy plants, avoid handling plants when wet, and workers should wash their hands frequently. Workers should avoid moving between tunnels (or fields) with contaminated clothing, shoes, or tools. Diseases such as fusarium wilt have been known to be transported in dirt on shoes. Sanitizing hands and tools after touching infected plants can also help prevent the spread of pests. Ideally, diseased plants should be carefully and quickly removed from the production area throughout the season. Diseased or dying plants can lead to increased levels of pathogens and insects while not yielding much fruit.

Image 8.9. Plant material and weeds left inside a tunnel after a crop was removed. Insect and disease pests can live on this debris and move into the next planting.

Weed management is also a crucial sanitation practice. The presence of weeds or volunteer plants in or around a tunnel can harbor insects and diseases and act as green bridges for many pests. Weeds can also negatively affect airflow within a tunnel, leading to higher disease pressure. Removing weeds in and around a tunnel can limit the survival of pathogens and lower the amount of disease inoculum in the production area.

At the conclusion of a production cycle, all plant material, specifically pest-infested material, should be removed from the tunnel and destroyed or composted (Image 8.9). Just as weeds can form green bridges, dying plants or decaying plant debris left within a tunnel can also create a green bridge as insects move from the dying plant in search of food.

To truly avoid a green bridge, any green plant material should be removed from inside and around the tunnel for at least one to two weeks before planting. Plant material is a reservoir for pathogens causing plant diseases. Repeated tillage of plant material into the soil can accelerate the buildup of disease in a high tunnel. Compost or debris piles should be kept as far from the high tunnel as possible. If piles are placed too close to a tunnel, they can also become bridges for diseases and insect pests as well as harbor rodents that may feed on tunnel crops.

Crop and Soil Management

Planting Arrangement: While it is often tempting to increase plant density when growing inside a tunnel, optimal plant spacing, adequate trellising and timely pruning can all help improve airflow within a canopy (Image 8.10). This will help keep intra-canopy humidity lower, decreasing disease pressure around the plants. Restrictions in air movement due to poor crop management can create "hotspots," or areas within the tunnel that have an elevated incidence of, or risk for, pest outbreaks. Irrigation systems that avoid wetting leaves and irrigation programs that water only as needed can also minimize pest pressure.

Soil Health: Plants grown in healthy soils have shown improved resistance to pest infestation. A healthy soil will have adequate, but not excessive, levels of nutrients, organic matter, minimal compaction and good water storage and drainage. Studies have shown that plants are more attractive to insect pests, such as aphids and mites, when there is an overabundance of nitrogen in the soil. Regular soil testing can help monitor soil nutrient levels and offer suggestions on fertility programs. Plants grown in soggy, or poorly drained soils will experience higher pressure for soilborne diseases and pests.

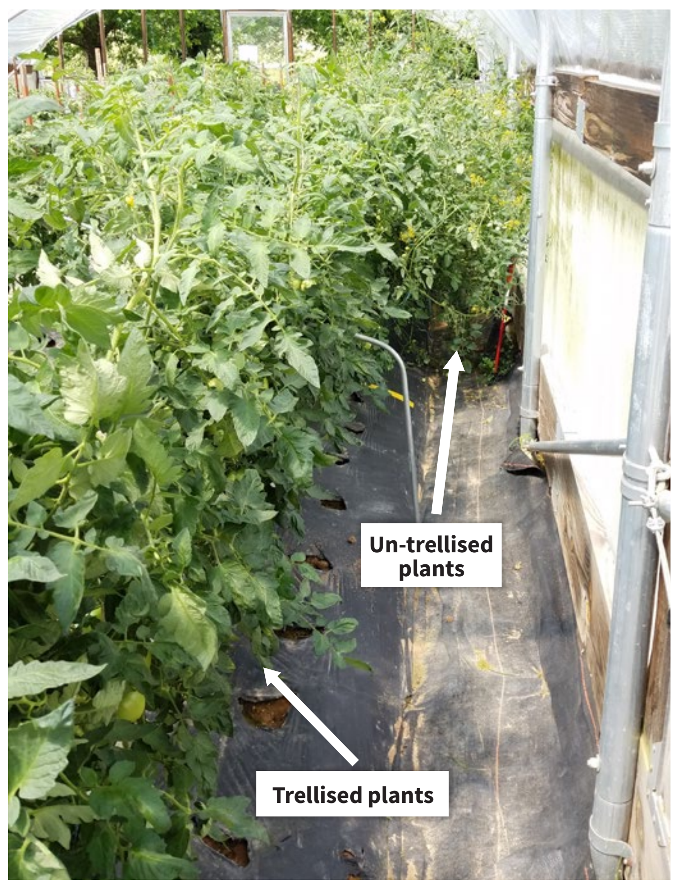


Image 8.10. A row of tomato plants where only half was pruned and trellised. Air flow in and around the pruned and trellised plants was notably better.

Table 8.1. Common vegetable plant families. Rotate successive high tunnel plantings to different plant families to help disrupt disease cycles.

PLANT FAMILY	COMMON CROPS
Composite family (Asteraceae)	Endive, lettuce, sunflower
Goosefoot family (Chenopodiaceae)	Beet, spinach, Swiss chard
Gourd Family (Cucurbitaceae)	Cantaloupe, cucumber, pumpkin, squash, watermelon
Grass family (Poaceae)	Ornamental corn, popcorn, sweetcorn
Lily Family (Alliaceae)	Chives, garlic, leek, onion
Legume Family (Fabaceae)	Bush bean, lima bean, pea, pole bean
Mallow Family (Mavaceae)	Okra
Mustard Family (Brassicaceae)	Broccoli, brussels sprouts, cabbage, cauliflower, collard, kale, mustard greens, radish, rutabaga, turnip
Nightshade Family (Solanaceae)	Eggplant, pepper, potato, tomato
Parsley Family (Apiaceae)	Carrot, celery, parsley, parsnip

Crop Rotation: Crops in the same plant family are often susceptible to the same disease and insect pests. When these crops are planted in succession in the same ground or tunnel, soilborne pathogens can balloon. A good, well-thought-out crop rotation plan will disrupt these disease cycles and prevent pressure from building. Avoid successive plantings of a crop, or crops in the same family, in the same high tunnel (Table 8.1). If only one tunnel is available, crop rotation can become difficult. Consider dividing the tunnel into distinct sections and rotate crops through these sections. A three-year rotation schedule is ideal to maximum the benefit of this practice, but even just rotating every other year will yield many benefits. If soilborne pathogens reach damaging levels, consider using soil fumigants, solarization or relocating the tunnel. For more information on crop rotation schedules see Chapter 7 – Cover Cropping and Crop Rotation.

Soil Solarization: Soilborne pathogens can cause significant reductions in crop productivity and profitability. Soil solarization is an environmentally friendly, non-pesticide method of controlling soilborne pests such as nematodes, bacterial diseases and weed seeds. This method works by trapping heat from solar radiation beneath a tarp or clear plastic sheet and raising soil temperatures to levels that can kill soil pests and weed seeds (Image 8.11). To work effectively, these high soil temperatures need to be maintained for extended periods. It is often recommended to keep soil covered for a minimum of four weeks during a hot sunny time of year. Soil solarization will also kill beneficial soil organisms and organic matter should be incorporated at some point afterward to help replace these beneficial organisms. If soil conditions continue to deteriorate and if pest pressure is extreme, it may be necessary to move the tunnel to a new location with healthy soils.

Steps for Soil Solarization:

Step 1: Prepare the area. Smooth and clear the soil of debris. Too many soil clods or litter will inhibit the plastic from creating a good seal over the soil.

Step 2: Wet the soil. this can be done before or after laying the plastic. If wetting before, cover the soil soon afterward to avoid drying. For the best results, try to wet the soil to a depth of at least 12 inches.

Step 3: Lay the plastic. The plastic should be pressed tightly against the soil and sealed along the edges. Soils heat better when the plastic is tight, and the edges completely sealed.

Step 4: Solarize the soil. To work properly, soils need to maintain a daily temperature of 110 – 125°F or higher in the top 6 inches. Cooler soils will need to remain covered longer. Done during the warmest time of year, covering the soil for 4 – 6 weeks is usually adequate for control of most soilborne pests or weed seeds.

Step 5: Remove the plastic: The treated area can be planted right away. While removing the plastic be careful not to disturb the soil near the edges where weed seeds or diseases may still be present. Cultivating too deeply can bring seeds or diseases from deeper soil layers, where lethal temperatures were not reached, to the surface.

Plastic selection: Plastic color and thickness can influence the effectiveness of a soil solarization treatment. For example, thinner plastics can achieve warmer temperatures but are more susceptible to tearing. Clear or black plastics are most common. When choosing a plastic type, select what will work best for the area and farm goals.

Image 8.11. A black plastic tarp covering the floor of a high tunnel to solarize it to help control soilborne diseases, nematodes, and weeds.

Pesticides

Both organic and conventional chemical control methods are generally available for use within a high tunnel, although label restrictions may exist. Before applying any chemical, read the product's label to understand all safety precautions and restrictions. Remember, the applicator is ultimately liable for any restrictions listed on the label. The label is the law.

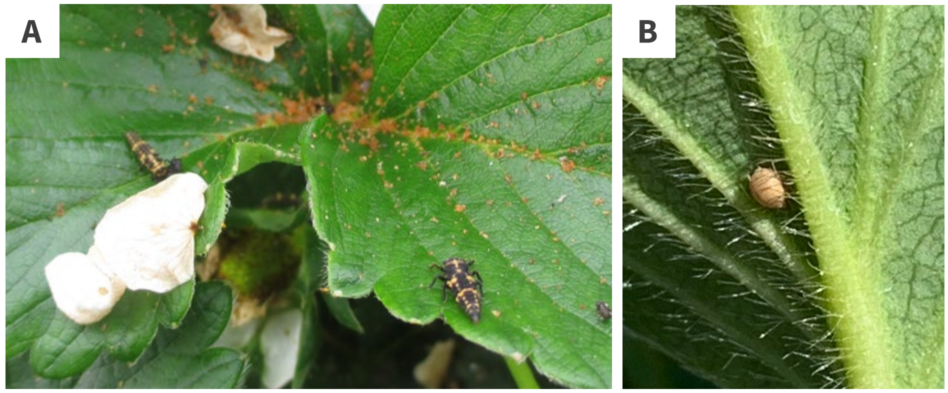


Image 8.12. Beneficial lady beetle larva released to control aphids in a strawberry planting (A) and an aphid that has been parasitized by a natural predator (B).

When applying a chemical inside a closed tunnel, follow greenhouse application restrictions. Many chemicals are specifically not labeled for use in greenhouses and should not be used in tunnels when sides cannot be opened. When applying a pesticide, keep an eye on chemical temperature restriction, as it is often warmer inside the tunnel. Be wary of applying any oil-based pesticide or emulsifiable concentrate formulations when temperatures reach 80-90°F, especially on the tunnel's west side in the evening.

The targeted pest should influence the selection and application timing of a pesticide. This will help avoid unnecessary applications, or the application of a pesticide that is ineffective in controlling that pest. Most pesticides will kill natural enemies, so a pesticide that does not kill the targeted pest will still negatively impact the free biological control received from these natural enemies. The MP144 guide (uaex.uada.edu/publications/mp-144.aspx) and the Southeastern Vegetable Crop Handbook (https://www.uaex.uada.edu/publications/pdf/MP584.pdf) are both available online and can help with pesticide selection and application timing. Remember that for many diseases, the most effective time to apply a fungicide is before symptoms become visible, and once symptoms are visible fungicides are less effective. Many economically damaging diseases are common in the southeast on almost all fruit and vegetable crops, and preventive fungicide sprays are necessary.

Biological Control – Release of Natural Enemies

Natural enemies, often called beneficials, can be introduced to a production system by purchasing and releasing them. (This is also called augmentative biological control.) If purchasing a beneficial, it is necessary to identify the targeted pest so the correct beneficial can be obtained and released.

A beneficial should be introduced while a pest population is still low. Releasing them too late can lower the impact a beneficial has on pest control. Often, multiple releases are necessary to maintain control throughout a crop cycle. Some commonly purchased natural enemies include predatory mites, lady beetles, praying mantises and parasitic wasps and flies (Image 8.12). Not all insects available for purchase will be effective at reducing pest populations.

Given the open nature of tunnels, predatory mites used to manage spider mites and other pest mite species are currently the only good augmentative biological control measure for tunnels. Populations of beneficials can be attracted to and encouraged within a tunnel by including flowers or other plants that attract them. Plants in the carrot, legume and mustard families are great for attracting beneficial insects.

The best way to encourage natural enemies is to avoid insecticide applications when possible. However, once pest populations reach economically damaging threshold, insecticides are necessary as natural enemies will not reduce pest populations quickly enough to save yields. A list of beneficials that can be purchased can be found in the Southeastern Vegetable Production Handbook (https://www.uaex.uada.edu/publications/pdf/MP584.pdf)

Image 8.13. Two spotted spider mites on strawberry leaves (A and B). Adults are identified by the two dark spots on either side of their bodies (C). Image C from Bruce Watt, University of Maine, Bugwood.org.

Common High Tunnel Insect and Mite Pests

Spider Mites

These tiny mites thrive in the warm, dry environment of a high tunnel. These favorable conditions lead to fast reproduction cycles and rapid population growth, making them one of the most damaging high tunnel pests. Spider mites feed on a wide range of crops with pepper and tomato plants being particular favorites. While there are many species of spider mites, the two spotted spider mite causes the most damage and is considered the most economically important mite. Two spotted spider mites are most often green, yellowish-green or nearly transparent in color. Adults are identifiable by two dark spots, one on each side of the body, that are easily visible with a 10x hand lens (Image 8.13). Overwintering females are often brown or red-orange.

Damage: With their rapid population growth, spider mites can cause a lot of damage in a short period. Spider mite feeding causes tiny yellow or white spots to appear on leaves, giving them a speckled or mottled appearance (Image 8.14). Under heavy infestations plants will become bronzed or bleached and may drop leaves. Plant vigor will be significantly reduced. Webbing on or between leaves indicates a heavy infestation.

Scouting techniques: Their small size can make mites difficult to detect. It is not uncommon to spot the signs of feeding damage first (Image 8.15). This, of course, is not ideal, as visible signs of feeding damage indicate a significant population. Plants should be scouted twice a week. If time and labor are limited, scout at least once a week to prevent population outbreaks. Use a 10-20x magnification lens and check the underside of leaves, as this is where mites prefer to feed.

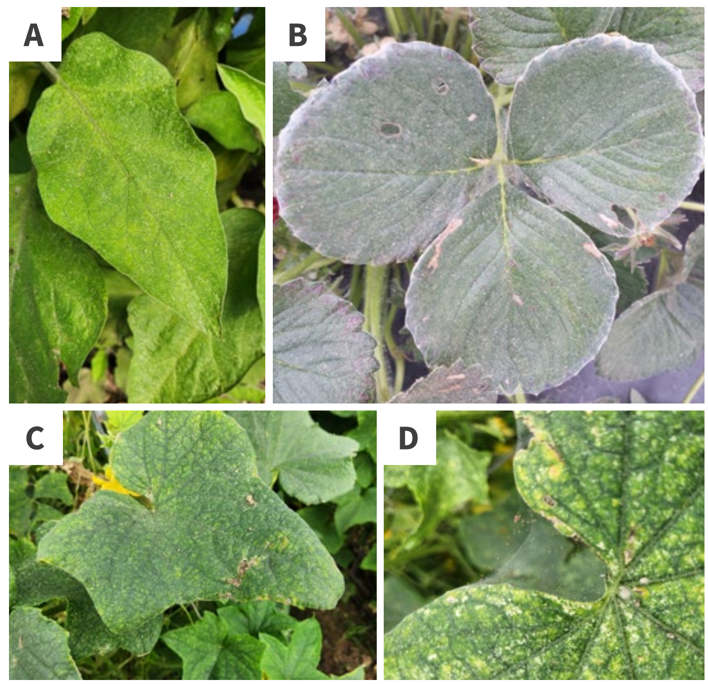


Image 8.14. Feeding damage of two spotted spider mites on eggplant (A) and cucumber leaves (C). Webbing on strawberry (B) and cucumber leaves (D).

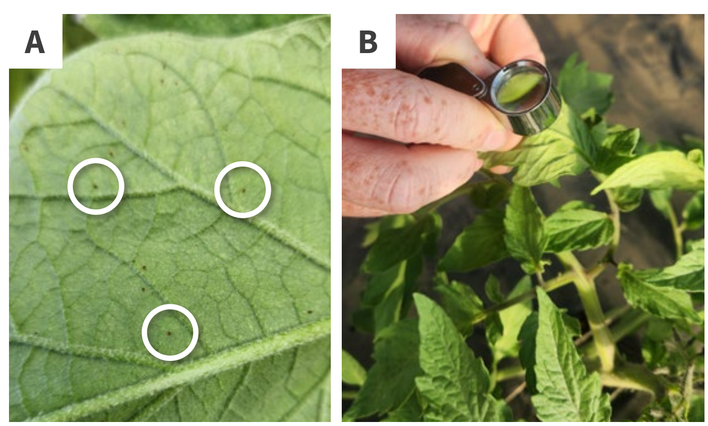


Image 8.15. Mites on the back of a leaf (A). Their tiny size can make them hard to see. A 10-20x magnifying lens will make scouting easier (B).

Management strategies: Good crop management strategies, such as adequate irrigation and nutrition, can make plants less appealing to spider mites. Excess nitrogen, however, can lead to an increase in mite damage. Natural predators, such as predatory mites, can be purchased and released to help control small populations. Because some natural predators feed only on a specific mite species on specific crops it is important to select the correct predatory mite species based on your specific crop and pest issue. Some predatory mite species do not do well in high temperatures and should be avoided in tunnels. Miticides are available for high tunnel use and will be necessary to combat large outbreaks.

Aphids

Aphids are a persistent insect pest in high tunnels. Like spider mites, aphids will feed on many fruit, vegetable and ornamental crops and like the warm and arid high tunnel environment. Aphids can reproduce asexually and can double in number in just a few days. This allows populations to rapidly increase to economically threatening levels. Aphid species vary in color, size, and the type of crops they prefer to feed on, though many aphid species are generalists that will attack a wide variety of crops (Image 8.16). Aphids are typically wingless insects, but winged adults become common when populations reach saturation levels.

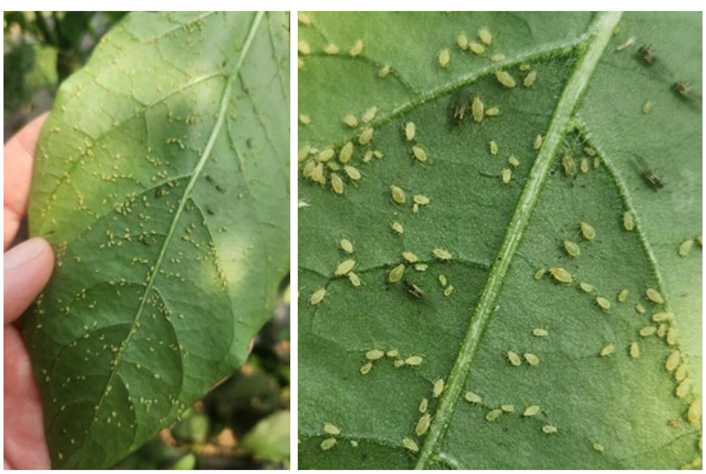
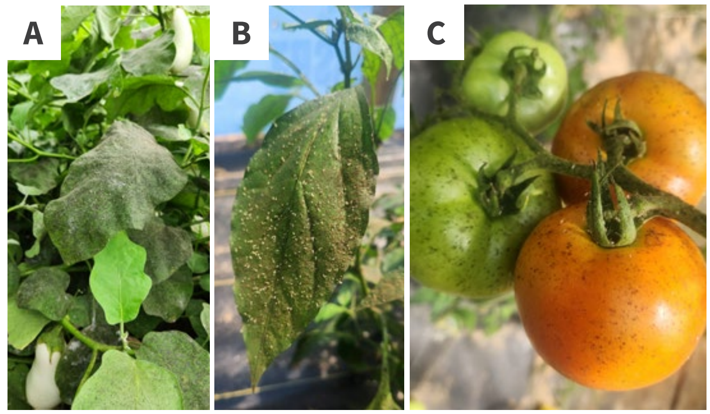


Image 8.16. A large aphid population on the back of a pepper leaf. The presence of winged aphids is an indication of an extremely high population density.

Damage: In small numbers, aphid feeding leads to little direct damage to plants. Severe infestations can cause leaves to yellow or twist and curl and plant growth can be stunted. If a population is large enough, it can kill young plants (Image 8.17). In addition to their feeding damage, aphids also produce honeydew, a sweet and sticky substance that can lead to the growth of sooty mold, which can cover leaves and reduce photosynthesis efficiency. Aphids also act as vectors for several plant viruses which can lower plant vigor further and even kill plants.



A B C

Image 8.17. Symptoms of aphid feeding on eggplant (A) and pepper leaves (B). The white debris on the pepper leaves are aphid exoskeletons stuck in the secreted honeydew (B). Sooty mold on tomato fruit (C). Sooty mold can also be seen on both the pepper and eggplant leaves.

Scouting techniques: Scouting practices for aphids and spider mites are similar. Though sometimes visible with the naked eye, a 10-20x magnifying lens will make scouting easier and more successful. Check for aphids on the underside of leaves and on stems, as this is where they tend to feed. Scout at least once a week, more often if time and labor allow. Regular scouting can help prevent population outbreaks. Always monitor for signs of feeding and honeydew. Sticky traps are not always an effective means of monitoring aphid populations but may capture reproductive adults as they move into tunnels.

Management strategies: Avoid over-applying nitrogen. Studies have shown that excess nitrogen fertilizer can lead to an increase in abundance and feeding. Additionally, aphids have been found to be more attracted to stressed or yellowing plants. Natural enemies, such as certain species of parasitic wasps and lady beetles, can be purchased and released when populations are small. It will be necessary to correctly identify the aphid species so the correct predator can be selected. If a tunnel has open sides, however, purchased natural enemies tend to be an ineffective investment, as adult insects fly away. Insecticides are available for high tunnel use and will be necessary to control large aphid populations.

<u>Thrips</u>

Thrips can be found feeding on many common high tunnel crops plus hundreds of weed species. Like many other common high tunnel pests, thrips prefer warm (86°F) and arid environments. This allows them to reproduce and develop more quickly inside a tunnel, particularly as temperatures warm in the spring and when they are unaffected by rainfall events. These tiny insects range in color from transparent white or yellow to a dark brown or black. Adults are elongated and slender with fringed wings. Nymphs are wingless, oblong and elongated (Image 8.18). Thrips often transmit plant diseases as they feed, most notably the tomato spotted wilt virus.

Image 8.18. Adult winged thrip (top) and nymph (bottom) on the back of a leaf. Image from Jack T. Reed, Mississippi State University, Bugwood.org.

<u>Damage:</u> Thrips feed on and damage many plant tissues including leaves, flower structures and fruits. Signs of thrip feeding include stunted plant growth and deformed and papery leaves with tiny pale spots, often called stripping or silvering. Fruits, such as strawberries, may become bronzed, silvery, scabby and scarred (Image 8.19). Heavy feeding can cause plants to curl or twist. Crop-specific symptoms also occur and being able to recognize how a crop may respond to thrips feeding could help with identification. Tomatoes, for example, will develop small indentations on unripe fruits when thrips lay eggs and bronzing will be evident on the shoulders of fruit.

<u>Scouting techniques:</u> Scouting should be done regularly and often. When checking plants directly, use a 10-20x hand lens and look on the undersides of leaves. Adult thrips can be monitored using yellow or blue sticky cards placed near the plants canopy, and flowers or leaves can be tapped on a white surface to knock thrips off and quantify. Monitor plants for visible symptoms of feeding. Remember that by the time visible symptoms appear, the thrips that caused the damage are often gone.

<u>Management strategies:</u> Once established, thrips can be difficult to control. Maintain good sanitation practices and inspect transplants before bringing them into a tunnel. Because thrips can live on weeds and other plant debris, removing weeds and preventing green bridges in or around the tunnel is important to help keep populations low and prevent the introduction of thrips to new plantings.

Thrips can sometimes be an induced pest, as natural enemies such as the minute pirate bug, which is killed by most insecticides, are vital in suppressing thrips. Natural predators have been used successfully to control small populations. Exclusion screens, such as insect netting and row covers, can prevent thrips from reaching plants. Insecticides are available, but their effectiveness can be limited if the applications are not timed correctly (multiple sprays are usually needed to achieve good control). Very few chemicals are effective in controlling thrips and identification of the specific thrips present will be key in choosing an effective insecticide.

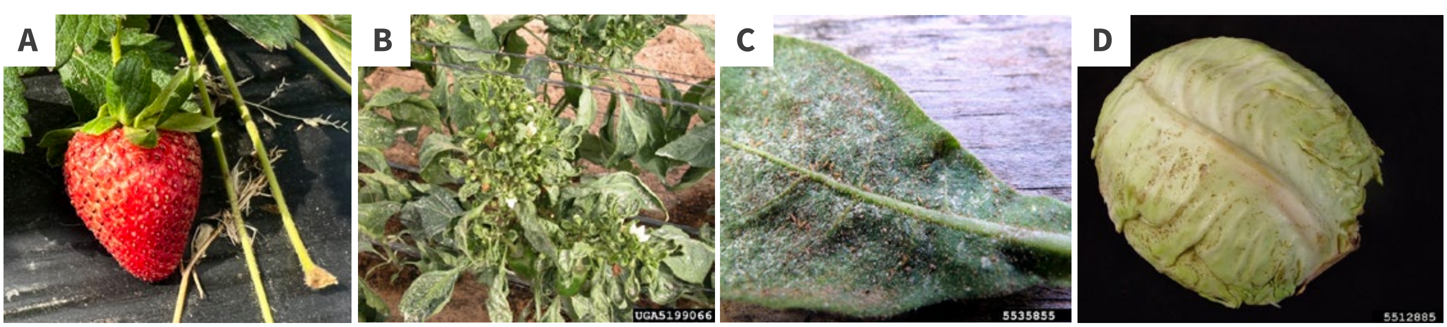


Image 8.19. Thrips damage on a strawberry fruit (A), pepper plants (B) a leaf (C) and a cabbage head (D). Image B from Florida Division of Plant Industry, Florida Department of Agriculture and Consumer Services, Bugwood.org. Image C from Metin GULESCI, Leaf Tobacco, Bugwood.org. Image D from Gerald Holmes, Strawberry Center, Cal Poly San Luis Obispo, Bugwood.org.

Whiteflies

These small and white winged insects feed on a large number of fruit, vegetable and ornamental crops (Image 8.20). They are common greenhouse pests and are well adapted to warm high tunnel environments. If left unchecked whiteflies can cause a large amount of plant injury and are a common pest of vegetables grown in warm climates. Like aphids, whiteflies reproduce rapidly and can serve as vectors for several plant viruses.

Image 8.20. Whiteflies on the back of cabbage leaves.

Damage: Plant vigor declines, and foliage will yellow. In some cases, leaves will drop prematurely. Large populations will cause plants to become visibly stunted. Like aphids, whiteflies secrete honeydew which can lead to sooty mold, causing a reduction in photosynthetic efficiency and attracting other insect pests.

Scouting techniques: Scout often and regularly to prevent outbreaks. Yellow sticky cards can be used to monitor for whiteflies. Place sticky cards close to the plant canopy to trap flying adults. Nymphs look very different from winged adults and are barely visible. Both nymph and adult stages can be found on the underside of leaves where they feed.

Management strategies: Whiteflies are often introduced to a high tunnel production system on infected transplants. Once established, they can be difficult to control. Carefully inspect transplants before bringing them into the tunnel to ensure they are insect free. Whiteflies are also great fliers and will move into tunnels naturally. Natural predators, such as parasitic wasps, have been successfully used to control small populations of white flies, although this works best in a closed growing environment. Good weed control, and the absence of green bridges in or around the tunnel, can help prevent infecting a new planting.

Other pests often seen in high tunnels:

Squash bug (Image 8.21):

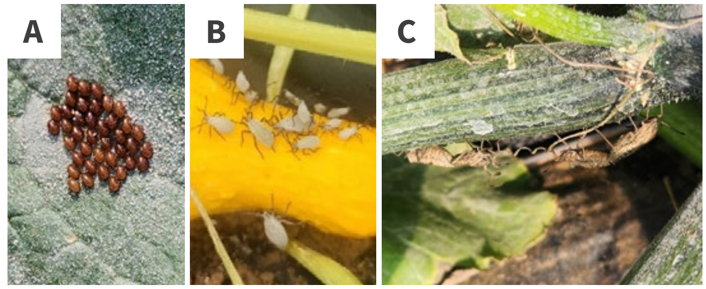


Image 8.21. Squash bug eggs (A) recently hatched (B) and adult squash bugs (C).

Various Lepidoptera larva

The insect order Lepidoptera includes pests such as caterpillars, armyworms, inchworms, cabbage worms, tomato hornworm and cutworms, etc. (Image 8.22).

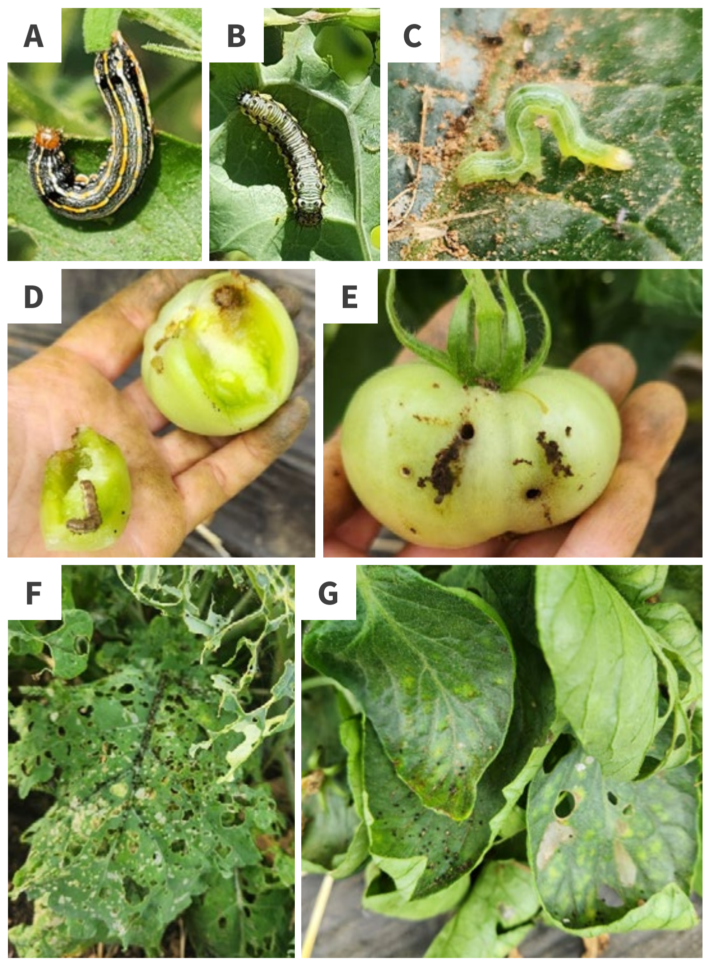


Image 8.22. Various lepidoptera larva feeding on different plants inside a high tunnel (A–C). Feeding damage on a tomato (D-E) and collard leaves (F). The presence of frass on leaves or other plant tissue is an easy way to identify an issue with lepidoptera larva (F and G).

Flea beetles (Image 8.23):

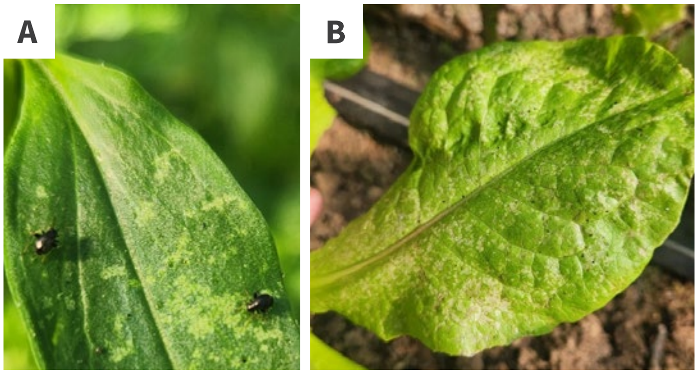


Image 8.23. Adult flea beetles (A) and flea beetle feeding damage on a lettuce leaf (B).

Common High Tunnel Diseases

Powdery Mildew

Because powdery mildew does not require free moisture (rain or overhead irrigation) for the causal pathogen to penetrate and infect plants, this fungal disease is becoming one of the most common foliar pathogens in high tunnel production. Many common high tunnel crops are susceptible to this disease and it can be devastating to tomatoes, peppers, eggplants, cucumbers and squash.

Symptoms: Early symptoms can differ depending on which pathogen species is present. They can appear as either irregular, chlorotic or purple areas or necrotic lesions on the upper surfaces of leaves. These early symptoms will be followed by white, “fluffy” lesions (Image 8.24). Infected plants may defoliate prematurely, experience low vigor and produce smaller yields. Fruiting crops may produce smaller fruit in addition to less fruit.

Image 8.24. Powdery mildew covering zucchini leaves (A) and growing on strawberry fruit (B) growing in a high tunnel.

Environmental conditions: Powdery mildew is greatly influenced by environmental conditions and its occurrence can be reduced by minimizing time spent under these favorable conditions. Powdery mildew prefers temperatures between 70-80°F and high relative humidity (greater than 70 percent), particularly at night. If these conditions are present for several consecutive days the incidence of powdery mildew could increase.

Management strategies: Ample ventilation and air movement within the tunnel will help keep relative humidity levels lower inside the plant canopy, minimizing favorable environmental conditions. When possible, select resistant varieties and avoid overcrowding plants. Plants placed too close together will restrict air movement and increase intra-canopy humidity. Plants should be scouted regularly for the early symptoms of powdery mildew to prevent outbreaks and spread. Consider preventative fungicide programs. Additional fungicides can be used to reduce the spread of powdery mildew once it is first observed.

Botrytis Gray Mold

Botrytis is a common and often devastating fungal disease that can infect many fruit and vegetable crops. Once established inside a tunnel, botrytis can be difficult to control and is easily spread through direct contact, air movement, tools or workers. Spores can overwinter and survive on plant debris or in the soil, easily infecting successive plantings.

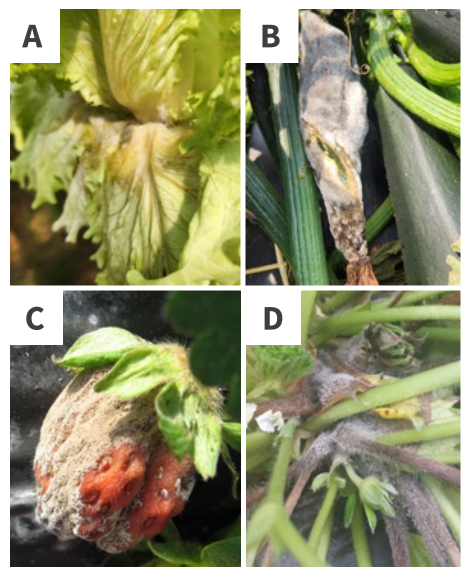


Image 8.25. Botrytis gray mold beginning to grow on a high tunnel lettuce plant (A). Gray mold growing on high tunnel zucchini and strawberry fruit (B and C) and covering a strawberry crown (D).

Symptoms: Beginning as tan or light brown water socked spots, these quickly become covered with a gray, “fuzzy” mold (Image 8.25).

Environmental conditions: Like powdery mildew, botrytis growth is heavily influenced by environmental conditions, with infected plants remaining asymptomatic until these conditions are present. Preferring cooler temperatures (between 60-70°F) and high humidity, botrytis can spread rapidly within a tunnel during the shoulder and winter seasons. Tunnel production during this time is very susceptible to botrytis infection because tunnels often remain closed for extended periods, exposing plants to high relative humidity and cooler temperatures for several consecutive days. As temperatures within the tunnel begin to rise in the late spring, the incidence of botrytis will decline, often disappearing. However, incidence can increase anytime favorable conditions return.

Management strategies: Climate management can be effective in keeping the severity of botrytis infection low. Venting a high tunnel and secondary covers, even during cooler months, can improve air movement and lower relative humidity levels (Image 8.26). Cultural and crop management practices such as avoiding overcrowding plants, good sanitation and fertility programs can also help keep pressure low.

Good cultural and crop management practices include pruning plants early in the afternoon, so wounds have time to dry, and removing any unharvested or aborted fruit and plant debris from the tunnel. When there are continuous days of cool, overcast conditions, it can be difficult to keep humidity levels low inside a tunnel, especially if secondary covers are being used. Venting to break up continuous days of high humidity can help minimize an outbreak, but a preventive fungicide program is often necessary to prevent widespread infection.

Image 8.26. Secondary covers opened during the day to vent excess heat and humidity.

Soilborne Diseases

Pathogens that infect plant roots, crowns, leaves and stems by way of the soil are referred to as soilborne diseases. While fungi make up the largest number of soilborne pathogens, bacteria, nematodes, viruses and protozoa can also infect plants from the soil. The buildup of soilborne pathogens in the soil has been one of the most difficult issues to avoid in high tunnel production in Arkansas — particularly in tunnels where crop rotation is not practiced or in tunnels that experience flooding events.

White mold, (also called Timber rot or Sclerotinia), is a soilborne disease that can cause significant losses to high tunnel crops, particularly crops like tomatoes. This fungus overwinters in the soil and infects plants when they are transplanted into these infected soils.

Symptoms: Plants infected with white mold will develop light, tan-colored lesions on stems near the soil line. These lesions cut off the flow of water and nutrients through the stem, causing plants to wilt (Image 8.27). Under the right environmental conditions, black sclerotia can develop on lesion surfaces or within an infected stem. Eventually, lesions will completely girdle a plant, killing it. As high tunnel tomato production has increased in Arkansas, the occurrence of this fungal disease has also become more common.

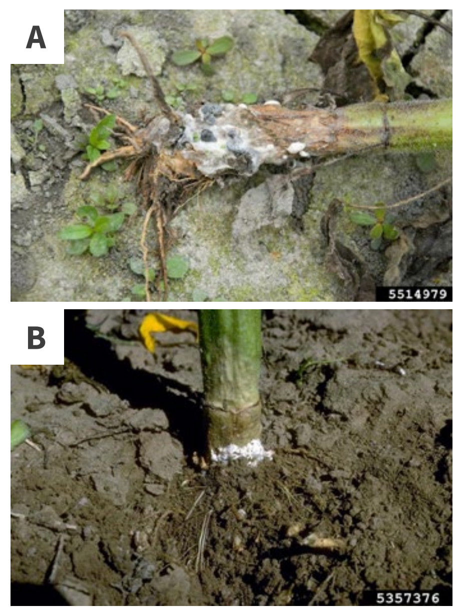


Image 8.27. A tomato plant girdled at the soil line by white mold (A). Tan-colored lesions on a tomato stem also near the soil line (B). Image A from Howard F. Schwartz, Colorado State University, Bugwood.org. Image B from Yuan-Min Shen, National Taiwan University, Bugwood.org

Management strategies: Preventive management is the best strategy for controlling the white mold pathogen. Once established in the soil it can be difficult to eradicate white mold. Implementing and following a good crop rotation plan and having a good fertility and soil management program can help prevent this pathogen from accumulating within the soil. If the pathogen is present, chemical fumigation and soil solarization can be an effective method to minimize or control white mold. If preventative and control methods are neglected and the level of soilborne pathogens becomes extreme, it may become necessary to move the tunnel.

Conclusion

High tunnels can be an effective and affordable method for growers to extend their growing season and protect plants from damaging weather conditions. Disease pressure, however, can remain high inside a tunnel if good climate and crop management practices are not implemented. Producers need to employ proactive IPM strategies early and continue throughout the life of the high tunnel to help prevent disease outbreaks. While a high tunnel can successfully mitigate conditions that can promote and spread diseases, insect and mite control can be more difficult. Tunnels should be scouted regularly and often so control methods can be executed quickly before an insect population gets out of control.

Additional Resources

Diagnostic Resources

The Arkansas Plant Heath Clinic can help diagnostic plant issues: lab: uaex.uada.edu/yard-garden/plant-health-clinic/default.aspx

Locate your local county Extension offices: uaex.uada.edu/counties/

Insect pest monitoring in Arkansas: uaex.uada.edu/farm-ranch/crops-commercial-horticulture/horticulture/vegetable-insect-pests-monitoring-in-ar.aspx

Disease Management in High Tunnel

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Insect Management in High Tunnels

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Altieri, M. A., Nicholls, C. I. and M. A. Fritz. Manage Insects on Your Farm. A Guide to Ecological Strategies. College Park, MD. Sustainable Agriculture Research and Education (SARE). 2014. www.sare.org/resources/manage-insects-on-your-farm/

Majumdar A. and C. Akotsen-Mensahm. 2022. Pest Management in High Tunnel Crop Production. Alabama A&M ad Auburn University Extension. ANR-1432. www.aces.edu/blog/topics/farming/pest-management-in-high-tunnel-crop-production/

Begin planning your IPM program

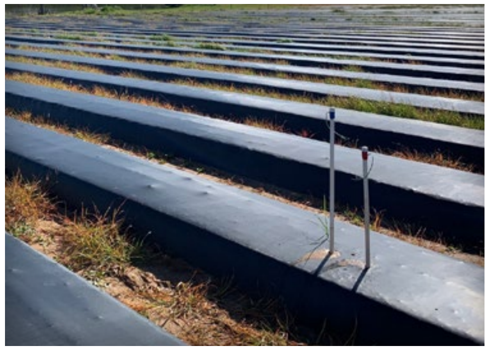
1. Do you plan on growing using organic practices?

2. Cultural Practices:

3. Biological Practices:

4. Physical/mechanical Practices:

5. Chemical Control:


CHAPTER 9

Irrigation Strategies

Introduction

An effective irrigation management strategy is critical for successful crop production. This is especially true for high tunnel production. The protected environment of a high tunnel means a grower is entirely responsible for supplying water to the crop. While this can make irrigation management more involved it also allows growers to tailor irrigation schedules and volume to perfectly meet a crop's needs and, when managed correctly, avoid any kind of water stress and even limit some diseases.

Image 9.1. Blossom-end rot on high tunnel tomato plants.

Underestimating a plant's water needs, as well as the rate at which water is lost from tunnel soils, are common issues in high tunnel production. This leads to under-irrigated and water-stressed plants. Inadequate water, especially during critical growth stages, will affect plant growth in several ways. For instance, an inadequate water supply during fruit development can cause the physiological disorder blossom-end rot on tomatoes and peppers (Image 9.1). Overwatering, which tends to be less of an issue in high tunnels, or irregular watering can also cause stress or damage to plants. An understanding of a plant's water requirements and how water moves through different soil types will help producers develop a good irrigation strategy and help avoid water stress.

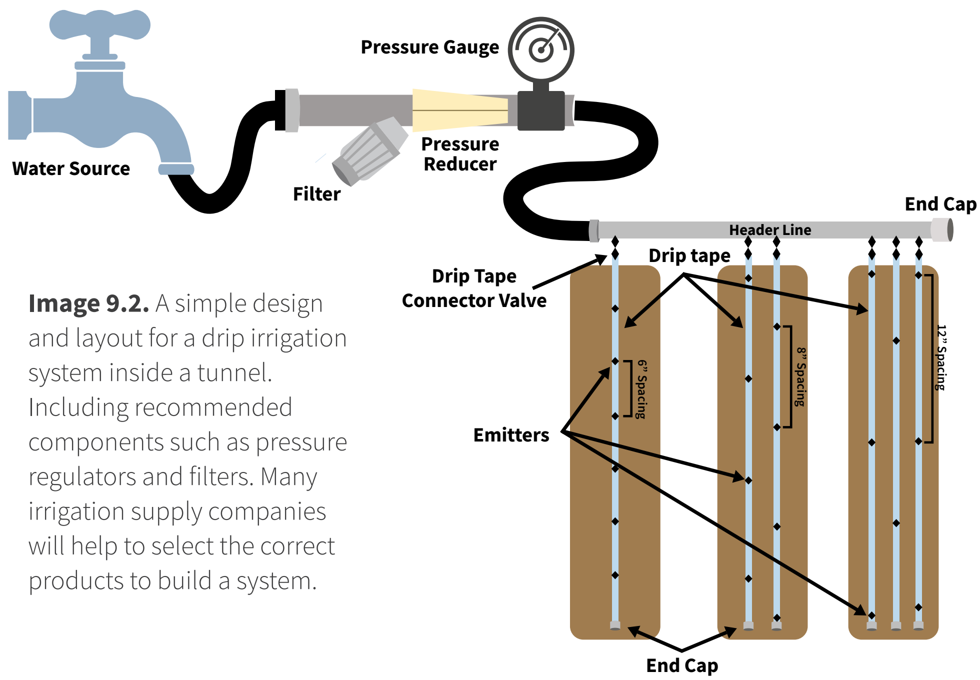


Image 9.2. A simple design and layout for a drip irrigation system inside a tunnel. Including recommended components such as pressure regulators and filters. Many irrigation supply companies will help to select the correct products to build a system.

Irrigation systems

Micro-irrigation systems — specifically drip irrigation — is the recommended irrigation method in high tunnel production (Image 9.2). While there are some disadvantages to using a drip system, such as the disposal and cost of drip tape, the advantages to these systems typically outweigh any disadvantages.

Advantages of Drip Irrigation:

- *Decreased weed pressure*: Because water is limited to the crop's root zone, non-cropped areas, such as between rows and tunnel edges, do not receive water. This helps prevent weed growth and reduces the amount of labor needed for weed management.
- *Decreased disease pressure:* Some key plant pathogens require splashing water to spread and develop. Drip irrigation eliminates splashing water caused by irrigation, reducing the incidence of several economically damaging foliar diseases and the need for fungicide applications.

- *Reduced water use:* A well-designed and properly managed drip irrigation system will improve water use efficiency by delivering water directly to the crop's root zone (Image 9.3). This limits water loss to runoff, evaporation and percolation beyond the root zone, making drip irrigation more cost effective. When a drip system is managed correctly, water use can be reduced by half or more when compared to overhead irrigation systems such as sprinklers.

Image 9.3. Drip tape stretched over a newly planted lettuce bed (A). Drip tape delivering water directly to the root zone of tomato plants.

- *Uninterrupted access to the tunnel:* Because drip irrigation limits water applications to crop rows, workers can continue to access the tunnel for crop management and harvest while irrigation is running.
- *Fertilizer applications:* A drip system can also deliver fertilizer directly to the root zone (Image 9.4). Fertigation (applying fertilizer through an irrigation system) allows nutrients to be applied at regular intervals throughout the cropping cycle. Fertigation also allows the grower to tailor fertilizer rates, either increasing or decreasing certain nutrients, based on plant need which improves nutrient use efficiency.
- *Automation:* Drip systems can be easily automated with a simple battery powered controller (Image 9.4).

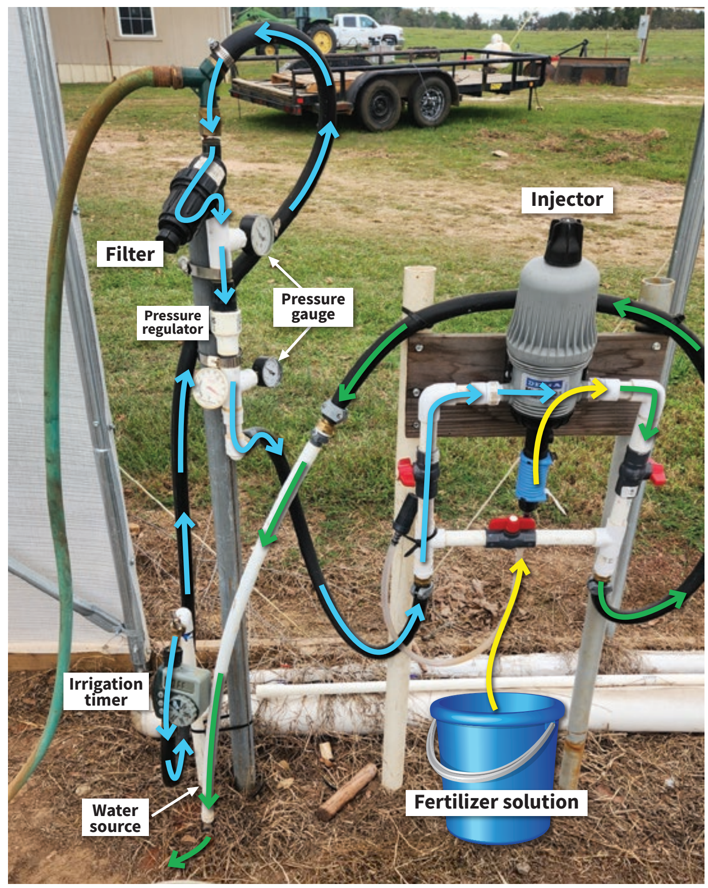


Image 9.4. A fertigation injector incorporated into a drip irrigation system. Once water enters the system it flows through a filter (to remove any contaminates that could clog drip emitters) continues through a pressure regulator and into the injector (blue lines). The injector pulls fertilizer solution from its source and injects it into the system (yellow lines). Fertilized water then flows out to the beds and plants (green lines). Many companies that supply fertigation injectors can help select products to build a system.

Overhead irrigation, such as sprinklers, is usually not recommended for general use inside a high tunnel. However, some high tunnel growers will use overhead sprinklers during key growth stages. Lettuce growers, for example, will use sprinklers to maintain even soil moisture across newly seeded or transplanted lettuce beds. For young lettuce plants, continuous and even soil moisture during the first two to three weeks after seeding or transplanting ensures optimum seed germination and good flavor. Once plants are established, growers usually shift to drip irrigation on lettuce crops. Sprinklers have also been used to irrigate a tunnel when it is planted in cover crops. Sprinklers can be attached to overhead trusses or placed near soil level (Image 9.5).

Image 9.5. Lettuce beds irrigated with a sprinkler system during the critical moist establishment period of young transplants (A). Sprinklers attached to the tunnels trusses (B).

Irrigation scheduling

The goal of a good irrigation program should be to provide enough water at the correct time to maintain even soil moisture levels throughout the cropping cycle. To achieve this, applying small amounts of water frequently instead of a large amount of water in a single irrigation cycle is typically recommended. Designing a good irrigation schedule takes some thought and effort. A crop's specific water needs, the flow rate of the irrigation system and the soil type will all influence how much and how often a high tunnel should be irrigated. Climatic conditions inside the tunnel will also affect water usage and should be considered when determining irrigation schedules.

Fundamental considerations for designing an irrigation schedule

First, determine the water needs for your crop. Many crops are sensitive to over-irrigation, under-irrigation or even irregular irrigation. Water stress during key growth stages can lead to poor fruit set, slowed or stunted growth and loss of yield or fruit quality (Image 9.1). While every crop has different water needs, most vegetable crops typically need 1 – 2 inches of water per week. However, the generally warmer climate and faster plant growth inside a high tunnel will increase a crop's demand for water. Because of this, the recommended 1 – 2 inches of water per week may not be enough, particularly during warmer times of the year. Nevertheless, it offers a good starting place when forming an irrigation plan for tunnel vegetable.

Next, monitor the high tunnel climate daily. Changes in air temperature and humidity will affect plant water needs. Irrigation schedules will need to be modified or adjusted based on climatic conditions inside the tunnel to ensure adequate soil moisture. Plants will lose more water on a hot sunny day than on a cooler or overcast day. Evaporative water loss from the soil surface will also be greater on warm sunny days. As a result, it will be necessary to irrigate longer, and more frequently, during periods of warm or hot sunny weather. The cooler and often overcast conditions experienced during high tunnel winter production in the Southeast will lessen the amount of water used by plants, and it may only be necessary to irrigate once or twice a week during this time. While irrigation needs are lower during winter production, plants still need water during the winter, and growers must make sure there is year-round access to a frost-free water source.

Persistently high humidity levels like those often experienced inside a tunnel will also limit a plant's ability to pull water from the soil and for water to evaporate from the soil surface. Ensuring adequate ventilation inside the tunnel will help lower humidity levels and alleviate this issue.

The use of plastic mulches is a common practice in many high tunnels, especially in the early production of warm-season crops. These mulches not only warm soils more quickly in the spring but will also reduce evaporative water loss from the soil. This drop in evaporative water loss means soil can retain water longer, lowering irrigation needs. Other common mulches such as weed fabric, straw or bark will have a similar effect on soil water retention.

Now, calculate how many inches of water your system applies per hour. To calculate this for a drip system, the following information will be needed:

- *Emitter flow rate (GPH):* Common flow rates range from 0.5 – 2+ gallons per hour (GPH) (Image 9.6). Soil type and the selected crop should guide the selection of emitter flow rate. Most companies that supply drip irrigation components will provide information to help select the best emitter size. Sandy soils can generally handle higher flow rates than clayey soils due to their higher rates of water infiltration.

- *Distance between emitters:* Emitter spacing on drip tape/tubing with inline emitters can range from 4 – 18 inches. As with emitter size, crop selection and soil type should dictate emitter spacing. Row length should also be considered when determining emitter spacing. Irrigation supply companies often provide information to help growers select appropriate spacing for their crops and soil type. Regional production guides often supply this information for various vegetable crops.

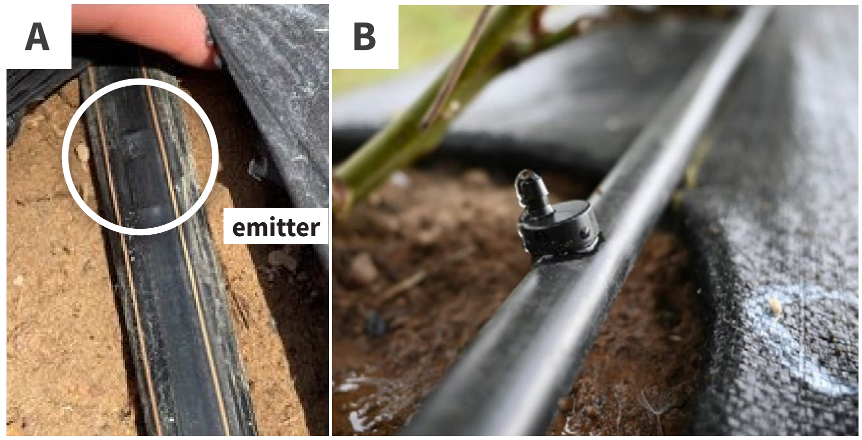


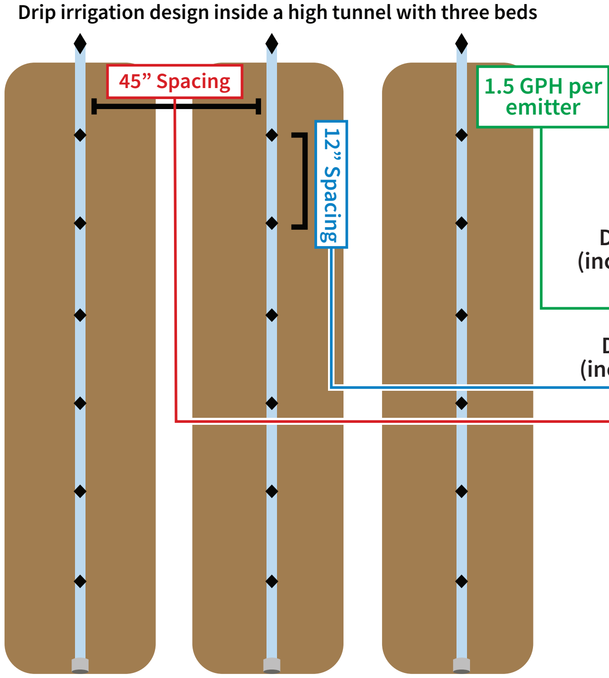
Image 9.6. In-line emitter tape (A) and point source emitters (B).

- *Distance between drip lines:* Line spacing can vary significantly depending on bed and row middle sizes as well as lines per bed (Image 9.2).

And finally, consider your soil type. Soil type will indicate how quickly water can move through the soil (infiltration rate) and how much water a soil can hold for crop use (water holding capacity) (Table 9.1). A soil's infiltration rate will determine how long a single irrigation cycle can run without causing runoff or leaching (Table 9.1). While a soil with a higher water holding capacity can go longer

Example:

Drip irrigation design inside a high tunnel with three beds



Formula to calculate inches of water applied per hour

$$\text{Drip Rate (inches/hour)} = \frac{(\text{emitter flow rate (GPH)}) \times (231.1)}{(\text{emitter spacing (inches)}) \times (\text{drip line spacing (inches)})}$$

$$\text{Drip Rate (inches/hour)} = \frac{(1.5\ \text{GPH}) \times (231.1)}{(12\ \text{inches}) \times (45\ \text{inches})}$$

Drip Rate = **0.64 inches/hour**

This means you would need to irrigate for **94 minutes** to apply **1 inch of water**.

Note: The constant 231.1 in the equation is used to convert to inches per hour.

between irrigation cycles. Sandy type soils, with their larger soil particles and pore space, drain more quickly (higher infiltration rate) and generally have a lower water holding capacity than loamy or clay type soils. This means sandy type soils can handle longer, more frequent irrigation cycles compared to clay type soils. Clayey soils, on the other hand, can quickly become waterlogged or flood if irrigated for too long or too often (Image 9.7). While sandy soils may need to be irrigated multiple times a day during hot weather and heavy crop loads, a clayey soil may only need a deep watering once or twice a week under the same conditions. Soil type can be determined though a soil test or by using the USDA-NRCS Web Soil Survey (websoilsurvey.sc.egov.usda.gov/App/HomePage.htm).

Table 9.1. Infiltration rates, water holding capacity, and the estimated maximum number of minutes per irrigation event for several types of soil. Table modified from the Southeastern US Vegetable Crop Handbook.

Soil type	Rate of Water Infiltration (inches per hour)	Available Water Holding Capacity (water per inch of soil)	Drip Tubing Flow Rate (gpm/100 ft.)		
			0.2	0.4	0.6
			Estimated maximum number of minutes per application*		
Coarse sand	0.75-1.00	0.02-0.06	20-60	10-30	7-20
Fine Sand	0.50-0.75	0.04-0.09	40-80	20-40	14-27
Loamy Sand		0.06-0.12	60-120	31-60	20-40
Sandy loam		0.11-0.15	102-140	50-70	34-48
Loam	0.25-0.40	0.17-0.23	163-218	82-115	54-77
Silty loam					
Sandy clay loam	0.10-0.30	0.13-0.18	120-180	60-92	40-60
Clay loam	0.04-0.2	0.14-0.21	143-200	70-100	48-70
Silty clay loam					
Sandy clay					
Silty clay		0.13-0.18	122-180	60-90	40-61
Clay					

**Assumes a 10-inch deep root zone and irrigation at 25% soil moisture*

Soil Moisture Sensors

Soil moisture sensors are a good way to track changes in moisture levels under the soil surface (Image 9.8). When used correctly, a moisture sensor can make watering decisions easier by reducing some of the ambiguity involved in irrigation management. Soil moisture sensors can show when water levels in the root zone are becoming depleted, indicating an irrigation event is needed. In addition to help determining when irrigation is needed a soil moisture sensors can also indicate if water is being over or under applied. This allows a grower to adjust irrigation run times as needed, greatly improving irrigation efficiency. When installing soil moisture sensors, it is recommended to place one sensor at the crops minimum rooting depth (the depth where the root zone starts) and a second sensor at its average rooting depth (center of the root zone) (Table 9.2).

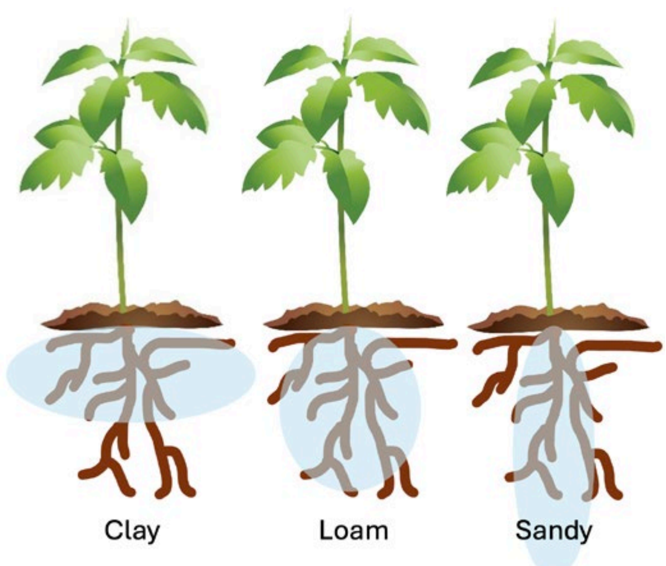


Image 9.7. Water moves differently in clay soil compared to loamy or sandy type soils. Water will move downward more quickly in a sandy type soil than a clay or loamy soil.

Table 9.2. Minimum and average rooting depths for several common high tunnel crops.

Crop	Minimum Rooting Depth (inches)	Average Rooting Depth (inches)
Beans	6	12
Cucumber	6	12
Lettuce	6	12
Pepper	6	15
Spinach	6	18
Summer squash	12	30
Tomato	6	18
Strawberry	6	12

Image 9.8. An example of a soil moisture sensor (A). A tomato planting with one sensor placed 6 inches into the soil and the second at 12 inches (B). Two sensors set up to monitor soil moisture in a strawberry field (C).

Conclusion

When irrigation inside a high tunnel is managed carefully, not only can water use be optimized, but plant health and productivity will also benefit. Irrigation management requires planning, regular monitoring and an understanding of a crop's water needs and how the tunnel's environment can impact a plant's water demand. Knowing the soil type inside a tunnel will help determine irrigation run times and frequences to avoid leaching and water runoff while maximizing crop production.

Additional Resources

Irrigation Management and Scheduling:

Drost, D., Black, B. and M. Stock. 2021. Irrigation Management in High Tunnels. Utah State University Cooperative Extension.

Hansen, S., Beddes, T., Barker, B. and A. Butler. 2023. Water Recommendations for Vegetable Crops. Utah State University Extension.

Maughan, T., Allen. L. N. and D. Drost. 2015. Soil Moisture Measurement and Sensors for Irrigation Management. Utah State University Cooperative Extension.

Sánchez, E. 2023. Determining how Long to Run Drip Irrigation Systems for Vegetables. PennState Extension.

Designing and Installing Drip and Fertigation Systems:

DeValerio, J., Nistler, D., Hochmuth, R. and E. Simonne. 2018. Fertigation for Vegetables: A Practical Guide for Small Fields. University of Florida IFAS Extension. HS1206. edis.ifas.ufl.edu/publication/HS1206

Ernst, T., McWhirt, A., Zimmermn, T., Henderson, E., Duncan, M. and A. Lay-Walters. 2023. Basics of Drip Irrigation and Fertigation for Speciality Crops. University of Arkansas Research and Extension. FSA6160. uaex.uada.edu/publications/PDF/FSA6160.pdf.

Moore, G., McSwain, K., S. Nix. 2016. High Tunnel Micro-irrigation Guide: A Practical Guide to Understanding and Implementing Micro-irrigation in High Tunnels. Carolina Farm Stewardship Association.

Schuch, U. 2016. Drip Irrigation: The Basics. The University of Arizona Cooperative Extension. Az1392.

Simonne, E., Hochmuth, R., Breman, J., Lamont, W., Treadwell, D. and A. Gazula. 2018. Drip-Irrigation Systems for Small Conventional Vegetable Farms and Organic Vegetables Farms. HS1144. University of Florida IFAS Extension. edis.ifas.ufl.edu/publication/HS388.

Think about your irrigation system:

1. What kind of irrigation system do you plan on using in your tunnel?

2. What parts and materials do you need to purchase?

3. Sketch the layout of your system:

4. For drip systems: Calculate the inches of water applied per hour.

Emitter flow rate (GPH): ______________
Distance between emitters: ______________
Distance between drip lines: ______________

$$\textbf{Drip Rate (inches/hour)} = \frac{\text{(emitter flow rate (GPH))} \times (231.1)}{\text{(emitter spacing (inches))} \times \text{(drip line spacing (inches))}}$$

CHAPTER 10

Soil Health and Fertility Management

Introduction

Soil fertility, a measure of a soil's ability to hold essential nutrients and make them available to plants, is only one aspect of soil health. Soil health is a measure of a soil's capacity to sustain plant growth. Other soil characteristics that contribute to the health of a soil include soil organic matter (SOM), soil structure, the degree of biological activity and soil water-holding capacity. Poor soil health and/or low soil fertility will cause a noticeable drop in crop yields (Table 10.1).

The high-intensity production methods used inside high tunnels can reduce soil health and soil fertility levels in several ways over time if proactive management strategies are not implemented. These include:

- Faster crop growth and extended cropping seasons can increase the demands on soil.
- Lack of rainfall can cause nutrients (salts) to build up to potentially toxic levels in the soil.
- Regular and more frequent cropping cycles, which mean more frequent soil preparation (including tilling).
- Warmer soil temperatures throughout the entire year can increase biological activity and accelerate the breakdown of organic matter resulting in soils low in SOM.
- While it's not usually recommended to place plants closer together inside a high tunnel, closer plant spacing is a common practice.

Table 10.1. The projected reduction in yields when key macronutrients (phosphorus and potassium) are low and not amended.

Soil Test Rating	Projected Reduction in Yield
Low	25-50%
Medium	0-25%
High	0%
Very High	0%

For these reasons, high tunnel growers need to pay close attention to soil conditions inside their tunnels. Implementing good short- and long-term soil management practices can improve most facets of soil health. This chapter will detail a few soil and fertility management practices that can help maintain soil health and fertility inside a tunnel.

Site selection and preparation

When selecting a location for a high tunnel, soil health should be an important consideration. Beginning with healthy soil will make growing high-yielding crops much easier for much longer. It is also easier to maintain healthy soil than it is to build it. Creating healthy soil takes time and while soils are being amended and improved, crop yields will be lower, hindering the profitability of the tunnel.

A simple soil test can measure several key soil health factors (see below) and indicate what amendments will be necessary to support crop production. Soil augmentation should begin six months to a year before tunnel construction. This will give adequate time for any recommended amendments to take effect, including increasing SOM, improving soil fertility and adjusting soil pH (if needed). For more information on selecting a site for high tunnel production see Chapter 3 – Site Selection.

Collecting a Soil Sample

When:

Soil samples can be collected any time throughout the year, but try to collect samples around the same time every year. Avoid collecting when the soil is extremely wet.

Tools needed:

- ☐ A soil probe or hand trowel
- ☐ One five-gallon bucket (or something similar)
- ☐ Soil sample box (from your local extension office) or sealable bag

How:

- Using the soil probe or hand trowel, dig a hole 6-8" deep and as wide as the probe or trowel blade
- Place this soil into the five-gallon bucket
- Repeat this sample process at random areas throughout your tunnel, placing all samples into the five-gallon bucket
- Collect between 6-10 samples for a 1,000 sq ft tunnel
- Once all samples are in the bucket, mix thoroughly
- Remove about 2 cups of soil from the five-gallon bucket and place it in the soil sample box or sealable bag
- A video demonstration can be found at www.youtube.com/watch?v=S8M_6oU4C28

What to do with the sample:

- Fill out the soil sample submission form (your local extension agent can help you)
- Drop the soil sample box or bag at your local extension office
- Wait for the soil report to show up in your email!

Soil Testing

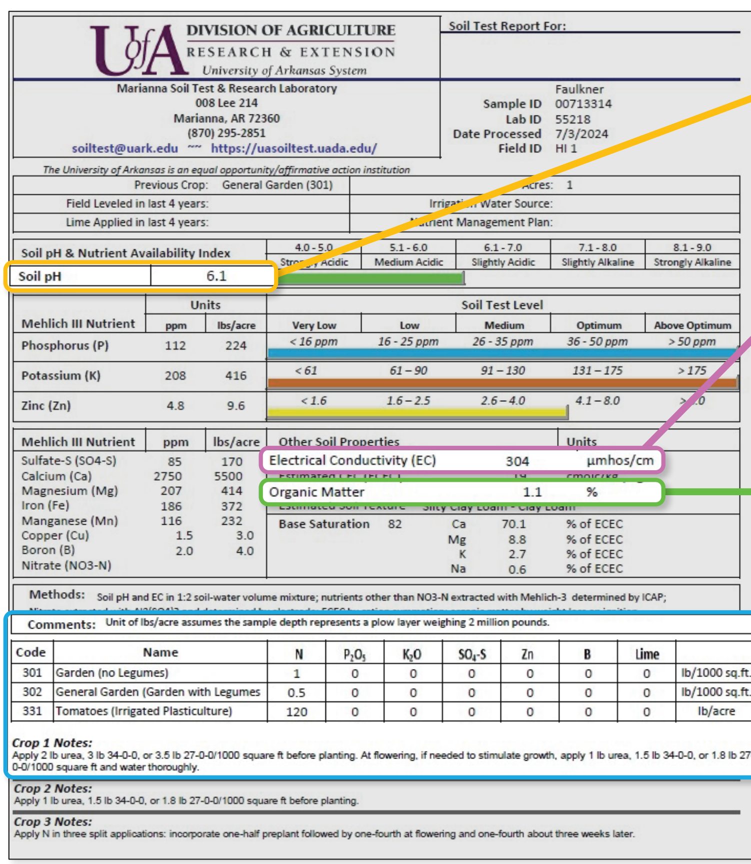
Once production begins in a high tunnel the soil should be tested regularly. For field production, soil testing should be conducted every two or three years. High tunnel soils, however, should be tested more often. When possible, soil sample the tunnel once a year to monitor changes in a soil's nutrient levels, salt content (soil EC), SOM and pH to ascertain which soil management strategies are needed. A standard soil test is free for Arkansas residents through the Arkansas Soil Testing Laboratory (aaes.uada.edu/technical-services/soil-testing-and-research-laboratory/). Soil samples are submitted to the laboratory through local county extension offices.

When collecting and submitting soil for testing, it is important to:

- Collect samples around the same time each year. This will allow for more accurate comparisons of changes in soil health parameters over time.
- Collect soil samples to a depth of 6-8 inches.
- Do not collect soil samples after fertilizing or if the soil is very wet.
- Soil amendment recommendations are based on the crop(s) planned for the area, so be sure to include that information when submitting a sample. Local county extension agents can help correctly fill out the necessary paperwork (find your local county extension office at www.uaex.uada.edu/counties/).
- Request the lab measure the salt content, or electrical conductivity (EC), of the soil. The standard free soil test does not include this measurement unless it is requested. The soil testing lab will charge a small fee to measure soil EC.
- Request the lab measure soil organic matter. As with EC measurements, the standard free soil test does not measure soil organic matter. The soil lab will charge a small free for this measurement. For pricing information visit aaes.uada.edu/technical-services/soil-testing-and-research-laboratory/.

A Quick Glance at a Soil Test Report

A sample report from the Marianna Soil Test & Research Laboratory



DIVISION OF AGRICULTURE
RESEARCH & EXTENSION
University of Arkansas System

Marianna Soil Test & Research Laboratory
008 Lee 214
Marianna, AR 72360
(870) 295-2851
soiltest@uark.edu ~~ https://uasoiltest.uada.edu/

Soil Test Report For:
Faulkner
Sample ID 00713314
Lab ID 55218
Date Processed 7/3/2024
Field ID HI 1

The University of Arkansas is an equal opportunity/affirmative action institution

Previous Crop: General Garden (301)	Acres: 1
Field Leveled in last 4 years:	Irrigation Water Source:
Lime Applied in last 4 years:	Nutrient Management Plan:

Soil pH & Nutrient Availability Index		4.0 - 5.0 Strongly Acidic	5.1 - 6.0 Medium Acidic	6.1 - 7.0 Slightly Acidic	7.1 - 8.0 Slightly Alkaline	8.1 - 9.0 Strongly Alkaline
Soil pH	6.1					

Mehlich III Nutrient	Units ppm	Units lbs/acre	Very Low	Low	Medium	Optimum	Above Optimum
Phosphorus (P)	112	224	< 16 ppm	16 - 25 ppm	26 - 35 ppm	36 - 50 ppm	> 50 ppm
Potassium (K)	208	416	< 61	61 – 90	91 – 130	131 – 175	> 175
Zinc (Zn)	4.8	9.6	< 1.6	1.6 – 2.5	2.6 – 4.0	4.1 – 8.0	> 8.0

Mehlich III Nutrient	ppm	lbs/acre
Sulfate-S (SO4-S)	85	170
Calcium (Ca)	2750	5500
Magnesium (Mg)	207	414
Iron (Fe)	186	372
Manganese (Mn)	116	232
Copper (Cu)	1.5	3.0
Boron (B)	2.0	4.0
Nitrate (NO3-N)		

Other Soil Properties		Units
Electrical Conductivity (EC)	304	µmhos/cm
Estimated CEC (ECEC)	19	cmolc/kg
Organic Matter	1.1	%
Estimated Soil Texture	Silty Clay Loam - Clay Loam	

Base Saturation 82 — Ca 70.1 % of ECEC; Mg 8.8 % of ECEC; K 2.7 % of ECEC; Na 0.6 % of ECEC

Methods: Soil pH and EC in 1:2 soil-water volume mixture; nutrients other than NO3-N extracted with Mehlich-3 determined by ICAP;

Comments: Unit of lbs/acre assumes the sample depth represents a plow layer weighing 2 million pounds.

Code	Name	N	P_2O_5	K_2O	SO_4-S	Zn	B	Lime	
301	Garden (no Legumes)	1	0	0	0	0	0	0	lb/1000 sq.ft.
302	General Garden (Garden with Legumes	0.5	0	0	0	0	0	0	lb/1000 sq.ft.
331	Tomatoes (Irrigated Plasticulture)	120	0	0	0	0	0	0	lb/acre

Crop 1 Notes:
Apply 2 lb urea, 3 lb 34-0-0, or 3.5 lb 27-0-0/1000 square ft before planting. At flowering, if needed to stimulate growth, apply 1 lb urea, 1.5 lb 34-0-0, or 1.8 lb 27-0-0/1000 square ft and water thoroughly.

Crop 2 Notes:
Apply 1 lb urea, 1.5 lb 34-0-0, or 1.8 lb 27-0-0/1000 square ft before planting.

Crop 3 Notes:
Apply N in three split applications: incorporate one-half preplant followed by one-fourth at flowering and one-fourth about three weeks later.

Soil pH determines how easily soil nutrients can be absorbed and used by plants. Most vegetable crops grow best in soils with a pH of 6.0 – 6.5. When soil pH is too far outside this range plants can experience nutrient deficiencies causing poor plant health and lower yields. Soil pH inside a high tunnel can rise over time if the irrigation water is alkaline.

Soil electrical conductivity, or EC, is a measure of soil salt concentrations (soil salinity). EC is also an indirect way to measure nutrients available in the soil for plant growth. Unless preventive methods are implemented, soil EC levels can increase to toxic levels in the protected environment of the high tunnel. EC levels should be monitored so corrective action can be taken before plant growth suffers. For more information on EC build up see the section on Common Soil Heath Issues in High Tunnels.

Soil organic matter (SOM) can be hard to increase or maintain inside a high tunnel. With continuous crop production and warmer year-round soil conditions SOM in tunnel soils can deplete rapidly. Changes in SOM should be monitored and augmented when needed. For more information on building and maintaining SOM see the section on Common Soil Heath Issues in High Tunnels. Most vegetable crops prefer soils with a SOM content of at least 3%.

This section includes fertilizer and lime (for pH management) recommendations. Fertility recommendations will be provided for the crop(s) indicated when the soil sample is submitted. If you are unsure of what crop you plan to plant you can list multiple crops, and recommendations for each will be provided on separate lines in this section. Fertilizer recommendation rates can be displayed in different units (lb/acre, lb/1000ft2, lb/100ft-row ft).

Interpreting a soil test report

It typically takes a few weeks for the soil test report to be returned after submitting a sample. At first glance, a soil test report can seem intimidating, but with a little direction it can become easy to quickly locate the necessary information to make soil management decisions. Some of the key features of the soil test report are highlighted in the image 'A Quick Glance at a Soil Test Report.' For a complete guide on how to interpret a soil test report see the University of Arkansas Extension factsheet “The Soil Test Report” (uaex.uada.edu/publications/pdf/FSA-2153.pdf) or “Understanding the Numbers on Your Soil Test Report (uaex.uada.edu/publications/pdf/FSA-2118.pdf).

While it may be tempting to add extra fertilizer to promote faster plant growth, it is important to follow the nutritional recommendations in the soil test report. Over-fertilizing can quickly lead to excess nutrient (or salt) accumulation in tunnel soils, which will hinder plant growth and lower yields (see “Common Soil Health Issues in High Tunnels” below). Excess nitrogen is also associated with higher aphid populations and excess vegetative growth.

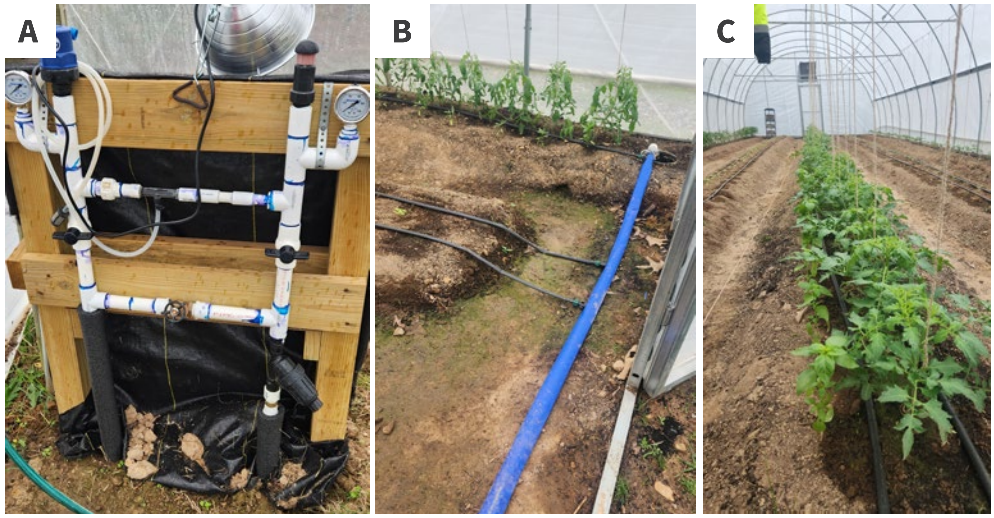


Image 10.1. A simple venturi style fertigation system installed inside a high tunnel (A) connected to drip irrigation (B) allowing water and nutrients to be delivered directly to the cropping area (C).

Fertility and Soil Amendment Scheduling

Organic matter, lime and some fertilizers should be applied and incorporated into the soil before planting crops. Generally, the full amount of phosphorus and lime required for the crop should be incorporated before planting. However, some additional nutrient applications will likely be needed after the crop is planted and actively growing. Since plants use different nutrients at different growth stages, applying a nutrient when it's most needed not only improves crop growth but also reduces fertilizer waste. For this reason, many high tunnel growers install fertigation systems that allow dissolved fertilizers to be applied through a drip irrigation system (Image 10.1).

Table 10.2. Possible drip fertigation schedule for tomato and pepper plants in soils with high potassium levels. When using fertigation, be sure to calculate fertilizer rates based on row size instead of the tunnel's total square footage. Table adapted from the 2024 Southeastern U.S. Vegetable Crop Handbook.

Days after planting	Tomato		Pepper	
	Daily Nitrogen* (lb/A)	Daily potash* (lb/A)	Daily Nitrogen* (lb/A)	Daily potash* (lb/A)
Preplant	50	125	50	100
0 - 14	0.5	0.5	0.5	0.5
15 - 28	0.7	0.7	0.7	0.7
29 - 42	1.0	1.0	1.0	1.0
43 - 56	1.5	1.5	1.5	1.5
57 - 77	2.2	2.2	1.8	1.8
78 - 98	2.5	2.5	1.8	1.8
Total Amount Applied:	**200.5**	**275.5**	**177.4**	**227.4**

Fertigation improves fertilizer nutrient use efficiency by allowing growers to spoon-feed fertilizer directly to a plant's rootzone and supply nutrients to plants when they most need them. For example, several split fertigation applications of nitrogen are recognized as the best method of nitrogen management for many crops (Table 10.2). It is common to apply only a small part of the nitrogen and potassium a crop requires before planting and apply the remainder through fertigation. Rates of nitrogen and potassium applied weekly through fertigation can be increased as the crop grows larger or starts to set fruit (Table 10.2).

Table 10.3. A sample list of common water-soluble fertilizers used in drip fertigation systems

Fertilizer	Percentage of N-P-K
Ammonium Nitrate Solution	20-0-0
Urea-ammonium Nitrate Solution	32-0-0
Calcium Nitrate	15.5-0-0-19 Ca
Potassium Nitrate	13-0-46
Urea Solid	46-0-0
Urea Solution	23-0-0

Fertigation does require the use of water-soluble fertilizers (Table 10.3). Simple fertigation systems can be constructed for less than a few hundred dollars and greatly increase the labor and nutrient management efficiencies of high tunnel production (see Chapter 9 - Irrigation Strategies).

For more information on designing and implementing a drip irrigation and fertigation system:

- "Basics of Drip Irrigation and Fertigation for Specialty Crop" (uaex.uada.edu/publications/PDF/FSA6160.pdf).
- How-to build a Venturi Injector (one example of a fertigator) youtube.com/watch?v=agPPZa9TEwU.
- Table 10.3 lists common water-soluble fertilizes used in drip fertigation systems.

The notes section on the soil test report will include suggestions on timing fertilizer applications for broadcast applications. The 2025 Southeastern Vegetable Crop Handbook includes suggestions on fertigation schedules for many vegetable crops (https://www.uaex.uada.edu/publications/pdf/MP584.pdf).

Common Soil Health Issues in High Tunnels

Soil health and fertility management inside a high tunnel is, in many aspects, very similar to managing soil health in a garden or open field. However, the modified and protected environment of a high tunnel does add a few complications. Notable issues in high tunnel soil management include the buildup of salts within the soil, the accelerated breakdown and loss of soil organic matter and increased risk for soil compaction.

Salt Accumulation

Under field conditions, excess soil nutrients not used by plants are washed (or leached) out of the soil profile with rainfall. This, of course, does not happen for soils under the plastic cover of a high tunnel. Over time, the lack of rainfall and leaching in high tunnel soils will cause a buildup of these unused nutrients, in the form of salts. After three or four years of crop production salt levels in high tunnel soils can reach levels toxic to many plants. A survey of high tunnel soil conditions in Maine showed that 27 percent of established high tunnels (three or more years in production) exceeded optimal soil salinity thresholds. This was true for both organic and conventional high tunnels.

The use of drip irrigation can accelerate salt accumulation in the root zone. Because water is applied only as needed with a drip system, salts are not washed below the root zone. To compound this, water is often pulled from drip-irrigated soils, through evaporation and transpiration, more quickly than it is replaced. This causes a natural

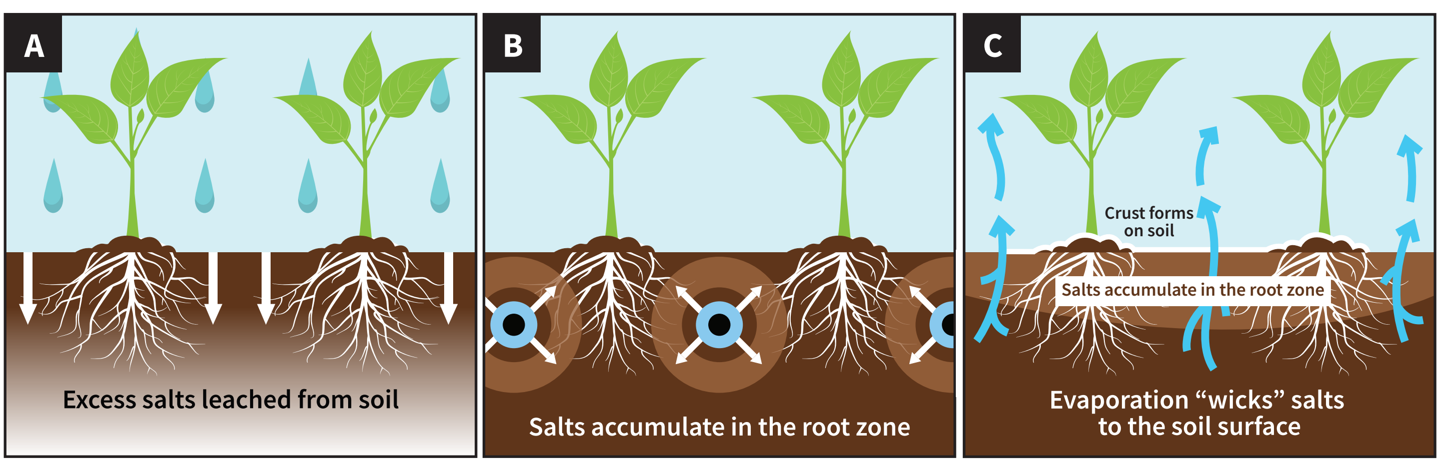


Image 10.2. Under field conditions excess salt (nutrients) are washed or leached out of the root zone during rainfall (A) while the lack of rainfall within a high tunnel can cause excess salts to accumulate within the root zone. Drip irrigation and the wicking effect caused by transpiration and water evaporating from the soil can accelerate this buildup of salts (B and C).

upward wicking movement of water within the soil. This upward movement of water draws the unused nutrients (salts) near the soil surface, causing them to accumulate within the root zone. This often forms a white crust on the soil surface (Image 10.2).

Crops grown in saline or high-salt soils often struggle to take up nutrients and water, resulting in nutritional deficiencies, poor plant vigor, low yields and leaf discoloration.

Image 10.3. Pepper plants damaged by excess salt in the soil (A). A white crust can form on the surface of soils with high salts (B). Image A borrowed from Burst 2021, and Image B borrowed from Langenhoven 2023.

Symptoms of salt stress also include "salt burn," which has the appearance of scorching on leaves, usually beginning at the margins (Image 10.3).

A soil's electrical conductivity, or EC, is a way to measure the amount of salt present in the soil. Optimal soil EC ranges are crop (and sometimes cultivar) specific, with some crops being more susceptible to salt toxicity stress or damage than others (Table 10.4). Some more tolerant plants can even experience some positive effects owing to moderately high EC levels. For example, spinach yields may initially increase.

Be careful when interpreting or comparing soil EC measurements. Soil testing labs may use one of several possible procedures for measuring soil EC and can report the results in various units. Soil EC values obtained using different sample preparation procedures will not be comparable, even if results are reported in the same units.

When comparing soil EC results from other sources, be sure to check what procedure was used and keep an eye on the units. Soil samples submitted by Arkansas growers through their local Extension office will be analyzed using the 1:2 soil-to-water ratio method. Table 10.5 contains guidelines adopted by the University of Georgia to help interpret soil EC results from a 1:2 soil-to-water ratio protocol. The

Table 10.4. Common high tunnel crops and their ability to tolerate soil salinity.

Salt Sensitive	Beans, Celery, Cucumber, Onion, Radishes, Strawberry
Moderately Sensitive	Broccoli, Brussel Sprouts, Bell peppers, Cabbage, Carrots, Cauliflower, Lettuce, Peas, Potatoes, Squash, Turnip
Moderately Tolerant	Beets, Zucchini, Spinach, Tomato, Kale
Tolerant	Asparagus

Table 10.5. Guidelines to help interpret EC results using a 1:2 soil to water ratio. Table adapted from the University of Georgia (Sonon et al. 2022).

Electrical Conductivity		Rating	Interpretation
(mmhos/cm)	(µmhos/cm)		
0 - 0.15	0 - 150	Very low	Plants may be starved of nutrients.
0.15 - 0.50	150 - 500	Low	If soil lacks organic matter. Satisfactory if soil is high in organic matter.
0.51 - 1.25	510 - 1,250	Medium	Okay range for established plants.
1.26 - 1.75	1,260 - 1,750	High	Okay for most established plants. Too high for seedlings or cuttings.
1.76 - 2.00	1,760 - 2,000	Very high	Plants usually stunted or chlorotic.
> 2.00	> 2,000	Excessively high	Plants severely dwarfed; seedlings and rooted cuttings frequently killed.

University of Georgia's publication on Soil Salinity contains tables to help interpret EC results obtained from other protocols as well (https://secure.caes.uga.edu/extension/publications/files/pdf/C%201019_4.PDF).

Over-fertilizing can accelerate salt build-up in high tunnel soils. To avoid over-fertilizing, follow soil test recommendations and calculate your rates based on the square footage being fertilized — not the total square footage of the tunnel. It may also be unnecessary to apply additional nitrogen fertilizer when transitioning from summer to winter crops. A few studies have suggested that, when the tunnel was adequately fertilized for summer crops, the addition of more nitrogen fertilizer when transitioning to winter grown greens had little effect on final yields. This is likely due to a leafy green's lower need for nitrogen and the amount of nitrogen remaining in the soil after the removal of summer cash crops. The incorporation of organic matter can also help lower the amount of fertilizer needed, but remember that compost and manure can also contribute to salt build-up in the soil.

The simplest way to lower soil EC is to "flush" or "wash" the soil. When replacing the tunnel's plastic (which should be done every four to five years) leave the tunnel uncovered and allow a few heavy rainstorms to wash excess salts out of the soil profile. If an intervention is needed before plastic replacement, irrigating with pure water in an overhead sprinkler system can help flush salts from the soil. Generally, 12-24 inches of water will be needed to flush 80-90 percent of salts out of the soil, though some studies indicate more water may be necessary. Planting salt accumulating cover crops in the off season might also help remove some of the excess nutrients.

Soil Organic Matter

Soil organic matter impacts many soil quality and health indicators including water absorption and retention capacity, soil biological activity and nutrient availability. It can be difficult to maintain a healthy level of soil organic matter inside a high tunnel. The accelerated depletion of SOM caused by the warmer year-round soil conditions inside a tunnel is compounded by the increased number of successive plantings. To help break disease and insect cycles, it is generally best to remove all plant residue from the tunnel at the end of a cropping cycle (see Chapter 8 – Pest and Disease Management Strategies). This removal of plants and plant residue not only removes existing SOM but also removes a significant source of potential organic matter. With the increased number of successive plantings inside a tunnel a significant amount of organic matter can be lost in a single year. To combat this, it will be necessary to add organic matter to the high tunnel soil.

Compost, manure and mulches are all good sources of organic matter and can be easily incorporated between plantings. Not all compost or manure sources, however, are good quality. When possible, test the compost for pH, EC and nutrient levels before bringing it into the tunnel. Purchase compost/manure/mulch from a reputable source to help minimize the risk of introducing potential soil issues such as pathogens or weed seeds. Herbicide residue can also be brought into a tunnel on contaminated manure, stunting or even killing plants. A vegetation-based compost is usually a better choice for high tunnels as many animal manures can contribute to salt buildup in the soil.

Incorporating cover crops into a crop rotation is a good way to increase SOM. Legume cover crops can even add nitrogen to the soil without increasing salinity.

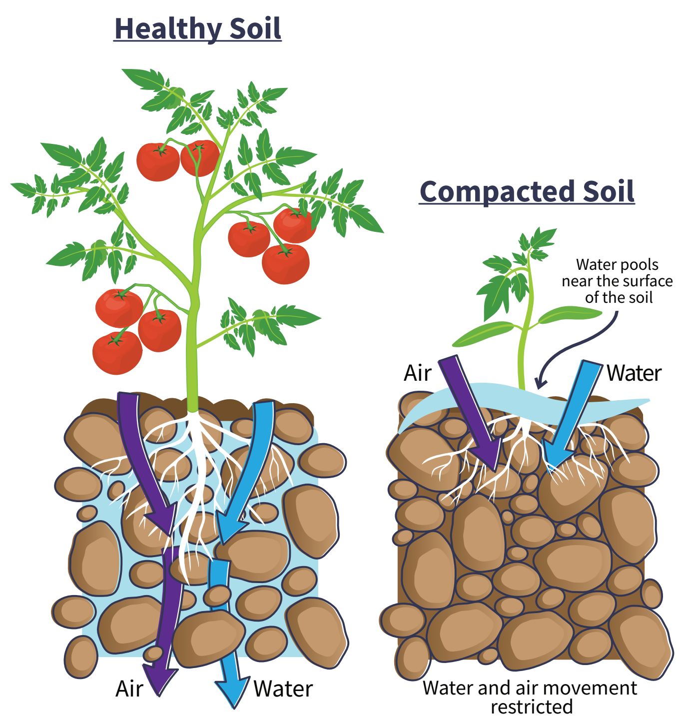


Image 10.4. The movement of air and water is restricted in compacted soils. Roots struggle to expand and cause low plant vigor.

A yearly soil test can help monitor and track changes in SOM over time. When developing a soil health plan, plan on incorporating a high-quality source of organic matter at least once a year. If unsure how much organic matter to add, a good rule of thumb is to apply about 1 inch of compost or well-cured manure across the entire floor of the tunnel. For a 30 ft by 96 ft high tunnel, this could be about 660 - 1320 pounds of compost. This material should be tilled into the soil unless observing no-till practices.

Soil Compaction

Soil compaction occurs when soil particles are pressed or compressed together, reducing space (pore space) between soil particles. Compacted soils struggle to drain and exchange gases, causing roots to struggle to expand and thrive (Image 10.4). This can result in plants with nutritional deficiencies and low vigor.

Many common soil and crop management practices can cause soil to compact. In high tunnel production, soil preparation tasks, such as tilling, are done more often due to the increased number of crop cycles. This damages soil structure more quickly, resulting in more compacted soils. A higher amount of foot traffic and the accelerated loss of organic matter also contribute to a higher degree of soil compaction in a high tunnel.

Implementing low-till strategies and annually incorporating organic matter can help minimize soil compaction. Some high tunnel growers, particularly organic growers, will use a broadfork in place of a tiller to help improve soil structure and reduce compaction (Image 10.5). This method is more labor intensive, but many growers have successfully used a broadfork to reduce compaction issues.

Conclusion

Soil and fertility management in a high tunnel are similar to common soil management practices used in garden or field production. However, the protected environment of a high tunnel will accelerate the breakdown and loss of soil organic matter, as well as the accumulation of salt in the soil profile. Regular soil tests can help monitor changes in these key soil health indicators, while implementing good soil health practices can help maintain or build healthy soils inside a high tunnel.

Image 10.5. Soil preparation using a tractor (A). While more labor intensive, a broadfork can be used in soil preparation and reduce damage to soil structure cause by tillage (B).

Additional Resources

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Langenhoven, P. 2023. Soil and Water Data is Critical for High Tunnel Growers. Vegetable Crops Hotline, a newsletter prepared by the Purdue University Cooperative Extension Service. vegcropshotline.org/article/soil-and-water-data-is-critical-for-high-tunnel-growers/.

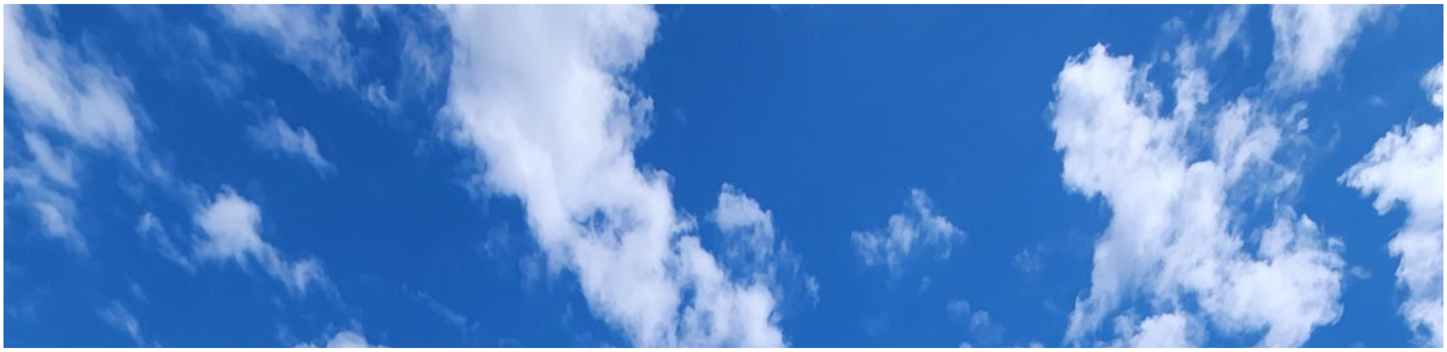
Soil Health:

1. Did you get your soil tested?

2. Soil test results: Do you need to add lime? Organic matter? Fertility? EC?

3. What kind of fertility program do you plan to use?

4. Notes:



CHAPTER 11

Financial Assistance for Purchasing a High Tunnel

The Environmental Quality Incentives Program

The Environmental Quality Incentives Program, or EQIP, is a USDA-NRCS program that provides financial and technical assistance for growers, ranchers, and forest landowners to help address natural resource concerns. EQIP aims to help growers improve production on their farms while conserving natural resources. Through EQIP, financial assistance for purchasing a high tunnel is available to those interested in extending their growing season. If awarded this funding, financial assistance can cover part of the cost of purchasing and installing a high tunnel.

Eligibility

To qualify for EQIP, applicants must be able to show ownership of or have control over eligible land for the entire lifespan of the program's contract. Before applying, be sure to talk with staff at your local USDA service center to learn about other eligibility criteria.

Application Process

Spend some time learning about NRCS processes and the EQIP program before meeting with your local NRCS conservationist and beginning the application process. There is a chance your local NRCS conservationist does not have extensive experience with high tunnels. For example, if you are in a county that is 90% cattle or row crops, you could be the first person interested in high tunnel production to meet with your county conservationist. Researching the program on your own could help make the application process go more smoothly by allowing the conservationist to focus on advocating for your funds instead of researching the process for you.

Before meeting with your NRCS conservationist and beginning the application paperwork, you will need:

1. An official tax ID (Social Security number or an employer ID)
2. A property deed or lease agreement (show you have control of the property)
3. A farm number. If you do not have a farm number, you can get one from the USDA Farm Service Agency (www.fsa.usda.gov). Often, the Farm Service Agency is in the same building as the NRCS offices.

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Once you have a farm number, Tax ID, property deed or lease agreement, and have done some research on the program, contact your local NRCS conservationist to set up an appointment to discuss your plan and begin the paperwork. The paperwork will require time and thought. While applications can be submitted anytime, funding periods only occur at specific times during the year. If you are awarded a contract, it can take several months before you are notified.

Strengthening your application

The application process is competitive. Submitted applications will be ranked, with the top-ranking applications being awarded. Applications are ranked based on:

- How effectively and comprehensively the planned conservation practice(s) or activity(s) address the identified natural resource concern(s).
- The degree of the expected benefits resulting from the conservation practice(s) or activity(s) and the priority of the natural resource concerns.
- The degree of cost-effectiveness of the proposed conservation project.
- Use of approved conservation practices or activities that provide long-term conservation benefit.

Other factors, such as the improvement of conservation practices or systems already in place at the time the contract is accepted, may also be considered. Incorporating other NRCS conservation practices into your high tunnel conservation plan can help improve your application's ranking. Other NRCS conservation practices that can easily be incorporated into and improve a high tunnel conservation plan include:

- Integrated pest management
- Mulching
- Roof runoff capture
- Cover cropping
- Crop rotation
- Micro irrigation
- Nutrient management

A full list of NRCS conservation practices can be found at your local NRCS office. Your NRCS conservationist can also help you incorporate other NRCS conservation practices into your high tunnel application.

Keep in mind that EQIP is a competitive program, and you may not be awarded funding the first time you apply.

Financial Assistance Payments

Those awarded an EQIP contract will initially be responsible for the entire cost of the tunnel. Once the tunnel is constructed, awardees will be paid the contracted amount. Historically underserved producers can be eligible for advance payments to help reduce out-of-pocket costs. Historically underserved producers include beginning farmers/ranchers and socially disadvantaged, veteran, and limited resource farmers/ranchers. Talk with your local NRCS conservationist to learn more.

While waiting

While you wait to hear about the status of your application, continue to learn about high tunnels and high tunnel production. The more you know, the more potential headaches you can avoid in the future. This time could be used to begin researching good high tunnel designs for your planned crops and climate. If you are awarded a high tunnel contract with NRCS, you will be responsible for finding, selecting and constructing your high tunnel kit. Before purchasing a kit ensure the design meets the NRCS standards and specifications for your state. This is also a great time to work on removing perennial weeds from the high tunnel site, test and amend the soil, and do other site preparations. Your county extension agent is a good resource for information and assistance in preparing the site for a high tunnel.

High Tunnel Specifications

Under EQIP, there are some design specifications that must be met to quality for funding. These design specifications can vary from state to state and can be adjusted each year. Before purchasing a high tunnel kit, make sure you know your state's design specification requirements. If your tunnel does not meet the design requirements, you could be denied the financial assistance payment. Your local NRCS office can provide information on high tunnel design requirements.

Helpful links

- Is EQIP right for me? www.nrcs.usda.gov/sites/default/files/2022-06/EQIP-Factsheet%20%282%29.pdf
- NRCS High Tunnel website: www.nrcs.usda.gov/getting-assistance/other-topics/organic/nrcs-assistance-for-organic-farmers/growing-all-seasons-high-tunnels
- NRCS - Small Farm and Urban Agriculture - Arkansas: www.nrcs.usda.gov/conservation-basics/conservation-by-state/arkansas/small-farm-and-urban-agriculture-arkansas
- EQIP factsheets:
  - www.nrcs.usda.gov/sites/default/files/2022-10/EQIP-fact-sheet.pdf
  - www.nrcs.usda.gov/resources/guides-and-instructions/get-started-a-guide-to-usda-resources-for-historically
  - www.nrcs.usda.gov/resources/guides-and-instructions/eqip-advance-payment-option
- NRCS county office locator: www.farmers.gov/working-with-us/USDA-service-centers

Notes

Additional Resources

A Check List for Assembling a High Tunnel Scouting Toolkit

A pre-assembled kit containing all the tools and supplies needed to scout effectively can save time by having everything you need in one location. This could also prevent making multiple trips to and from the field to acquire needed supplies.

Scouting Tools:

- ☐ **A hand lens or magnifying glass.** There are many options and styles available that range in price, magnification, and sophistication. Select one that works best for you and your situation. A 10X magnification is usually sufficient for spotting most insect pests.
- ☐ **A method for recording.** Records can be kept in a notebook, on paper, or electronically. Several apps have been created to assist growers in pest monitoring. Whatever method works best for you, make sure you are consistent and organized. Records should be easy to locate and documented in a way that the data collected can be used to benefit your IPM program.
- ☐ **Camera.** A photo of an insect, symptom or abnormal plant growth can be used by Extension personnel or the Arkansas Plant Diagnostic lab to help identify an unknow pest. These photos can also be kept with other records to serve as training material for farm staff, or as a reference if the problem occurs again.
- ☐ **Paper/plastic bags or vials.** Samples of disease symptoms, injured plants or insects that cannot be identified can be collected. These samples can be taken to the local Extension office or sent to the Arkansas Diagnostic Lab for identification. If it's hot, and you plan on being in the field for a while, a small cooler with an ice pack may be needed to keep the sample from wilting in the field.
- ☐ **A piece of laminated paper.** Also known as a beating card, this method can make finding insect pests simpler. Hold the card beneath foliage or flowers while gently beating the desired part of the plant. Non-flying insects will be dislodged and drop onto the paper where they are easily seen and can be either identified and counted or collected for later identification. This method works for aphids, thrips, and spider mites.
- ☐ **Flagging tape or colored flags.** Plants or locations where infestations are discovered should be marked. This allows the scouter to monitor and track any changes in pest levels which can help determine if management practices are working. These "indicator plants" can also be used to monitor the presence of natural enemies and determine the natural enemy/pest ratio.
- ☐ **Sticky Cards, marker, stakes/holders**. If sticky cards are being used, bring extra cards in case one needs to be replaced.
- ☐ **A small hand trowel.** When looking for root diseases or nematodes. Plants should be dug out not pulled to prevent the loss of root material, or insects located in the soil near the roots. Samples can be examined in the field or transported to another location.

Sample - Pest Scouting Sheet

Year:__________ Farm:__________ Scouter:__________

Date	Field name and crop (type, cultivar)	Areas Scouted (# rows, leaves, etc.)	Pests Observed				Observations and notes
			Tomato Fruitworm (TFW)	Mites	Aphids	Stinkbug	Average pests per plants? Diseased or discolored plants?
Ex: 4/23/24	High Tunnel 1, Tomato, Early Girl	2 rows, 60 leaves total	30 eggs	60	100	3 brown	0.5 TFW egg per leaf avg (above threshold), 1 mite per leaf
Ex: 4/23/24	High Tunnel 1, Tomato, Celebrity	2 rows, 60 leaves total	60	80	200	0	1 TFW egg per leaf (above), 1.3 mites, edges worse
Ex: 4/30/24	High Tunnel 2, Pepper, Olympus	2 rows, 60 leaves total	60	130	50	0	1 TFW egg per leaf (above thresh-old), ~2.5 mites (spray?), plants yellowing from mites
Ex: 4/30/24	High Tunnel 2, Eggplant, Thanos	2 rows, 60 leaves total	6	80	10	0	0.1 TFW egg per leaf (at thresh-old), 1.25 mites

Sample - Pest Scouting Sheet

Year:______________ Farm:______________ Scouter:______________

Date	Field name and crop (type, cultivar)	Areas Scouted (# rows, leaves, etc.)	Pests Observed				Observations and notes
			Tomato Fruitworm (TFW)	Mites	Aphids	Stinkbug	Average pests per plants? Diseased or discolored plants?

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Fax: (202) 690-7442; or

Email: program.intake@usda.gov.

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