Introduction

My Perspective

My first book, Sustainable Market Farming, was published in 2013. In that book, I described how to grow a wide range of vegetable crops sustainably in an efficient way, and how to organize production for a smooth flow. I included two chapters which introduced hoophouse growing. This book expands on the hoophouse growing information, adds design and construction information, and includes the details needed to make a success of hoophouse vegetable production. I have not repeated the basic details of growing the crops, seed counts, or yields, all of which can be found in Sustainable Market Farming. I also have not addressed sales and marketing, because I don't know much about these things. For us, marketing consists of equal parts presentation and education. We have a pre-determined market. For each chapter there are some resources at the end of the book. Web links don't always remain the same for long, so if one doesn't work, copy and paste the title of the publication into a search engine.

My perspective is as a Southeast/mid-Atlantic (non-certified) organic grower, producing food year-round for a community of a hundred people on a few acres. The South is traditionally under-served with books about farming and vegetable gardening, and I seek to remedy that, using my twenty-six (and counting) years of experience in Virginia. Before that, I grew food in the UK, so I know that climate too, and use that experience to express information in terms of climate, soil temperature and conditions, so that anyone can adapt this book for their own climate. Indeed, everybody's climate is changing, and we can no longer rely on the calendar to tell us when to plant.

My Work

I am a long-term member of Twin Oaks Community, an intentional community of around a hundred people of all ages living and working together in rural Virginia. We share decisionmaking, resources and responsibilities. We do not have a leader. We do not have a group religion; our beliefs are diverse. We care for each other and our environment through principles of nonviolence, egalitarianism, cooperation, equality and ecology. We are economically self-supporting, running collective businesses making hammocks and tofu, operating the wholesale office of Southern Exposure Seed Exchange, growing seeds, indexing books and a few other enterprises. These include me doing my bit, writing and speaking about sustainable food production. Less than half our work goes into income-earning; the balance goes into tasks that benefit our quality of life,

including farming, cooking, and childcare. We are partly self-sufficient in food. We are incomesharing and cost-sharing. A number of us choose to be politically active in issues of peace, ecology, racial justice and feminism.

We offer Saturday afternoon tours for the curious, if booked ahead of time (see our website twinoaks.org or call 540-894-5126 for more details). For those interested in possible membership, we offer a three-week visitor program. We are not open to people showing up at our home, our farm or our businesses uninvited.

I have a website sustainablemarketfarming .com where I write a blogpost every week. I also write posts for the *Mother Earth News* organic gardening blog, and articles for *Growing for Market* magazine and other publications. I present workshops at conferences and other gatherings of gardeners and farmers, and most of my slideshows can be seen on SlideShare.net. I also do some consultancy work.

The Twin Oaks Garden Hoophouse

We have a group of five to seven people running the hoophouse, each working a day in turn. We have a $30' \times 96'$ (9.1 × 29.3 m) Clearspan house, the Gothic arch type, with bows 4' (120 cm) apart. We use a double layer of plastic inflated with a small electric blower. We do not have roll-up or roll-down sides, because we wanted maximum winter coziness. The end walls have large high windows and double doors. In our climate, we don't normally need rowcover for our winter crops. We appreciate that the insulation provided by the double plastic means temperatures are mild enough so we don't have to deal with rowcover. In winter the amount of daylight is a limiting factor, and rowcover does reduce the light, so we are glad we don't need it. If you are in a colder climate than we are, the extra insulation from rowcover can be worthwhile. Compared to using rowcover outdoors, indoor rowcover is easy—no gusts of wind, no rain, no snow! There



Welcome to Twin Oaks. Photo by Kati Falger.

is no need to weigh down the edges of rowcover unless you have ground-level breezes blowing through. We have installed both in-ground perimeter insulation and short north wall insulation.

We chose to go with lengthwise beds, seven of them, and no regrets! The two edge beds are 2' (60 cm) wide and the other five are 4' (120 cm). Our paths are only 12" (30 cm) wide, the same size we use outdoors, and they work well for us, despite being so narrow.

We do all our hoophouse work manually-no tractor or rototiller. We use a broadfork to loosen all the soil once a year, when transitioning to cool weather crops. All isn't perfect in paradise-we are dealing with salt build-up and nematodes. But mostly, work is easier indoors. Because we use drip irrigation and we do not invert the soil, there are very few weeds. When we first put up the hoophouse, we closed it in the fall. The initial round of cool weather weeds like dead nettle and chickweed was replaced by a round of warm weather weeds! We all look forward to winter gardening in the hoophouse, protected from harsh weather, and heated by the sun. The intensive planting and the peaceful enclosed space add to job satisfaction.

In winter and early spring we grow a diversity of lettuces, other salad crops, cooking greens, turnips, radishes and scallions. We also use some of the space to grow bare-root starts to transplant outdoors in February and March. In our climate, spinach, collards, kale and leeks can survive outdoors all through the winter, although the rate of growth doesn't compare to what happens in the hoophouse! We start to harvest greens and turnips from the hoophouse in late fall, after the outdoor crops slow down.

In spring we plant a round of early warm weather crops, usually tomatoes, peppers, cu-

cumbers and yellow squash. We don't keep these all summer, as those in cooler climates might. Once the outdoor crops are coming in, we switch to our third season of hoophouse crops (except that we keep the peppers). We plant mostly legumes for the high summer, either as food crops or cover crops. We favor cowpeas (southern peas) and edamame.

Our goal with our hoophouse is to supply a wide range of fresh produce from late fall to spring, to feed a hundred people, and then make good use of the space the rest of the year. Every grower will need to grow the mixture of crops that suits their climate and their market. If your goal is to be on vacation for the whole of December, you might plant the hoophouse up with spinach in October, and harvest from January onward.

Grower Steve Moore points out that US mechanized agriculture uses 9.8 calories of mostly fossil fuel to produce one calorie as food. Using bio-intensive agriculture, such as with solar hoophouses, we can switch the ratio to one calorie in for 20 calories out. That's 200 times more energy efficient. I hope this book will help you move into hoophouse growing or (if you already have a hoophouse) improve your production by making use of my suggestions of varieties, techniques and planning methods.

For readers who want to know in a hurry: our Winter-Hardiness Zone in central Virginia is 7a, with an average annual minimum temperature of 0°F-5°F (-18°C to -15°C). Our average daily maximum temperatures are 47°F (8°C) in December and January. Our night lows average 26°F (-3°C) in January. Our outdoor frost-free period is around 176 days. The average date of the last spring frost is April 20 (one year in ten will be later than May 7). The average date of our first fall frost is October 14 (earlier than September 29 happens one year in ten).

PART I

Design, Siting and Construction





Hoophouse Siting and Planning

What Is a Hoophouse?

Hoophouses (also known as high tunnels) are plastic-covered hooped frames tall enough to walk in, for growing vegetables, flowers or fruit and extending their growing season. They are also called unheated greenhouses, polytunnels and cold frames. They can be used for year-round growing of seasonal crops, and although temperatures inside are not much higher than outdoors when the sun isn't shining, they manage to produce impressive rates of growth and beautiful quality crops. There are many variations on the theme, but generally they have no supplemental heating and crops are grown directly in the ground. Often they are double-skinned, meaning they have two layers of plastic film, with a small blower keeping the space between the layers inflated. This provides increased insulation and



A double-layer hoophouse sloping down to the west end, with no shading to the south.

improved strength against winds and snow or ice loads, and lengthens the life of the plastic by preventing flapping and abrasion. Winter night temperatures in a double-layer hoophouse can be about 8°F (4.5°C) degrees warmer than outside (provided winds are not strong). Hoophouse soil temperature rarely falls below 50°F (10°C) in Zone 7a. Hoophouses have risen in popularity since 2000, helped in part by USDA grants, but largely because of the many benefits they provide in making fresh local produce more widely available. See the resources at the end of the book for more information before you start.

NRCS (Natural Resources Conservation Service) Funding

Before going further, I must mention the USDA NRCS *High Tunnel System Initiative*, which provides grants for some types of hoophouses as part of the Environmental Quality Incentives Program (EQIP) in the US. Details vary from state to state, as do sign-up periods. State links and links to financial and technical assistance are on their website, or call your local extension office.

There are limits to the amount of grant you can receive (higher limits for historically underserved farmers), and various limitations on features (for example, you must grow crops in the ground), but as far as I could see there are no limits on the size of the structure. See the NRCS *High Tunnel System Code 325*. At Twin Oaks, we were ahead of the curve on putting up our hoophouse, so we didn't get any outside funding. Even so, it has been entirely worthwhile.

Siting

Sun exposure is probably the first important factor to consider. Hoophouses are solar powered growing zones. I recommend walking around your farm in mid-winter, pacing out and flagging several potential sites. In mid-winter the sun will be at its lowest angle, and shadows from obstructions will be at their longest. Your site needs as much sunlight as possible in winter, so make sure you aren't choosing a site in the shade. We looked at three or four sites at Twin Oaks and assessed them against all the criteria described here. We chose the best site, then had a last minute idea that shifting 100' (30.5 m) to the east would give us better drainage. It did, but we under-estimated the shade that would come from a group of nine loblolly pines about 100' (30.5 m) or so to the southeast. In winter, a third of our hoophouse was in shade after about 2:30 pm. Over the course of two winters, we cut down those trees. It would have been wiser to have paid them appropriate attention before putting up the hoophouse!

Build It Solar has a helpful DIY document *Evaluating Your Site for Solar Energy*. You could buy the Solar Pathfinder Sun Chart, but I think the DIY version is fine and helps make the rationale clear. You can plot trees and buildings that might block sunlight at your chosen site. I haven't yet used one of these, as I tend to plan far enough ahead that I can go and look for myself in mid-winter. There is no need for extreme accuracy. Orienting the hoophouse 10° east of true south is fine. Even at 30°E of south, you get 85% of the solar power.

Hoophouses are usually oriented with east and west ends and long south and north sides to get the most light. Some books recommend greenhouses in the south be oriented the other way, with long east and west sides and walls at the north and south ends. I don't think this is a good idea for hoophouses where winter crops are most important, and sunlight is at a premium. If tall vining crops will be your focus, having rows running north-south will provide the most even lighting.

Good soil with good fertility will be your goal. You can of course improve your soil as you use it. Just don't start out with a boulder field, a gravel pit, a clay pan—you get the idea.



Hoophouse Orientation

Your site ideally has a 1% slope lengthwise from east to west (or west to east). There are warm-season single-layer temporary structures such as the Haygrove tunnels, which can accommodate steeper slopes, but regular hoophouses will not. You can adjust the slope of your site by a foot or two over a hundred feet, but not much more. The NRCS funds specify a limit of 5% slope. The site needs to be fairly level side-to-side. If you need to do a lot of soil moving to meet the ideal, be sure to preserve the topsoil.

Even if you are not applying for NRCS funding, their website gives a brief useful checklist of factors to consider in planning your hoophouse.

You need a well-drained site, and you will need to accommodate rainwater runoff from the roof. Ours has a horseshoe-shaped V-profile moat around it. Some other growers leave extralong plastic from covering the roof and use it to lead water away from the hoophouse.

Some people who have roll-up or drop-down sidewalls install plastic guttering on the "hip-wall" lumber that these structures need, and collect the rainwater for irrigation. Bear in mind that the water catchment barrel will be low down and the water will need pumping or dipping and hauling to be useful. Read the NRCS *CPS Code* 558 *Roof Runoff Structure*.

When choosing your location, also look for sites protected from the full force of the wind (at a non-shading distance!). Choose a site with good frost-drainage, not at the bottom of a slope.



The hoophouse site needs to be open all around, with only low-growing plants in the vicinity. Photo Bridget Aleshire.

Consider road access and proximity to water and electricity. There are a couple of ways to not need mains electricity, but if it's relatively easy to hook up to the grid, do so. You can decide later if it's worthwhile to provide an alternative source of power. The inflation blowers use very little electricity, so the financial cost will be worthwhile. Probably you will want your hoophouse near your house, or your barn or main work area, where you can keep an eye on it, and pop over for the odd half-hour. It's best for winter crops if your packing shed is nearby, as you don't want crops to freeze in transit. Most growers don't heat their hoophouses, but if you want to heat with wood, plan for access for firewood, or for an underground pipe from a furnace elsewhere.

And lastly, choose the site for your first hoophouse with a second already in mind. After seeing the benefits a hoophouse brings, it'll be hard to resist building another! Alternatively, you can construct a wide house that is relatively short. At



If siting two hoophouses side by side, allow at least 10 ft (3 m) between them, as in this photo at Maple Spring Gardens.

a later date you can buy more hoops and bigger plastic and double the size of your original house. For two hoophouses side by side, allow at least 10 ft (3 m) between them, more if you get deep snow. In the north, the recommended spacing is two times the height of the house to the south.

Size

How much food do you intend to grow? Do you have markets already? I never met a grower who complained their hoophouse was too big. Height at the peak varies from about 6' (1.8 m)— the minimum for NRCS grants—to 17' (5.2 m); width from 10'–30' (3-9 m) and length up to 100' (30.5 m), the size of the most commonly found plastic film.

Consider the surface to volume ratio: you can get a lot more volume, for not much of an increase in surface area. The cost of materials is related to the surface area. In other words, it pays to go as big as sensible. But 20' (6 m) wide structures need less bracing than 30' (9 m) ones, so the price of the frames for the same area may end up less than for wider houses. 100' (30.5 m) may be the maximum length that works without forced airflow. Having a good amount of fresh air helps your plants stay healthy. High windows in the endwalls help ventilation of stale warmed air, without chilling your plants at ground level.

Soil and air act as heat stores during sunny days in cold weather. At night, the heat is released, to the benefit of the plants. Therefore, the more air and soil you have inside your house, the better, up to a point. Small structures do not store much heat. Also, edge beds are usually colder, so the more center beds you have compared to edge beds, the cozier the plants will be. Steve Moore, a high tunnel pioneer, calculated that a 28' or 30' wide by 96' long ($8.5-9 \times 29$ m) hoophouse seems the best.

If you have a preferred bed width, choose a hoophouse width that works for that. We have

a 30' (9 m) wide hoophouse with five lengthwise 4' (1.2 m) wide beds and two 2' (0.6 m) edge beds, with 1' (30 cm) paths throughout. Kentucky growers Alison and Paul Wiediger chose 20' (6 m) wide houses to accommodate their preference for three 40" (1 m) beds and two 30" (0.76 m) edge beds with 15" (38 cm) aisles. Don't make beds wider than you can cultivate comfortably. If you plan to drive a cultivating tractor through there, fit the beds to the wheel axle space.

If you plan to use rowcover, either match the size of your hoophouse beds with your outdoor beds, or buy special rowcover for your hoophouse.

The Framework

Is DIY worthwhile? Although some people advocate using PVC piping rather than galvanized steel, it does not seem wise in my opinion. PVC is not strong enough for large hoophouses; it degrades rapidly in sunlight (of which you hope to have plenty); it reacts with the polyethylene sheeting and degrades both; and the manufacturing, burning, and ultimate dumping of PVC all release dioxins which cause a wide range of health problems. Some people like to buy and bend their own steel tubing, but on a large scale this is hard work. In England we bent scaffolding tubing (used while constructing houses) round a series of wood stakes hammered into the grass to make hoops for a polytunnel. It's possible, but for most of us, the price of pre-shaped galvanized steel tubing is worth paying. You might be looking at making 25 hoops (50 half-hoops) from 25'- (7.6 m-) long tubes. If you are a good grower and have the markets, your hoophouse could pay for itself after the first year. Don't skimp too much. Commercial frames have the advantage of all having the same curve, all fitting together and being the right length. And you might even get an assembly manual. When we bought our hoophouse in 2003, we went with a bargain deal from a company new to supplying these "coldframes" as they were called. The manual wasn't terribly helpful. Information on constructing hoophouses has come a long way since then.

Consider the snow loading and wind force you might experience. Bows (hoops) at 6' (1.8 m) spacing are adequate for snow loads up to 9" (23 cm) or so. We decided to go with 4' (1.2 m) spacing because I was a Nervous Nellie. I sleep easier with 4' (1.2 m) spaced bows out there. If you are unlikely to get more than 9" (23 cm) snow and you're not a nervous type, save money and use 6' (1.8 m) spacing. If you'd rather be prepared for climate change and more extreme precipitation, go with 4' (1.2 m) spacing. We researched past weather extremes at our location before building, and learned that there has been snow 32" (0.8 m) deep and wind speeds with a maximum sustained velocity of 60 mph (97 kph), with higher gusts (trees blew down). That was sobering but we went ahead anyway. The house is still standing 15 years later. Other growers tell me that winds in the 75-80 mph (121-129 kph) range will take out a hoophouse. And then they rebuild.

Shape

The Gothic shape sheds snow more easily than the round Quonset shape. Gothic provides more head-room over more of the area, and also better sun angles. If you are bending your own tube, round is probably easier, however.

How much sidewall height do you need? Determine the standing room you need 2' (60 cm) in from the sidewalls. You'll probably want to be able to stand upright to work the edge beds.

Choosing a Manufacturer and Supplier

Bear in mind that shipping can be a considerable cost for heavy materials, and investigate local suppliers. Some brands are more strongly built than others—check not just the cross-bracing and end bracing provided but also the gauge of steel tubing. The more snow, ice and wind you get, the stronger the structure you will need. Gothic arch structures are stronger than Quonset (round) shapes, and 4' (1.2 m) bow spacing is stronger than 6' (1.8 m). Double plastic is stronger than single layer. Weigh up all these factors and also your budget and your willingness to take risks. Think not only about the likelihood of collapse at your site (ask other local growers), but also the other dimension of risk: the impact of collapse. Growers generally rebuild if their tunnel collapses. You risk losing your crops, but so long as you are sensible in storms, not life or limb.

Are you considering a moveable hoophouse? Consider that you need to pay good attention to anchoring the hoophouse very thoroughly at each site. It's easier for a movable hoophouse to blow away in strong winds. I have heard from several growers who constructed movable houses with the intention of moving them several times a year to cover a series of crops. However, it is inconvenient enough that they now only move them once a year, cover-cropping the uncovered part of the land. Perhaps two stationary tunnels would be better than one movable one? Do you intend to hang things from the rafters or train plants up twine or wires from the rafters? If so, check with manufacturers and get one with strong rafters. Most frames are not designed to support the extra weight of crops. An alternative is to install a separate support framework in the ground.

Double Layer Plastic or Single Layer?

Single plastic does not retain heat at night—inside temperatures will be much the same as outdoors. Double plastic gives an 8–10 Fahrenheit degrees (4.4–5.6 Celsius degrees) difference. This difference really counts in climate zones where the crops are not just being stored till spring, but are actually growing some of the time. Both spinach and kale make growth whenever the temperature rises above 40°F (4.4°C). This happens more often in a double-skinned structure. The extra expense is paid for by the extra income from the faster growing crops.

Double plastic is stronger against wind and the weight of accumulated snow or ice, as the whole shape pushes out against the load and spreads the force of the weight over the whole area. In Iowa, a double-layered structure with-



Be sure any construction after the hoophouse is in place will not shade it. Photo Bridget Aleshire.

Type of film	% PAR transmitted
Single-layer standard 4-year 6 mil (0.15 mm) polyethylene	92
Double-layer standard 4-year 6 mil (0.15 mm) polyethylene	85
Double-layer: outer standard poly, inner infrared heat retention poly	81
Single layer of IR heat retention poly	88
Double layer of IR heat retention poly	77

Photosynthetic active radiation (PAR) light transmission through polyethylene films

stood 80 mph (129 kph) winds, because the "bubble" stopped any ripple effect on the plastic.

In 2007 there was a debate about single versus double plastic on the High Tunnels Listserv. A proponent of single layer claimed that the loss of light from using a second layer was a problem. A 1% reduction in light transmission results in about a 1% reduction in yield. This must be balanced against the loss in yield that could come from a single layer hoophouse with colder nights.

Nick Calabro from Klerks Plastics (a source of hoophouse plastic film), reported on research into Photosynthetic Active Radiation (PAR) light transmission through various combinations of film. See the table in the next column. We use regular 6 mil (0.15 mm) outer plastic and inner IR plastic, and are happy with our choice. The inner plastic is also Condensate Control, meaning condensation does not gather and "water bomb" us or our plants.

KoolLite Plus is a film designed to provide daytime cooling while still transmitting 84% PAR.

A different option is Solarig from Robert Marvel in Pennsylvania. This is a woven poly film, ten times stronger than regular polyethylene film. It will not tear in wind storms even when punctured. It comes with a 4 or 6 year limited warranty, depending which type you use. It transmits 88% of the light compared to standard poly (see below) and about 45% of the light transmitted is diffused, which reduces plant burning and evapotranspiration, and claims to increase photosynthesis and increase yields. I have not yet seen this material in use. It has Condensate Control and IR additives and UV blockers. It can be used as a single layer with strapping over the top, or a double layer using the lighter version for the inner layer.

A newer possibility without inflation that still has the advantages of a double layer is SolaWrap, a very strong material that looks like bubble wrap. It comes in rolls 4', 5', 6' or 2 m wide, so must be fastened to every bow, using specialized channels. It provides 83% light transmission and 83% light diffusion.

How Will You Inflate a Double-Layer Structure?

Double plastic does generally require an inflation system. If the site is too remote for grid access and the other options are prohibitive in cost or complexity, then a second layer is not easily workable. There are three main off-grid options for running inflation blowers: solar with batteries, air-driven motor and wind-powered. Steve Moore in *Home Power* magazine Feb/Mar 2004 reported on a UniSolar 32W PV module, two golf cart batteries and a Morningstar PS-30 charge controller which worked out at about \$700 back then. You can read the article online.

Information on wind-powered systems is hard to find. There are some photos in Bob Schultheis's slideshow from the 2014 Midwest Vegetable Producers Conference.

Another option is to have two layers and use Styrofoam blocks attached to the bows to preserve an air gap between the two layers without inflation at all. This gives some of the insulating value but not the increased structural strength of using inflation.



Style and Design

Style of the Structure

Decide between Quonset and Gothic shapes, and choose the bow spacing to suit your needs. Know what likely snow loads and wind force your tunnel will be called on to deal with. Look at what is available. Rimol in New Hampshire, Zimmerman in Missouri, Atlas in Georgia and Ledgewood Farm Hoophouses (also in New Hampshire) are brands that are strongly built and good for heavy snow areas, or if you intend to hang heavy plants from the structure. There are other well-built ones too. Look at the steel thickness or gauge—most commercial houses are 13 or 14 gauge (2.4 or 2 mm) galvanized steel for strength. The smaller the gauge number, the thicker the steel. The thickness increases by 10% for each lower gauge number. The tubing has a diameter of 1.7"–2.4" (4.3–6 cm) for the bows (bigger tubing for the bigger models), 1.3" (3.3 cm) for the purlins (the tubes running the length of the hoophouse, joining the bows).

For windy areas, look for diagonal bracing at the end walls ("corner braces"), and trusses running across the width at each bow. Wellmade tunnels can last 20 years and more. Lighter weight tunnels have lengthwise purlins but no



Anatomy of Hoophouses

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crosswise trusses. There are designs that make the use of overhead support wires, hoses and sprinkler systems easier. If you want to run services overhead, take a close look at the arrangement and strength of the trusses and purlins.

Drop-Down or Roll-Up Curtain Walls, or Fixed Walls?

Opening sidewalls are a way of increasing the ventilation without using fans. The air passing over the hoophouse creates enough of a pressure



Diagonal end bracing at Nourishing Acres Farm.



Diagonal end bracing retro-fitted at Twin Oaks.



A Gothic hoophouse without trusses. Photo Kathleen Slattery.



Simple trusses on this hoophouse at Nourishing Acres Farm.



Strong trusses on this hoophouse at Maple Spring Gardens.

difference to pull air though opened sides. Therefore it is best to have both sidewalls open, not just one. See the High Tunnels website on this question of ventilation.

If your top priority is growing winter crops or you live in a Zone 5 or colder climate, you might do better without drafty separate sidewalls. If you are in a climate warmer than winter Zone 8, you might be more concerned about ventilation than about heat-preservation. Fixed sidewalls may deter pollinators and beneficial insects from entering, although I've had no problem with that. We have fixed sidewalls in central Virginia (Zone 7a) and I have no regrets on that score.

For opening sidewalls, install a rail or bar joining the bows 3'–5' (1–1.5 m) above the ground. The main roof plastic attaches to this. Be sure to get a good seal to make inflation effective. You could install insect netting inside your opening sidewalls. For roll-up sides, a separate length of plastic for the wall hangs from this hipboard. The bottom of this plastic is attached to a length of tubing, which in turn is attached to a crank for rolling it up, opening the walls. Usually some kind of zigzag retaining cord or tape holds the wall loosely in place, preventing billowing. Roll-up sides open first at ground level.

Drop-down sides have the advantage that they can be partially opened to leave a short sidewall protecting young plants. Partially open drop-down sides will deter small animals from entering the tunnel. The bottom edge of the sides is firmly fastened to the baseboard, eliminating ground-level drafts. The top edge is fastened to a length of tubing. A system of cables and pulleys raise or lower the walls either manually or via a motorized winch.

Heavier duty plastic may be used for the curtain walls, although this will make the system harder work to operate. Manual cranks are easier

A Gothic style single-layer hoophouse with roll-up sides at Nourishing Acres Farm.

to use if a universal joint is included. They are easier still with the addition of a gearbox with a gearbox ratio of 10:1 or 15:1. A battery-powered drill can be used for a simple method of mechanization. Helpful photos can be found at the Rimol website. Top-of-the-line motorized gearboxes can be controlled by timers and thermostats. Limit switches are needed to tell the motor when to stop. If you have rolling sides, add roll lock clamps for windy areas.

Air leaks are a disadvantage of opening walls, especially on windy days (and nights!). If you go for opening walls, add an extra section of plastic between the end two bows at each corner to ensure a good seal when the side is closed. Industrial strength loop-and-hook fastener tape is another method of minimizing air leaks.

Roof Vents

Some double-layer models have ridge vents, surprising as this may seem. This does add considerably to the cost, although a ridge vent combined with roll-up sides provides very good passive ventilation for high tunnels.

Plan for Road Access and In-Ground Utilities

Plan for the traffic you expect and more. Growers using only hand tools and garden carts can get by just fine with mowed pathways, but those using trucks will need to build near a road or make a road nearby.

You will need a reliable source of piped water and if you already hooked up to the electricity grid, go ahead and map out how these utilities will get to your site. Plan for any possible future needs too. Call the people who scan for existing lines below ground before you dig, and look up any records you have of previous utility work in that area. Renting a Ditch Witch saves a lot of hard manual labor, and will do a better job than hand digging. It's hard to get a trench deep enough while keeping it narrow. You will need to put water lines below the frost level for your climate region. Install a frost-proof hydrant at one end of your tunnel, to one side of the main doors. That is, in a convenient place that will not be an inconvenience for some other task, like bringing in bulky loads of compost.

Do You Need In-Ground Insulation?

In Pennsylvania, Steve Moore recommends inground perimeter insulation in the form of 1" (2.5 cm) styrofoam blueboard 2' (60 cm) wide in the ground angled at 45° like a skirt all around the perimeter. The foamboard is then covered by soil. We did this with ours in central Virginia, using 16 4' \times 8' (1.2 \times 2.4 m) sheets, at a cost of a few hundred dollars, but if I were constructing another, I would not use the in-ground insulation. It was a lot of extra work, excavating and backfilling, and I don't think it paid off in our climate. In colder climates, obviously the balance shifts. Steve also used interior pathway insulation. He collected data with microclimate monitoring equipment, and proved the insulation to be worthwhile in southeast Pennsylvania. See Chapter 4, Preparing the Site and the Base, for installing insulation before making drainage swales, and Chapter 6, Frame Assembly, Baseboards and Hipboards, for installation after fitting baseboards.

Do You Need In-Ground Heating?

Most growers appreciate having a structure that uses only passive solar heating rather than supplemental heating. We realize the irony of using fossil fuels to farm sustainably! But in some climates and for some crops, you may find that a small amount of added heating can produce a lot more food. For instance, if you have no frost-free greenhouse, you may want to build an inner tent or curtained-off area and heat that for your seedlings. Or if you have long cold winters

followed by short summers, a few weeks of heating may enable you to grow a lot more crops. Consider heating the soil rather than the air and save on energy use and fuel bills. Although relatively expensive to install, in-ground radiant heat systems, which circulate a heated fluid, reduce fuel costs over time. In this system, a mixture of water and antifreeze is heated and pumped through buried polyethylene tubing. As well as saving money, heating the soil has the advantage of directly stimulating the root-zone, speeding seed germination and root growth.

One of the case studies in the University of Vermont High Tunnels publication is Slack Hollow Farm in upstate New York. When they built their second high tunnel, the farmers (with the help of a plumber) installed a radiant heating system that uses standard PEX tubing buried 18" (0.5 m) deep, in rows 12" (30 cm) apart. A propylene glycol/water mixture heated by an oil-fired hot water heater is pumped around the tubing. For the first winter they set 47°F (8°C) as their goal for soil temperature at a 6" (15 cm) depth. Under the inner row covers at night, the lowest air temperature was 27° F (-3° C). It took a single tank of oil (275 gallons [1,041 L], costing \$500 in 2006) to maintain this temperature. For the following spring tomato crop, they warmed the soil to 70°F (21°C). This consumed three-quarters of a tank of oil in several weeks during that cold spring. After these first trials, they hope to calculate an answer on how much heating is financially worthwhile.

Basic End Wall Design

"Your high tunnel is only as strong as its end walls," according to Richard Stewart. End walls can be framed with metal tubing or with wood, or you can simply use a big plastic curtain that rolls up, or a pair of curtains attached to long battens which can draw the doors open and be fastened at the sides. This minimalist approach suits mild climate areas, where the tunnel will be cultivated by tractor and the crops are not extended too far from their outdoor season. Curtain walls do not add any strength to the structure, and do not provide a framework for attaching tool racks, pedestrian doors or graduated ventilation. See Chapter 7, End Walls, for the details of construction.

Installing Inflation Blowers and Manometers

Most double-layer hoophouses are adequately inflated with a small 60 cubic feet per minute (cfm) (1.7 m^3 /minute) blower. See Chapter 5, Utilities, for details.

How Will You Cultivate?

Tractor? Walk-behind tiller? Manual tools only? This decision will influence the size of doors you need in the end walls, and the bed layout. It is easily possible to rid the hoophouse of weed seeds in just a season or two, and after that keep it free of weeds by timely hand-weeding. "Let no weed seed" is one of our mantras. Personally, I like a small manageable area that we work entirely by hand.

After ten years, we started to be concerned that the soil was compacting, especially along the edges of the beds where our feet would sometimes stray. We solved this by buying a broadfork and by delineating the edges of the beds with thin nylon cord pinned into the ground with 6" (15 cm) soil staples. We level the paths using a floor ice scraper—a steel blade on a 60" (1.5 m) handle, about \$30-40 from hardware suppliers. We found that a smooth level path really does feel wider, and makes it easier to avoid stepping in the beds. Our broadfork is an all-steel model from Way Cool Tools, which we are very happy with. We use it once a year when clearing summer crops from the beds and preparing for fall and winter crops.

Bed Layout

There are designs that maximize the planted area (the ratio of plants to paths). We've gone about as far as it's possible to go in that direction. Our paths are only 1' (30 cm) wide, with most beds 4' (1.2 m) wide. Edge beds are 2' (0.6 m). We have a little staging area at each end, so our ratio of plant growing area to paths ends up at 2.6:1. It is fairly common to have 30% of the hoophouse taken up by paths (2.3:1 ratio).

If you will be driving a tractor through, you'll need lengthwise beds to fit the wheel axle size. If you will be hand-weeding, you need beds no wider than you can comfortably reach from each side without stretching.

If your hoophouse will often have large numbers of students or visitors walking through, or people with limited mobility, you will need wider paths for ease of access.

The most usual layout is lengthwise beds. This shape fits well with growing tomatoes or other trellised crops, and with long runs of drip tape and rowcover.

Some growers make lateral (width-ways) beds, for example the Michigan State University student organic farm high tunnel. The high tunnel needs to have high sidewalls and edge paths to make this design work.

Some growers use a center path and two sets of "comb-shaped" lateral beds separated by paths. This is another design tried at MSU. This design makes for easy access to beds without leaping over other beds, and can work well with fairly tall rowcover supports made by bending metal electrical conduit in a curved right angle. One set of bows covers each half of the hoophouse. Large pieces of rowcover can be rolled and unrolled over the frames each night and morning.

Steve Moore used a hybrid system with "comb-shaped" north side beds and lengthwise south beds. See slide #7 in his *Winter Production in High Tunnels 2009 Small Farm Field Day Presentation.* Some growers maximize use of space in spring by setting flats of seedlings in pathways.

One factor to keep in mind is the height of your sidewalls. In Quonset style hoophouses, the height near the walls is not much. It can be very hard, even for short people, to cultivate edge beds if the walls are short. You may even need to make special short-handled hoes and rakes.

Will You Want Inner Covers?

If so, what to use? In Zones 6 and 7 and warmer, growers resist using inner covers (rowcover or clear plastic on hoops or wicket frames). The work is time-consuming and we don't gain a lot. In colder climates, the story is different. Steve Moore tested various inner covers in Pennsylvania in 2002–2003. He found that 6 mil (0.15 mm) hoophouse poly warmed and kept plants warmer at night than Agribon-70 (2 oz/yd², 68 gm/m² spun polyester), Aluminet and Tufbell (PVA). Used poly worked as well as new, and cost nothing. It was more effective to cover half the width of the hoophouse with a single sheet than to cover individual beds. The inner covers are opened on sunny days. See Home Power magazine Feb/Mar 2004.

If you decide to use inner covers, there are designs that make it easier to roll and unroll the rowcover (or bunch it up on horizontal wires) during the day.